UNIVERSITAT DE BARCELONA

Multi-hazard assessment and risk management in volcanic islands

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PHD THESIS – EARTH SCIENCES
2023

Department of Earth and Ocean Dynamics – University of Barcelona (UB)

Geosciences Barcelona (GEO3BCN) – Spanish National Research Council (CSIC)

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Doctoral thesis presented by

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for the degree of Doctor in Earth Sciences at the University of Barcelona.

This thesis has been developed within the Doctoral Program in Earth Sciences (Geological Hazards and Geomorphology research line) and has been carried out under the direction of

Dr. Joan Martí Molist (CSIC) and **Dr. Dario Pedrazzi (CSIC)**,

and under the tutorship of

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Barcelona, July 2023

The Ph.D. candidate has benefited from a doctoral FPU grant (*“Formación de Profesorado Universitario”*) (FPU19/02413) in the period between 2020 and 2024, funded by the *Ministry of Science, Innovation and Universities* of the *Government of Spain*.

This work was carried out in the *Geosciences Barcelona (GEO3BCN – CSIC)* research institute within the Consolidated Research Group *“Estructura i Dinàmica de la Terra”* (Structure and Dynamics of the Earth), financed by the *Generalitat de Catalunya* (2017 SGR 1022). The author received support from the *EG grant EVE* (DG ECHO H2020 Ref. 826292) and the *CSIC grant MAPCAN* (CSIC Ref. 202130E083). Part of this work was also carried out at the *Institute of Earth Sciences, University of Iceland*, through a *Supplementary Mobility Grant for beneficiaries of the FPU program* (EST22/00368), funded by the *Ministry of Education and Professional Training* of the *Government of Spain*.

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A la Marta del pasado.

Acknowledgements

I used to believe that what you reap is directly proportional to what you sow. With that premise, I became a farmer who worked tirelessly from sunrise to sunset, regardless of rain, cold, heat, night, or day. But my obsession with expecting my hard work to yield the desired results led me to demand perfection and be overly critical of myself. Instead of rewards, I encountered frustration, misunderstanding, disappointment, and eventually, fear. Opportunities sometimes need to be stopped from being sought so that they can arrive. Other times, they don't come at all. And sometimes, they come in the most unexpected ways. I won't say that all my efforts were in vain and that everything was just luck. However, the fixation on attaining something greater prevented me from enjoying the smaller things and plunged me into one of the most challenging periods of my life so far. Depression and anxiety are widely discussed topics today, but there is still a lack of open and heartfelt discussion. We talk about this common issue, for example, in the academic world, but it is behind closed doors, in private, where some of us truly open up and share.

That is why I wanted to reserve a space in this section to address it, taking the risk of being judged for it, or even having my work judged, with the hope that this narrative can accompany those who can relate. Because this problem is still undervalued, and it is still associated with weakness. But only those who have battled invisible giants can claim bravery. And this thesis is proof of that.

Fortunately, I realized how I was sinking deeper into that hole until I touched the bottom. It's ironic how the world keeps spinning mercilessly while you remain down there. Some people glance and see you, but they keep walking. Others offer their hand, but sometimes it's you who says, "I'm fine here, thank you." Some then leave, but others sit on the edge of that hole to accompany and wait for you until you are ready to climb out. And that day came. The day I wanted to resurface. Although I couldn't do it alone. It was when those who had waited by my side, along with others who came at that moment to help me, offered me their hand to get out, and I decided to take it. This section is for them.

The first person is you, mami. Without all your sacrifices, I couldn't count on even half of my achievements. I couldn't have come this far, or perhaps not in the way I have. Thank you for always being there, for spreading your wings and providing shelter when it rained, for enduring my demands and mood swings, for joining me on the "roller coaster" even though you couldn't feel what I felt, just to keep me company and make sure I wasn't alone. Thank you for giving me everything without expecting anything in return. For moving heaven and earth at eleven at night to deliver the cardboard the next day. For bringing me food so I wouldn't have to cook and could continue working on this thesis. For enduring long venting conversations on the phone when everything was falling apart. For walking with me at three in the morning when anxiety robbed me of sleep. For sleeping beside me when intrusive thoughts haunted me. For supporting every decision I've made. For celebrating with me, for crying with me, for sharing with me. For giving me everything you couldn't have. For walking by my side. They say that behind every successful man is a great woman. I'm not a man, and I don't know if I'll be great, but what I do know is that I have a great woman behind me, and that's you, mami.

But I am fortunate to have experienced another unconditional love. Yours Roger. I know that on many occasions I have demanded a lot from you. And so have my decisions. But you have always let me fly, holding my hand. Sometimes you've flown with me, and sometimes you've blown me higher. I couldn't have found a better life partner than you, because you haven't hesitated to ride the "roller coaster" with me and make it all a party and a laugh. You bring the fun that I lack in life and the drive that I sometimes need. Thank you for your patience while I was immersed in this project. Thank you for being there with me in the face of adversity.

This thesis project would not have been possible without a string of people who came forward one after another at the right times. I like to tell the story the same way every time, and that's how I'm going to share it with you, because that's how it happened. First of all I have to thank Ignacio and Sharon, from GeoTenerife, for giving me the opportunity to do my internship with you in Tenerife. From this work together with the team of the Instituto Tecnológico y de Energías Renovables (ITER) and the Instituto Volcanológico de Canarias (INVOLCAN), to whom I thank you for your welcome and your teachings, I was able to present a publication at the congress of the European Geosciences Union (EGU). Despite the excitement, once there I felt completely out of place. Everyone had started their professional careers and fit into one discipline or another. But I was still finishing my degrees in Geology and Environmental Sciences and did not know what the next step would be. Tired of wandering around the congress aimlessly, I sat down to rest in a room where a talk on a volcanic monitoring project was about to start. And coincidentally the speaker was my current thesis director. The opportunities were coming.

Joan, you, without knowing it, also helped me to get out of that hole. You offered me a path at a time when I had no fixed direction. And you trusted me blindly. Without knowing me at all, without having any references, you bet on me. You gave me what I needed most at that moment: the next step. In five minutes you showed me a path to follow. And here we are now. If this thesis project has come to fruition, it is thanks to you. To all your experience and professionalism, to your vision of things, to your tireless hard work, to your support, and also to Ana, another great woman. Thank you for teaching me everything I know so far, for continuing to give me opportunities. For counting on me, for trusting me, for treating me as an equal. For understanding that I was recovering, for giving me time and waiting for

me. Thank you for introducing me to this world and making me enjoy it, whether it was walking the trails of Las Cañadas or listening to rock in a pub in Tenerife. Thanks for the meetings with beers and tequila from which the best conversations and the best projects have come out. But above all, for allowing me to have a voice and vote, decision-making power, freedom of choice, and for helping me to become the person and professional that I am now.

The one who really taught me to discover the tools I had to pave the way and overcome it on my own was you Miguel. You have not only been my psychologist, you have also been my confidant, my friend, my handkerchief of tears and my compass along the way. Thank you for teaching me that things cannot be controlled, that everything has to flow, to not worry about what is outside my circle of occupation. Thank you for helping me to overcome the fear of fear. For giving me the courage that I need on so many occasions. For pushing me to expose myself, to get out of my comfort zone, to be resilient. Thank you for turning off the autopilot button with me and living in the present. To take advantage of every difficulty and enjoy the journey. Thank you for helping me to be living the best moment of my life.

I keep a special place also for you, Juan and daddy, for supporting me in your own way and sharing the moments of success and failure with me. For opening your arms to me when I needed it. To escape from the stress of work either with intermittent games of Call of Duty in the afternoons, or tuning my little Dacia. Thank you for calming me down in times of turmoil, for bragging about my accomplishments and showing off your pride with your friends. For giving me everything I needed to get where I've come and supporting my journey. Thank you for being there. Thanks also to you grandfather, who watches over me from heaven, and to you grandmother, who does it from Earth. And I can't forget my furry and feathered family. You, without speaking, transmit me much more with your eyes. Thank you Tana, Whipper, Grumpy, Ninona, Lola, Golfa and Kira, for sitting next to me when I didn't want to see anyone else. For listening to my problems and my doubts without perhaps understanding what I was saying. Or maybe you did, because your cuddles and your presence said much more. How much I need your hugs, because you have also been part of this project, and of my life, but I know that now you run free and rest in peace. Thank you Yoda for cheering me up with your squeals all my working days. There are many hours shared while I was typing and you were preening your feathers.

Part of my improvement has also been thanks to my coaches. Víctor (“Látigo”) and Mari, from Club Boxeo Vega, and Joel (“El Leñador”) and Javi (“Zurdo”), from Club Boxeo Rubí. Without your encouragement and support, I would not have been able to finish even half of the field campaigns. I remember the anxiety I felt when I found myself in the middle of the mountains, far from civilization, far from my comfort zone, far from hospitals, physically and mentally

exhausted, unable to run away, but wanting to do so at every moment. I did not eat, I did not drink, I was the last one, unable to carry my backpack on my back. And several times I thought of abandoning this doctorate at the beginning, so as not to have to go through those bad experiences that the project required. You have taught me that it is possible. You have helped me to break so many physical and mental barriers that I put myself. But above all, thank you for producing the opposite effect, to love the mountain and physical effort. To enjoy every field campaign, every route, every trip. Thank you for giving me the strength to reach the top. And here I also have to thank Eulàlia M., my tutor, and together with her, Óscar G., Josep Maria C., and Pablo M., who knowing this, stood by my side, being patient and understanding. Thank you for encouraging me in the ascent of "Lo put* pi", for not giving up. Thank you for teaching me another part of geology, for allowing me to learn from your skills as teachers. I would like to also express my gratitude to Eulàlia, together with my co-director, Dario P., for their assistance in reviewing my thesis. Their attention to detail and expertise have greatly improved the quality of my work.

On this road I have also been fortunate to meet people like you, Jose Luis. You have taught me a lot, but you have also become someone I know I can always count on. Whether to make axial compressions to the rocks, or to calculate safety factors. Whether it's to go on a wedding or a landslide visit. Thank you for teaching me when no one else would. To my Dani and my David, whose rare but productive get-togethers have relieved me of the pressure of work, always encouraging me to move forward and pursue my dreams. Thanks for the philosophical and daring conversations. To my “titas”, Marina, Juli, Juani, Cris, Pili, for being my cheerleaders since I was a little girl, and for following my progress as if I were just another daughter. To my classmates of the double degree of Geology and Environmental Sciences, for initiating us in this world together. Especially in memory of Òscar Molina, who lost his life in the tragic accident at the Súria mine while working in this beautiful but sometimes dangerous profession. And to my "mountaineers", Lara, Olaya, Lydia, Alejandra and Alba, for finishing this stage by my side, sharing our therapeutic anecdotes and our love for painting.

I would also like to thank Ármann H., my supervisor during my stay at the University of Iceland. Thank you for your help and dedication, and for your welcome in a country that changed my life. A country where I arrived with my backpack of fears and insecurities, and from which I returned with the same backpack full of experiences, anecdotes, security, fulfilled dreams, incredible memories, and great people. I want to highlight the help received by Will M., as well as my group of "Mediterraneas", Diana B. and Jacqui G., who welcomed me as one more and made my stay in the volcanology lab more pleasant. And thanks to all the people who accepted my request to be interviewed. Without their collaboration, part of this study would not have been possible. I would therefore like to acknowledge their willingness and kindness to Ásgrímur L. Ásgrímsson (Icelandic Coast Guard), Sigrún Karlsdóttir (Icelandic Meteorological Office), Sara Barsotti (Icelandic Meteorological Office), Elín Björk Jónasdóttir (Icelandic Meteorological Office), Birgir Vilhelm Óskarsson (Icelandic Institute of Natural History), Árni Guðbrandsson (Isavia), Friðfinnur Freyr Guðmundsson (Isavia), Elva Tryggvadóttir (Isavia), Aðalheiður Jónsdóttir (Icelandic Red Cross), Guðný Björk Eydal (University of Iceland), Guðrún Pétursdóttir (University of Iceland), Úlfar Lúðvíksson and Gunnar Ó. Schram (Police in Suðurnes), Guðbrandur Arnarson (ICE-SAR), Thor Thórðarson (University of Iceland), Elísabet Pálmadóttir (Ministry of the Environment, Energy and Climate), Hafsteinn Pálsson (Ministry of the Environment, Energy and Climate), Hulda Ragnheiður Árnadóttir (Natural Catastrophe Insurance), Jón Örvar Bjarnason (Natural Catastrophe Insurance).

I have also met the generosity of Marc Martínez, who has helped me enormously in analyzing my data with his incredible computer and programming skills. Thanks to all the conversations I have had with you, I have experienced in my own flesh what I have promoted so much during my doctoral thesis project: transdisciplinarity. It is fascinating to see how two disciplines such as geology and computer science can come together to develop useful tools for society. Thank you for giving me your support and extending your knowledge to raise my own and allow me to squeeze until the last moment this process. The preparation of the algorithm for processing my data is your work, and without your professionalism, this part of the thesis would not have been possible. I am excited to continue working on with you and expanding this part in the future, which will surely bring us great results and benefits. Although I also have to thank the advice and expertise of Rosa Sobradelo, who did not hesitate to guide us in the processing of my data. Thanks to the collaboration and dedication of Carlos Rodríguez, from the Provincial Historical Archive of Santa Cruz de Tenerife, my data is now more complete and detailed. Thank you for remembering me every time you found a flood or an earthquake among the historical documents. Likewise I would like to thank Karim Kelfoun for providing the VolcFlow code for the tsunami simulation as well as his help in processing the data and obtaining results.

And what can I say about Llorenç P., another of those people whose kindness and generosity I have been able to experience. Thank you for trusting me too, for offering me other opportunities and little by little, teaching me another world and other ways of working.

This research was supported by the European Commission (EC) DG ECHO Horizon 2020, grant number 826292, and the CSIC grant MAPCAN (CSIC Ref. 202130E083). I received an FPU PhD grant (FPU19/02413) from the Ministerio de Ciencia, Innovación y Universidades of Spain, a CSIC JAE Intro grant (JAEINT 19 01465), and a complementary grant for beneficiaries of grants (FPU) for a short stay

(EST22/00368).

We would like to express our gratitude to the Editor Gillian Foulger, the reviewer Amiel and some anonymous referees, for their valuable reviews and comments made to part of the text already published when presenting this thesis. Part of English text was reviewed and revised by Dr. Grant George Bufett of Terranova Scientific, and Michael Lockwood from Walking Catalonia. We would also like to acknowledge the assistance of Marc Español (CSIC) with computing. Special thanks to Dr. Silvia Peppoloni for inviting us to contribute to the Geoethics for the Future book.

We thank the projection authors for developing and making the sea-level rise projections available, multiple funding agencies for supporting the development of the projections, and the NASA Sea-Level Change Team for developing and hosting the IPCC AR6 Sea-Level Projection Tool.

I apologize for any inadvertent omissions and reiterate my gratitude to all those who have been part of this process. Your help and support have been invaluable, and I am sincerely grateful for your valuable contribution to my work.

But I would like to end here in an unconventional way, by thanking the most important person who has made this a reality. That is me. I cannot imagine this work without the help of all the people I have mentioned, but even so, the full commitment has been mine. The hard work, the effort, the sweat, the stress, the sleepless nights, the days without food, and the days of overeating, the anxiety crises, the forced meditations, the laughter, the crying, the successes, the failures, the fears, the impulses, the "I have to reach everything", the "I can't do it anymore", the "come on, a little more", the "I'm getting out of life", the "I can do this", the endless hours of writing, the sacrifices, the renunciation of free time and much more desirable plans, the pats on my back and the acceptance of a salary that does not even come close to matching the productivity achieved. For all of us, who are the ones who really suffer the pressure of a doctorate and still choose that path. Because all this makes up for seeing the person and the professional I have become. And above all, to be able to do my bit, hoping that my contribution can serve to improve the resilience of societies in the face of natural hazards. But above all, serving as an inspiration to all those little Martas who at some point dreamed of working in what they wanted, no matter how hard the road may be.

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Abstract

Our planet is impacted by diverse natural and human-induced events, including weather-related events (floods, droughts, forest fires, etc.) and geological events (landslides, earthquakes, volcanic eruptions, etc.). These events disrupt the geosphere and the biosphere. Understanding these hazards is crucial to anticipate and provide warnings to exposed populations. Interconnections between phenomena are being discovered, such as volcanic eruptions impacting the ocean, atmosphere, and climate. These events can lead to economic losses, fatalities, infrastructure destruction, and mental health burdens. The frequency and magnitude of these events, especially weather-related hazards, are increasing due to climate change. Preparation, information, and decision support systems are needed to mitigate their impact. Volcanic islands are highly vulnerable due to their isolation, fragile economies, and multi-hazard nature, being often the source of complex successions of disastrous events. Moreover, climate change exacerbates vulnerability by increasing the magnitude and frequency of these events, as well as contributing to rising sea levels. Anticipating and preparing for such events are crucial to ensuring safe and sustainable lifestyles.

The island of Tenerife in the Canary Archipelago is an excellent example of where both cascading non-extreme and extreme hazards have occurred along its history and could occur again in the future. Both phonolitic and basaltic volcanic eruptions on Tenerife have occurred frequently during the Holocene. These eruptions cause ash falls, lava flows, and explosive projections of pyroclasts. They also generate seismic activity, risking damage to buildings and infrastructure, which adds to the tectonic seismicity experienced by the region, with a lower magnitude and intensity. Therefore, the probability of a volcanic eruption on the island in the next few years is not negligible. This is higher for basaltic eruptions along the rift zones, as they have been all the historical eruptions, which today could have a significant affectation on the surrounding areas, as most of them are now highly populated. However, the probability of an eruption from Teide is also high, assuming the level of current activity and the fact that its last eruption occurred 1,000 years ago. In this case, volcanic and associated hazards would be of much higher intensity and could affect mostly the northern side of the island, in particular the Icod and La Orotava valleys. In addition, annual floods and torrential episodes, triggered by storms, produce severe human and economic losses and affect cities like Santa Cruz de Tenerife and San Cristóbal de La Laguna. Sediment transport, debris flows, and rock falls occur during these events. The island also experiences phenomena such as Sahara haze, forest fires, and the possibility of tsunamis in the surrounding Atlantic Ocean. On the other hand, a cascading sequence involving a caldera-forming eruption, high-magnitude seismicity, mega-landslides and tsunamis occurred at least twice during the construction of this island and could occur again in the future. Its population growth and consequent urban expansion, especially focused on the construction of tourist infrastructure on the coast, lead to the population encroaching on areas with higher risk of these events. However, scientific knowledge and protocols mainly focus on individual hazards and risks. Predicting the outcomes of multi-hazard scenarios remains challenging. The multi-hazard concept emerged in the 1990s to address this issue. However, conflicting perspectives hinder its implementation in disaster reduction policies.

This contribution presents a methodological development based on scientific knowledge for decision-making in vulnerable regions facing natural hazards, using Tenerife as a case study. To accomplish this, we first explored and clarified the issues surrounding the implementation of a multi-hazard perspective in disaster risk reduction strategies to understand the main challenges of this approach. Following this, a comprehensive long-term multi-hazard assessment was conducted for the island of Tenerife, covering both non-extreme and extreme events. For the former, a Bayesian-inferred Event Tree framework was applied to calculate the probabilities of natural hazards in Tenerife based on its historical event records from 1496 to 2020. On the other hand, to address the existing gap in risk management protocols regarding cascade effects for extreme events, we simulated the extent and potential impact of a multiple, extreme geohazard episode similar to the last recorded one that took place on the island of Tenerife around 180 ka. According to these analyses, the island is facing a high probability of future floods, which have caused the most significant human and economic losses to date in the island. Furthermore, a potential caldera-forming eruption in Teide could generate Pyroclastic Density Currents that would cover almost the entire island, along with high-magnitude seismic activity that could trigger large-scale landslides in the north resulting in tsunami waves reaching up to 200 meters in height.

Land management based on long-term assessments of multiple hazards, as carried out here, is crucial to strengthen Tenerife's current risk mitigation plans. This will enable the sustainable development of the island through the sustainable use of currently exploited energy and material resources, as well as through a two-way relationship between sustainable tourism exploitation and the education of its population, both focused on the conservation of its geological heritage. All of this will contribute to increasing society's resilience to multiple hazards in the context of climate change, without having to forego the opportunities offered by volcanic regions like Tenerife. For this reason, this doctoral thesis emphasizes the importance of establishing a cross-cutting, climate change-oriented, socially inclusive, and scientifically based multi-hazard risk management system. This system should be aligned with the critical needs and solutions of society.

Resumen

Nuestro planeta se ve afectado por diversos eventos naturales e inducidos por el ser humano, como eventos relacionados con el clima (inundaciones, sequías, incendios forestales, etc.) y eventos geológicos (deslizamientos de tierra, terremotos, erupciones volcánicas, etc.). Estos eventos perturban la geosfera y la biosfera. Comprender estos peligros es crucial para anticiparse y proporcionar advertencias a las poblaciones expuestas. Se están descubriendo interconexiones entre fenómenos, como las erupciones volcánicas que impactan en el océano, la atmósfera y el clima. Estos eventos pueden provocar pérdidas económicas, víctimas mortales, destrucción de infraestructuras y cargas para la salud mental. La frecuencia y magnitud de estos eventos, especialmente los peligros relacionados con el clima, están aumentando debido al cambio climático. Se necesitan sistemas de preparación, información y apoyo a la toma de decisiones para mitigar su impacto. Las islas volcánicas son altamente vulnerables debido a su aislamiento, economías frágiles y naturaleza multi-peligro, siendo a menudo el origen de sucesiones complejas de eventos desastrosos. Además, el cambio climático exacerba la vulnerabilidad al aumentar la magnitud y frecuencia de estos eventos, así como contribuir al aumento del nivel del mar. Anticipar y prepararse para tales eventos es crucial para garantizar estilos de vida seguros y sostenibles.

La isla de Tenerife en el archipiélago de Canarias es un excelente ejemplo de donde han ocurrido tanto peligros no-extremos como extremos a lo largo de su historia y podrían volver a ocurrir en el futuro. Tanto las erupciones volcánicas fonolíticas como basálticas en Tenerife han ocurrido con frecuencia durante el Holoceno. Estas erupciones, que duran no más de tres meses, causan caídas de cenizas, flujos de lava y proyecciones explosivas de piroclastos. Generan actividad sísmica, con el riesgo de dañar edificios e infraestructuras, que se suma a la sismicidad tectónica experimentada por la región, de menor magnitud e intensidad. Por lo tanto, la probabilidad de una erupción volcánica en la isla en los próximos años no es despreciable. Esto es especialmente cierto para las erupciones basálticas a lo largo de las zonas de rift, ya que todas las erupciones históricas han sido de este tipo, lo que hoy podría afectar significativamente a las áreas circundantes, ya que la mayoría de ellas están ahora altamente pobladas. Sin embargo, la probabilidad de una erupción en el Teide también es alta, dado el nivel de actividad actual y el hecho de que su última erupción ocurrió hace 1,000 años. En este caso, los peligros volcánicos y asociados serían de mucha mayor intensidad y podrían afectar principalmente el norte de la isla, en particular los valles de Icod y La Orotava. Sin embargo, las inundaciones anuales y los episodios torrenciales, desencadenados por tormentas, causan graves pérdidas humanas y económicas y afectan a ciudades como Santa Cruz de Tenerife y San Cristóbal de La Laguna.

Durante estos eventos ocurre el transporte de sedimentos, flujos de escombros y caídas de rocas. La isla también experimenta fenómenos como la calima del Sahara, incendios forestales y la posibilidad de tsunamis en el océano Atlántico circundante. Por otro lado, se han producido al menos dos veces en la construcción de esta isla secuencias en cascada que involucran una erupción de formación de caldera, sismicidad de alta magnitud, mega-deslizamientos y tsunamis, las cuales podrían volver a ocurrir en un futuro. El crecimiento demográfico y la consecuente expansión urbana, especialmente centrada en la construcción de infraestructura turística en la costa, hacen que la población se adentre en zonas con mayor riesgo de estos eventos. Sin embargo, el conocimiento científico y los protocolos se centran principalmente en peligros y riesgos individuales. Predecir los resultados de escenarios de múltiples peligros sigue siendo un desafío. El concepto de multi-peligro surgió en la década de 1990 para abordar este problema. Sin embargo, las perspectivas contradictorias dificultan su implementación en las políticas de reducción de desastres.

Esta contribución presenta un desarrollo metodológico basado en el conocimiento científico para la toma de decisiones en regiones vulnerables frente a peligros naturales, utilizando Tenerife como caso de estudio. Para lograr esto, primero exploramos y aclaramos los problemas relacionados con la implementación de una perspectiva multi-peligro en las estrategias de reducción de riesgos de desastres para comprender los principales desafíos de este enfoque. A continuación, se realizó una evaluación integral de múltiples peligros a largo plazo para la isla de Tenerife, que abarcó tanto eventos no-extremos como extremos. Para los primeros, se aplicó un marco de Árbol de Eventos con inferencia Bayesiana para calcular las probabilidades de peligros naturales en Tenerife basándose en su registro histórico de eventos desde 1496 hasta 2020. Por otro lado, para abordar el vacío existente en los protocolos de gestión de riesgos con respecto a los efectos en cascada de eventos extremos, simulamos la extensión y el impacto potencial de un episodio múltiple y extremo de geopeligros similar a la última erupción de formación de caldera que tuvo lugar en la isla de Tenerife alrededor de 180 mil años atrás. Según estos análisis, la isla se enfrenta a una alta probabilidad de futuras inundaciones, que hasta la fecha han causado las mayores pérdidas humanas y económicas en la isla. Además, una erupción de formación de caldera en el Teide podría generar Corrientes de Densidad Piroclástica que cubrirían casi toda la isla, junto con una actividad sísmica de alta magnitud que podría desencadenar deslizamientos a gran escala en el norte resultando en olas de tsunami de hasta 200 metros de altura.

La gestión del territorio basada en evaluaciones previas a largo plazo de múltiples peligros como la llevada a cabo aquí es crucial para fortalecer los planes actuales de mitigación de riesgos de Tenerife. Esto permitirá el desarrollo sostenible de la isla mediante, por un lado, el uso sostenible de los recursos energéticos y materiales actualmente explotados, y por otro una

relación bidireccional entre la explotación del turismo sostenible y la educación de su población, ambas orientadas hacia la conservación de su patrimonio geológico. Todo ello contribuirá al incremento de la resiliencia de la sociedad frente a múltiples peligros en el contexto del cambio climático, sin tener que renunciar a las posibilidades que ofrecen regiones volcánicas como Tenerife. Es por ese motivo que esta tesis doctoral destaca la importancia de establecer un sistema de gestión de riesgos multi-peligro, transversal, orientado al cambio climático, inclusivo socialmente y basado en el conocimiento científico. Este sistema debe estar alineado con las necesidades críticas y las soluciones de la sociedad.

PART I

INTRODUCTION

Motivation

Communities around the World are yearly struck by natural and human-induced events of diverse typology (e.g. extreme weather events, such as floods, droughts, forest fires, etc., and geological hazards, such as landslides, earthquakes, volcanic eruptions, etc.). These events potentially lead to important economic losses (e.g. Eyjafjallajökull eruption in 2010, Iceland), fatalities (e.g., Turkey and Syria earthquake in 2023), the destruction of vital infrastructures (e.g., floods in Tenerife in 2018, Canary Islands, Spain), and the burden in citizen’s mental health and well-being. Our increasing globalization and technological progress can contribute to a better response to natural disasters through the sharing of resources and knowledge. However, this increased global connectedness, coupled with an increase in our technological dependence and the continuous demographic expansion, makes modern global society progressively more vulnerable in front of such natural destructive phenomena. In consequence, relatively small events, which in other times would have had mainly a local impact, have caused economic losses and, indirectly, impacts on other sectors of the population, both regionally and globally. In the case of extreme events, the consequences can be catastrophic, as had occurred in the seismogenic tsunamis of Sumatra (Indonesia, 2004) and Tohoku (Japan, 2011). This is even more worrying when it is considered within the context of the current global climate change, for which there is clear evidence of the progressive increase in the occurrence of extreme events and of their interactions (IPCC, 2022), which will increasingly cause severe damage to our society.

According to Munich Re (2022), natural disasters have produced economic losses of US$ 5,200 trillion USD since 1980, with >70% of this total being uninsured. This trend, which continues today, shows a lack of preventive culture even in the 21st century, with several cases of major disasters already behind us. During all this time, it is true that the frequency of some types of events, especially weather-related ones, has increased due to Climate Change. However, other types of non-weather-related events, such as earthquakes and volcanic eruptions, have not increased in frequency, but the impact of both types of events has shown an increasing trend (Munich Re, 2022). The reason for this is, on the one hand, the increased exposure, complexity and, as a consequence, vulnerability of society, and, on the other hand, the increased magnitude, frequency and impact of the interrelationships between hazards in multi-hazard scenarios. In 2021 alone, natural disasters caused overall losses of 280bn USD, of which roughly 120bn USD were insured, the second costliest ever for the insurance sector (record year 2017: 146bn USD, inflation-adjusted), and almost 10,000 people have lost their lives (Munich Re, 2022).

Natural hazards are inherently complex phenomena. To date, most of the scientific knowledge and hazard assessment and risk management protocols focus on individual hazards and risks. After Hurricane Katrina in 2005 (which caused damages to many bridges due to winds, storm surges, and flooding loads followed by the impact of debris) and the 2011 Tohoku earthquake in Japan (with coastal structures and bridges exposed to the cascading action of the tsunami following the earthquake, resulting in the destruction of >100,000 buildings and the triggering of a nuclear disaster), the scientific and engineering community have paid increasing attention to approaches enabling multi-hazard exposures for the design of structures (Ellingwood, 2010). At the same time, an effort is ongoing to bridge research and policy (Collins et al., 2017). Many studies address performance-based frameworks for buildings and infrastructure design by taking into account all possible simultaneous and/or non-simultaneous events that could potentially cause structural damage (Jalayer et al., 2011; McCullough & Kareem, 2011; Petrini & Palmeri, 2012; Cao et al., 2016; Cao et al., 2018; Gong et al., 2020; Zhao et al., 2020). Li et al. (2012) provide a literature review and the state-of-the-art of multiple hazard assessment, design, and mitigation, while Bruneau et al. (2017) expose a selection of examples that represent the multi-hazard state-of-the-art in engineering, highlighting considerations for improving resilience against multiple hazards in bridges.

However, most of the multi-hazard engineering strategies and assessments take into account each single threat individually, usually addressing only wind, earthquakes and blasts, neglecting complex scenarios with simultaneous and/or cascading hazards (Petrini & Palmeri, 2012). This fact is not something that only occurs in the engineering context. At present, the research into single hazards is mature, but when multiple hazards occur simultaneously, with or even without interrelations, the results of risk analyses are often inaccurate and incomplete, as multi-hazard risk analysis is not simply the sum of single hazard risk examinations (Kappes et al., 2012). The main obstacles that have been identified in the implementation of the multi-hazard perspective in disaster risk reduction research and policies will be presented later in Chapter 1 "State of the art" of this PhD thesis project report.

The year 2015 marks a step change in multi-hazard risk management with many global initiatives. The last global agreement on international action for disaster risk reduction came on 18 March 2015, when the UN Third World Conference on Disaster Risk Reduction adopted the Sendai Framework for Disaster Risk Reduction 2015–2030 (UN-ISDR, 2015), the successor instrument of the Hyogo Framework for Action 2005–2015. The Sendai Framework is the first major agreement of the post-2015 development agenda, with seven targets and four priorities for action that advocates for a multi-hazard approach for the management of disaster risk through developmental planning and practices across all the sectors. One of the targets is to substantially increase the availability of and access to Multi-Hazard Early Warning Systems (MHEWS) and disaster risk information and assessments to people by 2030. At the same time, one of the key guiding principles for the implementation of the framework emphasizes promoting multi-hazard and inclusive risk-informed decision-making for the effective reduction and management of disaster risks. Also in 2015, the General Assembly began the negotiation process on the post-2015 development agenda. The process culminated in the subsequent adoption of the 2030 Agenda for Sustainable Development—with 17 Sustainable Development Goals (SDG) at its core—at the UN Sustainable Development Summit in September 2015, with the importance of MHEW recognized as the 13th goal. This goal is focused on the strengthening of the resilience and adaptive capacities to address climate-related hazards and disasters in all countries by integrating climate change measures into national policies, strategies, and planning, something that the Paris Agreement supports in order to reduce vulnerabilities and losses due to climate change.

At this point, we can say that we have become aware of the problem and, as a result, society is considering solutions. But we still do not know the science to achieve them and despite the demands of the international agenda, multi-hazard scenarios where several hazardous phenomena may occur in a simultaneous or consecutive way have not yet been well constrained. We are still far from a full understanding of the potential inter-relations (cause/effect) between different hazards and their related cascading effects and potential impacts. Also, we have not yet developed or implemented effective combined monitoring and early warning systems, as well as complete vulnerability and risk analysis to confront multi-hazard cascading effects. But one thing is clear: advancing on this scientific basis will allow us to make progress in multi-risk prevention, prognosis, and mitigation. This PhD thesis project is aligned precisely with that need.

Aim and objectives

The aim of this PhD thesis is to develop the scientific basis for carrying out long-term multi-hazard assessments of a territory that can be implemented in its risk management system to improve its capacity to cope with future catastrophic scenarios. Here, we propose a methodological development according to the typology of events, whether extreme or non-extreme, and we apply them to volcanic islands. These particular islands are regions with a higher risk than other areas in the world because of the coexistence of five factors: 1) the elevated exposed value, due to the urban population density in a small piece of land; 2) the high likelihood of occurrence of major events (volcanic eruptions, landslides, earthquakes, floods, forest fires, etc.); 3) the vulnerability of the urban settlements to hazards events in such environments; 4) the isolation and the consequent difficulty in receiving help and in carrying out evacuations; and 5) the fact that they may pose a threat to other countries due to their potential to trigger tsunamis, a common catastrophic event quite exclusive to these areas. Furthermore, due to their socio-economic and political particularities, explained later, the risk management of these territories also differs from other societies. However, the results of this PhD thesis project are expected to be applicable to other regions with similar potential problems. To increase the success of the extrapolation of the results to other regions of the world, particular attention has been paid to applying methodologies that were, as far as possible, accessible and affordable, to be carried out for any region regardless of its technological and/or economic level.

Specifically, we chose the island of Tenerife (Canary Islands) because it belongs to Spanish territory, whose risk management system was already known before starting this PhD thesis project, and because it has a higher risk than other Spanish volcanic regions imposed by the presence of the Teide volcano, one of the most hazardous volcanoes in Europe. However, throughout this PhD thesis not only volcanic hazards have been taken into account, but also other natural hazards such as non-volcanic geological hazards and weather-related hazards. Although mentioned at some point, the aim of this project is not to analyze the hazard of biological, ecological or human-induced events (apart from Climate Change itself).

The specific objectives of this PhD thesis are: (a) to identify the main constraints and obstacles to fully implementing the multi-hazard perspective in disaster risk reduction strategies, (b) to elaborate a long-term multi-hazard assessment for the island of Tenerife, (c) to analyze the risk management capacity associated with these future multi-hazard events on Tenerife in particular and on volcanic islands in general, identifying the needs for adaptation and updating of emergency protocols, and (d) to establish the minimum parameters necessary to transfer scientific knowledge to the risk management system in an ethical, effective and as accurate way as possible. We have taken advantage of a grant for a three-month stay in Iceland to focus on analyzing risk management at this volcanic island, in comparison with the island of Tenerife. The results obtained from the compilation and analysis of information from Iceland are utilized in the discussion chapter for comparison with Tenerife, as well as to propose improvement solutions for the risk management system in Tenerife.

The specific results of this transdisciplinary work will be essential to establish the scientific knowledge necessary for reducing uncertainty in assessments of future multi-hazard scenarios, which are intended to be implemented in areas with potential hazards such as those described here. The general results of this doctoral thesis will represent a turning point in disaster risk management in particularly vulnerable areas threatened by the effects of Climate Change and demographic expansion.

Structure of the thesis

The content of this doctoral thesis is based on the results of four articles published and indexed in the Journal of Citation Reports (JCR), and two chapters of two books, one of them still in preparation at the time of writing, together with other results that have not been published to date. However, in accordance with the regulations of the University of Barcelona, this thesis is presented in "classic" format and not as a compendium of publications.

This contribution aims to offer an integrated approach to better understand multi-hazards on volcanic islands, and then to develop the scientific basis to strengthen the emergency planning and risk reduction policies in these territories. To this end, this doctoral thesis should be understood as a methodological development to deal with a new topic, that of the multi-hazard perspective in active volcanic regions. To facilitate its understanding and guide the reader through all the stages of this methodological development, this thesis is structured as detailed below. The report is divided into two parts: Part I corresponds to the main content, while Part II contains all the Annexes.

Part I is structured in 6 chapters, with a total of 15 sections and 24 subsections, in addition to the current Introduction chapter. The bibliographical References are also included at the end of this first part, where they are divided into those that appear in the main text, and those that belong to the supplementary material collected in the Annexes.

Chapter 1 introduces the reader to the State of the Art of the multi-hazard perspective. Since multi-hazard is a relatively new concept and there is still a lot of confusion about it, this chapter is intended to clarify and clean up the current understanding on such complex issue. To this end, its origins, evolution and application to disaster risk reduction policies have been explored (section 1.1.), and the main obstacles to the application of this perspective have been compiled from a literature review (section 1.2.). Section 1.3. helps the reader understand the concept of multi-hazard through the exposition of one of its main challenges, which is precisely the conflict in its definition. In this way, a starting point has been established from which to work and develop a methodology for approaching this perspective, in particular for volcanic islands.

Chapter 2 summarizes the main characteristics of active volcanic islands. This, in turn, is divided into two sections. Section 2.1. highlights the particularities of volcanic islands in general. It contextualizes the importance and challenges of studying these particular systems (subsection 2.1.1.), summarizes the main interrelationships between events that can occur in these environments (subsection 2.1.2.), and presents some examples of multi-hazard initiatives and their limitations that have been applied on real volcanic islands (subsection 2.1.3.). On the other hand, section 2.2. introduces the reader to the study area, the island of Tenerife (Canary Islands), and does so by contextualizing its geography and geology (subsection 2.2.1.), its climatology and hydrology (subsection 2.2.2.), its socio-economic and political system (subsection 2.2.3.), its resources and territorial planning (subsection 2.2.4.), and also highlights the main natural and socio-economic challenges faced by the island (subsection 2.2.5.), and its current risk management structure to address many of them (subsection 2.2.6.). The aim of this chapter is to provide an overview of the additional difficulties that may be involved in applying this multi-hazard perspective to this type of environment, and the particular characteristics, such as those of Tenerife as an example, that should be taken into account in such studies.

Chapter 3 describes the methodology used. To facilitate its understanding, first a section (3.1.) is dedicated to give an overview and summary of the methodological development used, for which several procedures have been followed and which are detailed in the rest of the sections. These are the multi-hazard assessment for non-extreme events that has been carried out for Tenerife (section 3.2.). In here, subsection 3.2.1. describes how the event data were obtained to prepare the historical record: subsection 3.2.2. describes the qualitative anaylisis; and subsection 3.2.3. describes a quantitative probabilistic analysis to be applied to the long-term multi-hazard assessment of this island. Section 3.3. describes the application of multi-hazard assessment to extreme events. In addition, this chapter also explains how the comprehensive examination of the Icelandic risk management system was carried out (section 3.4.), which will be later used to compare with Tenerife. As we have already mentioned above and as this section specifies again, this contribution arises from a grant stay in Iceland to carry out a series of interviews with personnel involved in risk management in order to provide improvements and solutions to the problems in Tenerife and other regions with similar potential problems. However, the results obtained from this experience are not presented as such, so they are not described in the Chapter 4 “Results”, but have served as a basis for proposing such improvements and discussing their applicability in Tenerife's risk management system in Chapter 5 “Discussion”.

Chapter 4 gathers all the results of this doctoral thesis, dividing them into two sections that correlate directly with the two main sections of the methodology. These are: section 4.1., which details the results of the multi-hazard assessment for non-extreme events (divided into subsection 4.1.1, which presents the results of the qualitative analysis, and subsection 4.1.2, which contains the results of the probabilistic quantitative analysis); and section 4.2., which describes the results obtained from the long-term multi-hazard assessment for extreme events. In the latter case, to facilitate their visualization, the results have been divided according to the type of hazard scenarios obtained, being these the Pyroclastic Density Currents scenarios (subsection 4.2.1.), the Maximum Ground Acceleration scenarios (subsection 4.2.2.), landslide scenarios (subsection 4.2.3.), and tsunami scenarios (subsection 4.2.4.).

Chapter 5 puts into context all the results obtained and discusses the methodology used to evaluate with expert criteria the capacities of risk management in volcanic islands and specifically in Tenerife. This section aims to provide solutions, proposals for improvement and recommendations for greater effectiveness in mitigating and reducing disaster risk in this type of area. To this end, it is structured in a series of sections that follow a logical order, discussing the obstacles and proposing recommendations for the different stages of risk management, from the development of scientific knowledge, through the transmission of this knowledge to decision-makers, to proposals for future action in terms of emergency management, territorial planning and resilience, throughout the example of Tenerife and Iceland. All of this is included in section 5.1., which contains an extensive summary of the key considerations to be taken into account for risk management from a geoethics perspective, which will be the guiding thread of the entire chapter. This begins with subsection 5.1.1., which discusses the contributions and limitations of the methodology developed for long-term multi-hazard assessment in Tenerife, and continues with subsection 5.1.2. where the capacity of Tenerife's management of such natural events is compared with the Icelandic risk management system. With the main findings through these two sections, the following sections are elaborated. Subsection 5.1.3. highlights the difficulties in applying this perspective to volcanic islands in particular, but this time it does so in a critical manner, based on the results and experience obtained. Then, subsection 5.1.4. discusses how information should be transmitted from the scientific community to decision makers. Subsection 5.1.5. compiles all that has been learned in order to present the limitations of the multi-hazard perspective in multi-risk assessments and propose a basic and holistic risk management structure oriented to this approach. Finally, subsection 5.1.6. intends to go one step further and propose long-term future strategies to improve the resilience of Tenerife, applicable to other regions with similar possibilities, which will allow its sustainable development according to the problems that have been presented throughout the report. A second section is presented in this chapter (section 5.5.) with the next steps to be taken to continue exploring and improving the methodology used in this doctoral thesis, in addition to serving as a roadmap for decision-makers in regions with these particularities.

Finally, Chapter 6 summarizes the general conclusions derived from this doctoral thesis project (section 6.1.) and sets out the main strategies for strengthening risk management in Tenerife (section 6.2.), with special emphasis on those that can improve its effectiveness in the context of the future challenges facing the island.

Part II contains a total of 6 Annexes containing supplementary material grouped by subject or typology. Annex 1 shows all the publications in Science Citation Index Journals that have resulted from this thesis. Annex 2 lists the abstracts presented at international congresses. Annex 3 contains the two book chapters published or in process of publication. Annex 4 includes all those tables that, due to their size, did not fit next to the text describing them, and/or all those of results to maintain uniformity. Similarly, Annex 5 contains all the maps corresponding mainly to the results derived from the analysis carried out, while Annex 6 contains all the interviews carried out during the stay in Iceland. Finally, Annex 7 provides instructions on how to access the supplementary material for the tsunami propagation simulations in AVI video format.

CHAPTER 1

STATE OF THE ART

1.1. The “multi-hazard concept”. Evolution and application.

The UNISDR Terminology on Disaster Risk Reduction (UN-ISDR, 2009) refers to a hazard as “a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage”. In the case of natural hazards, just change "dangerous phenomenon, substance, human activity or condition" to natural process. Natural hazards include physical phenomena such as landslides, tsunamis, volcanic eruptions, earthquakes, hurricanes, floods, droughts, fires, etc. When dealing with more than one hazard at a time the terms multi-hazard and compound hazard (or compound event) are often used (Kappes et al., 2012; Seneviratne et al., 2012; Leonard et al., 2014). Each hazard has an associated magnitude, frequency and area of occurrence that can usually be measured or calculated with more or less precision. However, these three characteristics for multi-hazard scenarios have a higher uncertainty associated with them. This is because the interaction of different hazards can lead to an impact that is different than the sum of the single hazard effects (Terzi et al., 2019).

World history is full of real multi-hazard events where the occurrence of several phenomena at once, some of which could have been triggered by others, has led to greater than expected social, natural and economic losses. In 2018, the occurrence of several wildfires in California increased the severity of flash floods (AghaKouchak et al., 2018). In 2013, heavy rains caused landslides in the Azores that, due to blockage of some river channels, led to flooding in several places (La Voz de Galicia, 2013). Or the famous case of the 2004 Sumatra earthquake, which generated a tsunami that devastated the Indian Ocean coastline, resulting in famine and the spread of disease due to contamination of food and water supplies and lack of hygiene measures over a long period of time (WHO, 2006). Another case appeared in 2003, when heavy rains coupled with seismic swarms caused the collapse of the lava dome that had grown in the crater of the Soufrière Hills Volcano on the island of Montserrat (Caribbean), triggering a volcanic eruption that produced pyroclastic density currents, ash fall, phreatomagmatic explosions, and tsunamis. As can be seen, each hazard can be linked to other hazards or processes resulting in a multi-hazard scenario. And the assessment of a multi-hazard event requires a multi-hazard approach, abandoning the practice we have used so far of analyzing each hazard separately.

However, awareness of this need is not new. The term “multi-hazard” in reference to this approach has its origins in international policy and was primarily used in the context of risk reduction. The first reference appears in the United Nations' Agenda 21 for sustainable development (UNEP, 1992), where a “complete multi-hazard research into risk and vulnerability of human settlements and settlement infrastructure […]” was called in order to aid pre-disaster planning of human settlement in disaster-prone areas. The term reappears in the United States' National Mitigation Strategy (FEMA, 1995), which expresses the “need for coordinated, multi-hazard approaches” for natural disaster reduction, especially with regard to “the design and construction of buildings”, for which the establishment of a National Multi-Hazard Mitigation Council within two years, and the incorporation of national multi-hazard standards into building codes for all new structures were proposed. These first appearances are framed by the International Decade for Natural Disaster Reduction 1990–2000, with the subsequent creation of the United Nations International Strategy for Disaster Reduction (UNISDR) in 1999 (later renamed United Nations Office for Disaster Risk Reduction, UNDRR).

Later, the Johannesburg Plan (UN, 2002), expressed that “[a]n integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery, is an essential element of a safer world in the twenty-first century”. In this context and along the lines of the Johannesburg Plan, some initiatives with a multi-risk perspective at global and regional levels began to emerge. In 2002, the Munich Reinsurance Company developed a comprehensive risk assessment method to evaluate the disaster losses suffered by the World's 50 largest cities (Munich Re, 2002). Since then, it has drafted several annual reviews of natural catastrophes and statistics from around the world (e.g., Munich Re, 2005; Munich Re, 2010). In 2004, the Federal Emergency Management Agency (www.fema.gov) launched a multi-hazard risk assessment software package (HAZUS-MH) for the comprehensive assessment of multiple individual disaster risks at all regional administrative levels of the USA (FEMA, 2004). A year later, the Joint Research Center of the European Commission presented a multi-hazard assessment method and conducted comprehensive risk assessments and mapping of weather disasters in 10 European countries (Lavalle et al., 2005). In parallel, the European Spatial Planning Observation Network (ESPON) conducted, from December 2002 to March 2005, the thematic project called “The spatial effects and management of natural and technological hazards in general and in relation to climate change”, which developed an initial integrated hazard and risk assessment of natural and technological disasters on the European territory (Schmidt-Thomé et al., 2005). Between 2004 and 2006, GNS Science (www.gns.cri.nz) and NIWA (www.niwa.co.nz) developed and launched RiskScape software (GNS NIWA, 2010; https://riskscape.org.nz/) for the quantification of direct and indirect losses due to river floods, earthquakes, volcanic activity (ash), tsunamis, and windstorms on people's lives. In 2008, a partnership between the Center for Coordination of Natural Disaster Prevention in Central America (CEPREDENAC), the United Nations International Strategy for Disaster Reduction (UN ISDR), the Inter-American Development Bank (IADB) and The World Bank contributed to developing CAPRA

(Probabilistic Risk Assessment: https://ecapra.org/), a software package that facilitates probabilistic analysis and assessment of related losses in the Central America of multiple individual hazards in addition to the secondary hazards arising from the primary (triggering) ones.

The ideas of the Johannesburg Plan were further specified to the risk reduction focus at the Second World Conference of Disaster Risk Reduction (Japan, 2005), with the Hyogo Framework for Action 2005–2015 (UN-ISDR, 2005). The framework included mainstreaming of an integrated and multi-hazard approach into developmental planning and post-disaster or post-conflict phases across relief, rehabilitation, and recovery activities (UN-ISDR, 2005). In line with what was agreed in the Hyogo Framework, some policies, strategies, and frameworks, such as the Internal Security Strategy (SEC 2010, 1626 Final), which evolved into the European Agenda on Security, the EU Community framework on disaster prevention (Regulation 1313/2013/EU), or the European Disaster Risk Reduction Strategy (COM 2008, 130), began to adopt and express the need for an all-hazard/multi-hazard approach. In science, this move towards a multi-hazard perspective would not come until much later, reflected in the creation of the multi-hazard risk subdivision at the European Geosciences Union in 2019 (Ward et al., 2022).

This whole movement in the international sphere has managed to capture the attention of stakeholders, politicians, researchers and local people who over the last decades have become increasingly concerned about the potential loss of victims due to the occurrence of multiple events in a region, such that the understanding of multi-hazard risks has greatly improved. With the adoption of the Sendai Framework for Disaster Risk Reduction 2015 - 2030 by 187 United Nations (UN) Member States on 18 March 2015, a new stage of transition from single-hazard to multi-hazard approach begins. To this end, the aim is to guide the multi-hazard management of disaster risk in development at all levels as well as within and across all sectors. It calls for decision-making to be inclusive and risk-informed, using a multi-risk approach. This is intended to address one of the greatest challenges of the 21st century: integrating Climate Change, development and urbanization. To meet the targets of the Sendai Framework, many international, national, and regional initiatives have been developed on multi-hazard forecasting and early warnings in recent years, such as the French Rainfall Flood Vigilance System in France (Hemachandra et al., 2020), or the National Disaster Management Plan of India (Government of India, 2016).

However, the call for incorporating science into the policy process carries the risk of politicizing science and, therefore, may blur the boundaries of each role of the actors involved in risk management. These difficulties are aggravated in the context of an emergency or natural disaster, where scientists should act as advisors to authorities. In these situations, decision-makers need to respond with the utmost precision to what phenomena will occur, when will they occur and where will they impact. Despite the efforts of the scientific community to conduct increasingly accurate studies of these natural events, uncertainty is often high and/or unavoidable. For that reason, on the other hand, this uncertainty, in an environment of pressure, urgency and ineffective communication, can lead to the transmission of non-consensual, incomprehensible, misunderstood and erroneous information.

This is the case of the 2009 L'Aquila earthquake, when six scientists together with a public official were sentenced each of them to 6 years in jail and put on trial in 2011 for advice they gave at a meeting of an official government advisory committee. The judge concluded that the experts' advice was unjustifiably reassuring and led some of the 309 victims of the earthquake, to underestimate the threat posed by the ongoing "swarm" of tremors and so remain indoors on that fateful night rather than seek shelter outdoors (Cartlidge, 2015). In this case, the advice to the population to stay at home or not should have been given by the authorities and not by the scientists. On the other hand, the scientists' predictions about the magnitude of possible future earthquakes were not accurate either. So here we have an example of imprecise and inaccurate scientific basis, confusing, erroneous and unethical transmission of information and data to the authorities and the population, and overstepping of boundaries.

Another example is the volcanic crisis in Guadeloupe in 1976. In this case, an evacuation order prompted by a misdiagnosis by scientists led to political and economic problems in the region. For months, the volcano had been showing signs of what appeared to be an unrest, and the population feared an imminent eruption. Many people decided to leave early. But it was not until a group of scientists studying La Soufrière announced that the ash being erupted from the volcano contained fresh volcanic glass, a sign of rising magma and an imminent eruption, and on the recommendation of another group of French scientists, that the governor ordered the immediate evacuation of 72,000 people (Fiske, 1984). However, this analysis was flawed and the ash contained no fresh volcanic glass, and there was no evidence of magma rising to the surface. But the damage was done. The evacuation led to serious political conflicts and economic problems. Massive aid was required from France to provide shelter and food for the evacuees, and the island's productivity fell drastically. The situation was further aggravated by the number of scientists who travelled to study the volcano, the disagreements that arose between teams of scientists, discussions to which journalists had access and which spread around the world like wildfire, and the bewilderment of the authorities who did not know who to believe. One of the reasons for all this confusion about what the volcano was going to do was that all the monitoring techniques used during that episode had not been deployed until a year after the first sign of an unrest at La Soufriére (Fiske, 1984). Therefore, there were no adequate baseline observations to be able to compare changes at the volcano.

The common factor in such situations is often twofold: (1) the overstepping of the boundaries of responsibility of each actor involved, and (2) the lack of sound and accurate scientific knowledge. And as seen in the examples above, both factors feedback on each other, because the lack of accurate science leads to uncertainty, and uncertainty leads to misunderstandings and confusion, so that some do not know what decisions to make and others make recommendations without knowing the consequences of these. So one thing is clear: building on this scientific basis will allow us to make progress in prevention, prognosis and mitigation of multiple risks.

1.2. Contemporary challenges in the multi-hazard approach: a summary of relevant literature

A number of authors have attempted to analyze the main obstacles to conducting comprehensive and thorough multi-risk analyses for any type of territory. This is highlighted by Kappes et al. (2012), which indicate that while research on individual hazards is well-developed, the accuracy and completeness of risk analyses are often compromised when multiple hazards occur concurrently, either with or without interrelations. It is important to recognize that multi-hazard risk analysis goes beyond the mere aggregation of individual hazard risk assessments.

According to Petrini and Palmeri (2012), the reason why accurate multi-hazard assessments are complicated to carry out lies in the following difficulties:

1. The different levels of knowledge obtained in different fields.
2. The modeling of hazard interactions with a lack of raw data and the unavailability of concurrent hazards models.
3. The need to consider uniform hazard levels for different types of threats.
4. The need to give similar safety levels to different multi-hazard scenarios.
5. The development of opposing strategies due to different philosophies.

Similarly, Ward et al. (2022) outline the key challenges hindering the movement towards this approach that relate to existing knowledge gaps in multi-(hazard-)risk assessment and management:

1. Diverse language on multi-(hazard-)risk and a lack of overview of existing methods and tools.
2. Lack of a clear framework and guidelines for multi-(hazard-)risk assessment and management.

3. Poor understanding of dynamic feedbacks between hazards, exposure, and vulnerability (Gill & Malamud, 2014, 2016).
4. Focus of many past multi-(hazard-)risk projects and accompanying software on multiple single hazards under current conditions without focusing on multi-(hazard-)risk interactions or future scenarios (Gallina et al., 2016).
5. Assessment of only a few studies on the effectiveness of disaster risk management measures across hazards, sectors, and time horizons.
6. Distinct lack of in-depth case-studies on multi-(hazard-)risk assessment and management.

On the other hand, Gill and Malamud (2014) expose the following obstacles throughout their study:

1. The spatial and temporal scales over which natural hazards impact upon the natural environment cover many orders of magnitude.
2. The existence of very few detailed reviews or broad characterizations of hazard interactions within the scientific literature.
3. The effective visualization of large amounts of diverse information is a challenging task. It should collate information from multiple disciplines and represent this in an effective way that allows multiple stakeholders to interpret the information in a clear and easy manner.
4. The spatial overlap and temporal likelihood of secondary hazards occurring, and the complexity of forecasting of the spatial location, timing and magnitude of these secondary hazards.
5. Uncertainty of the intensity of the interrelationships.
6. Knowledge bias.
7. Exclusion and resolution of hazards.
8. Use of older and grey literature.
9. Contrast between slow versus rapid onset secondary hazards.
10. Parameter uncertainties and hazard chains.
11. Occasions where there are very few or no case studies for a given hazard interaction.
12. Controversial interaction relationships.

According to Wang et al. (2020), despite the sometimes-contradicting definitions and terminology, the wide variety of potential interactions in a multi-hazard scenario, regardless of the term used to refer to them, leads to difficulties in prediction and prevention of hazards, making multi-hazard assessment and risk management a complex issue, which requires an interdisciplinary approach.

From the review of these main authors, the following key shortcomings were deduced: (1) lack of transdisciplinarity; (2) lack of consensus in many respects; (3) lack of standardization; (4) lack of basic science, based on reality.

1.3. Multi-hazard interactions and terminology conflicts

Since the first time that the term appeared, different perspectives of the concept have been put forward showing an increasing use of it. However, differing terminology, partly conflicting definitions, and vaguely defined approaches have arisen due to the strict separation of disciplines (Kappes et al., 2012; Chondol et al., 2020; Wang et al., 2020). Even though many hazard assessments refer to “multi-hazard” with respect to the multiple types of hazards to which an area or infrastructure may be exposed (Marzocchi et al., 2009; Asprone et al., 2010; Jalayer et al., 2011; Kappes, 2011; McCullough & Kareem, 2011; Kappes et al., 2012; Petrini & Palmeri, 2012; Cao et al., 2016; Cao et al., 2018; Sadegh et al., 2018; Gong et al., 2020; Wang et al., 2020; Zhao et al., 2020), not all studies on multiple hazards consider all relevant processes of a defined area, but rather they are described as more-than-one-hazard approaches (Kappes et al., 2012), usually without considering the interrelations between hazards and/or the combined impacts.

Nevertheless, associated with the concept of “multi-hazard”, understood as the multiple simultaneous or non-simultaneous events that an area can be exposed to, other related terms have emerged together with the evolution of multi-hazard analyses. For example, Sadegh et al. (2018) discuss “compound events”, “compound extremes”, “compound impacts” or “compound hazards” as those “events with multiple concurrent or consecutive drivers (e.g., oceanic and fluvial flooding, drought, and heatwaves)”. They may not necessarily be extreme events individually, but they can nonetheless lead to significant extreme impacts (Leonard et al., 2014; Wahl et al., 2015; Vahedifard et al., 2016; Mehran et al., 2017). In this sense, the multi-hazard scenarios resulting from these compound events are often ignored in many risk assessment and design applications (Sadegh et al., 2018). According to the IPCC (2012), compound events may occur as a result of one of the following situations:

1. Two or more simultaneous or successive extreme events (e.g., simultaneous extreme precipitation and storm surge, Moftakhari et al., 2017),
2. combinations of extreme events with underlying conditions that amplify the impact (e.g., droughts and heatwaves, Mazdiyasni & AghaKouchak, 2015), or,
3. combinations of events that are not by themselves extreme, but which collectively lead to an extreme event or impact (e.g., a moderate coastal flood occurring during or above average tide, Moftakhari et al., 2015).

Even though Marzocchi et al. (2009) use the term “multi-risk” instead of “multi-hazard” to refer to all anthropogenic and natural risks that can affect a territory, the underlying concept is that of a multi-event approach. At this point it is necessary to stress the difference between “multi-hazard” and “multi-risk”. “Multi-hazard” refers to the set of physical phenomena, i.e., the occurrence, extent, and intensity of the possible impact of a multi-hazard event. On the other hand, “multi-risk” considers the damages (economic and social) of the impact of a multi-hazard event. For this multi-hazard approach, Marzocchi et al. (2009) distinguish two perspectives: (1) all possible events that can occur in an area during a period of time without any cascading relation, and (2) those sequences of parallel events that are interrelated. All these authors introduce the synergistic (adverse) events as a series-parallel sequence of adverse events generated by different sources that trigger one or more sequential events, in the context of a multi-hazard analysis. In the case of a multi-risk analysis, it would require a previous multi-hazard assessment.

These last terms that have emerged over the years, together with the increasing need to consider a multi-hazard approach in risk reduction management, highlight what has already been presented by Petrini and Palmeri (2012): the complex interactions that can occur between multiple hazards can change significantly the results compared to single-hazard analysis, as they cannot be simply superimposed (Kappes et al., 2012). For that reason, it is crucial to understand the wide variety of possible interrelations between hazards and the consequences of the different multi-hazard scenarios for a correct multi-hazard assessment. However, despite growing awareness of hazard relationships, a multitude of terms remains in use to describe several types of relations between processes, without a uniform conceptual approach or generally used terminology (Kappes, 2011). In the same way as for the term “multi-hazard” defined here, different definitions may exist for the same concept, sometimes overlapping and contradicting one another, while at the same time there may be multiple terms for the same definition. Kappes (2011), Kappes et al. (2012), and Wang et al. (2020) summarize the existing terms and definitions from the literature related to the multiple types of relationships between hazards, shown in Table 1:

Table 1. Terminology and Existing Definitions for Hazard Relationships. Source: modified from Kappes et al. (2012).

Term(s)	Existing definitions	References
Cascades, cascading effects, cascading failures, cascade events, cascading disasters, cascading hazard	1. The triggering of one hazard by another, eventually leading to subsequent hazard events. 2. A failure in a system of interconnected parts, where the service provided depends on the operation of a preceding part, and the failure of a preceding part can trigger the failure of successive parts. 3. Hazards occurring as a direct or indirect result of an initial hazard. 4. Effects following the main one. 5. The triggering and transmission process of events. 6. Extreme events, in which cascading effects progressively increase over time and generate unexpected impactful secondary events. 7. The dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption.	*Delmonaco et al. (2006)* *Carpignano et al. (2009)* *European Commission (2011)* *Zuccaro and Leone (2011)* *Pescaroli and Alexander (2015)* *Cutter (2018)*
Chains, disaster chain	1. Chain reaction of cause and effect in a disaster. The upper level of disasters leads to the subsequent level. It refers to the triggering relationship between natural disasters. 2. One or more disasters (parent disasters) that lead to other disasters (sub-disasters). According to the relationship between parent disasters and sub-disasters, disaster chains can be divided into straight chains, divergent chains, centralized chains, and complex networks.	*Shi (2002)* *Erlingsson (2005)* *Guo et al. (2006)* *Shi et al. (2014)*
Coincidence of hazards in space and time	1. Simultaneous hazards occurring in the same area.	*Tarvainen et al. (2006)*
Coinciding hazards	1. Disasters and accidents that are independent of one another and are not related to one another in cause of formation are referred to as coinciding hazards. They occur in the same time and space only by chance. Occasionally when multiple hazards occur, there may be no obvious correlation or common cause; they occur together only by coincidence. 2. Coinciding hazards can be considered as follow-on events, knock-on effects, domino effects, or cascading events.	*European Commission (2011)* *Wang et al. (2020)*
Complex	1. Term used to describe the fuzzy relationships between hazards.	*Cutter (2018)*
Compound hazards, compound disasters, compound events, compound extremes, compound impacts	1. Several elements acting together above their respective damage threshold—for instance, wind, hail, and lightning damage in a severe storm. 2. Two or more (extreme) disaster events that have no genetic relationship but which occur at the same time or in sequence. Even if a single event itself is not extreme, it will cause extreme expansion due to a compound effect. 3. Follow-on sequences of other events that occur as a direct or indirect result of the initial triggering event.	*Hewitt and Burton (1971)* *Saarinen et al. (1973)* *Alexander (2001)* *Kelly (2009)* *Shi et al. (2014)* *Liu and He (2017)* *Cutter (2018)* *Sadegh et al. (2018)*
Concurrent hazards	1. When hazards that are not related in origin occur at the same time, their interaction can cause consequences more serious than if the hazards had occurred individually. The interaction between concurrent hazards can be examined from two perspectives: one is that the physical processes of different hazards interact	*Wang et al. (2020)*

Term(s)	Existing definitions	References
	with one another, which may lead to an increase in their intensity or overall impact; the other is that the vulnerability of victims may change due to a certain hazard, and another kind of hazard may have more serious consequences for such victims.	
Coupled events	1. Term used to describe those related events, to differentiate them from individual events.	*Marzocchi et al. (2009)*
Cross-hazard effects	1. Interrelation between hazards that includes exacerbating or ameliorating effects.	*Greiving (2006)*
Domino effects	1. The chain relationship of technological accidents, or the transmission of technological accidents between equipment. 2. An accident in which a primary event propagates to nearby equipment, triggering one or more secondary events and resulting in overall sequences more severe than those of the primary event. 3. It can be associated to the "escalator vector", which means that the final consequence is far more serious than the initial accident. 4. In addition to technological accidents, the domino effect can be also observed in other events (e.g., landslides induced by earthquakes as a domino effect).	*Cozzani et al. (2005)* *Luino (2005)* *Perles and Delmonaco et al. (2006)* *Cantarero (2010)* *European Commission (2011)* *Chen et al. (2018)*
Follow-on events	1. Term used to refer to coinciding hazards, knock-on effects between hazards, or the situation where one hazard causes one or more sequential hazards.	*European Commission (2011)*
Hazard sets	1. This term refers to the phenomenon in which the relationship between hazards can be disregarded. They may be affected by the same environmental and geographical factors (for natural disasters), or they may be affected by the same hidden dangers and omissions in management or production (for technological accidents). Hazard sets can be divided into natural disaster sets and technological accident sets.	*Wang et al. (2020)*
Human-induced hazards	1. Human activities (including technological accidents) may trigger natural disasters.	*Gill and Malamud (2016)* *Gill and Malamud (2017)* *Wang et al. (2020)*
Interactions	1. Mutual influence between two processes. 2. Vice versa interactions and interactions during which only one process exhibits a significant influence on the other are distinguished.	*Tarvainen et al. (2006)* *De Pippo et al. (2008)* *Marzocchi et al. (2009)* *Zuccaro and Leone (2011)*
Interconnections	1. Term used to describe the fuzzy relationships between hazards.	*Perles and Cantarero (2010)*
Interrelations	1. Term used to describe the fuzzy relationships between hazards.	*Delmonaco et al. (2006)* *Greiving (2006)*
Knock-on effects	1. The triggering of one hazard by another. 2. Term used to refer to coinciding hazards, follow-on effects among hazards, or the situation where one hazard causes one or more sequential hazards.	*European Commission (2011)*

Term(s)	Existing definitions	References
Multiple hazard	1. Quite different types that accidentally coincide, or more often, following one another with damaging force—for instance, floods in the midst of drought, or a hurricane followed by landslides and floods	*Hewitt and Burton (1971)*
Natech events	1. Natural hazard events that trigger technological emergencies.	*Showalter and Myers (1994)* *Cruz (2012)*
Synergic effects, synergistic event	1. A series-parallel sequence of adverse events generated by different sources. For example, an earthquake and a landslide generated by it.	*Tarvainen et al. (2006)* *Marzocchi et al. (2009)*
Triggering effects	1. Series-parallel cascade scenario, the triggering of one hazard by another.	*Marzocchi et al. (2009)*

Some authors have tried to group this wide variety of concepts into a few main categories, each of which would represent the fundamental process behind each term in order to facilitate the development of multi-hazard risk reduction strategies. Han et al. (2007) classified potential hazard interactions into four hazard chains induced through: (1) spatial and temporal conditions, (2) exogenic geological processes, (3) endogenic geological processes and (4) anthropogenic activities. Kappes et al. (2010) distinguish between two types of hazard relations: (1) those in which one process triggers the next (cascades, domino effects, etc.) and (2) those in which the disposition of one hazard is altered by another, whenever a process modifies the disposition or the frequency and/or magnitude of another process. Gill and Malamud (2016) categorized a possible hazard interactions relationship into three types: (1) triggering, (2) increased-probability, and (3) catalysis/impedance. Tilloy et al. (2019) group hazard interrelations into five types: (1) triggering, (2) change condition, (3) compound, (4) independence, and (5) mutually exclusive. Wang et al. (2020) make a similar distinction to that of Kappes et al. (2010) and distinguish between two main situations of interaction: (1) one hazard is triggered by another, which leads to a series of hazards in a chain or network form, or (2) hazards have complex or vague relationships. In this regard, Wang et al. (2020) divide multi-hazard scenarios into three more general categories, as Fig. 1 shows on the right, in three boxes with black borders and white background: (1) mutually amplified hazards, (2) mutually exclusive hazards, and (3) non-influential hazards.

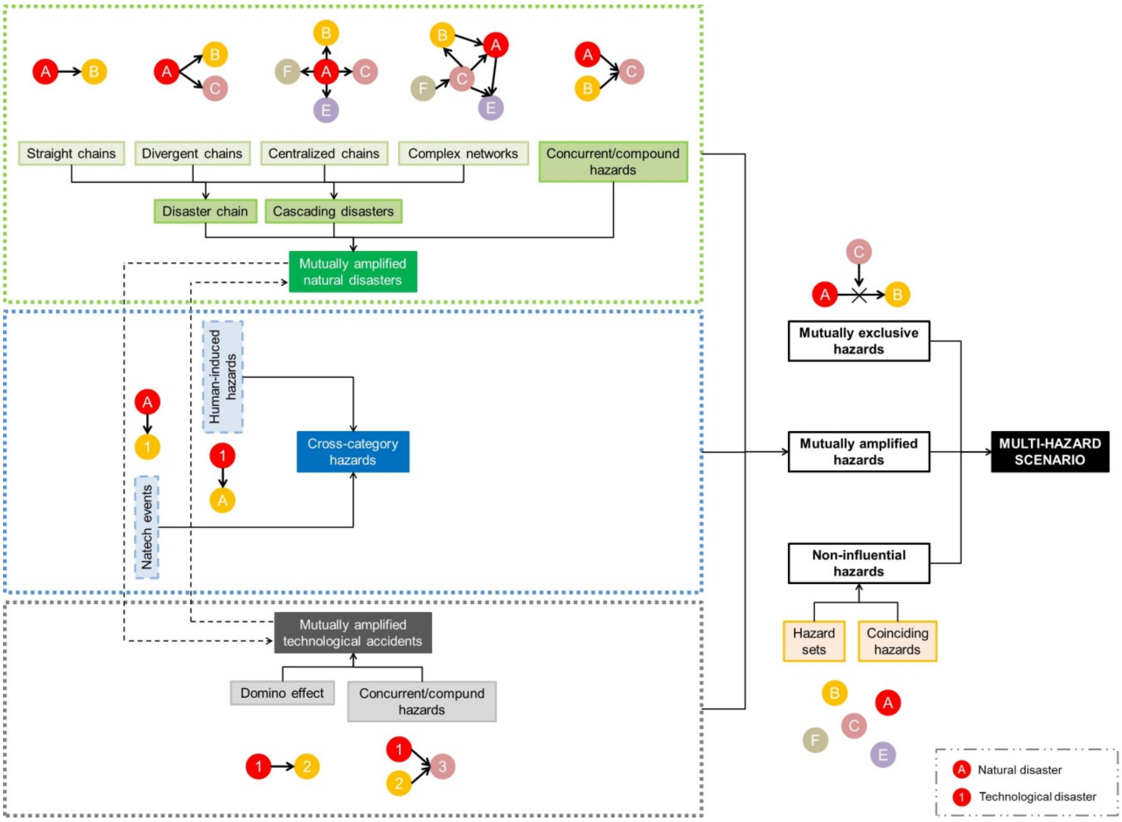

Figure 1. Classification of the existing terminology for hazard relationships. Source: modified from Wang et al. (2020).

In the case of mutually exclusive hazards (Fig. 1), when one event occurs, another cannot occur or its impact is reduced. Regarding the non-influential hazards, there may be a set of hazards or several hazards coinciding in space and/or time, but having no influence on each other. Finally, one or several hazards may be amplified by the occurrence of others previously or at the same time. In this last category we distinguish mainly between natural disasters (upper part of the figure, in the green box on the left with dashed lines, and the events symbolized by letters A to F in a circle) and technological accidents (at the bottom, in the gray box on the left with the dashed lines, symbolized by numbers 1 to 3 in a circle). In the case of the former, depending on the relationship established, we can distinguish between disaster chains or cascading disasters, which include straight chains, divergent chains, centralized chains and complex networks, and, on the other hand, concurrent hazards. As for technological accidents, the relationships may be the same but are given different names, having the domino effect or the aforementioned concurrent hazards. However, sometimes both types of events, natural and technological, can be related to each other giving rise to cross-category hazards (in the central part, in the blue box with dashed lines). These include natural disasters caused by technological accidents, usually caused by human-induced hazards, and technological accidents caused by natural disasters, called Natech events.

CHAPTER 2

MAIN CHARACTERISTICS OF ACTIVE VOLCANIC ISLANDS. THE CASE OF TENERIFE

2.1. Key features of active volcanic islands

2.1.1. Volcanic islands in focus: contextualizing the significance and challenges of studying volcanic island systems

Volcanoes represent the culmination of complex geological processes that involve the generation of magma at depth, its rise, accumulation and differentiation in shallower reservoirs, and finally, its appearance at the Earth's surface in the form of volcanic eruptions. These eruptions can occur at the seafloor, giving rise to a large number of the volcanoes found on Earth. Some of these volcanic edifices rise above sea level, changing from submarine to subaerial volcanism and forming volcanic islands. These islands are one of the most prominent and fastest-forming geographical features on Earth (Pimentel et al., 2020). In this sense, volcanic islands are created by the growth of oceanic volcanoes having evolved and been modified by geological, biological, and human activity.

The origin of the magmatism of oceanic islands is a matter of debate. It cannot be explained by conventional plate tectonics alone. Volcanic islands develop in virtually all geodynamic contexts on Earth, from mid-oceanic ridges (Iceland, Azores, Ascension, St. Helena, Tristan da Cunha) to intraplates (Hawaii, Canary Islands, Cape Verde) and volcanic arcs (Aeolian Islands, Aleutian Islands, Lesser Antilles) (Bonforte et al., 2022). For this reason, all the main pristine magmas related to mantle melting anomalies can be found in these islands, from MOR basalt to enriched tholeiitic and alkali basalts of hot spots, as well as from subduction-related calc-alkaline to shoshonite basalts. This gives rise to all the liquid-descent evolutive degrees, from primitive compositions up to strongly evolved rhyolite and trachyte lavas, erupted from a wide range of eruptive styles, from effusive to explosive eruptions (Bonforte et al., 2022). Therefore, we must understand the origin of these geological features as mantle anomalies that may be due to the rise of mantle plumes, as well as tectonics that facilitate the ascent of magma, or a combination of both.

Active volcanic areas—and so, volcanic islands among them—tend to generate very diverse landscapes, which depend on the style of volcanism. These are mostly demonstrated by large and steep stratovolcanoes (composite or polygenetic volcanoes) or relatively flat areas containing a diversity of small volcanic cones and lava fields (monogenetic volcanic fields) (Cotton, 1968). However, these particular environments can be affected by multiple natural hazards; these can be weather-related events (e.g., hurricanes, typhoons, droughts, floods, forest fires, etc.) and geological events (volcanic eruptions themselves, but also earthquakes, landslides, tsunamis, etc.). In some cases, some of these hazards can be triggered, amplified, or exacerbated by processes driven by Climate Change (e.g., changes in atmospheric conditions, sea level rise, coastal erosion, glacial melting, etc.). In any case, the landscape is modulated by the presence of this volcanism and subsequent morphological agents (erosion, weathering, sedimentation, etc.), and depending on climate conditions, it will constitute the basis for the development of diverse ecosystems. For that reason, the geological evolution of volcanic islands is governed by the alternation or coexistence of constructive (eruptions, sedimentation, intrusions, uplift, etc.) and destructive periods (aerial and wave erosion, landslides, subsidence), as a result of the balance of various processes such as volcanism, tectonics, and weather-related events, among others.

Dealing with a complex system such as a volcanic island further requires a great commitment to risk management with a multidisciplinary approach that crosses scientific, social, and economic boundaries. These specific systems have: (1) conditioning factors, understood as those that modify the characteristics of the area, favoring or aggravating the occurrence of certain events; and (2) triggering factors, understood as those that trigger the event or chain of events. Both types of factors sometimes do not exist in other non-volcanic regions or they occur less intensely (e.g. steep slopes, pronounced relief, microclimates and/or high climatic variability, more or less permeable soils, disintegrated material, volcanic seismicity, etc.). This type of volcanoes presents many characteristics that are often different from on-shore volcanoes. One of the main ones is the development of an important and complex hydrothermal system due to the interaction with and circulation of seawater at depth, which may interact with the magma or its gases, and with the hot country rocks, accentuating the instability of these edifices under seismic and ground deformation conditions, and being able to trigger phreatic-phreatomagmatic eruptions, with consequent tsunami waves (Bonforte et al., 2022). Another important issue of off-shore volcanoes compared to on-shore ones is that in the case of the former, most of the edifice is submerged, which makes it more difficult to develop monitoring systems and more complex to understand the functioning of the volcanic system (Bonforte et al., 2022).

Natural hazards may repeat at different frequencies depending on each island, according to their proper magmatic systems and environmental conditions. When considering the potential hazards that may affect volcanic islands, we must include the proper volcanic and non-volcanic hazards that may act simultaneously or in succession, sometimes with evidence of some that trigger the others (e.g., volcanic eruptions triggering seismicity and avalanches, avalanches triggering tsunamis, etc. (Martí, 2019) (see Fig. 2).

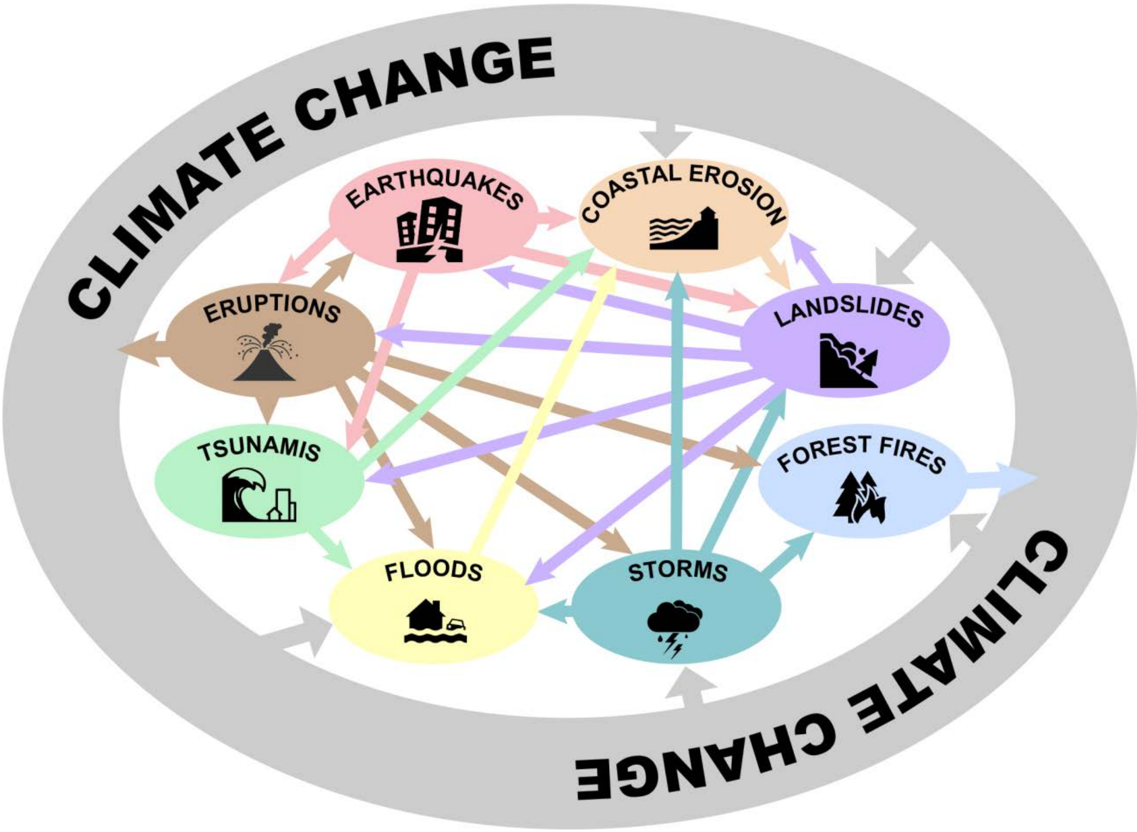

Figure 2. Example of possible interactions (cause/effect) among some of the most important natural hazards. Source: López-Saavedra and Martí (2023) (CC BY-NC-ND 4.0).

In the case of volcanic eruptions, they may generate a large diversity of products (lava flows, pyroclastic fragments and deposits, and gases) depending on the characteristics of each eruption (effusive or explosive), and they may also leave signs of its potential future activity in the form of thermal anomalies, fumaroles, hydrothermal alteration, etc. The solid products of volcanism (lavas and pyroclastic deposits) tend to accumulate around volcanic vents, but may also extend to distal regions depending on the magnitude and intensity of the eruption. Depending on magma composition, most of these products are very rich in chemical components that, under adequate climate conditions, may transform into fertile soils.

However, at the same time, volcanic hazards are inherently complex and therefore difficult to predict due to their intrinsic multi-factor nature, in which different volcanic products (lavas flows, fallout, lahars, and pyroclastic flows) and associated hazards (seismic shocks, landslides, tsunamis, and floods) interact or impact together or sequentially (Martí, 2017). Hence, when evaluating the potential impact of volcanic eruptions, we must identify what direct and indirect hazards can be derived in each case and develop knowledge of their cause-effect relationships. Volcanic eruptions span a broad diversity of hazards that directly derive from the volcanic activity (e.g., lavas flows, fallout, pyroclastic density currents –PDC–, lahars, gases, etc.), as well as indirect hazards triggered by the action of the direct hazards (debris flows, rock avalanches, seismicity, tsunamis, etc.). Eruption durations are known to be very variable, ranging from a few hours to several years, with sizes ranging from a few millions of cubic meters to several thousands of cubic kilometers, and may involve very distinct phases, from effusive to highly explosive, generating a variety of products. These products result from different dynamics and emplacement modes and so will generate different potential hazards (e.g., Tilling, 2005; Martí, 2017). These variations in volcanic eruptions and their products and, consequently, their potential impacts, depend to a large extent on magma composition, which controls its rheology and volatile content. Therefore, the impact of a volcanic eruption will depend on its size, which determines the extent of its erupted products. The impact is also dependent on the type of products generated and the degree of hazard they may represent. In this sense, PDCs, lava flows, and lahars are considered the most destructive products, but fallout and gases may also have important implications in proximal areas (Blong, 1984; Blong, 2000; Tilling, 2005). The reconstruction of the eruptive history of a volcano together with a comprehensive understanding of the physics of volcanic processes allows us to identify eruptive scenarios. This, in turn, allows us to determine which have been the most frequent in the past and hence to estimate the probabilities of future eruptions. This is the essence of volcanic hazard assessment (Martí, 2017).

Despite being subjected to the constant threat of volcanic eruptions, which may have highly devastating effects, active volcanic areas also offer a number of important advantages that have made them so attractive for human settlements through the whole history. More than 80 percent of the Earth's surface—including both above and below sea level—is of volcanic origin. Volcanoes are responsible for the magnificent landscapes and fertile soils that provide the essential basis for the development of some of the richest ecosystems on Earth (Steutermann Rogers, 2018). As a consequence, in recent years, an emerging prosperity associated with active volcanoes has come from tourism, which in many places already represents one of their main incomes. Furthermore, volcanic areas are the source of important energy and mineral resources that remain essential for the development of societies (e.g., Martí & Ernst, 2005). This is even more relevant in our modern globalized society in which certain technological requirements (e.g., mobile phones, computers, etc.) contain primary elements derived from volcanic products. For that reason, the intrinsic multi-hazardousness of these islands has not prevented from also being a focus of interest for colonization and settlement. But the geographical location of these territories, spread across the Earth's various seas and oceans, also made them strategic locations for trade and warfare, as well as for the export of resources to sovereign countries on the continent. For this reason, many of these islands belong to countries far away from them (e.g. Réunion Island or Guadeloupe of France, Canary Islands of Spain, Azores of Portugal, Tristan da Cunha or Montserrat of the United Kingdom, Hawaii of the United States). In other cases, these islands constitute a country of their own, although they became independent at some point in the history of the former countries (e.g. the Philippines, Mauritius, Indonesia, Vanuatu, Iceland, New Zealand). In the case of the former, although they have the support of a country on the mainland that can reinforce assistance in the event of a disaster, this aid comes from far away and this can hinder response and risk mitigation efforts, although in the majority of cases, it is the administration of each island that must take charge of managing the natural hazards that occur in its territory. In the case of the second type of political context for these islands, the management of emergencies caused by natural phenomena falls to their own government without having external support from which to reinforce aid. It is worth mentioning that sometimes it is difficult to access the affected area immediately (e.g., Tonga eruption in 2022). The COVID pandemic has proven to be yet another factor that can contribute to complicating emergency management, thus requiring additional protocols and resources (e.g., also during Tonga eruption in 2022). Anyway, in both cases, risk management is more complex and demanding than in other parts of the world.

Nevertheless, the positive aspects of active volcanic areas sometimes cause societies living on them to ignore or underestimate their risks. This disequilibrium between potential economic benefits and the perception of potential risks is often the cause for turning volcanic eruptions into disasters, as the obvious income may reduce the perception of risk to levels at which the necessary prevention and preparedness actions vis-a-vis volcanic threat are simply ignored. For that reason, due to their natural isolation, intrinsic multi-hazard nature, and strong dependence on external supply chains, volcanic islands tend to have fragile economic systems and are thus highly vulnerable communities with their main monetary incomes coming from the tourism industry and local economic activities such as fishing (e.g., El Hierro, Canary Islands, Spain; Iceland) or viticulture (e.g., Pico Island, Azores, Portugal). For that reason, natural hazards may not only affect the islands' natural ecosystems, but also may temporarily suspend the touristic and local industrial activities in the area (e.g., fishing, commercial diving, etc.). Any interruption in any of these activities would lead to a serious, and in some cases irreversible, economic contraction (e.g., Monserrat Island, Caribbean). The great impact, sometimes in terms of deaths or evacuations, sometimes in terms of economic decline, of events that are often quite rapid, i.e. occurring in a few days, hours or even minutes, produce effects that last much longer.

In addition, the continuous demographic expansion of many volcanic islands, caused mainly by the steadily increasing tourism, is a critical factor that exponentially increases the risk in such environments. Moreover, the latest climate models for this century project increases in the number and intensity of storms and hurricanes, as well as significant sea level rise (IPCC, 2022). These phenomena will contribute to increasing the vulnerability of coastal areas on volcanic islands, where the main tourist resorts are located.

However, many societies that have developed around volcanoes have demonstrated a high degree of resilience and adaptation, successfully recovering after each volcanic impact (e.g., Torrence, 2016). The socio-economic development of the different societies around volcanoes is diverse and ranges from very poor societies where people get just enough to survive on a daily basis, to rich societies where part of their wealth comes from the extraction of natural resources (energy and minerals) associated with volcanoes. However, in all cases it is the very existence of volcanoes that determines their socio-economic development. Moreover, in recent years a direct source of income has emerged: nature tourism, with tourists becoming increasingly interested in visiting active volcanoes and places where active geological processes can be observed, even in remote and underdeveloped areas (e.g., Erfurt-Cooper, 2014). This effect has been particularly noticed on volcanic islands (e.g., Hernández-Martín, 2021). Therefore, by mitigating volcanic risks we transform the effects of volcanoes using nature-based solutions. This approach aims to sustainably strengthen and enrich all these societies that, in one way or another, depend on active volcanoes for their subsistence. Therefore, understanding the functioning of volcanoes and finding ways to mitigate their associated risks is crucial for ensuring the safety of residents and visitors living in proximity to them.

For that reason, for multi-risk management in these territories, we should also consider their proper environment and ecosystems, from deep sea to the highest peaks, which are dynamic environments responding to the changes in the volcano, the global environment and the local influence of human activity. In the same way it is also important to take into account their social infrastructure, including their greatly varying social, cultural, economic, and demographic distributions, due to their global position, colonial history and the nature of each island. Each site, therefore, presents a different case for resource development and the society of each island will respond differently to changes from hazard impacts. As a result, predicting, preparing for, and recovering from natural disasters are clearly urgent matters of concern for volcanic islands.

Generally, humans and volcanoes are not incompatible but living near volcanoes implies knowledge of how they work and therefore when they may represent a risk or a benefit. To minimize the risk from active volcanoes it is important to first to conduct a long-term hazard assessment, which will inform us on the spatial and temporal probabilities of volcanic and associated hazards (Martí, 2017). Similarly, these assessments can also be carried out for other types of hazards or even considering multi-hazard scenarios. This methodology will constitute the basis for correct land-use planning of the area toward an adequate risk management plan. This will permit implementing the necessary mitigation actions and will help those concerned to think about the importance of constraining the potential benefits and their associated risks, prior to a development action plan.

For all these reasons, developing a proper risk management frame with a multi-hazard approach for these regions is a greater challenge. However, considering that they are highly populated regions—and in some cases, even overpopulated and very touristic areas—risk assessment and management based on scientific knowledge is an unavoidable need. The following is a brief compilation of several real historical events of natural disasters to exemplify the range of hazards volcanic islands face.

2.1.2. Unraveling the interrelationships between events and unexpected outcomes

The Table 16 shown in Annex 4 lists several multi-hazard events in volcanic islands that have caused significant impacts to society and the environment throughout Earth's history. This table exemplifies the main cause/effect relationships, the consequences on the population in terms of deaths, injuries and displaced persons, as well as the economic impact in this type of regions. In addition, the main emergency response and recovery actions are summarized. The main chains of hazards observed are then extracted and detailed.

Geohazards

Starting from their complex geology, volcanic islands are by definition volcanic terrains made of magma, solid rock, altered rock, hydrothermal systems, sediments, etc., sometimes deposited over very short periods of time compared to other sedimentation processes unrelated to volcanic eruptions. These conditioning factors lead to more unstable terrains compared to many continental areas. Their steep slopes due to the rapid growth in height favor this instability and can even aggravate or trigger other gravitational events, such as flash floods or rock falls. In addition, they are weak structures affected by intense faulting, alteration, and avalanche structures, which respond to the succession of constructive and destructive processes that account for their entire evolution. We will divide geohazards into volcanic and non-volcanic hazards.

Volcanic activity is already a multi-hazard event (e.g., lava flows, gas emissions, seismic activity, Pyroclastic Density Currents –PDCs– emplacements, landslides, lahars, tsunamis, etc.) that may include cascading effects, which may have a severe impact on the population, the infrastructure and the economy of the affected region. The Soufrière Hills Volcano (Montserrat Island, United Kingdom) offers a good example of such catastrophic events. A period of nearly 18 years of volcanic activity (from 1995 to 2013, but with different phases), mainly represented by lava dome growth, collapse and explosive phases, generated different primary volcanic hazards (dome collapses, ash fall, PDCs, gases, etc.) and other related hazards (lahars, debris flows, tsunamis, etc.) (Herd et al., 2005) (see Table 16 of Annex 4 for more information). These events have caused roof collapses, impacted spring water sources, and destroyed most of the infrastructure of the island.

As can be seen in Table 16 (Annex 4), other examples of multi-hazards related to volcanic eruptions are provided by the 2018 eruption of Krakatau, which triggered a sector collapse and, consequently, a tsunami when the sliding flank impacted the sea surface (Walter et al., 2019), or the recent eruption of the Hunga-Tonga-Hunga-Ha'apai volcano, in 2022, that produced a caldera collapse and an explosion, triggering a large tsunami (The Prime Minister's Office, 2022). More cases of such types of interactions among natural hazards include lava flows and incandescent tephra fall that cause forest fires, as had occurred during the Gamalama eruption (Ternate Island, Indonesia) in 1980 (Hidayat et al., 2020a, Hidayat et al., 2020b), and during the Kilauea eruption (Hawaii island, USA) in 2018 (Hopps, 2018; Klemetti, 2018; Hawaii Emergency Management Agency, 2020), or lava flows generating PDCs due to a gravitational collapse of the lava front, as occurred during the Karangetang eruption (Siau Island, Indonesia) in 1992, killing six people (Hidayat et al., 2020a). The eruptive column can also cause lightning due to particle friction, as occurred during the Vulcan and Tavurvur eruption (New Britain Island, Papua New Guinea), in 1994, with one person killed due to a lightning strike (International Decade for Natural Disaster Reduction, 1996). Lahars, mudflows, debris flows, and floods are also a common hazard related to ice melting, like during the Eyjafjallajökull eruption (Iceland) in 2010—a small event that caused $4.7 billion USD loss in the global GDP (Carlsen et al., 2012; Ellertsdottir, 2014), and to heavy rainfall or contact with water streams, as had occurred two days after the eruption of Mt. Gamalama (Ternate Island, Indonesia) in 2011 (Smithsonian Institution, 2013). In this last case, the National Disaster Mitigation Agency (Badan Nasional Penanggulangan Bencana, BNPB) allocated $121,000 USD in emergency funds for the residents affected by the eruption. However, a year later, up to 3,490 people were still being housed in ten different emergency shelters.

The size of these events and of their impacts may be very variable and may include extreme events, which may even have global effects. A common sequence during large eruptions is the triggering of landslides or flank collapses due to seismicity or explosions, and the associated tsunami produced by the impact of the sliding mass with the ocean. Tsunamis can also be triggered by PDCs impacting the ocean and both are the deadliest hazards in such cascading sequences of events, accounting for between 36,417 and 120,000 deaths in the case of the tsunami during the Krakatau 1883 eruption (Indonesia) (BBC News, 2018), or the more extreme case of Tenerife (Canary Islands), where such a succession of catastrophic events, involving a large explosive eruption, caldera collapse, seismicity, large sector collapse, and tsunami, has occurred at least twice, 560 ka and 170 ka ago, respectively (Martí et al., 1994; Hürlimann et al., 2000; López-Saavedra et al., 2021) (see Table 16 from Annex 4 for more information).

Furthermore, there is the case of the Thera eruption, in Santorini (Greece), in 1610 BCE ± 14 years, where an explosive caldera eruption triggered a large tsunami severely affecting most of the Mediterranean coasts (Sparks, 1979).

Non-volcanic hazards, although they may be associated with magmatic or volcanic activity, include landslides. Due to its unstable terrain and steep slopes, this hazard is one of the most common phenomena on volcanic islands. These events can be of variable magnitude and can occur without necessarily being provoked by an eruption. As these environments are completely surrounded by the sea, one of the most frequent hazards during large landslides or rock falls is the generation of tsunamis in the same way as discussed above for those related to eruptive events. An example is the landslide and the subsequent 5–7 m-high tsunami produced on the NW coast of Flores Island (Azores) in 1847, which killed 10 people and injured >100 (Gaspar et al., 2011), or the flank collapse and the related tsunami produced at Ritter Island (Papua New Guinea) in 1888, responsible for several hundreds to 1,000 deaths (Ward & Day, 2003). In this last case, the relief effort apparently came from commercial interests instead of concern for the condition of people.

Many of these landslides are caused by earthquakes, other natural phenomena that are common in these places, either of volcanic or tectonic origin. In 1522 in Vila Franca (São Miguel Island, Azores), an earthquake and four aftershocks produced a landslide and a tsunami. In turn, the landslide produced lahars, another commonly associated hazard, which killed between 3,000 and 5,000 people (Silveira, 2002). Many other landslides are produced in these places due to extreme weather, which can cause heavy rainfall and strong winds. These gravitational collapses, in turn, can clog river channels and cause flooding and mudflows. This was the case for the floods and mudflows that occurred in Madeira (Portugal) in 2010, causing the death of 42 people and having had serious effects on the populations (Lusa, 2010; Pita, 2010). Full restoration of all affected infrastructure may take up to a few years, but most of the island is fully functional (see Table 16 from Annex 4 for more details). Landslides on Mt. Pelée (Martinique Island) in the same year, caused serious effects that were also due to the occurrence of lahars, such as the destruction of essential bridges (Aubaud et al., 2013), and in 2013 in the Azores (Portugal), where they caused three deaths (La Voz and de Galicia, 2013).

Earthquakes by themselves are very destructive events. Most volcanic islands are concentrated at plate boundaries, especially in subduction zones, where major and frequent earthquakes originate. For this reason, these islands are also subject to earthquakes of a tectonic origin. Many others, although not in this geodynamic context, such as intra-plate islands, are also closely related to regional faults or fault systems that give rise to earthquakes. An example is the earthquake produced in 1839 in the west of the subducting St. Lucia Ridge, which affected the east of Martinique Island (Lesser Antilles), killing 700 people due to building destruction and causing $14.5 million USD losses (Nicoletti, 2015). Periods of volcanic unrest, while sometimes not ending with an eruption, also lead to seismic crises, such as the one that occurred in 2005 in the Fogo-Congro seismogenic zone, where >46,000 earthquakes caused landslides and environmental damage due to the incorporation of large amounts of sedimentary load into rivers (Marques et al., 2006).

On the other hand, while volcanic islands can be the source of tsunamis themselves, as we have seen before, their location in active tectonic settings makes them susceptible to the influence of tsunamis originating from tectonic earthquakes, which can occur far away from their coasts. In addition, their relatively small size, their demographic concentration, especially along the coast where the topography is flatter and more accessible for urbanization, and their location, sometimes in the middle of the ocean unprotected by other pieces of land, make them more vulnerable to tsunamis. A well-known example is the 2004 Indian Ocean tsunami, whose epicenter was located north of the coast of Sumatra, but which devastated every coastline around the Indian Ocean and every island in its path, causing between 230,000 and 260,000 deaths (Inderfurth et al., 2005; Unicef USA, 2020). A case that also deserves attention was the 2011 Tohoku tsunami in Japan, as it passed over the Galapagos Islands, where many animals died, such as the flightless cormorant (which suffered some nest destruction), sea turtles, and marine iguanas. By all accounts the overall natural environment was not drastically disturbed, and critically endangered species, such as the mangrove finch, fortunately were unharmed (UNESCO, 2011).

Weather-related hazards

The topographic relief of volcanic islands, with high natural barriers, deep valleys, and the influence of the sea that surrounds them, means that over a small region, the meteorology is very varied, creating weather contrasts in different parts of the island and sometimes unexpected changes in the same area. Environmental processes make volcanic islands subject to both the development and erosion of soils, due to rainfall, flash floods and flooding, heavy swell, periods of intense drought, rock alteration, or thermal contraction and expansion. Likewise, many volcanic islands are located in the cyclone pathways, so they are also affected by hazards associated with extreme weather events. An example is the flooding that occurred on Martinique Island in 1891 due to the passage of Cyclone San Magin, which caused 700 deaths, brought with it numerous diseases and caused economic losses of between 11.6 and 14.5 million USD (Aubaud et al., 2013; Church, 2014). Another example is Cyclone Pam on its passage through Vanuatu (South Pacific) in 2015, where it left between 11 and 16 deaths, with 132,000 people affected and 33,000 displaced, in addition to losses of 600 million USD (Handmer & Iveson, 2017). On occasions, the development of these soils between layers of volcanic materials from eruptions can act as a conditioning factor for the generation of landslides, as they often correspond to the décollement surface (Bravo, 1962; Coello, 1973; Boulesteix et al., 2012; Iribarren, 2014; Le Friant et al., 2020). The same applies to the deposits created after a landslide that remain in situ with subsequent layers of volcanic materials deposited on top of it.

In addition, these climatic conditions entail a wide range of non-volcanic hazards of different types, such as the occurrence of plagues, forest fires, problems for the refilling of aquifers, landslides caused by floods, such as those mentioned before, damage to coasts due to sea waves, damage to crops both in dry and humid periods, damage to livestock, snowfall, gelifraction, heat waves, etc. A clear example is the Canary Islands (Spain), where many of these hazards have occurred. In 2004 for example, an extreme haze brought a plague of locusts to Lanzarote (Arroyo, 2009). At the same time, a squall formed over the Canary archipelago causing strong gusts of wind and rainfall. On the beach of Maspalomas (Gran Canaria), the waves broke into the dune area and penetrated almost 500 m, causing considerable damage along the coastal area.

On the other hand, global climate change will increase the frequency and severity of many of these events that may impact these vulnerable environments. This is the case for hydrological and coastal hazards, which will increase the flux of material from the subaerial part, extending to the sea through flooding and landslides, producing coastal erosion, thus changing stability of the island slopes and coasts. These effects can get worse in the case of volcanic eruptions, because if there are conditions that favor these processes, the cascade of events following an eruption can become increasingly common and extreme.

Other hazards

Geohazards of volcanic and non-volcanic origin may cause other hazards since they may relate to the contamination of water and food supplies, worsening hygienic conditions and affecting people's health. Examples of this are the Tambora eruption of 1815 (NOAA, 2020), the Martinique Island floods of 1891 (Aubaud et al., 2013; Church, 2014), the Pinatubo eruption of 1991 (Floret et al., 2006), or the Indonesian tsunami of 2004 (WHO, 2006) (see Table 16 from Annex 4 for more details).

Furthermore, human activities should be also considered, as they may severely alter the natural conditions of each site, a factor that may increase risk considerably. On the one hand, volcanic areas often host significant agricultural activity because they contain very fertile soils, forcing more and more settlements to be established in hazardous areas, increasing the risk due to greater exposure. In addition, the creation of terraced crops, for example, modifies the topography and, in turn, its surface runoff. The change in land use alters its properties and the processes that take place there, so a comprehensive impact study of these types of activities is necessary, not only of those that create crops, but also those that transform natural land into urban land, in order to analyze the consequences of such types of land modifications. Moreover, the lack of space forces companies to build dangerous infrastructure, such as oil refineries, gas depots, power and thermal power plants, and even nuclear power plants, in areas at risk because of the high probable occurrence of the above-mentioned natural events. It is worth recalling the nuclear disaster in Japan following the 2011 Tohoku tsunami.

Additionally, resources are also limited due to natural space constraints. If we add to this the fact that most of these volcanic islands are popular tourist destinations, overpopulation and a large influx of tourists can endanger reserves and, therefore, supply, often resulting in the overexploitation and degradation of aquifers, the destruction of forests and other green areas for urban expansion, coastal overpopulation, the modification of riverbeds and streams, the destruction of natural heritage, overfishing, increased influx of cruise ships, planes and cars, increased pollution, etc. It also increases the risk exposure of people, who are more vulnerable as they are often unaware of the existing hazards in the area, especially if they come from regions where there is no comprehensive training in natural hazards, and they do not know how to behave in the event of an emergency. In addition, there are a number of irresponsible actions, such as the waste dumping near Truk Island that provoke a cholera epidemic, negligent or intentional fires, access and exposure to dangerous or prohibited areas, etc., among tourists and locals alike. One example were the 2019 fires in the Canary Islands, where arson combined with a heat wave and strong winds resulted in 10,000 ha burned, 84% of which were protected areas, as well as the displacement of 9,000 people, the death of some livestock and up to 50 million bees (Minder, 2019; Portillo, 2019).

Overview

From the analysis of the interrelationships between hazards occurring in this sample of real examples of catastrophes, Fig. 3 was developed.

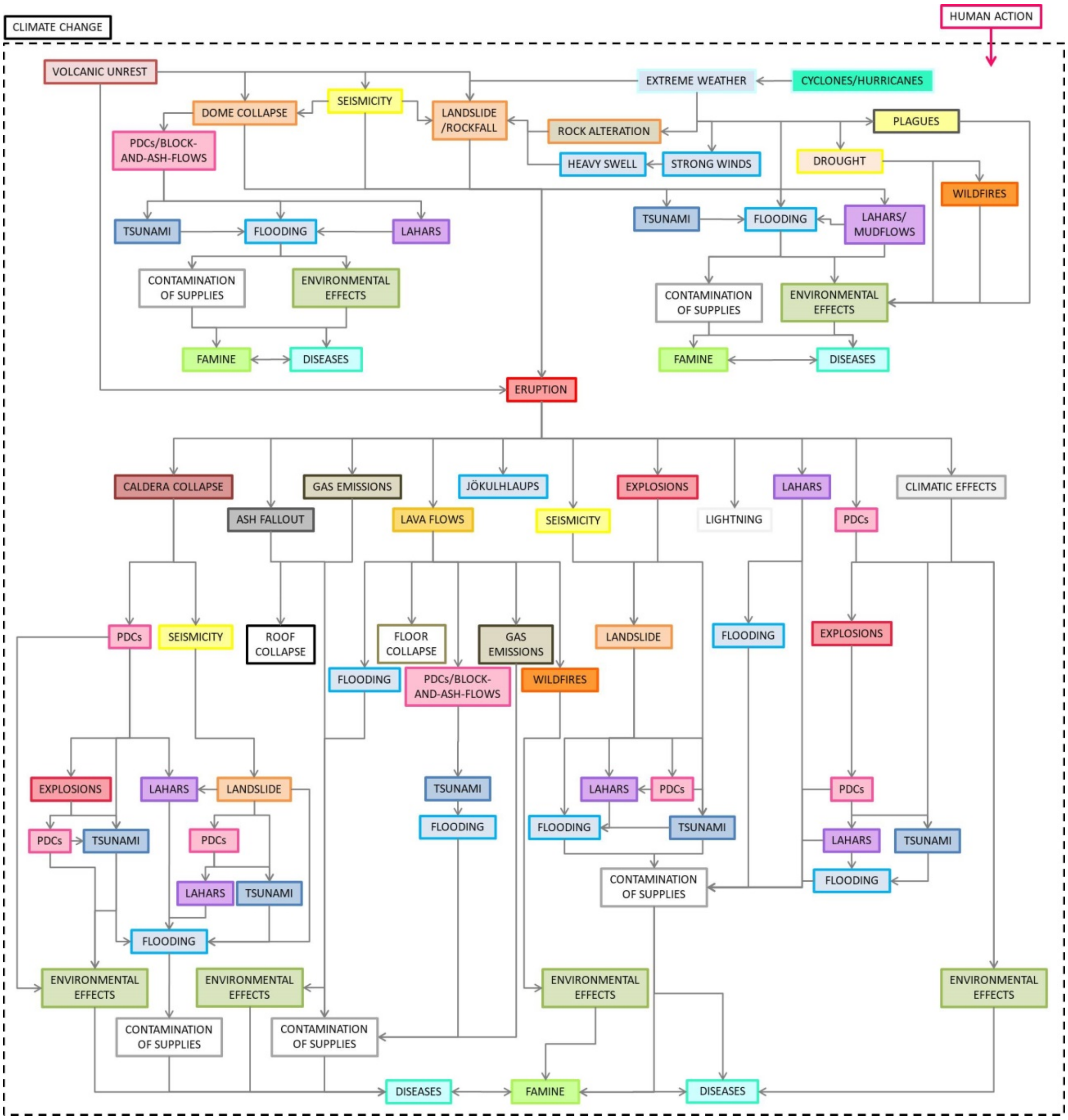

Figure 3. Diagram of the possible interrelationships and cascading effects of different geohazards that may occur on volcanic islands. Source: own elaboration prepared on the basis of the actual events shown in Table 16 from Annex 4.

**Note: The diagram in Fig. 3 should normally be read vertically in a downward direction but it can also be read horizontally, in order to understand the relationships of events. It should be noted that, although this diagram shows all possible sequences of events and relationships based on real cases, especially those collected in the Table 16 from Annex 4, not all events shown need to occur, or need not occur simultaneously in space and time. Similarly, some sequences of events can be initiated by any event that is related above or to the side, without necessarily having to be the first in the sequence. Likewise, chains do not necessarily have to be produced complete. Some relationships that affect some repeated events have been omitted due to lack of space and so as not to make their visualization more difficult, as they are already present in another box of the same event, such as the direct relationship between lahars and the contamination of supplies. In the same way, the fact that some boxes are related to one event and others of the same typology are related to other events does not mean that in both cases there are different sequences, but for reasons of space and overlap, it has been more convenient to draw an arrow towards one box in one case and another towards another in the other case, but it means that in case this event occurs, both sequences can occur, as in the case of the relationship of environmental effects with disease and with famine.*

Fig. 3, far from pretending to show a simplified and clear summary that allows the reader to follow in detail all the possible derived hazards that may occur along a chain of events, seeks to show the complexity of the interactions, the wide range of possibilities, the aspect that multi-hazard scenarios may acquire, and the same uncertainty that the reader may feel when viewing the figure to predict whether one event or another, or several, will occur. All this complexity is aggravated by human action and climate change, both of which are indicated at the top of the figure as external inputs and frames.

2.1.3. Examples of multi-hazard initiatives in volcanic islands: main shortcomings

In the context of growing concern about the effects of Climate Change, many international organizations have begun to adopt a multi-risk approach for the assessment of climate change impacts (e.g., Dilley et al., 2005; IPCC, 2012) at a range of spatial scales, both at global and European scales (European Commission, 2011). Some even started prematurely, prior to the post-2015 era. Others, as shown below, were established after the occurrence of some of the events mentioned in the previous section 2.1.2. "Unraveling the interrelationships between events and unexpected outcomes".

In the case of Hawaii (Pacific Ocean), the first approved State Multi-Hazard Mitigation Plan went into effect on October 27, 2004. Wildfires, floods, landslides, volcanoes, earthquakes, and tsunamis are common natural disasters in this region. For that reason, the Plan identifies both the hazards and risks posed by natural and technological disasters and the actions and activities employed to reduce the derived losses, by establishing priorities and a long-term process to implement them (Hawaii Emergency Management Agency, 2018).

The Azores (Atlantic Ocean) are in a similar situation. Due to its tectonic and volcanic environment, this archipelago is affected also by earthquakes, volcanic eruptions, landslides, floods, costal erosion, etc. The AZORIS Geodatabase acts as the support for multi-hazard analysis, vulnerability assessment, crisis scenarios and alert and warning systems in the Azores region (Gaspar et al., 2011). The data acquired by field monitoring stations, for example, are transmitted to the Emergency Operations Centre (COE) of the Institute of Volcanology and Risk Assessment Research (IVAR) of the University of the Azores, and stored in AZORIS.

According to Moananu (2019), Vanuatu (South Pacific Ocean) "is continuously affected by at least one to three cyclones and up to two Magnitude 7 earthquakes with tsunami-triggering potential annually, between 100 to 300 earthquakes per month, and has six permanently active volcanoes which erupt at least once every two years." For that reason, the Vanuatu Meteorology and Geo-hazards Department (VMGD) merged with the Institute of Research for Development (IRD) in Noumea, New Caledonia, to share resources and create a joint volcano and seismic monitoring network. After its recognition by the Intergovernmental Oceanic Commission for the Pacific Tsunami Warning and Mitigation System (PTWS), the Oceania Regional Seismic Network (ORSNET) was created in 2014 through collaboration with other Pacific islands countries that were running their own national seismic networks, particularly Fiji, Papua New Guinea, Samoa, Solomon Islands, and Tonga (Moananu, 2019).

A new MHEWS sub-regional hub for the Pacific in Papua New Guinea (South Pacific Ocean) was inaugurated at the Third Regional Integrated Multi-hazard Early Warning Systems (RIMES) ministerial conference in Port Moresby on 25 August 2017. It is a significant cornerstone in supporting World Meteorological Organization (WMO) Members and their ongoing and future programs in this region (WMO, 2017).

In the case of Samoa and Tonga islands (South Pacific Ocean), their MHEWS are in the process of strengthening through nationally implemented projects as part of the World Bank funded Pacific Resilience Program (PREP) (Pacific Community, 2019). At the same time, during a technical meeting held in Nadi, Fiji, from 7 to 8 October 2019, senior officials from technical agencies in Samoa and Tonga, representing their respective meteorological, hydrological and disaster management offices met to address the implementation of their MHEWS (Pacific Community, 2019).

The Caribbean region, on the other hand, is also exposed to multiple natural hazards; especially hurricanes and tropical storms, floods, landslides, storm surges, but also earthquakes and tsunamis. Health shocks are also present. For this reason, a project has been carried out titled ‘Strengthen integrated early warning systems for more effective disaster risk reduction in the Caribbean through knowledge and tool transfer.’ The aim of this Project is to progress in the regional and global framework for disaster risk reduction according to the Sendai Framework goals. On February 1, 2019, the meeting titled “Multi-Hazard Early Warning Systems in the Caribbean: Achievements and Strategic Path Forward” was held on Saint Lucia island to raise awareness among the political directorate on the required support for achieving integrated, fully functional MHEWS (Caribbean Disaster Emergency Management Agency, 2022).

Other volcanic island regions are currently implementing projects, such as in Comoros (Southwest Indian Ocean), where the project titled "Supporting regional cooperation to strengthen seamless operational forecasting and multi-hazard early warning systems at national levels in the South-West Indian Ocean" is underway and expected to be completed by 2025. The objective of this project is to enhance the adaptive capacity and climate resilience of communities and economic sectors in five countries of the South-West Indian Ocean (SWIO) region.

On a lower scale, many studies have been carried out in some regions using the approach of multi-hazard risk assessment (Chondol et al., 2020). De Pippo et al. (2008) carried out hazard risk assessment and mapping for a coastal region in Italy by investigating the primary hazards in the region and mapping the overall multi-hazard risks by ranking not just the hazards but also their interactions. Neri et al. (2013) estimated the multi-hazard risk associated with the volcano Kanlaon, in the Philippines, using an event tree method that combines probabilistic frequencies of three potential categories of hazardous events, and the secondary hazards associated with them. Kappes et al. (2010) analyzed the multi-hazard risk for Barcelonnette Basin, in the Alps, by analyzing the relationship between different types of hazards taking into the account disposition and triggering concerns. One of the latest multi-hazard assessments that highlight the importance of the study of cascading hazards for future forecasting come from Patrick et al. (2020), which analyses the 2018 Kilauea eruption.

However, most analyses consider hazards individually, without taking into account the nature of the interrelationships that can be established between different types of events occurring simultaneously, or at different times but in the same place (e.g., a torrential rainfall triggering a landslide on a slope previously affected by an earthquake, the latter having reduced the slope's cohesion; or a landslide triggering a tsunami). After reviewing and understanding the operation and content of each of these initiatives, it is observed that most of them are based on what Gill and Malamud (2014) define as the multi-layer hazards approach, where interrelations are not truly considered, and hazards are superposed in a region. As detailed in the section 2.2.6. “Risk management structure”, Tenerife's risk management system (and that of the Canary Islands in general) is built on this same multi-layer single hazard approach. In this case, there is an emergency plan for each individual hazard.

Gill and Malamud (2014) define further approaches, which they call steps within the multi-hazard framework, to progress from a multi-layer single hazard approach to a multi-hazard approach. These four key aspects include: hazard identification and comparison, hazard interactions (interrelationships), hazard coincidence, and dynamic vulnerability. According to them, “a multihazard risk assessment should identify all possible and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also taking into account the dynamic nature of vulnerability to multiple stresses.” Later, this doctoral thesis will show the results of developing our methodology with a multi-hazard perspective in line with this, for the island of Tenerife.

2.2. The case of the island of Tenerife (Canary Islands)

2.2.1. Geographical and geological context

With a surface area of 2,034 km^2, Tenerife is the largest of the eight volcanic islands that make up the Canary Islands. The Canary Islands are an intra-plate volcanic archipelago located in the east-central Atlantic Ocean, about 300 km off the southern coast of Morocco in northwest Africa (Fig. 4), within the African plate, the western continental margin of which is a passive rim with no volcanic activity (IGN, 2023b). The archipelago is connected to a long-lasting mantle plume whose structure and geodynamic evolution still evoke considerable debate (e.g., Hernández-Pacheco & Ibarrola, 1973; Anguita & Hernan, 1975, 2000; Schmincke, 1982; Araña & Ortiz, 1991; Hoernle & Schmincke, 1993: Carracedo et al., 1998; Fullea et al., 2015). Tenerife, which is considered active, is located in the center of the archipelago, at coordinates between 28–29ºN latitude and 16–17ºW longitude, and is a large pyramid-shaped volcanic stack that rises nearly 8,000 m above the Miocene oceanic crust (Watts et al., 1997). Teide volcano is the highest point of elevation on the island, at 3,718 m above sea level, making Tenerife the 3rd largest and one of the most complex volcanic system in the world, after Mauna Loa and Mauna Kea in Hawaii. Although they are far from the Iberian Peninsula, the Canary Islands belong to the Spanish State. The reason for their remoteness lies in their colonial history. In the case of Tenerife, it was conquered at the end of the 15th century by the Spanish.

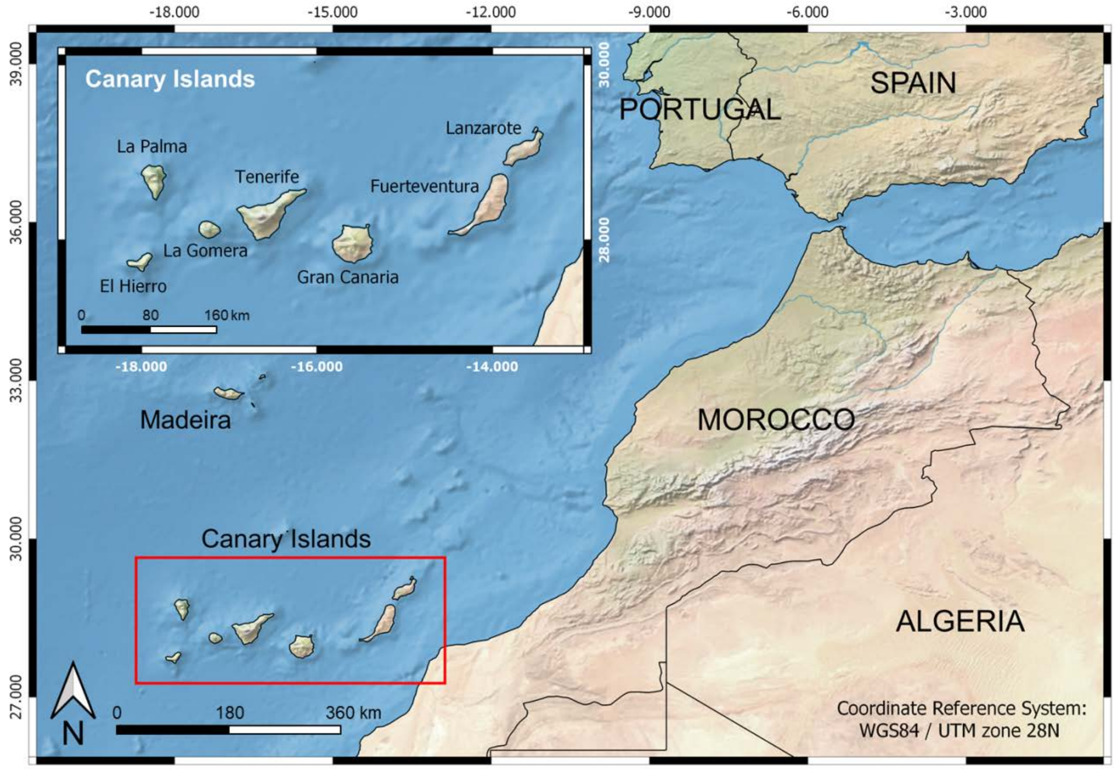

Figure 4. Geographical location of the Canary Islands in general, and Tenerife in particular. Source: own elaboration.

The geological evolution of Tenerife involved the construction of two principal volcanic complexes (Fig. 5): a basaltic shield complex (>12 Ma to present, Abdel-Monem et al., 1972; Ancochea et al., 1990; Thirlwall et al., 2000) and a central complex (<4 Ma to present, Fuster et al., 1968; Araña, 1971; Ancochea et al., 1990; Martí, Mitjavila, et al., 1994). The basaltic shield complex is mostly submerged and forms about 90% of the volume of the island. Although it is not known at what age the fissure eruptions began on the oceanic floor, which gave rise to the shield volcano, the first subaerial volcanic materials on the island emerged 12 Ma years ago in the northeast of the island, on the Anaga peninsula, according to existing radiometric dates (K—Ar and Ar—Ar) (Ancochea et al., 1990; Thirlwall et al., 2000). This period of construction of the basaltic shield is characterized by basaltic emissions from large magmatic chambers that formed three separate sectors that probably created three independent islands: the Anaga peninsula (in the northeast), the Teno peninsula (in the northwest) and the Roque del Conde sector (in the southwest). The three areas were formed, at different times, by piles of basaltic lava flows crossed by numerous dykes in the case of Anaga and Teno, and by a smaller number of dykes in the case of Roques del Conde. However, in the case of Anaga, the oldest area, more basaltic lavas from large Strombolian edifices with massive pyroclastic cones were deposited on this lava pile. On the other hand, the Teno lava pile underwent a landslide in one sector, generating a breccia deposit of several meters and leaving a depression, which was filled by more sub-horizontal basaltic lava flows (IGN, 2023a).

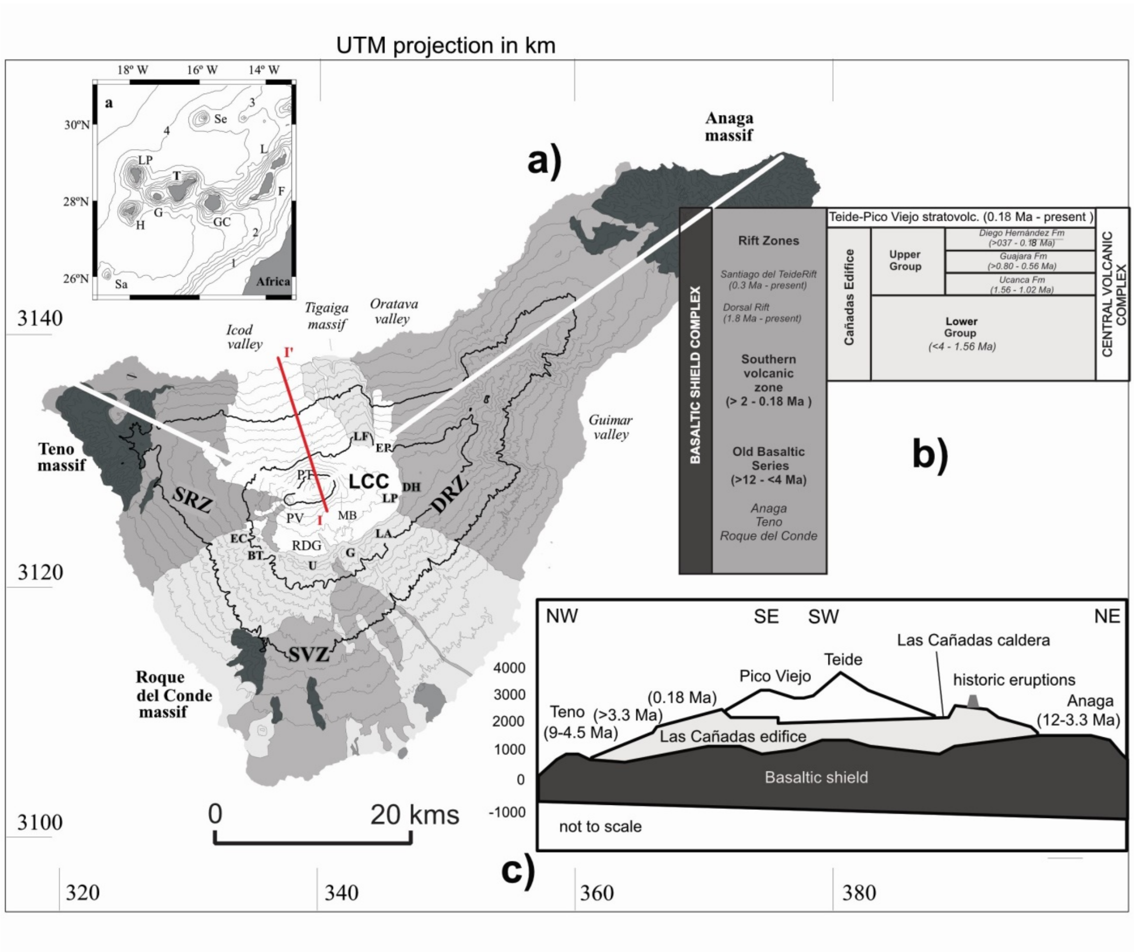

Figure 5. (a) Simplified geological map of Tenerife (modified from Ablay & Martí, 2000), (b) stratigraphy of Tenerife, and (c) schematic cross-section of the island. Source: López-Saavedra et al. (2021) (CC BY-NC-ND 4.0).

**Note: Las Cañadas caldera wall localities: EC-El Cedro; BT-Boca Tauce; U-Ucanca; RDG-Roques de García; G-Guajara; LA-Las Angosturas; LP-Las Pilas; DH-Diego Hernández; EP-El Portillo; LF-La Fortaleza. Main vent systems of the Teide–Pico Viejo formation: PT-Teide volcano; PV-Pico Viejo volcano; MB-Montaña Blanca. Post-shield mafic volcanic zones: SRZ-Santiago rift zone; DRZ-Dorsal rift zone; SVZ-Southern volcanic zone (locally known as Bandas del Sur). Names and locations of landslide valleys are also shown. Contour interval is 200 m. Isotopic ages are from Ancochea et al. (1990) and Martí, Mitjavila, et al. (1994). Inset map shows the location and distribution of the Canary Islands. Main islands: LP-La Palma; EH-El Hierro; G-La Gomera; T-Tenerife; GC-Gran Canaria; F-Fuerteventura; L-Lanzarote. The white lines correspond to the cross-section of part (c) of this figure, and the red line I–I' corresponds to the cross-sections in Fig. 19 and Fig. 20.*

The central complex corresponds to Las Cañadas edifice (<4–0.18 Ma), a composite volcano characterized by abundant explosive eruptions of highly evolved phonolitic magmas, and the active Teide—Pico Viejo twin stratovolcanoes (0.18 Ma to present). After a slowdown in the construction of the basaltic shield and following an important erosive period affecting part of it (about >3.5 Ma) (Ancochea et al., 1990; Martí, Mitjavila, et al., 1994), a more intensive phonolitic volcanism began, alternated with basaltic episodes, at the center of the island. The resulting volcanic products from several volcanic centres were deposited on the basaltic shield, together with the eroded materials, originating the mafic to felsic Lower Group (Martí & Gudmundsson, 2000), which ranges from > 3.5 Ma to < 2 Ma (Martí, Mitjavila, et al., 1994). A change in the eruptive dynamics of Tenerife between 2 Ma and 1.5 Ma initiated a period consisting of three long-term cycles of phonolitic explosive activity, with volumetrically larger and more extensive eruptions, that constructed Las Cañadas edifice Upper Group and ranges from 1.57 to 0.17–0.18 Ma (Ancochea et al., 1990, 1999; Mitjavila & Villa, 1993; Martí, Mitjavila, et al., 1994; Bryan et al., 1998; Huertas et al., 2002; Brown et al., 2003; Edgar et al., 2007; Boulesteix et al., 2012). Each of these phonolitic volcanic cycles terminated with a caldera collapse episode, giving rise to a central depression on the island known as the Las Cañadas caldera (Martí, Mitjavila et al., 1994; Martí & Gudmundsson, 2000; Martí, 2019). The formation of the caldera of Las Cañadas, of which the Teide-Pico Viejo stratovolcanoes are part (Fig. 5c), truncated the edifice of Las Cañadas, which was transformed by several vertical collapses occasionally associated with lateral collapses on the volcano's flanks (Martí, Mitjavila, et al., 1994; Martí et al., 1997; Martí & Gudmundsson, 2000). This is the case of La Orotava and Icod valleys, on the northern flank of Tenerife, which are coeval with the formation of the central (Guajara, 0.56 Ma) and eastern (Diego Hernández, 0.17 Ma) sectors of the caldera, respectively (Ibarrola et al., 1993; Martí et al., 1997; Martí & Gudmundsson, 2000; Carracedo et al., 2011; Hunt et al., 2011, 2013a, 2013b, 2018; Martí, 2019). This alternation of constructive (accumulation of volcanic and non-volcanic materials) and destructive (sector collapse, caldera collapse, erosion) periods is a characteristic that Tenerife shares with many other oceanic islands (e.g. El Hierro and La Palma in the Canary Islands, Anak Krakatau in Indonesia, Stromboli in the Aeolian Islands, Ritter Island in Papua New Guinea, Mount Pelée in Martinique).

The formation of the Icod valley in the north of Tenerife, for example, coincided with the eruption of El Abrigo (Martí, Mitjavila, et al., 1994; Martí et al., 1997; Hunt et al., 2011; Boulesteix et al., 2012; Paris et al., 2017), the last caldera-forming eruption that culminated the final phonolitic cycle of the Upper Group (0.179 Ma, Martí, Mitjavila, et al., 1994). According to Martí (2019), the inland stratigraphy of the related deposits reveals the temporal sequence of these catastrophic events and contrasts with that proposed by other authors (e.g., Paris et al., 2017; Hunt et al., 2018). The lack of El Abrigo deposits in the Icod valley contrasts with their presence throughout the rest of the island in a continuous 2–20 m-thick layer (Pittari, 2004; Pittari et al., 2008), which indicates that this eruption preceded the subaerial landslide. The landslide may have started on the submarine flanks during the unrest period preceding the eruption (Hunt et al., 2011, 2013a, 2013b, 2018), probably as a response to strong continuous seismicity and ground deformation caused by the inflation of the associated magma chamber (Andújar et al., 2008; Martí, 2019). This initial submarine landslide, involving volumes of 240–

264 km^3 (Hunt et al., 2011, 2013a, 2013b, 2018), would have continued on land during the caldera collapse episode and would have led to the removal of approximately 60 km^3 of the northern sector of the volcanic edifice (Iribarren, 2014). The result would have been a multistage retrogressive failure with stages separated by periods of several days (Hunt et al., 2011; Paris et al., 2017).

The subaerial landslide would have caused a tsunami whose deposits are preserved in thicknesses of 0.4–3 m on the north-west flanks of Tenerife at altitudes up to 132 m a.s.l. (Paris et al., 2017). A characteristic of these tsunami deposits found on the northern coast of Tenerife is that they contain pumice clasts from El Abrigo (Paris et al., 2017). This indicates that the tsunami and, consequently, the landslide that originated it, occurred once the eruption had ended or whilst it was still underway and the pumices were already deposited and floating on the surface of the sea.

An avalanche breccia, known as "Mortalón", with an inclination of 9.42° in Icod (Iribarren, 2014) and interpreted by Bravo (1962) and Coello (1973) as an old breccia deposit generated by previous mass wasting processes affecting the basaltic shield and the beginning of the construction of the Las Cañadas edifice, is thought in fact to represent the décollement surface for both La Orotava and Icod landslides.

Hürlimann et al. (2000) proposed adjacent and shallow seismic shocks caused by the seismogenic slip on the ring fault originated by the caldera collapse as the main driving forces triggering the large-scale subaerial slope failure; such shocks are capable of applying faster and more dynamic stress to slopes than other mechanisms such as dike intrusion (e.g., McGuire et al., 1990; Voight & Elsworth, 1997) and the inflation and deflation of the magma chamber (e.g., Lo Giudice & Rasa, 1992). According to stability analyses, an unstable state is reached for a seismic shock with a horizontal acceleration over 0.3 g. Assuming a magnitude of 5.0 for a seismic shock related to the caldera collapse at a distance of 5 km, a maximum horizontal acceleration coefficient (PHAC) of 0.29 would be generated (Hürlimann et al., 2000). Comparing these results with other observational data from some recent calderas (e.g., Filson et al., 1973; Abe, 1992; Riel et al., 2015; Alvizuri et al., 2020), a Mw magnitude of 5–7.2 is required for seismic shocks to have triggered the Icod landslide (Hürlimann et al., 2000).

After the El Abrigo caldera-forming eruption, the central volcanic complex has continued to build up from around 170—180 ka years ago to present, with the formation of the Teide—Pico Viejo complex on the northern margin of the Las Cañadas caldera (Martí, 2019). Over the last 35 ka years, these twin stratovolcanoes have given rise to strombolian, violent strombolian, and sub-plinian eruptions, as well as some phreatomagmatic eruptions, both from the central and flank vents, and have erupted both mafic (basalts, tephro-phonolites) and felsic (phono-tephrites and phonolites) magmas. According to Martí, Geyer, Andújar, et al. (2008), comparison of the volcanism associated with Teide—Pico Viejo with previous cycles of activity in the central complex reveals that they all follow a similar pattern in petrological evolution. However, Teide—Pico Viejo is dominated by effusive eruptions, what can be explained in terms of the different degree of evolution of Teide—Pico Viejo compared to the preceding cycles. Even so, the explosive potential of the latter complex should not be underestimated and the possibility of a fourth phonolitic cycle of Tenerife volcanism should be considered, leading to a new caldera-forming eruption in the future (Marti, 2019; López-Saavedra et al., 2021).

However, the basalt shield building volcanism has been acting in parallel and continues building up the subaerial part of the island to the present through eruptions along the northeastern (Dorsal Rift Zone) and northwestern (Santiago Rift Zone) fissure vent systems, as well as from several small scoria-lava cones at the heads of the major landslide valleys (La Orotava, Icod and Güímar) and from a broad monogenetic volcanic field to the south of the island (Martí, 2019). Proof of this is provided by the two most recent eruptions on the island: the Chahorra eruption (1798), which occurred on one of the flanks of Pico Viejo stratovolcano, and the Chinyero eruption (1909), which took place in the Santiago Rift.

The seismicity of Tenerife is closely related to historical eruptions, highlighting the high intensity earthquakes that occurred during the triple eruption of Siete Fuentes, Fasnia and Arafo (1704-1705) (Sánchez-Sanz, 2014). In fact, all historical eruptions have been preceded and/or accompanied by felt earthquakes (Romero, 1991). Currently this moderate-magnitude (no more than 2.0 or sometimes 3.0) and shallow seismicity related to magma intrusion and hydrothermal system dynamics is centered along the Santiago Rift Zone, especially around the volcanoes of Chahorra (1798) and Chinyero (1909), but also along the Rift Ridge Zone, at the volcanoes of Arafo, Fasnia and Siete Fuentes (1704-1705), and at the head of the southern monogenetic volcanic field (IGN, 2023a,b). But to this seismicity must be added the seismic swarms that occasionally occur on the island and that are concentrated in four outstanding seismogenic zones: the western area of Caldera de las Cañadas, where two seismic swarms of hundreds of low magnitude earthquakes occurred in 2016 and 2019; the Izaña area, with quite a lot of activity between 2009 and 2011; around Pico del Teide, where seismicity occurs recurrently; and the Vilaflor area, at the head of the southern monogenetic field, remaining intermittently until the present (Domínguez Cerdeña et al., 2019).

On the other hand, Tenerife is also affected by seismic activity due to regional tectonics in this area of the African plate. From GPS seismicity and cortical deformation studies (Jiménez-Munt et al., 2001; Jiménez-Munt & Negredo, 2003; Serpelloni et al., 2007; Jiménez-Munt et al., 2011; Cunha et al., 2012; Bezzeghoud et al., 2014) a simple extensional deformation field has been determined from west to east in the area of the Canary Archipelago, perpendicular to the Meso-Atlantic and Terceira ridges. In this tectonic context, Mezcua et al. (1992) defined two main fracture families that affect the area in which the islands are located: the African and the Atlantic families. As far as the African is concerned, the fractures are oriented ENE-WSW, coinciding with the axes of the islands of El Hierro-La Gomera and Tenerife, and NNE-SSW, coinciding with the Fuerteventura-Lanzarote axis (Fig. 6). On the other hand, the Atlantic family is oriented WNW-ESE, aligned with the La Palma-la Gomera-Tenerfie and Gran Canaria group of islands. The main seismicity in the area comes from the fractures located between Gran Canaria and Tenerife, belonging to the African family (Bosshard & Macfarlane, 1970; Mezcua et al., 1992). This seismicity can give rise to earthquakes of greater magnitude, such as the 5.2 earthquake of May 9, 1989 occurred between Gran Canaria and Tenerife (Bosshard & Macfarlane, 1970; Mezcua et al., 1992). This set of fractures could facilitate the ascent of magma to the surface, responsible of the volcanism in the Canary Islands (Anguita and Hernán, 2000).

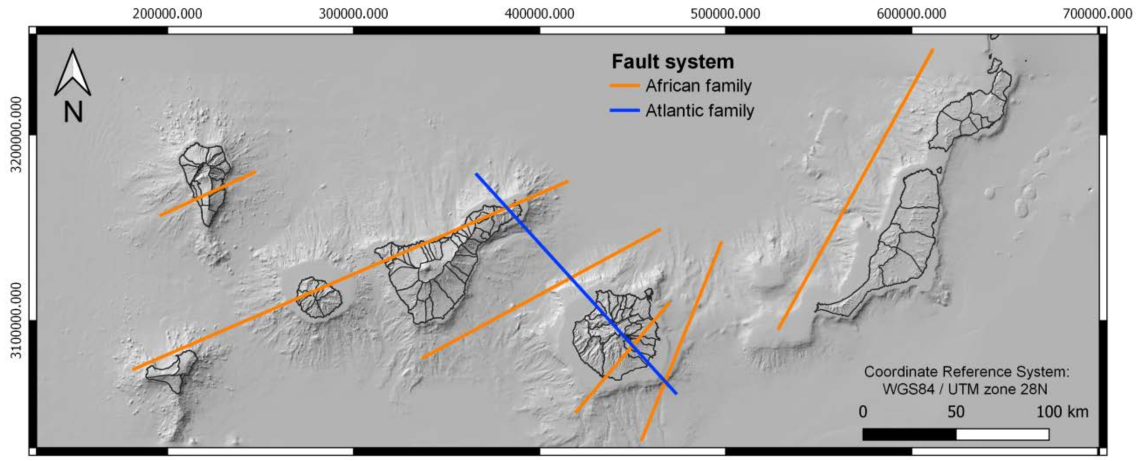

Figure 6. Volcano-tectonic lines of the Canary Islands' region. Source: own elaboration based on Bosshard & Macfarlane (1970), and Mezcua et al. (1992).

**Note: Orange lines = African family of faults; blue lines = Atlantic family of faults. Fault traces are not to scale nor is the location accurate, but are indicative.*

2.2.2. Climatology and hydrology

The Canary Islands have a subtropical climate characterized by warm air temperatures throughout the year (mild winters with a mean air temperature >20 °C), low precipitation (<225 mm/year) and many hours of sunshine (2800 h/year) (Azorin-Molina et al., 2018; Megías & García-Román, 2022). However, due to its location, the weather variability in the Canary Islands is influenced by the interaction between the semi-permanent Azores subtropical high-pressure system, and its relation with the Icelandic Low, and the air masses coming from the Sahara (Cropper and Hanna, 2014; Cabildo de Tenerife, 2020; Megías & García-Román, 2022).

For this reason, there are three main types of weather on the islands (Cabildo de Tenerife, 2020):

1) The trade winds regime, characterized by stable, warm and not very rainy weather, which originates mainly in summer, when the Azores Anticyclone withdraws towards the Portuguese coast.
2) The Atlantic squalls, which leave more unstable and rainy weather, especially in autumn and spring, originating when the Azores Anticyclone withdraws towards the center of the Atlantic and a Polar Front squall approaches.
3) Saharan weather, warmer and drier, especially in the winter months, although it can occur at any time of the year, and is caused when the Azores Anticyclone withdraws towards the center of the Atlantic and a dry air mass from the Sahara arrives. It is often accompanied by the well-known "calima" or Saharan dust in suspension.

However, Tenerife's climate is especially conditioned by its orientation and altitude (Cabildo de Tenerife, 2020; Megías & García-Román, 2022). This causes great differences in weather between the windward or northern part of the island, which receives the influence of the trade winds, causing more rainfall, higher humidity, and less sunshine, and the leeward or south of the island, a much drier and arid area. There are also great differences within each slope depending on the altitude (e.g., precipitation and average annual temperature, respectively, of 223 mm and 21 ºC on the coast of Santa Cruz de Tenerife, 559 mm and 16.8 ºC in the middle zone of Los Rodeos, and 487 mm and 10 ºC on the summits of Izaña) (Cabildo de Tenerife, 2020) (Fig. 7 and Fig. 8).

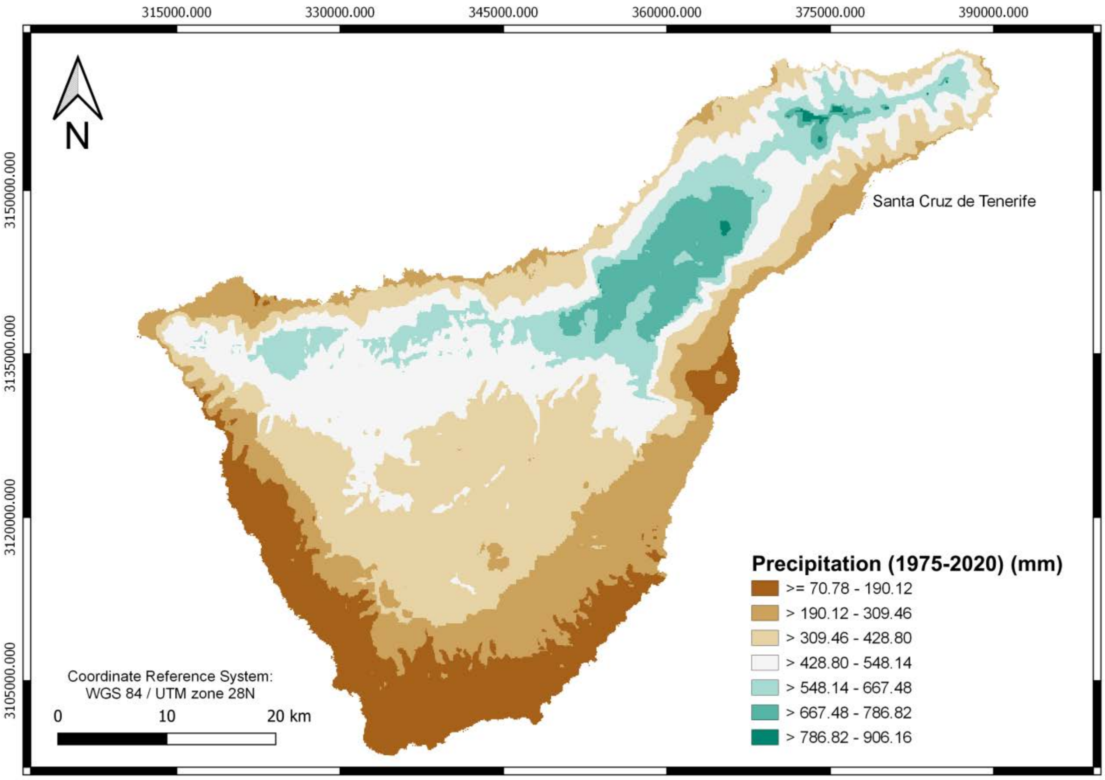

Figure 7. Precipitation of Tenerife (Canary Islands) during the period 1975-2020 measured in millimeters (mm). Source: own elaboration based on data and maps of the Government of the Canary Islands (2023b).

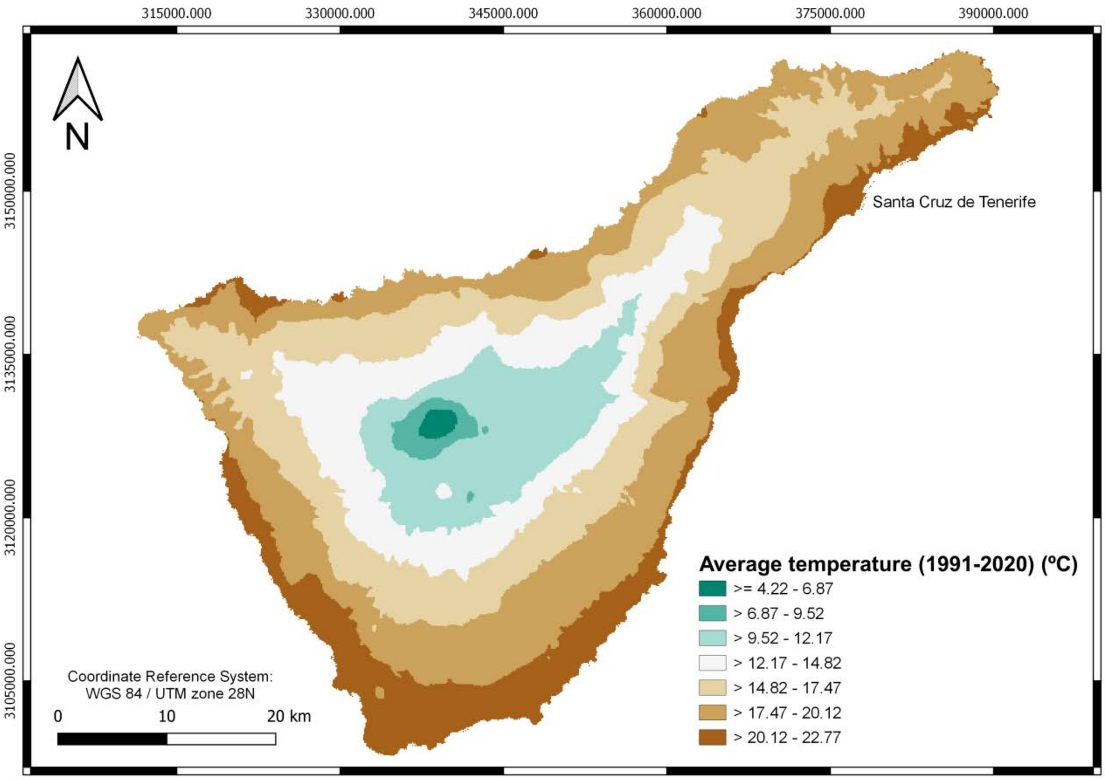

Figure 8. Average temperature of Tenerife (Canary Islands) during the period 1991-2020 measured in degrees Celsius (ºC). Source: own elaboration based on data and maps of the Government of the Canary Islands (2023c).

According to the Climate Atlas for the Archipelago of the Canary Islands, Madeira and Azores (AEMET-IM IP, 2012), and according to the Köppen climate classification (Köppen, 1884), which defines different types of climate based on the monthly mean values of precipitation and temperature, there are up to eight climatic zones on the island of Tenerife (Fig. 9). These are the following:

- BWh: hot desert, predominantly in the south.
- BWk: cold desert, on the southwestern slopes.
- BSh: warm steppe, on the eastern slopes and northern coasts.
- BSk: cold steppe, mainly on the southern slopes.
- Csa: temperate with dry and warm summer, in areas of higher altitude, as in the slopes and ravines of the Anaga area.
- Csb; temperate with dry and warm summer, widely spread in the interior.
- Csc: temperate with dry and cool summer, only in a narrow strip around the Pico del Teide between 2,600 and 2,900 m altitude.
- Dsc: cold without dry season and cool summer, only in the highest areas, from about 2,900 m altitude to the summit of Teide.

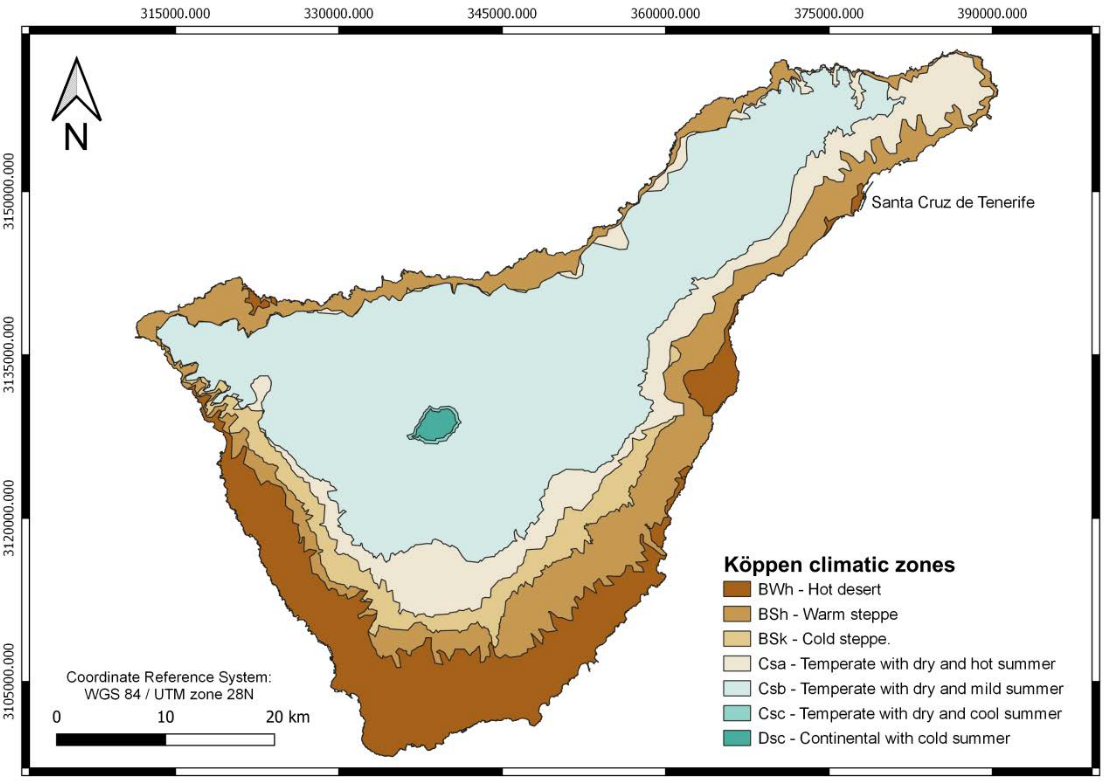

Figure 9. Köppen-Geiger climate classification in Tenerife (Canary Islands). Source: own elaboration based on data and maps of the Government of the Canary Islands (2023a).

The great irregularity of rainfall and the small size of the basins that contribute to each of the existing ravines on the island, combined with the high permeability of the geological materials that make up the substrate, mean that the nearly 4,500 ravines of Tenerife are dry throughout the year (Cabildo de Tenerife, 2020). These ravines, with a radial distribution from the center of the island towards de coasts, have been eroded over millions of years by water and wind, and are characterized by deep incisions in the terrain, very vertical walls, and steep slopes. In these watercourses, surface runoff is scarce, being greater at the headwaters than in the intermediate sections or at the mouth, where barely 2% of the total precipitation is discharged into the sea. A large part of the water infiltrates and recharges the aquifers at a rate of about 175 mm/year, accounting for 44% of precipitation (Cabildo de Tenerife, 2020). The rest is evaporated, absorbed by vegetation, retained by humans or lost in other ways.

Although some groundwater can circulate and may accumulate in loose pyroclastic and alluvial deposits, most of it accumulates in fractured volcanic rocks. According to Marrero (2010), the aquifer of Las Cañadas del Teide, in the central part, is the main water reserve of the island, which has a close interaction with the volcanic-hydrothermal system of Teide (Fig. 5). The rocks that make up the aquifer have primary porosity (bubbles formed by gas escape, lava tubes, shrinkage crack during the cooling of lava), secondary fractures (formed by tectonism, local contact metamorphism, or weathering, after the cooling of lava), baked tuffs, soils, and paleosols (locally named “almagres”, are red horizons between some lava flows), and dikes (injected in profusion into the Cañadas Series) that facilitate the circulation and formation of this water reservoir (Ecker, 1976). Ecker (1976) distinguishes three main hydrological zones: (1) the upper vadose zone, which runs from the surface to the lower vadose zone, and is characterized by permeable and impermeable materials, where infiltration occurs through fractures and fissures, and some small reservoirs may form. This zone has an average thickness of 200-400 m in the mountainous areas of the island. (2) The lower vadose zone, which goes from the upper vadose zone to the saturated zone, and is characterized by compartments or reservoirs of groundwater separated by dry zones and connected by flows. This zone is almost parallel to the topographic slopes of the island and has an average thickness of about 1,000 m, although in many coastal areas, this layer is non-existent. (3) The saturated zone located below the lower vadose zone, with closely-placed aquifers or compartments and a high percentage of saturated fractures, and is characterized by an oblique subterranean water flow towards the sea, with a gradient of about 0.3‰ in Güímar, but with a much steeper gradient in the Anaga and Teno area. This layer is strongly influenced by the tides, forming a temporary barrier of subterranean water parallel to the coast at high tide.

It should be noted that, in the Orotava-Tigaiga Valley area, the Mortalón (previously described in section 2.2.1. “Geographical and geological context”), constitutes a wedge-shaped impermeable unit that slopes northwards towards the sea. When infiltrated water comes into contact with this unit, it flows over it towards the sea through some of the paleovalleys (Ecker, 1976).

2.2.3. Socio-economic and political context

The Canary Islands is a former Spanish colony, conquered in the late 15th century by the Spanish. Previously this region was inhabited by the Guanches, Tenerife's ancient aborigines from North Africa. The entire archipelago corresponds to one of the 17 autonomous communities into which Spain is divided. An autonomous community is a territorial entity that is endowed with autonomy, with its own institutions and representatives and certain legislative, executive and administrative powers. Each autonomous community is divided into provinces, a Spanish administrative demarcation whose government and administration is constitutionally attributed to the provincial councils, representative corporations based on municipal corporations. Tenerife, together with the islands of La Palma, La Gomera and El Hierro, makes up the province of Santa Cruz de Tenerife, one of the two provinces into which the autonomous community of the Canary Islands is divided. However, both provinces are an exception, since their government and administration, in the aspects that do not correspond to the autonomous community, is not carried out by the provincial councils as it happens with the rest of Spanish provinces, but by the island councils, such as the Tenerife Council (Cabildo de Tenerife in Spanish). These types of exclusive administrative entities of the Canary Islands have, among their competences, the protection of the environment, the management and conservation of protected natural spaces, forestry services, livestock trails and pastures, the subrogation in the municipal competences on urban planning, or the approval of the Insular Plans of Works and Services elaborated in collaboration with the Town Councils of each island. At the same time, the whole area of Tenerife is divided into thirty municipalities, as it is shown in Fig. 10.

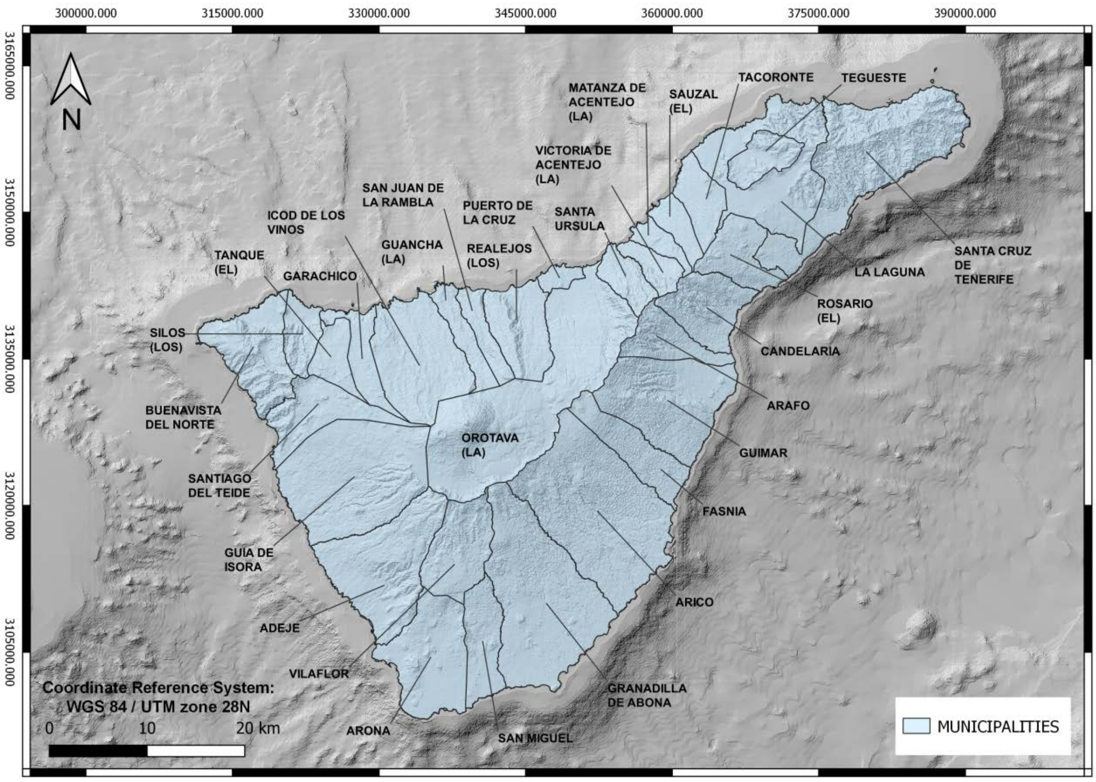

Figure 10. Municipalities of Tenerife (Canary Islands). Source: own elaboration based on material from ISTAC (2021).

According to the ISTAC (2021), Tenerife's economy is mainly based on the Services sector, which contributes nearly 78% of the island's Gross Domestic Product (GDP). Commerce, transportation, lodging, and communications account for 32% of the total GDP of the island, totaling almost EUR 6.5 billion. Construction, on the other hand, contributes nearly 6% of Tenerife's GDP, ahead of industry at 5%. Agricultural activity on the island generates 1.7% of the GDP. With this situation, Tenerife is the most socio-economically important of the Canary Islands.

According to the PEIN (Cabildo de Tenerife, 2020), the primary sector has lost its traditional importance in the island's economy in favor of services. The agricultural sector is developed on the northern slope, where crops are distributed on the basis of altitude: in the coastal or lower zone tomatoes and bananas are grown, both highly profitable products since they are exported to the Peninsula and the rest of Europe; in the intermediate zone there are rainfed crops, especially potatoes, vegetables and corn; in the southern zone tomato and banana crops are important but in intensive production and normally under greenhouses, with the priority objective of exporting them to the rest of Europe. The total cultivated surface area amounts to some 16,000 hectares—some 10% of the island's territory— (ISTAC, 2021). Linked to the main traditional agricultural production processes is livestock farming, predominantly goats, followed by pigs, and to a lesser extent sheep and cattle. And we must not forget the fishing subsector, and the related activities of industry and distribution. This subsector contributes to the diversification of the social and economic fabric and acts as an asset to the tourism sector (Cabildo de Tenerife, 2020).

Industrial activity is not very significant, although there are some industrial estates (Güímar, Granadilla, El Mayorazgo, etc.). The most important activities in this sector are the Santa Cruz refinery, currently being dismantled, the Granadilla and Las Caletillas power stations, and the food and tobacco industries (Cabildo de Tenerife, 2020). Within the industrial sector, the construction sector is also noteworthy. Anyway, cement sales have declined considerably in recent years, underscoring the slowdown in this sector. However, construction continues to grow, albeit at a slower pace, driven by the demand for infrastructure to accommodate the growing influx of tourists and for housing construction and civil works to cope with population growth (Cabildo de Tenerife, 2020).

The tertiary sector, and specifically tourism, is the predominant sector and the one exclusively responsible for maintaining the current productive structure and consequently the basic parameters of the material life of the population (employment, consumption, standard of living, etc.) (Cabildo de Tenerife, 2020). Tourism industry adds between 4 and 4.5 million visitors every year (ISTAC, 2021). For these reasons, the island's economic development plans find no alternative to maintaining and consolidating tourism.

2.2.4. Resources and land-use planning

Tenerife has a great variety of natural resources, especially because of its great geodiversity and geological heritage (e.g., Dóniz-Páez, Beltrán-Yanes, et al., 2020; Dóniz-Páez, Hernández, et al., 2020; Marrero & Dóniz-Páez, 2022; Martí et al., 2022). Its geographical location not only makes it a strategic commercial point in the Atlantic, but also gives it several unique properties. On this island, as in so many other active volcanic regions of the planet, the initial and main cause of the proliferation of population centers is to be found in the richness of its soils, which favors, especially in regions with tropical and temperate climates, the development of intensive agricultural and forestry operations on the slopes of volcanic edifices, sometimes even in areas located in the proximity of the eruptive mouths. This cause of development, which was predominant throughout the 18th and 19th centuries, changed during the 20th century, with the increase in the location of the population in urban centers and the expansion of the urban and industrial fabric, together with the lack in many cases of adequate protection or planning. This has led to an increasing number of settlements being located in the immediate vicinity or directly on high-risk areas.

Since its colonization by the Spanish (late 15th century), Tenerife has been used for intensive agriculture. The volcanic materials provide the soil with a great variety and quantity of nutrients that are ideal for the crops grown here, especially bananas, as well as tomatoes, potatoes, and grapes. Until the mid-1960s, agricultural sector was the mainstay of the island's economy. However, the pressure on agricultural land for other uses, especially tourism and residential use, has led to the abandonment of large areas of cultivated land. In parallel, farms have increased in coastal areas, particularly in the arid lands of the southwest coast, leading to a higher water consumption and expansion of infrastructure near the coasts (Günthert et al., 2011, 2012). These volcanic materials are also used as building materials in what the island seeks to be sustainable architecture. The main materials exploited are ignimbrites, as ornamental or facing stones, and the main quarries are located at the south of the island, such as Cantera Guama-Arico S.L. (Arico, southeast, Fig. 10).

On the other hand, its climatological characteristics, especially the high sunshine, allow the island to have several photovoltaic parks in the municipality of Arico (southeast) and some in Granadilla de Abona (south), with a total power of more than 300 kW, in addition to several more parks in the process of being approved for the same municipalities and for Arona (southwest) (IDE Canarias, 2022). The southeastern coast of the island also hosts several existing wind farms, with several more planned for development in the future. The topography of the island, which causes significant variations in altitude, together with the consequent distribution of rainfall and winds, leads to the existence of a wide variety of ecosystems and unique landscapes in a small area. This has caused the island to have abundant and diverse flora and fauna. This biodiversity, coupled with the existing geological heritage, transforms these natural resources into a significant tourist resource. Moreover, in recent years, there has been a rise in rural and nature tourism.

But it should not be forgotten that the most precious resource of any territory with these exploitable resources is the land. And on an island, with limited space, land is scarce and the pressure exerted by some sectors on others forces land use to change according to economic interests, to abandon some areas, to conquer others, sometimes in high-risk areas, to expropriate areas or to enter into conflict with protected areas. Furthermore, we must take into account that the population density of Tenerife, only residents, was around 451 inhabitants/km^2 in 2021; including tourists, it exceeds 500 inhabitants/km^2. But if we take into account that 45% of the island's territory is protected, the population density in the remaining 55% of "useful land" is almost 1,000 inhabitants/km^2, surpassing that of Mallorca Island (Spain) and Japan (Canarias Ahora, 2021).

At present, the Tenerife's land uses are divided into urban areas, agricultural areas, environmental protection areas, and territorial protection areas (Fig. 11) (Cabildo de Tenerife, 2011). With regard to the first use, ISTAC identifies two main urban nuclei, the metropolitan area of Santa Cruz de Tenerife-San Cristóbal de La Laguna (northeast) and the tourist center of Puerto de la Cruz-Los Realejos (north) (Fig. 12). To these we must add the tourist center of Los Cristianos and Las Américas (Arona, southwest), and the industrial and tertiary urban areas of Güímar (east), Granadilla de Abona (south), and Santa Cruz de Tenerife (northeast). Urban centers correspond to a minimum population density of 1,500 inhabitants/km^2 and a minimum population of 50,000 inhabitants. However, the majority of urbanization corresponds to semi-dense urban agglomerations, i.e., with a minimum density of 300 inhabitants/km^2 and between 5,000 and 49,999 inhabitants. The remainder corresponds to dense urban agglomerations (≥1,500 inhabitants/km^2 and between 5,000 and 49,999 inhabitants), rural and low-density conglomerations (≥300 inhabitants/km^2 and ≥50 inhabitants/km^2, respectively, but in isolated nuclei without contiguity), and urban periphery (≥300 inhabitants/km^2 and 500–49,999 inhabitants) (ISTAC, 2021) (Fig. 12).

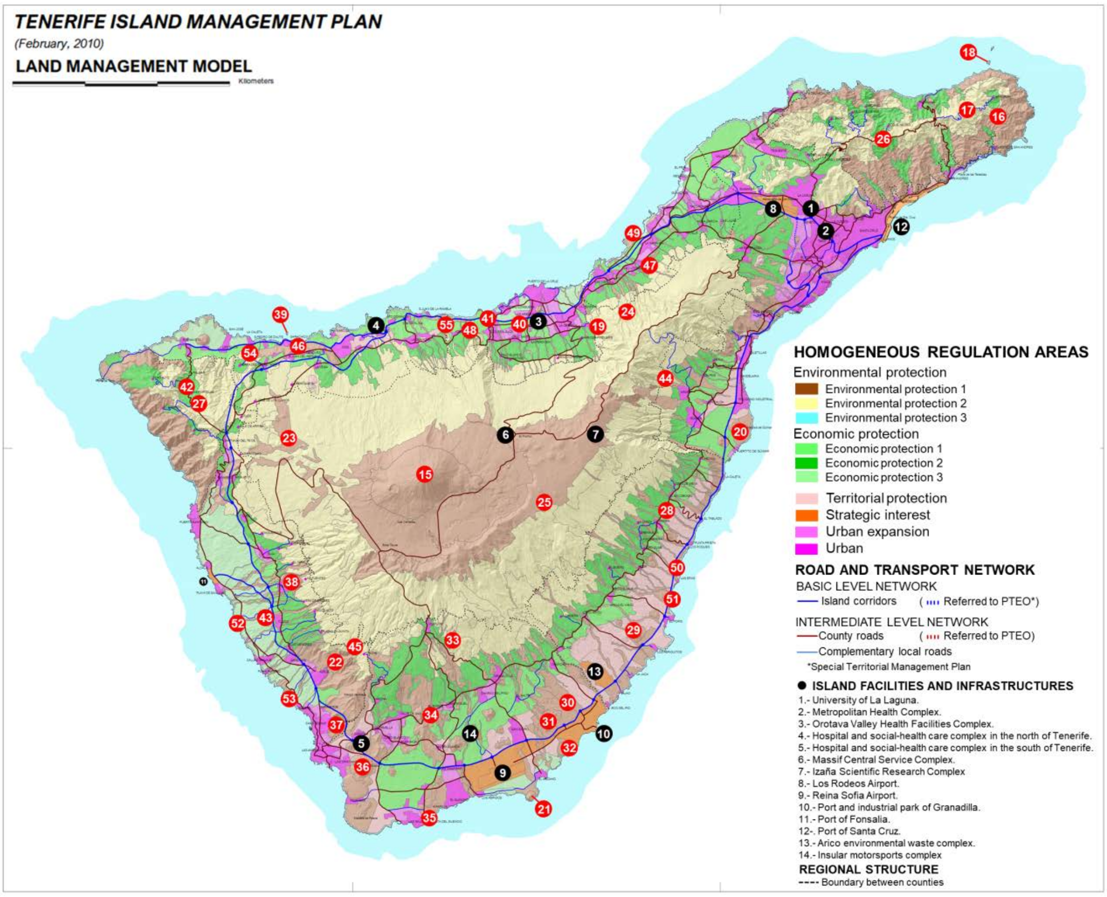

Figure 11. Land management model of the Tenerife Island Management Plan (PIOT). Source: modified from Cabildo de Tenerife (2011).

**Note: Numbers in red circles are the locations of the sites mentioned in Table 2.*

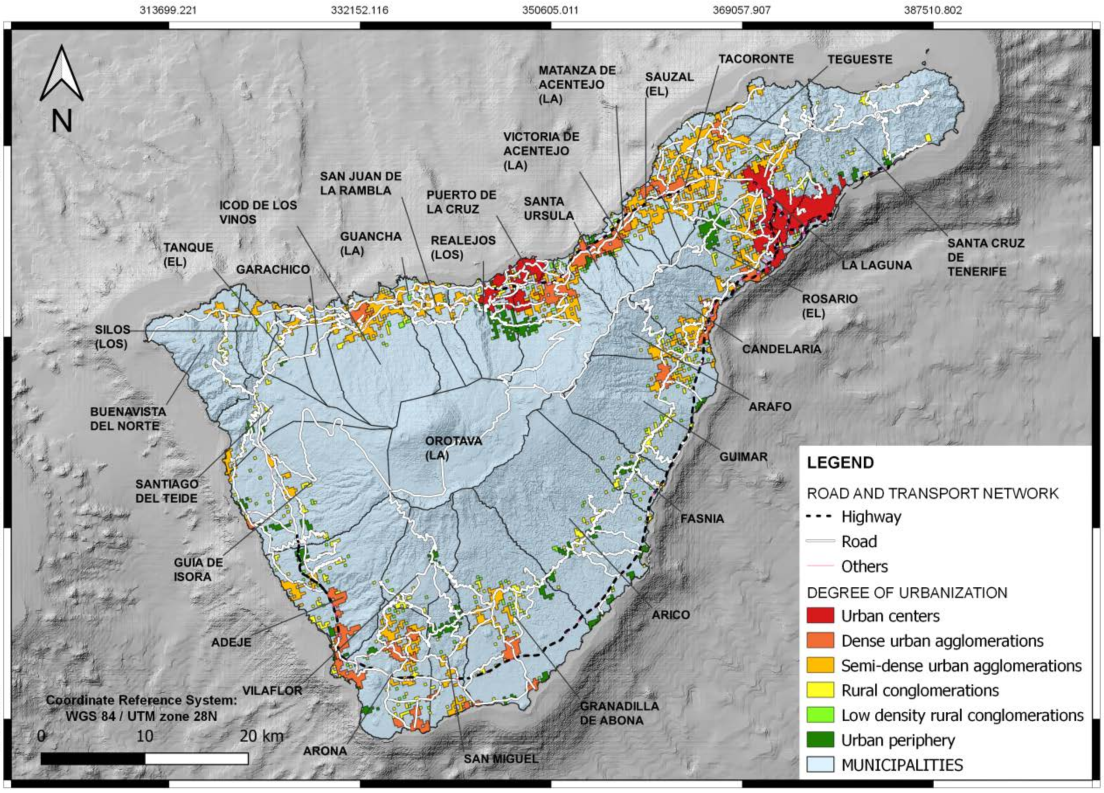

Figure 12. Urbanization and road and transport network of Tenerife (Canary Islands). Source: own elaboration based on material from ISTAC (2021).

The entire urbanized area, which would include the categories described above, is distributed peripherally around the central part of the island, where Teide National Park (TNP) is located (compare Fig. 11 and Fig. 12) and, therefore, the central depression of the Caldera de las Cañadas, which houses the Teide-Pico Viejo volcanic complex (Fig. 5). The main areas of future growth of the island highlighted by the Tenerife Island Land Management Plan (PIOT) are the metropolitan area of Santa Cruz-La Laguna, the Orotava Valley (north), and the southern zone comprising Las Américas-Los Cristianos (Arona) (Fig. 12). In contrast, the land for agricultural use is configured in a ring at the base of the central volcanic edifice, divided into the coastal part, with intensive crops, and the inland part, with traditional crops. Separately, the environmental protection areas include most of the forest areas in the central part of the island, the TNP, declared on 22 January 1954, spanning 18,990 ha, and the surrounding forest crown, the two extreme massifs (Anaga and Teno), and the rest of the Protected Natural Spaces. Finally, the territorial protection areas are those considered to be land reserves for the future, which preserve the vacant territory as a fundamental resource, the main ones being Las Américas and the northern midlands.

The distribution of communication routes follows this same peripheral pattern, except for a few roads that reach the two main entrances to this central depression—one to the southwest and the other to the northeast, joined by a road that crosses the Caldera de las Cañadas (Fig. 5 and Fig.

12). According to the PIOT, there are two levels of the road and transport network. The basic level network, made up of what are known as island corridors, corresponding to the TF-1 highway, which runs along the entire south from west to northeast, the TF-5, which runs through the northeastern half of the island, the TF-2 that joins both in the east, and a series of roads that connect all the towns closest to the coast around the island. In addition, there is the intermediate level network, composed of county roads and complementary local roads that, following the same ring distribution, connect the rest of the municipalities.

In terms of facilities and infrastructure, the island has two airports, Los Rodeos in the northeast and Reina Sofia in the south, as well as three ports, Santa Cruz in the northeast, Granadilla in the south, and Fonsalía in the west (Guía de Isora municipality) (Fig. 12). It also has two hospital complexes and health care partners—one in the north and the other in the south, and a further health facility complex in the Orotava Valley. Santa Cruz de Tenerife is also the administrative center of the island as it is home to several political and administrative bodies (such as the Parliament, Government of the Canary Islands, Cabildo Insular). In addition, in Tenerife there are four thermal power plants located in Candelaria (fuel oil/diesel, which are in the process of being dismantled), Granadilla de Abona (fuel oil/diesel), Santa Cruz de Tenerife (fuel oil, next to an oil refinery, both in the process of being dismantled) and Arona (diesel).

The high diversity and uniqueness of its landscapes, ecosystems, natural resources, among other features, have provided Tenerife with an extensive network of protected natural areas (Fig. 11). More than 50% of the island is protected as a natural monument, nature reserve, national park, site of geological interest, protected landscape, rural park, or natural park. In addition, the important geodiversity of volcanic products and the many sites of special geological interest (Cardozo-Moreira et al., 2014; Dóniz-Páez, 2014; Martí et al., 2022) have endowed the island with a unique geological heritage. Given the wide extension of protected areas and the fact that some of the reasons for their protection or conservation interest are due to elements formed from volcanic and/or geological processes of other origin, it is to be expected that in many of these areas a natural hazard will prevail. This is shown in Table 2.

Table 2. Relationship Between Tenerife's Protected Natural Areas, Their Geological Heritage, and Their Main Geological Hazards. Source: own elaboration based on information from Cabildo de Tenerife (2011).

Type	Site	Geological Heritage	Geological hazards sensitivity
National parks	Teide (15)	Volcanism	Volcanic eruption
Strict nature reserves	Ijuana (16)	Erosion	Landslide
	Pijaral (17)	No	No
	Los Roques de Anaga (18)	Erosion	No
	Pinoleris (19)	No	No
Nature reserves	Malpaís de Güímar (20)	Lava flow	Volcanic eruption

Type	Site	Geological Heritage	Geological hazards sensitivity
	Montaña Roja (21)	Volcanism / Erosion	Volcanic eruption
	Barranco del Infierno (22)	No	Mud Flows / Alluvial Fan
	Chinyero (23)	Volcanism	Volcanic eruption
	Las Palomas (24)	No	No
Natural Parks	La Corona Forestal (25)	No	No
Rural Parks	Anaga (26)	Erosion / Old Volcanism	Landslide
	Teno (27)	No	No
Natural Monuments	Barranco de Fasnia y Güímar (28)	Erosion	Landslide
	La Montaña Centinela (29)	Volcanism	Volcanic eruption
	Los Derriscaderos (30)	Volcanism	Volcanic eruption
	Las Montañas de Ifara y Los Riscos (31)	Volcanism	Volcanic eruption
	Montaña Pelada (32)	Volcanism	Volcanic eruption
	La Montaña Colorada (33)	No	No
	Roque de Jama (34)	Old Volcanism	No
	La Montaña Amarilla (35)	Volcanism	Volcanic eruption
	La Montaña de Guaza (36)	Volcanism	Volcanic eruption
	La Caldera del Rey (37)	Volcanism	Volcanic eruption
	La Montaña de Tejina (38)	No	No
	Teide (15)	Volcanism	Volcanic eruption
	Roque de Garachico (39)	Erosion	Landslide
	La Montaña de Los Frailes (40)	Volcanism	Volcanic eruption
Protected Landscapes	La Rambla de Castro (41)	No	Mud Flows / Alluvial Fan
	Las Lagunetas (42)	No	No
	Barranco de Erques (43)	Geomorphology	Mud Flows / Alluvial Fan
	Las Siete Lomas (44)	Volcanism	Volcanic eruption
	Ifonche (45)	No	No
	Los Acantilados de la Culata (46)	Geomorphology	Landslide
	La Resbala (47)	No	No
	Los Campeches, Tigaiga y Ruíz (48)	Geomorphology	Mud Flows / Alluvial Fan
	Costa de Acentejo (49)	Geomorphology	Landslide
Sites of Scientific Interest	Acantilado de La Hondura (50)	Geomorphology	Landslide
	Tabaibal del Porís (51)	No	No
	Los Acantilados de Isorana (52)	Geomorphology	Landslide
	La Caleta (53)	No	No
	Interián (54)	No	No
	Barranco de Ruiz (55)	No	No

**Note: The numbers in brackets are the locations shown in Fig. 11 in red circles.*

The TNP was classified as a UNESCO World Heritage Site in 2007 and now receives around 3.5 million visitors annually (Martí et al., 2022). Among the many visitors, there have always been many students and academics from universities and research centers. The reason for this is the visibility of most of the park's geological outcrops, where most textbook volcanic processes and products can be directly observed and studied (Martí et al., 2022). The park embraces the Las Cañadas caldera complex and the twin stratovolcanoes of Teide and Pico Viejo, as well as numerous intra- and extra-caldera volcanic vents, some of which are related to the Dorsal and Santiago del Teide active rift systems (Fig. 5). High interest within the international scientific community has led to a considerable number of studies (see Martí, 2019) and the consequent volume of information (geological, volcanological, geophysical, geomorphological, hydrogeological, petrological, etc.) about Las Cañadas and El Teide-Pico Viejo and their formation. However, the information available to visitors on the wide geodiversity of this area is small or non-existent—or even erroneous when compared to existing scientific information. Likewise, available outreach and dissemination resources for visitors and park guides are few and far between, and are often out-of-date and lack the scientific rigor to be expected for such a geologically important site (Martí et al., 2022).

However, we must not forget that all these activities require the supply of one of the most precious and currently most threatened resources: water. The increase in population, the increase in tourism, the increase in the exploitation of building materials to supply this demographic and urban expansion, and the intensification of agriculture, especially in more arid areas, all have one factor in common: the increase in demand for water. In an area where we have already seen that the only fresh water is groundwater, this means overexploitation of aquifers, with associated risks such as salinisation or contamination of aquifers and shortages, or the need to import it from outside, with the consequent need for increased boat traffic and associated infrastructure. According to Rodríguez-Urrego et al. (2022), groundwater extraction in recent years (2010–2019) has caused a water depletion in aquifers, represented by a 7.0% decrease in natural water extracted by wells and a 15.0% decrease in galleries. Currently, Tenerife has 401 wells from which 145 are producing freshwater (in exploitation), and most of them are located in the coastal areas, where most of the socioeconomic activities are based (Rodríguez-Urrego et al., 2022).

But in addition, the availability of fresh water is strongly affected by climate change, due to altered precipitation patterns, acidification of waters due to pollution, and degradation of freshwater ecosystems (Rodríguez-Urrego et al., 2022). Considering that Spain is among the 33 countries that will face extreme water stress by 2040 according to the World Resource Institute (WRI) (Maddocks et al., 2015), and being an island with limited resources and unstoppable economic development, the need for nature-based solutions becomes more and more evident.

2.2.5. Future natural and socio-economic challenges

Tenerife meets practically all the characteristics described in section 2.1. "Key features of active volcanic islands". However, some peculiarities make it particularly vulnerable compared to other similar islands.

As an active volcanic island, volcanic risk is the flagship natural risk of this region along with the rest of the islands of the Canary archipelago —which differentiates it from the rest of the national territory— given that the Canary Islands is the only volcanically active region in Spain. Tenerife is among the most likely to host an eruption in the future, having recorded up to four historical eruptions (i.e. the period from the conquest in 1496 to the present day). But in addition, with its more than 8,000 meters above the sea floor, this island is one of the largest volcanic structures in the world, together with Mauna Loa in Hawaii. The fact to host Teide volcano, an active stratovolcano that has given rise to large explosive eruptions in the past that may recur, puts Tenerife at the center of concerns about suffering a volcanic catastrophe in the future. But we must not forget that volcanic phenomena, although striking and, in extreme conditions, catastrophic, are not the only and most frequent phenomena in this region.

As we mentioned, Tenerife has experienced several major eruptions in historical times, all corresponding to basaltic volcanism, the last being the Chinyero eruption in 1909. Furthermore, this region is also the scene of multiple hazards that cause annual economic losses and sometimes even the loss of human life. Throughout its history, the people of Tenerife have lived through floods, storms, landslides, earthquakes, epidemics and volcanic eruptions. The Guanches, for example, referred to *Guayota* (The Evil One) who lived on *Echeyde* (the volcano of Teide), which proves that these people lived through volcanic manifestations, a fact corroborated by the geological record. This geological record also shows that Tenerife experienced extreme events in the past, which could be repeated in the future. However, this intrinsic multi-hazard nature of the island has not slowed down its demographic expansion and urban development. Nor has this potential risk scared off tourism.

The Territorial Insular Emergency Plan for Civil Protection of the Island of Tenerife (PEIN) (Cabildo de Tenerife, 2020) identifies hydrological risks, seismic movements, volcanic eruptions, adverse atmospheric phenomena, slope movements, locusts pests, and forest fires. In addition, the PEIN carries out a comparative risk analysis to classify the different phenomena according to their probability of occurrence and their consequences, in order to assign them a priority in the programming of planning actions. This is based on the information available on the occurrence of events that can potentially cause damage in the island territorial space (hazard estimation), as well as on the analysis of the elements that can be affected (vulnerability estimation), such as the population, basic infrastructures, historical heritage, protected areas, etc. When assessing risks, probability (in relation to the estimated or foreseeable frequency) and severity (dimension of the damage) are considered. Thus, quantitatively, the level of risk has been estimated on the basis of an index, which combines the degree of probability of occurrence of an event and the damage it may cause, expressed as follows:

Risk Index (RI) = Probability Index (PI) × Severity Index (SI).

The PI and SI can be as follows (Table 3):

Table 3. Risk Probability and Severity Indices. Source: Cabildo de Tenerife (2020).

Probability of occurrence of the hazard		Severity of risk	
0	Practically zero	0	No damage
2	Very low. No constancy	1	Minor material damage
3	Low. One occurrence every several years.	2	Minor material damage and/or some people affected
4	Medium. Every few years (less than 10 years)	5	Large material damage and/or many people affected
5	High. Once or several times per year	10	Major material damage and/or fatalities

Based on the value obtained after multiplying each PI and each SI given to each phenomenon, we can classify the risks according to their RI as follows (Table 4):

Table 4. Risk Index (RI). Source: Cabildo de Tenerife (2020).

LOW	0 ≥ IR ≥ 5	Minimal or virtually no risk
MEDIUM	6 ≥ IR ≥ 8	A risk to be considered in the PEIN
HIGH	10 ≥ IR ≥ 15	It is recommended that specific civil protection measures be adopted within the PEIN
VERY HIGH	20 ≥ IR ≥ 50	In addition to the recommendations included in the PEIN, reference is made to the Special Plan corresponding to the risk in question

Thus, the following risk classification included in the PEIN has been obtained (Table 5):

Table 5. Classification of the Level of Risk of Different Natural Phenomena in Tenerife According to Their Probability and Severity. Source: Cabildo de Tenerife (2020).

NATURAL RISKS					
Type of risk	**Phenomenon**	**PI**	**SI**	**RI**	**Level of risk**
Hydrological risks	Floods	4	10	40	Very high
	Ruptures of large storage infrastructures	2	5	10	High
Seismic movements	Earthquakes	3	2	6	Medium
	Tsunamis	3	2	6	Medium
Volcanic eruptions		3	10	30	Very high
Adverse atmospheric phenomena	Snowfall	5	1	5	Low
	Torrential rains	5	10	50	Very high
	Hailstorms and frost	5	1	5	Low
	Strong winds	5	5	25	Very high
	Coastal storms	5	2	10	High
	Heat waves	5	2	10	High
	Haze and dust in suspension	5	5	25	Very high
	Droughts	3	5	15	High

NATURAL RISKS					
Type of risk	**Phenomenon**	**PI**	**SI**	**RI**	**Level of risk**
Slope movements	Rockfall	5	2	10	High
	Landslides	4	2	8	Medium
	Coastal erosion	4	2	8	Medium
Locust pests		2	2	4	Low
Forest fires		5	10	50	Very high

According to this PEIN classification, forest fires and torrential rains would be the phenomena that pose the greatest risk to the population of Tenerife, as they are the most frequent and the most severe. These risks would be followed by floods, volcanic eruptions, strong winds and haze or suspended dust. On the other hand, snowfall, hailstorms, frost, together with locust pests, would be the phenomena with the lowest risk.

However, these events are not the only natural risks facing Tenerife. One of the most alarming problems for a territory that is surrounded by water on all sides is precisely the rise in sea level. NASA has produced several future sea level projections based on the assessment presented in the IPCC Sixth Assessment Report (Fox-Kemper et al., 2021; Garner et al., 2021; IPCC, 2022; Garner et al., in prep.), and has made them available in an online tool where sea level rise for different parts of the globe can be viewed (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool; Creative Commons Attribution 4.0 International License: https://creativecommons.org/licenses/). Sea level projections considering only processes for which projections can be made with at least medium confidence are provided, relative to the period 1995–2014, for five Shared Socioeconomic Pathway (SSP) scenarios and five different future Global Mean Surface Temperatures (from 2080-2100). Sea level projections are also provided at five specific future Global Mean Surface Temperatures (from 2080-2100): 1.5°C, 2°C, 3°C, 4°C and 5°C.

According to these data, the worst-case scenario for Tenerife would imply a sea level rise of 1.53 m (SSP5-8.5, see Fig. 13). Under a best-case scenario (SSP1-1.9, see Fig. 13), sea level rise would be 0.75 m.

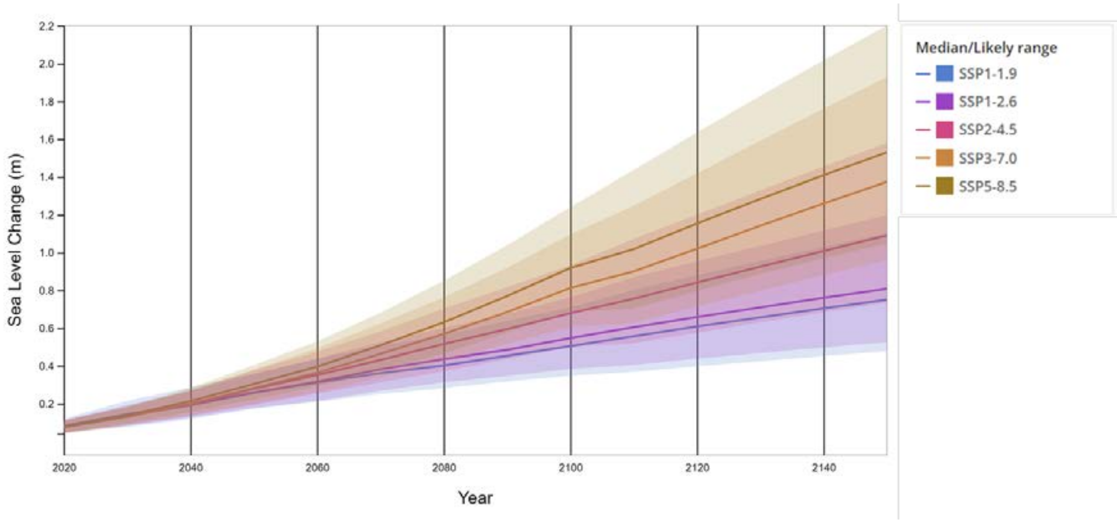

Figure 13. Projected sea level rise under different SSP scenarios for Tenerife. Source: Fox-Kemper et al. (2021), Garner et al. (2021), Garner et al. (in prep.), Creative Commons Attribution 4.0 International License.

**Note: SSP1-1.9 holds warming to approximately 1.5°C above 1850-1900 in 2100 after slight overshoot (median) and implies net zero CO2 emissions around the middle of the century. SSP1-2.6 stays below 2.0°C warming relative to 1850-1900 (median) with implied net zero emissions in the second half of the century. SSP2-4.5 is approximately in line with the upper end of aggregate Nationally Determined Contribution emission levels by 2030. SR1.5 assessed temperature projections for NDCs to be between 2.7 and 3.4°C by 2100, corresponding to the upper half of projected warming under SSP2-4.5. New or updated NDCs by the end of 2020 did not significantly change the emissions projections up to 2030, although more countries adopted 2050 net zero targets in line with SSP1-1.9 or SSP1-2.6. The SSP2-4.5 scenario deviates mildly from a 'no-additional- climate-policy' reference scenario, resulting in a best-estimate warming around 2.7°C by the end of the 21st century relative to 1850-1900. SSP3-7.0 is a medium to high reference scenario resulting from no additional climate policy under the SSP3 socioeconomic development narrative. SSP3-7.0 has particularly high non-CO2 emissions, including high aerosols emissions. SSP5-8.5 is a high reference scenario with no additional climate policy. Emission levels as high as SSP5-8.5 are not obtained by Integrated Assessment Models (IAMs) under any of the SSPs other than the fossil fueled SSP5 socioeconomic development pathway. Shaded ranges show the 17th-83rd percentile ranges. Projections are relative to a 1995-2014 baseline. The plot below shows the projection and uncertainties for 'Total Sea Level Change'.*

In this region, as in the rest of the world, climate change will also lead to a change in average annual temperature and precipitation. According to data extracted from the IPCC WGI Interactive Atlas: Regional information (https://interactive-atlas.ipcc.ch/) (Gutiérrez et al., 2021; Iturbide et al., 2021), for a 1.5 ºC global average increase, Tenerife's average temperature could increase by 1.1 ºC (SSP5-8.5), while, for the same scenario, total annual average precipitation would be reduced by 18.5%. These future trends may aggravate the already mentioned risk of forest fires, torrential rains, flash floods and haze worrying the population of Tenerife, together with the decrease in water reserves. And although the change in these variables has no direct effect on the frequency and magnitude of eruptions or earthquakes in this region, it can aggravate their many associated indirect hazards by acting on other terrain conditions (e.g., increased soil instability due to desertification and erosion, facilitating the generation of landslides during seismic periods or volcanic unrest).

Parallel to these trends in natural parameters and phenomena, other socio-economic variables are also undergoing alarming changes. The most significant is the population growth (Fig. 14). The population of Tenerife has grown from 66,354 inhabitants in 1768 to 927,993 inhabitants in 2021, making it the most populated island in the Canary Islands (ISTAC, 2022). This inevitably implies an increase in potential risk. The larger the population exposed, the greater the risk, even if the danger of the events does not increase. This is what Fig. 14 shows, with the superposition of the historical eruptions that have occurred in Tenerife (yellow bars), whose frequency and magnitude do not seem to be related to the effects of climate change, and the population curve of the island (red line). As can be seen, despite having a smaller population than at present, around 1909, almost double the population was exposed to the eruption compared to the previous one in 1798, due to a population growth of around 190% between both eruptions, thus increasing the volcanic risk on the island, despite being two eruptions with similar magnitudes (Smithsonian Institution, 2013).

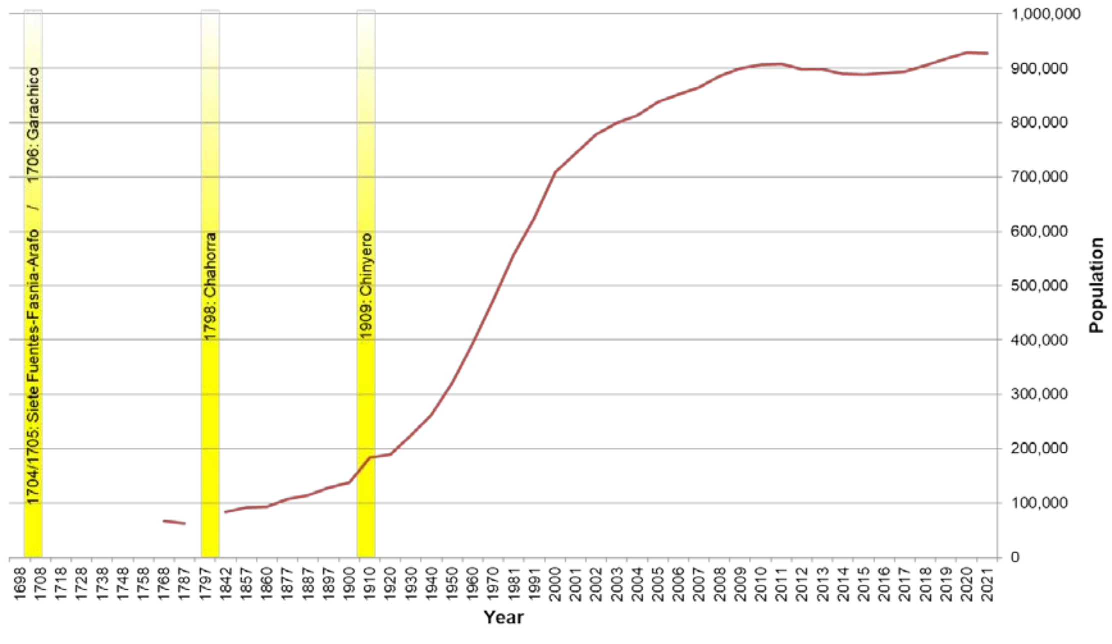

Figure 14. Relationship between the historical evolution of the population of Tenerife from 1768 to 2021 and the historical eruptions on the island. Source: own elaboration based on data from ISTAC (2022) and Smithsonian Institution (2013).

**Note: Population data from 1768 to 1991 are based on the Aranda Census (1768), while data from 2000 to 2021 come from the National Statistics Institute (INE). Note that in the graph only historical eruptions (i.e. since there is a written record of the population, which for Tenerife is from 1492 onwards) are shown as yellow overlapping bars. Note that these bars are placed on the time axis as a guide, but not to an exact scale due to lack of space, which is why the year of each eruption is indicated within each bar.*

This population growth leads to urban sprawl. However, the economic and technological development of the island means that this urban expansion is uneven across the territory. The municipalities which have by far experienced this demographic development are Santa Cruz de Tenerife (the island's capital) and San Cristóbal de La Laguna (Fig. 15a), both cities which concentrate the main municipal infrastructures. On the other hand, smaller municipalities, such as Los Silos, Garachico, Santiago del Teide, El Tanque, Fasnia and, lastly, Vilaflor, have hardly experienced any significant demographic increase or have experienced a downward trend in recent decades (Fig. 15b).

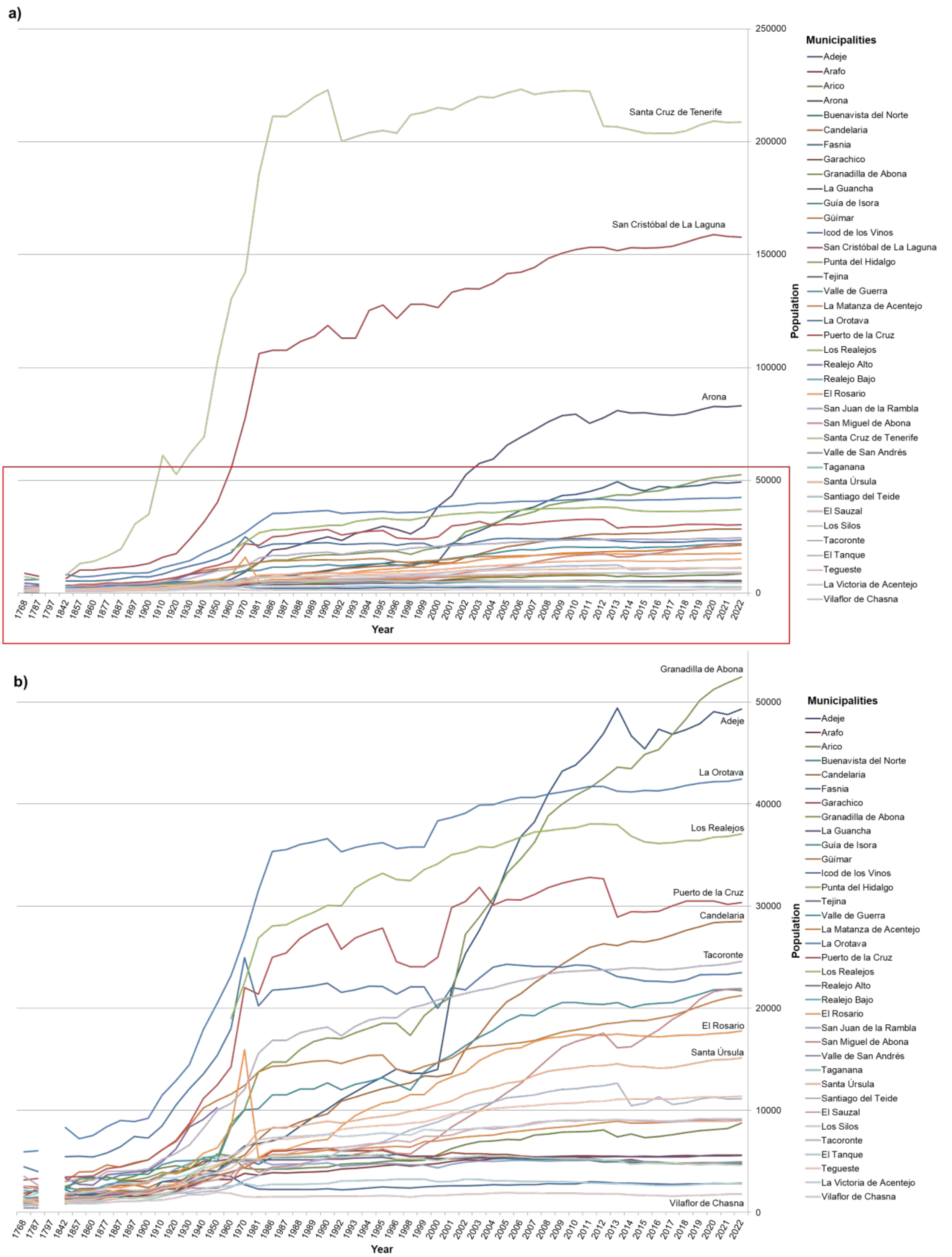

Figure 15. Evolution of the population of Tenerife by municipality (1768 - 2022). a) Graph for all available data by municipality. b) Zoom of the data shown in the red box of graph a) to improve its visualization. Source: own elaboration based on data from ISTAC (2022).

**Note: Population data from 1768 to 1981 are based on the Aranda Census (1768), while data from 1986 to 2022 come from the register or register renewals. In both graphs, only the names of some municipalities have been indicated next to the population curves, in order to facilitate their identification due to the large number of colors that appear.*

The fact that the main municipalities of the island continue to increase their population while the villages and small municipalities hardly experience an increase, or in some cases, even tend to suffer a decrease in population, is due to what has been worrying the Canary Islands Government in recent years: the depopulation of rural areas and the exodus to cities (e.g., Europa Press, 2021; Consejería de Obras Públicas, Transportes y Vivienda, 2022; Domingo, 2022; Radio Televisión Canaria, 2022). This rural depopulation does not only lead to the transmission of increased pressure to already densely populated urban areas. The abandonment of agricultural and livestock practices and the lack of economic and technological development in rural areas where some people are still living, will aggravate many of the risks already mentioned above. A clear example of this is the increase in the number and intensity of forest fires, which find fields that, after being abandoned, accumulate combustible material that allows them to reach population centers with greater force and more quickly.

This urban expansion has also brought about a change in land use in order to accommodate the high demand for urbanization. To this we must include a tourism industry that adds between 4 and 4.5 million visitors every year (except in 2020, due to COVID-19 restrictions), over the last decade. This tourism is especially concentrated in July, followed by August, whose overnight stays are focused in the municipality of Adeje (southwest), followed by Puerto de la Cruz (north) (ISTAC, 2022). The interest in accommodating this mass tourism exacerbates land-use competition between agriculture and building. This in turn leads to the overexploitation of resources, some of which are scarce in Tenerife, such as water and, most importantly, land.

Therefore, in a naturally limited space, where urban expansion can only take place inland due to the high colonization of the coastline, more and more areas exposed to natural risks are being conquered. For this reason, the evolution of spatial planning in Tenerife will need to address the future scenarios of multiple risks that lie ahead. The only way to achieve this is by establishing a multi-risk management approach based on scientific knowledge of these phenomena, tailored specifically to this region.

2.2.6. Risk management structure

According to Law 17/2015, dated July 9, on the Spanish National Civil Protection System, "Civil Protection, as an instrument of public safety policy, is the public service that protects individuals and properties by ensuring an adequate response to different types of emergencies and disasters caused by natural or human-induced factors, whether accidental or intentional." Therefore, according to the law, Civil Protection is the organization responsible for risk management and emergency planning in Spain. Law 17/2015, along with Royal Decree 407/1992, dated April 24, which approves the Basic Civil Protection Regulations, form the current legal framework that establishes the planning, preparedness, and response system for situations involving serious collective risks, public calamities, or extraordinary disasters. The Minister of the Interior holds the highest authority in Civil Protection matters and oversees the Directorate General of Civil Protection and Emergencies. This Directorate General plays a crucial role in planning and coordinating various stakeholders involved in Civil Protection, including the Autonomous Communities, the Cities of Ceuta and Melilla (located in northern Africa), as well as supranational and international organizations. It provides the necessary resources for managing major emergencies or situations with a high probability of occurrence.

It should be recalled that the Canary Islands make up one of these Autonomous Communities in its entirety, whose duties are detailed in subsection 2.2.3. "Socio-economic and political context". Article 8.2 of the Basic Civil Protection Regulations, establishes that the Autonomous Communities shall draw up and approve the special plans whose territorial scope of application does not exceed that of the Autonomous Community itself, attributing the management and coordination of such plans to the corresponding Autonomous Community, except when declared to be of national interest in accordance with the provisions of the aforementioned Basic Regulations. In this respect, as long as the emergency does not go beyond the borders of the Autonomous Community, the Canary Islands will be responsible for managing their own natural risks.

For this reason, the Canary Islands Council of Government approved the Territorial Civil Protection Plan of the Autonomous Community of the Canary Islands (PLATECA) on November 12, 1997. This plan is activated when a regional-level emergency is declared. Simultaneously, Regulations 5 and subsequent regulations of the aforementioned Basic Civil Protection Regulations govern the Special Plans, which are also included in PLATECA. These special regional plans serve as planning instruments to address specific risks that require an appropriate technical-scientific methodology for each of them. Additionally, these special regional plans are subject to specific Basic Guidelines for each risk approved by the General State Administration. They are divided into Basic Plans, such as nuclear and war emergencies, which fall under the responsibility of the State, and Special Plans for other risks, including floods, earthquakes, chemicals, transport of dangerous goods, forest fires, and volcanic activity. If we focus on geohazards, the following Special Plans for the Canary Islands are included:

- Special Plan for Civil Protection and Attention to Emergencies due to volcanic risk in the Autonomous Community of the Canary Islands (PEVOLCA).
- Special Plan for Civil Protection and Emergency Attention due to seismic risk in the Autonomous Community of the Canary Islands (PESICAN).

- Special Plan for Civil Protection and Emergency Attention due to Forest Fires in the Autonomous Community of the Canary Islands (INFOCA).
- Special Plan for Civil Protection and Emergency Attention due to Flood Risk in the Autonomous Community of the Canary Islands (PEINCA).

In addition to these, there are two Specific Plans:

- Specific Plan for Civil Protection and Emergency Attention of the Autonomous Community of the Canary Islands due to risks of adverse meteorological phenomena (PEFMA).
- Specific Plan for accidental marine pollution emergencies in the Canary Is-lands (PECMAR).

PLATECA also includes other territorial plans, divided by the geographical area they cover, which are activated depending on the area and extent of each emergency. Therefore, each Island Council is responsible for developing its own island plan, as the island serves as the fundamental reference area due to the special administrative organization of the Autonomous Community of the Canary Islands. In the case of Tenerife, its Island Council adopted the Island Territorial Emergency Plan (PEIN) on December 17, 2004. The PEIN, revised and approved again by Decree 98/2015 on May 22, is activated when a natural disaster affects the entire island. However, in recent years, several regulatory innovations have arisen, necessitating a review and update of the Plan. At the municipal level, the Municipal Emergency Plan (PEMU) is activated.

On the other hand, there are several institutions designated by law responsible for monitoring and studying these natural phenomena, in coordination with Civil Protection for the management of natural risks in Spain. The observation, monitoring, and communication of volcanic activity and seismic movements in Spain, as well as the determination of associated risks, fall under the purview of the Directorate General of the Spanish National Geographic Institute (IGN), headquartered in Madrid with a department in Santa Cruz de Tenerife, in accordance with ROYAL DECREE 1476/2004 of June 18, 2004. However, there are other networks, such as the Spanish National Research Council (CSIC), and other institutions like the ITER Group (Technological and Renewable Energy Institute) or the Volcanological Institute of the Canary Islands (INVOLCAN), which specialize in volcanic monitoring. Additionally, the Spanish Geological and Mining Institute (IGME), in accordance with its Statute approved by Royal Decree 1953/2000 of December 1, 2000, has responsibilities in the area of forecasting, prevention, and mitigation of geological risks. Moreover, according to Law 12/1990 of July 26, 1990, the Island Water Council of Tenerife (CIATF) is responsible for the management, organization, planning, and administration of the waters of the island of Tenerife. The Council of Tenerife, through the Natural Environment Management and Safety Area, is responsible for the prevention and extinguishing of forest fires in accordance with Decree 111/2002 of August 9, 2002. In terms of weather-related hazards, the State Meteorological Agency (AEMET) is responsible for predicting and monitoring adverse weather phenomena, as stated in Article 1.3 of Royal Decree 186/2008 of February 8, 2008.

Some of these hazards also have other types of plans, such as Action Plans, Self-Protection Plans, Awareness and Education Plans, Training Plans, Essential Basic Services Continuity Plans, Emergency Plans for more specific risks within the risk event itself, etc. Some of mentioned institutions, in collaboration with the Government of the Canary Islands and the different local councils, have drawn up some of these documents that manage some of the natural risks described here. Table 6 summarizes the main documents in force, whether regional or insular in the case of Tenerife, which are responsible for the prevention, action and mitigation of natural risks on this island.

Table 6. Summary of Documents Covering the Management of the Different Natural Hazards on the Island of Tenerife. Source: Cabildo de Tenerife (2020)

NATURAL RISKS		
Type of risk	**Phenomenon**	**Documents**
Hydrological risks	Floods	• Tenerife Flood Defense Plan (PDA) / Hydrological Plan of the Tenerife Hydrographic Demarcation (First Cycle 2009-2015) • Flood Hazard and Risk Maps of the Tenerife Hydrographic Demarcation of Tenerife
	Ruptures of large storage infrastructures	
Seismic movements	Earthquakes	• Special Civil Protection and Emergency Care Plan for Seismic Risk in the Autonomous Community of the Canary Islands (PESICAN) • Special Territorial Management Plan for the Prevention of Risks (PTEOPRE)
	Tsunamis	
Volcanic eruptions		• Emergency Plan for Volcanic Hazards in the Canary Islands (PEVOLCA) • Tenerife Volcanic Hazard Cartography (IGME) • PTEOPRE
Adverse atmospheric phenomena	Snowfall	• Specific Civil Protection and Emergency Response Plan of the Autonomous Community of the Canary Islands for risks of adverse meteorological phenomena (PEFMA) • Hydrological Plan of the Hydrographic Demarcation of Tenerife (First Cycle 2009-2015)
	Torrential rains	
	Hailstorms and frost	
	Strong winds	
	Coastal storms	
	Heat waves	
	Haze and dust in suspension	
	Droughts	
Slope movements	Rock fall	• PTEOPRE
	Landslides	
	Coastal erosion	
Locust pests		-
Forest fires		• Civil Protection Emergency Plan for Forest Fires in the Canary Islands (INFOCA) • Action Plan for the Risk of Forest Fires in Tenerife (INFOTEN) • High Risk Forest Fire Zones (ZARI)

The different plans for natural hazards operate in much the same way. However, it is precisely this feature that is in need of reform and improvement. The protocol for dealing with the different types of events is practically the same, with some minor variations, which makes it independent of the phenomenon. These plans lack a multi-hazard perspective from the point of view of the concatenation of events. This sometimes underestimates the potential for cascading effects or other types of interrelationships and, hence, their consequences. It is true that, in the case of PEVOLCA, different types of hazards that may occur during an eruption are considered, but it does so separately, with separate actions for each of them, and without taking into account non-volcanic hazards derived from the eruption itself. Furthermore, it does not take into account the fact that the occurrence of a previous independent event can establish favorable conditions for aggravating the impact of another event in the same region but after a period of time (for example, a storm and heavy rainfall in an area where there had previously been a forest fire and soil erosion, or the same rainfall in an area shaken by an earthquake some time ago, reducing the cohesion and stability of the soil and favoring the occurrence of landslides). In a more global sense, these plans also do not take into account the influence of climate change, which could bring about processes and relationships between events that are somewhat different from those observed so far (e.g., soil erosion due to a rise in sea level not only along the coasts, but also at river headwaters as a result of a readjustment of the equilibrium profile of rivers, thus increasing the occurrence of landslides and debris flows).

On the other hand, there is the Insurance Compensation Consortium (CCS) as an instrument serving the Spanish insurance sector. The CCS is a public business entity under the Ministry of Economic Affairs and Digital Transformation, through the Directorate General of Insurance and Pension Funds. It performs various functions in the insurance field, including those related to coverage of extraordinary risks, mandatory motor insurance, combined agricultural insurance, and liquidation of insurance companies. It has its own legal personality and full legal capacity, and its specific framework of action is determined by its Legal Statute. It also has separate assets from the State and its activities are not dependent on any public budget. The Consortium compensates for damages to individuals and property caused by certain natural phenomena and specific events derived from political or social events, provided that a policy has been taken out in one or more of the branches for which current legislation establishes the obligation to include coverage for these risks. The legal framework for coverage of the so-called Extraordinary Risks in Spain is currently governed by the Legal Statute of the Consortium, approved by Law 21/1990 of December 19, and which, after successive modifications, has been included in the consolidated text approved by Royal Legislative Decree 7/2004 of October 29, with various subsequent modifications. Extraordinary natural events include earthquakes and tsunamis, extraordinary floods, volcanic eruptions, atypical cyclonic storms, and falls of celestial bodies and meteorites. The Consortium also insures accidents caused by forest fires, covering any person injured as a result of their participation in firefighting work by the Ministry for Ecological Transition and the Demographic Challenge.

Among the various Spanish Security Forces and Corps that provide support during emergencies caused by natural disasters, the National Police and the Guardia Civil stand out. The National Police is a civilian force under the Ministry of the Interior, while the Guardia Civil is a military force that reports to both the Ministry of the Interior and the Ministry of Defense. Both bodies have a directorate general structure and report to the Secretary of State for Security. Below them in the hierarchical structure are the different regional and local police forces. On the other hand, the Spanish Armed Forces also have the Military Emergency Unit (UME), a joint force organized on a permanent basis, whose mission is to intervene anywhere in the national territory to contribute to the security and well-being of citizens, together with state institutions and public administrations, in cases of serious risk, catastrophe, calamity, or other public needs, in accordance with the provisions of Organic Law 5/2005 of November 17 on National Defense and other applicable legislation. Royal Decree 1097/2011 of July 22, 2011, approves the Intervention Protocol of the Military Emergency Unit and establishes that the UME's intervention may be ordered in emergency situations arising from natural hazards (floods, earthquakes, landslides, heavy snowfalls, and other significant adverse weather phenomena, forest fires, among others). Its intervention was also significant during the eruption of La Palma in 2021.

The Spanish legal system defines the Spanish Red Cross as a voluntary humanitarian institution of public interest, which carries out its activities as an auxiliary and collaborator of public administrations under the protection of the State while retaining its independence and autonomy. Royal Decree 1474/1987 of November 27, 1987 (updated by Royal Decree 369/2021 of May 25) brought the rules governing the Spanish Red Cross in line with the evolution of sociological structures, and the institution's statutes were reformed by Order of April 28, 1988. Thus, the Spanish Red Cross provides a range of capabilities to collaborate with the administration in minimizing the effects of emergencies and crises, alleviating human suffering, protecting health and the environment.

CHAPTER 3

METHODOLOGY

3.1. General overview

Having identified the main obstacles to the implementation of the multi-hazard perspective in risk management, we proceeded to develop a methodology to assess the impact of multi-hazard scenarios to better guide decision-makers and strengthen disaster action plans. This PhD thesis project is intended not only for a scientific audience, but also for Civil Protection, Government, other authorities, and first responders involved in risk and emergency management. That is why in this section we aim to develop a tool to answer the main questions that these actors need to know in order to mitigate natural risk:

1. What are all the possible multi-hazard scenarios in the region?
2. Which future multi-hazard scenario is the most likely?
3. Which zone has the highest probability of any scenario occurring?
4. For each zone on the map, which scenario is the most likely?
5. Where each hazard is most likely to occur?
6. Which scenario causes the most damage?
7. Which event requires the greatest utilization of resources for recovery?
8. What is the worst-case scenario?
9. What would be the impact of such a scenario?
10. Is the region prepared to face such an event?

We took the island of Tenerife as a case study for the reasons described above, and we proceeded to develop a methodology to assess its multi-hazardousness. In this sense, we must differentiate between the evaluation of multiple non-extreme hazards (understood as those events that occur within the average of events experienced in a region) and extreme hazards (those extraordinary and infrequent events that rank above a threshold value near the upper or lower ends of the range of historical measurements).

For non-extreme events, all the events in Tenerife that have had some kind of impact or have been recorded in written form in the island's historical record were compiled. The data collected were analyzed qualitatively and quantitatively to answer as many of the questions posed as possible. The qualitative analysis was carried out through expert observation and description of the obtained results that couldn't be quantified, either due to the nature of the data or the lack of numerical values due to incomplete records. This analysis not only provided answers to some of the questions that couldn't be quantitatively answered, but also helped process the information and prepare the data for the quantitative analysis. Furthermore, it roughly covered some of the limitations of the latter, which will be detailed later on. For the quantitative analysis, we applied an event tree developed using Bayesian methodology to conduct a long-term multi-hazard assessment for Tenerife. This methodology allows the evaluation of hazard scenarios in a probabilistic way, which can help answer many of the questions related to forecasting of future multi-hazard scenarios.

In the other hand, given their intrinsic multi-hazard nature, volcanic eruptions are the most common extreme geohazards liable to trigger concatenated effects in this type of environment. Tenerife is an excellent example of a site exposed to cascading extreme geohazards that have occurred several times in the past and could occur again in the future, since the geophysical conditions that determine the occurrence of such catastrophic events are still present. A cascading sequence of a caldera-forming eruption, high-magnitude seismicity, a mega-landslide and a tsunami occurred at least twice during the construction of the central and eastern sectors of the caldera of Las Cañadas, and gave rise to the Orotava and Icod valleys (see subsection 2.2.1. “Geographical and geological context”). Despite being the most populated island in the archipelago and receiving millions of tourists every year, no detailed multi-hazard assessment for extreme events has ever been conducted for Tenerife.

In order to fill the gap in the information necessary for a correct emergency planning and include the most catastrophic scenario possible for the island into the whole multi-hazard assessment done during this study, we also conducted a long-term multi-hazard assessment for a succession of extreme events. The aim of this assessment was to quantify the extent and potential impact of an episode of multiple extreme geohazards similar to the one that occurred on Tenerife around 180 ka (El Abrigo eruption) if it occurred today. We first reviewed the stratigraphic evidence to determine the temporal succession of events and the relationship of cause and effect (see subsection 2.2.1. “Geographical and geological context” for more details). Then, we analyzed each of the processes that occurred during the succession separately, but considering the nature and consequences of the possible relationship between the described events. To do this, we described the main characteristics, magnitude and area of occurrence and impact of each hazard (details can be read in subsection 2.2.1. “Geographical and geological context”), but we adjusted some of these properties depending on the results obtained from the previous event along the cascading simulation. This linkage was done specially for the seismicity-landslide and landslide-tsunami sequence pairs. We also took into account the current topography of the island and its demographic distribution to assess the potential impact of the multi-hazard scenario. Then, we analyzed the overall result of all the simulated scenarios to quantify the potential extent and impact of the occurrence of these multi-hazards today.

Finally, we examined the implications of these multi-hazard scenarios at local, regional and global scales, and we attempted to integrate this multi-hazard perspective into a multi-risk management approach in order to resolve some of the conflicts raised above. The experience gained from the knowledge of the Icelandic risk management system is used to propose strategies for disaster risk reduction in Tenerife, which can be extrapolated to other similar areas. Furthermore, possible solutions to exploit the potential resources available in Tenerife are discussed as an example, in line with risk mitigation measures. For this purpose, nature-based solutions based on the exploration and knowledge of the study area and geoethics as a procedural guide are used.

3.2. Non-extreme event multi-hazard assessment for Tenerife (Canary Islands)

3.2.1. Acquisition of data and elaboration of the historical record of events

We first proceeded to make a historical record of all the events of interest that have had an impact on the island of Tenerife. Historical record is understood as that for which there is written evidence of each of the events collected. For Tenerife, this would be from its colonization by the Castilians around 1494 to the present day. Since this part of the project was carried out during the year 2021, in order to standardize data it was decided that the historical record would then be carried out from 1494 to 2020, both included, being a sufficient time window to obtain results of good quality.

For this study we focused on geological hazards, so the event categories of our registry were the following: volcanic eruptions, earthquakes, landslides, floods, tsunamis. For each event we collected information on the following variables:

- Event (i.e. type of event, specific name, etc.)
- Start date and end date
- Location (i.e. place of origin)
- Cascading effects/hazards
- Main affected areas
- Fatalities
- Injuries
- Displacements
- Economic, social and natural losses
- Management and resilient measures (actions before, during, and/or after the emergency, recovery actions)
- Observations (measurement data, magnitudes, curiosities, etc.)

As a documentary basis, historical records previously made by other authors for each type of event were used. For historical volcanic eruptions, the Volcanism Program database from the Smithsonian Institution (2013) and the works of Carracedo (2008) "El volcán Teide: volcanología, interpretación de paisajes e itinerarios comentados" (*The Teide Volcano: volcanology, landscape interpretation, and guided itineraries*), and Romero (1991) "Las manifestaciones volcánicas históricas del archipiélago canario" (*Historical volcanic manifestations of the Canary Islands archipelago*) were used as starting points. For earthquakes, the Catalog and seismic bulletins for the Canary Islands area were used from the National Geographic Institute (IGN, 2021), supplemented by the Review of the Seismic Catalog of the Canary Islands (1341-2000) (IGN, 2020). In this case, the search area for epicenters was delimited for the zone between latitudes 29º and 27º and longitudes -15º and -18º, coinciding with the area of Tenerife and surroundings. Additionally, earthquakes were filtered according to their magnitude, selecting those with a magnitude greater than 3.5, as they are considered to release enough energy to be perceived by the population and cause damage, as well as being potential precursors to volcanic eruptions. As for landslides, the Movements Database of the Geological and Mining Institute of Spain (IGME, 2016) was used. For floods, the event catalogs of Arroyo (2009) "Cinco siglos de la temperie canaria: cronología de efemérides meteorológicas" (*Five centuries of the canary temperate: chronology of meteorological ephemeris*), Quirantes et al. (1993) "Los aluviones históricos en Canarias" (*Historical floods in the Canary Islands*), Dorta (2007) "Catálogo de riesgos climáticos en Canarias: Amenazas y vulnerabilidad" (*Catalog of climatic risks in the Canary Islands: Threats and vulnerability*), and Pinto (1954) "Canarias Prehispánica y África Occidental española" (*Pre-Hispanic Canary Islands and Spanish West Africa*) were combined, in addition to information collected in the Plan de Defensa Frente Avenidas de Tenerife (PDA) from the Tenerife Water Council (Consejo Insular de Aguas de Tenerife, 2004). Finally, for tsunamis, the work of Galindo et al. (2021) "A review on historical tsunamis in the Canary Islands: implications for tsunami risk reduction." was used.

However, we updated and expanded these records mainly by means of news and chronicles from the Provincial Historical Archive of Santa Cruz de Tenerife, the Diocesan Historical Archive of San Cristóbal de la Laguna and the Municipal Historical Archive of San Cristóbal de La Laguna. Documents housed in the Digital Press Archive (Jable) of the University of Las Palmas de Gran Canaria (ULPGC), and in the Virtual Library of Historical Press, managed by the Subdirectorate General of Library Coordination of the Ministry of Culture and Sport of the Government of Spain, were also explored. These documentary sources were complemented with numerous scientific articles, historical press articles collected in newspaper archives of current newspapers (such as El Día, La Provincia, Información, Europa Press, among many others), contrasted scientific forums and blogs, official documents of the Cabildo of Tenerife and other islands, as well as laws collected in the Official State Gazette (BOE) of Spain (Royal Decrees–Law, Decrees, Laws, Orders, etc., approved after a disaster). The complete bibliography can be found both in the section “Supplementary Material References" and in the Table 17 in Annex 4. Cross-checking information with various sources also made it possible to check the data set for inconsistencies, errors, or missing values. This step increased the reliability and accuracy of the data set.

3.2.2. Qualitative analysis

The historical record of Tenerife was first evaluated qualitatively, as it contains variables for which it was very difficult to establish a quantitative analysis methodology. For this analysis we looked at and evaluated the frequency of each type of event and their respective durations, as well as the place of origin and impact of each one. Patterns or trends were sought in terms of their distribution throughout the period studied and throughout each year. In addition, we evaluated the socio-economic consequences of the hazards to understand the severity of their impact on the affected population, taking into account the calculated losses and/or approved budgets, the typology and quantity of damaged infrastructure, and the type and extent of damage (flooded, burnt, damaged, destroyed, devastated, affected, etc.). This assessment can help prioritize future preparedness and response efforts. Then we analyzed the management measures implemented during and after the events, and we assessed the effectiveness of these measures in mitigating the impacts and promoting resilience. This allowed us to identify successful strategies and areas for improvement in the management of natural hazards. Based on these analyses, we extracted valuable insights and lessons learned from the dataset. Looking for patterns or common trends, we could identify common vulnerabilities, recurring challenges, and successful resilience measures. All this together contributed to generate recommendations and guidelines for future hazard preparedness, response, and recovery efforts in Tenerife.

This preliminary assessment also provided insight into the possible scenarios that could occur in Tenerife. In this case, the possible causes of each event were determined or, in the same way, classified according to whether the events recorded were the primary triggering events of the rest of the associated hazards or were themselves part of chains of events produced by a previous original event. All this information was subsequently used for the quantitative probabilistic analysis explained in the following subsection 3.2.3. "Long-term multi-hazard assessment for non-extreme events on Tenerife (Canary Islands)".

3.2.3. Long-term multi-hazard assessment for non-extreme events on Tenerife (Canary Islands)

Long-term hazard assessment is based on historical and geological data and is principally used for territorial planning and for defining emergency plans. It uses quantitative analysis of past events, and aims to determine possible hazards and future scenarios that may repeat (Fig. 16) (Marzocchi et al., 2010; Sobradelo et al., 2013; Martí, 2017). Long-term hazard assessment calculates the spatial and temporal probability that a new event will take place and characterizes its resulting impacts. Therefore, hazard assessment must identify the main physical mechanisms that control the predicted phenomena. In this way it aims to determine a given hazard's extent, potential impact, and destructive capacity, while placing temporal constraints on the framework in which they occur (e.g., Blong, 2000; Martí, 2017).

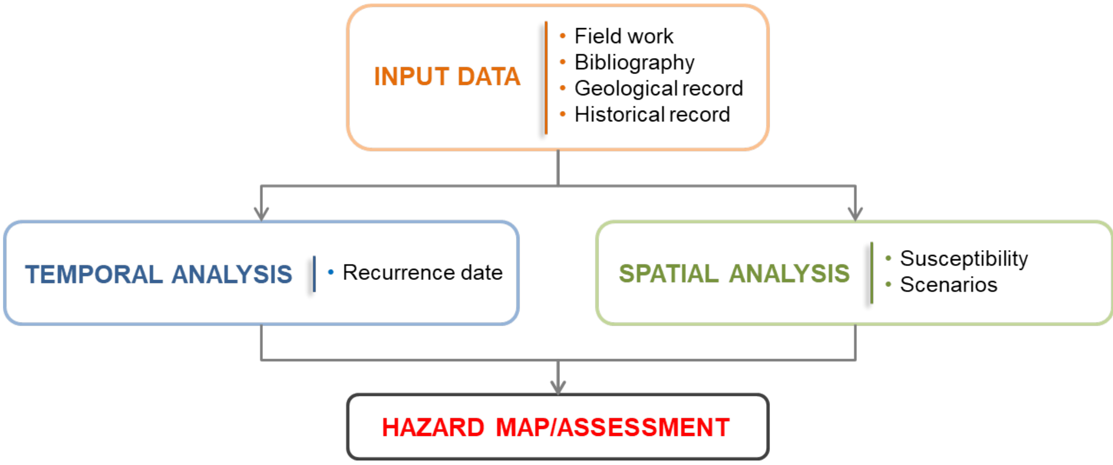

Figure 16. Flow chart for the development of a long-term hazard assessment. Source: modified from López-Saavedra et al. (2023).

This probabilistic methodology began to be developed for volcanic hazard assessment several decades ago (e.g. Newhall, 1982; Barberi et al., 1990; Connor & Hill, 1995; Connor et al., 2001; Newhall and Hoblitt, 2002; Aspinall et al., 2003; Sparks, 2003) and in recent years has become a standard methodology for predicting future volcanic hazard scenarios (e.g. Marzocchi et al., 2008, 2010; Bayarri et al., 2009; Sobradelo & Martí, 2010; Jenkins et al., 2012; Marzocchi & Bebbington, 2012; Bebbington, 2013, 2014; Del Negro et al., 2013; Hincks et al., 2014; Connor et al., 2015; Neri et al., 2015; Newhall & Pallister, 2015; Whelley et al., 2015; Bevilacqua et al., 2016; Biass et al., 2016; Mead & Magill, 2017; Tierz et al., 2017; Sandri et al., 2018). The alternative approach is deterministic (e.g., Hill et al., 2001; Kilburn, 2003).

Tilloy et al. (2019) presents a compilation of quantification methodologies for multi-hazard interrelationships. However, it does not include methods such as agent-based modelling or event trees because according to Terzi et al. (2019) these are weak in addressing uncertainties, especially when considering multi-hazard scenarios. In contrast, Sobradelo et al. (2013) argues that event tree structures constitute one of the most useful and necessary tools in modern volcanology to evaluate probabilities of occurrence of possible volcanic scenarios. It should be noted that volcanic eruptions are already multi-hazard events in themselves, so this could be a first attempt to move from individual hazard assessments to a multi-event perspective.

Sobradelo and Martí (2010) carried out a long-term assessment of the volcanic hazard of the Teide-Pico Viejo stratovolcanoes using event tree structures. This work was based on the previous attempt made by Martí, Aspinall, et al. (2008), which proposed an event tree using elicitation of expert judgment to assign a probability of occurrence to each possible eruptive scenario. However, according to Sobradelo and Martí (2010), on one hand, the nature of this methodology required the event tree to be as simple as possible, grouping events, which may require to be analyzed individually, and leaving out relevant nodes, and it had still a strong human decision component which added an additional source of bias to the final results. For that reason, Sobradelo and Martí (2010) introduced an event tree structure that uses Bayesian inference. Bayesian inference is based on the principle that every state of uncertainty can be modeled with a probability distribution. It provides a numerical instrument, based on rigorous mathematical modeling, to define and interpret uncertainties. The stochastic uncertainty, also known as aleatoric uncertainty, arises from the inherent complexity of a system, posing a limitation on our ability to predict the system's evolution with certainty. It introduces an element of randomness in the outcomes, regardless of our understanding of the system's physical aspects. On the other hand, the epistemic uncertainty is closely tied to our knowledge of the system, including the quality and quantity of available data. As we gather more data, our understanding of the system improves, leading to a reduction in epistemic uncertainty (Woo, 1999). Subsequently, Sobradelo et al. (2013) developed HASSET (Hazard Assessment Event Tree), a probability event tree tool to evaluate future volcanic scenarios using Bayesian inference.

The application of this methodology and this tool has not been performed before for a multi-hazard scenario considering different unrelated events and at the same time each one with its chains of events. Due to the experience of previous authors in relation to event tree and Bayesian inference, its applicability in volcanic hazard assessment, already a multi-hazard phenomenon, as well as the availability of a historical record for Tenerife, but with a lack of knowledge and data that may aggravate uncertainties, we decided to develop this methodology and attempt to apply it to multi-hazard assessments. For this purpose, we based our analysis in the methodology described by Sobradelo and Martí (2010), and Sobradelo et al. (2013) to perform our multi-hazard assessment. In doing so, we intend not only to try to answer as many of the questions posed above as possible, but also to find and expose the main limitations of the method to serve as an initial step towards a more accurate, efficient and complete multi-hazard analysis.

According to Sobradelo and Martí (2010), an event tree is a tree graph representation of events in the form of nodes and branches. Each node represents a step and contains a set of possible branches (outcomes for that particular category). Thus, each possible scenario is a combination of one branch per node evolving from a more general node of the area from which the triggering event has occurred to the more specific node of the impact zone of the multi-hazard scenario. We described the nodes shown in Fig. 17 according to the data available to us (see subsection 3.2.1. "Acquisition of data and elaboration of the historical record of events"). Below is a detailed explanation of each node and corresponding branches (see Sobradelo & Martí, 2010, for further details on the event tree methodology). It is possible to stop at a particular node if we want to evaluate the hazard at a more general level. All nodes should be independent and the corresponding branches should be mutually exclusive and exhaustive. That is, they cannot happen simultaneously and they sum up to 1. These are initial conditions set for simplicity and practical application of the Bayesian inference methodology.

Each possible scenario for our historical record is made up from the following nodes and branches:

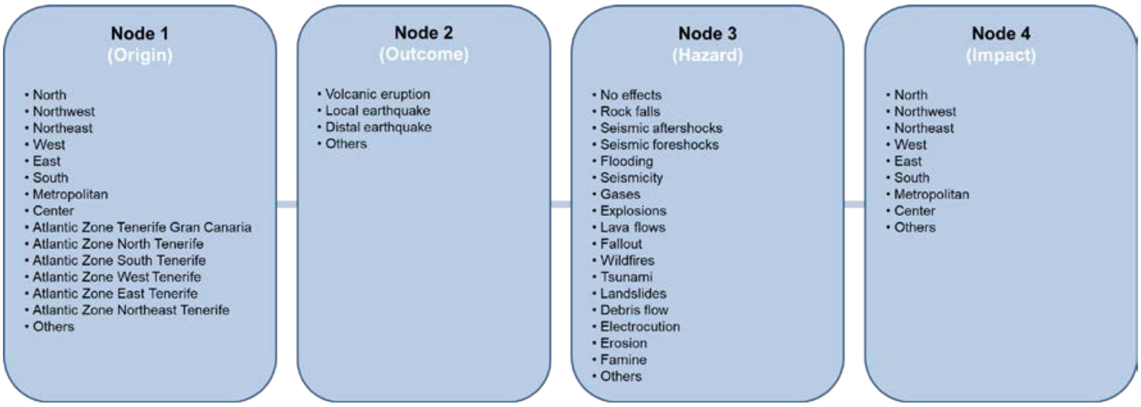

Figure 17. Event tree structure formed by eight nodes and corresponding mutually exclusive and exhaustive branches to account for all possible scenarios likely to occur in Tenerife according to the historical record (1496 – 2020) compiled in Table 17 from Annex 4.

Node 1: Origin

The "origin" node refers to the zone of the island of Tenerife or its surroundings in which the phenomenon that later gave rise to the rest of the cascading hazards, was originated (Fig. 18). These zones were divided according to geomorphological and geological aspects, as well as urban distribution and territorial planning, but they were also determined after a general visualization of the data and the detection of clusters of events. For this purpose, a 50-m resolution Digital Elevation Model provided by the National Geographic Institute (IGN, www.ign.es) was used, in combination with the digital bathymetry around the Canary Islands at the same resolution generated by the Spanish Institute of Oceanography (IEO, www.ieo.es), and urbanization data from the Canary Islands Government (http://www.gobiernodecanarias.org/).

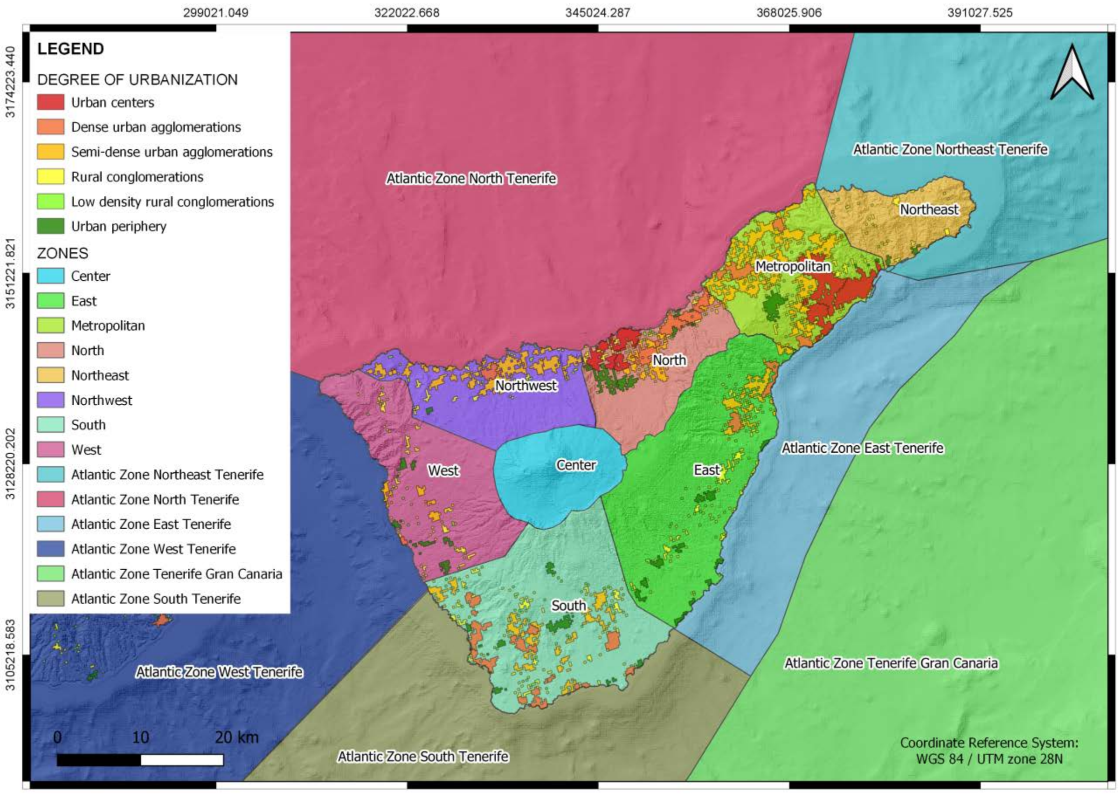

Figure 18. Map of the zones into which the island of Tenerife and its surroundings have been divided for the event tree probabilistic analysis. Source: own elaboration based on material from ISTAC (2021), the National Geographic Institute and the Spanish Oceanographic Institute.

The "Center" zone coincides with the central depression of Las Cañadas and includes the stratovolcanoes of the Teide-Pico Viejo complex (see Fig. 5 for a reminder). It is delimited by the wall of Las Cañadas to the south, and approximately the municipal boundaries along the rest of the perimeter. The "Northwest" zone includes mainly the entire valley of Icod and it is separated from the "West" zone by following the topography of the Teno massif, a relief that is included in the latter zone, also separating the urban centers (more densely populated in the "Northwest" zone) and following approximately the direction of the Santiago Rift Zone. On the other hand, it is separated from the "North" zone by the Tigaiga massif, whose steeper eastern escarpment is used as a dividing line, and because the “North” zone includes the more densely populated nuclei of Los Realejos, Puerto de la Cruz, La Orotava, among others (see Fig. 12 for a reminder). The "Metropolitan" zone includes the two main population centers of the island, which are San Cristóbal de La Laguna and the capital, Santa Cruz de Tenerife, while the “Northeast” zone includes most of the Anaga Massif, with small urban centers. The "East" zone includes the population centers of this side of the island, and is separated from the "North" zone by the dividing line established by the municipalities that in turn follow the direction of the Rift Zone of the Dorsal. The "South" zone is separated from the “East” zone by the dividing line between the municipalities of Arico ("East”) and Granadilla de Abona ("South") due to the higher population density and greater tourist infrastructure of the latter. Similarly, this "South" zone is separated from the "West" zone by the border between the municipalities of Adeje ("South") and Guía de Isora ("West"), for the same reasons.

As for the maritime zones, these do not follow geomorphological, geological, or any other type of pattern, with the exception of the Tenerife Gran Canaria Atlantic Zone, but they were distributed according to the location of the earthquakes with epicenter in the sea. These are the North Atlantic Zone Tenerife, the Northeast Atlantic Zone Tenerife, the East Atlantic Zone Tenerife, the South Atlantic Zone Tenerife, the West Atlantic Zone Tenerife, and the Atlantic Zone Tenerife Gran Canaria. It should be noted that the Tenerife Gran Canaria Atlantic Zone was defined separately because it is the main seismic zone due to the fault running between the two islands (see subsection 2.2.1. "Geographical and geological context" for a reminder). Therefore, the East Atlantic Zone of Tenerife includes those epicenters close to this coast of the island but not located above the zone around the previous fault.

In order to make the node exhaustive, and to include those events that originate outside this region, at greater distances as will be seen later with some earthquakes that originate tsunamis that affect the island, the branch of “Others” was included.

Node 2: Outcome

This node refers to the natural phenomenon that triggers the chain of hazards that form the recorded events. Four main branches were defined for this node: "volcanic eruptions", "earthquakes" (referring to local earthquakes, those with an epicenter within the map shown in Fig. 18.), "distal earthquakes" (those whose epicenter is outside the area shown on the map in Fig. 18) and "others". It should be noted that both volcanic eruptions and earthquakes were already taken as the first event in the chain of hazards that then produced themselves. However, for the recorded tsunamis, the branch of "distal earthquakes" was created because it was understood that these phenomena did not originate alone, but as a consequence of local or distal earthquakes. Similarly, we understand that both floods and landslides are not the initial event in the chain of hazards, but may have been caused by other triggering natural phenomena. However, since the cause of many of the landslides recorded was unknown, which could well be due to rainfall, floods, earthquakes, human factors, or others, and since the origin of the floods, although most of them were caused by rainfall, was uncertain (others may have been caused by heavy swells) and also depended on the human factor, the "Others" branch was created. This branch refers to all those other possible origins not described in the other branches, and also makes the node exhaustive, as mentioned above.

Node 3: Hazard

The "Hazard" node gathers all those hazards that were described for the entire record of events occurred on Tenerife and that were considered to be triggered by any of the events described above as "outcomes". According to our records, the following hazards were identified: "rock falls", "seismic aftershocks" (we considered those earthquakes of lower magnitude that occurred after a main one in the same area and in the same day or days following this mainshock, established as "earthquake" in the node "outcome"), "seismic foreshocks" (those earthquakes of lesser magnitude that occurred prior to a mainshock or on the same day and in the same area), "flooding", "seismicity" (in this case of volcanic origin only, to differentiate it from mainshocks, foreshocks and aftershocks of tectonic origin), "gases", "explosions", "lava flows", "fallout", "wildfires", "tsunamis", "landslides" (when described as such and differentiated from rock falls), "debris flow" (which encompasses all those flash floods with high sediment load), "electrocution", "erosion", "famine", plus the "others" branch to make the node exhaustive, as there may be many other possible hazards triggered but not appearing in our record.

Node 4: Impact

This node refers to the area that was affected either by the triggering event ("outcome") or by one of the derived hazards ("hazard"). For this reason, it contains the same branches as node 1 "origin", but in this case the branches referring to maritime areas were not considered, since this information was not available and was not of interest for our analysis.

Preparation and operation of the algorithm

Volcanbox Desktop (Martí et al., 2015; Martí et al., 2016; Bartolini et al., 2017) is an application that allows users to create comprehensive Volcanic Risk assessments without the need for extensive knowledge of GIS or computer science. To carry out this experiment, the Long-Term Temporal Analysis section of the application was utilized. This section of the application is based on HASSET by Sobradelo et al. (2013), with some changes introduced to enhance the user experience, which are summarized here. By being integrated within the Volcanbox application, the results of the Long-Term Analysis can be combined with those of other sections such as Long-Term Temporal Analysis, Susceptibility Map, etc., to create risk maps by combining different techniques. For our analysis, the original code was translated into a single language —Python—, with optimization tasks performed through bindings to C++. Additionally, some bug fixes affecting the results were implemented. A new user-friendly graphical interface was added, adapted to current visualization styles. This interface allowed for changes in the input data, with modifications in the results being visualized in real-time

—without the need to repeat the entire experiment—. The function of customizing the quantity and names of nodes, as well as the number of branches and their names, was provided, allowing users to create a customized event tree. The possibility of working with datasets was now supported —in the original version, the user had to manually count events, whereas now they are extracted directly from a dataset—. To differentiate it from the Long-Term Temporal Analysis section, a new section called MultiRisk LT was created within the application, with the necessary modifications to adapt to the functioning of the methodology described here.

After studying different solutions, we decided to assign a weight to events from different branches within the same node when they occur within the same time window. This weight corresponds to 1 divided by the total number of events from different branches recorded in that specific time window. In our case, since we had one-year time windows (because we were interested in knowing the probability of the occurrence of one scenario or another in a future year, as well as being the minimum time window that adjusted to those annual events, without reducing it to a smaller window that would have required more computational resources), if we have multiple records with events from different branches belonging to the same node in the same year, we will no longer add 1 for each event to the event count of that particular branch. Instead, we will add 1/number of different events in that same window. With this new approach, we ensured that the contribution of each time window remained 1 in total. However, in this case, that value was divided among the different events from different branches recorded within that window. It should be noted that if an event occurs multiple times within the same window, it will be counted as a single occurrence, as the time windows are used to determine whether events from different branches have occurred or not, and not their frequency.

Preparation of the dataset for the probabilistic quantification tool

All the information for each event described in Table 17 of Annex 4 was classified according to the branches of the nodes described above. As we mentioned above, most events contained several branches for the same node. This is the case for the "origin", "hazards", and "impact" nodes. The reason lies in the fact that, in the case of floods, it is understood that many were originated by rains, and it is assumed that these rains were originated in the same place where the flooding occurs, which would be equivalent to saying that the area of origin is the same as the area of impact of the event. And since floods occurred simultaneously in different zones, giving rise to different branches for the "impact" node, they also had different branches for the zone of origin ("origin" node). Similarly with the impact zone, which in many cases affects different zones, so that different branches of "impact" must be assigned to the same "outcome". But this also occurred with hazards, where the same outcome could produce more than one hazard at the same time.

Taking into account all the possible scenarios that occurred in our registry, the following table of definitions (Table 7) was created, which was later used by the algorithm to process the information.

Table 7. Table of Definitions to Classify the Data Extracted From the Historical Record to be Probabilistically Analyzed by the Algorithm.

ID	NODE	ABBREVIATION
Node 1: Origin		
0	North	N
1	Northwest	NW
2	Northeast	NE
3	West	W
4	East	E
5	South	S
6	Metropolitan	M
7	Center	C
8	Atlantic Zone Tenerife Gran Canaria	AZTGC
9	Atlantic Zone North Tenerife	AZNT
10	Atlantic Zone South Tenerife	AZST
11	Atlantic Zone West Tenerife	AZWT
12	Atlantic Zone East Tenerife	AZET
13	Atlantic Zone Northeast Tenerife	AZNET
14	Others	O
15	North + Northwest + Center + West + South + Metropolitan + East + Northeast	N-NW-C-W-S-M-E-NE
16	Northwest + Metropolitan + North + South	NW-M-N-S
17	Metropolitan + Northeast	M-NE
18	Metropolitan + North + Northwest + Northeast + East	M-N-NW-NE-E
19	East + Northeast + Metropolitan	E-NE-M
20	North + Northwest	N-NW
21	Metropolitan + North	M-N
22	West + East + Metropolitan + North + Northeast	W-E-M-N-NE
23	East + Northeast	E-NE
24	West + East	W-E
25	North + Center + West + South + East	N-C-W-S-E
26	Northwest + North + Metropolitan	NW-N-M
27	North + Metropolitan + Northeast + Northwest	N-M-NE-NW
28	Metropolitan + Northeast + North + East + South + Northwest	M-NE-N-E-S-NW
29	Northwest + Metropolitan	NW-M
30	Metropolitan + North + Northwest + East	M-N-NW-E
31	South + North + Metropolitan	S-N-M
32	Metropolitan + Center	M-C
33	South + Northeast + East + Northwest + West + North + Metropolitan	S-NE-E-NW-W-N-M
34	Metropolitan + South + East + Center	M-S-E-C
35	Northwest + West + North + Metropolitan + South	NW-W-N-M-S
36	North + Northwest + East + South	N-NW-E-S

ID	NODE	ABBREVIATION
37	North + Metropolitan + Northeast	N-M-NE
38	Metropolitan + East + North	M-E-N
39	South + East + West + North + Metropolitan	S-E-W-N-M
40	Metropolitan + East	M-E
41	Metropolitan + Northwest + East + South	M-NW-E-S
42	South + West	S-W
43	South + East	S-E
44	Metropolitan + South	M-S
45	Northwest + East	NW-E
46	South + East + West + Northwest + Metropolitan	S-E-W-NW-M
47	Metropolitan + West	M-W
48	East + South + Metropolitan + Northeast	E-S-M-NE
49	South + East + Northwest + West + North + Metropolitan	S-E-NW-W-N-M
50	Northwest + West	NW-W
Node 2: Outcome		
0	Volcanic eruption	VE
1	Distal earthquake	DE
2	Earthquake	E
3	Others	O
Node 3: Hazards		
0	Seismicity + Gases + Explosions + Lava flows + Fallout	S-G-E-LF-F
1	Seismicity + Gases + Explosions + Lava flows + Fallout + Rock fall	S-G-E-LF-F-R
2	Seismicity + Gases + Lava flows + Fallout + Wildfires	S-G-LF-F-W
3	Seismicity + Gases + Lava flows + Fallout + Rock falls	S-G-LF-F-R
4	Tsunami + Flooding	T-FL
5	No effects	NE
6	Rock falls	R
7	Seismic aftershocks	SA
8	Seismic foreshocks	SF
9	Rock falls + Seismic aftershocks	R-SA
10	Seismic foreshocks + Seismic aftershocks	SF-SA
11	Flooding + Rock fall	FL-R
12	Flooding + Landslides	FL-L
13	Flooding + Debris flow + Rock fall	FL-DF-R
14	Flooding + Debris flow + Landslides + Wildfire	FL-DF-W
15	Flooding + Debris flow + Landslides	FL-DF-L
16	Flooding + Debris flow + Landslides + Rock fall	FL-DF-L-R
17	Flooding + Landslides + electrocution	FL-L-EL
18	Flooding + Debris flow	FL-DF
19	Flooding + Debris flow + Erosion + Famine	FL-DF-ER-FA
20	Flooding	FL
21	Landslide + Tsunami + Flooding	L-T-FL
22	Others	O
23	Seismicity	S

ID	NODE	ABBREVIATION
24	Gases	G
25	Explosions	E
26	Lava flows	LF
27	Fallout	F
28	Wildfires	W
29	Tsunami	T
31	Landslides	L
32	Debris flow	DF
34	Electrocution	EL
35	Erosion	ER
36	Famine	FA
Node 4: Impact		
0	North + Northwest + Center + West + South + Metropolitan	N-NW-C-W-S-M
1	Center + North	C-N
2	Northwest	NW
3	North + Northwest + Center + West + South + Metropolitan + East + Northeast	N-NW-C-W-S-M-E-NE
4	Metropolitan + Northeast	M-NE
5	North	N
6	West + Northwest + North + Metropolitan + Northeast	W-NW-N-M-NE
7	South + Northeast + East + Northwest + West + North + Metropolitan	S-NE-E-NW-W-N-M
8	South + West + Northwest + North	S-W-NW-N
9	East + South + Metropolitan + North	E-S-M-N
10	South	S
11	No zone	NZ
12	Metropolitan + North	M-N
13	Northwest + North + Metropolitan	NW-N-M
14	East	E
15	Metropolitan + East + North	M-E-N
16	East + North	E-N
17	Metropolitan + South	M-S
18	Metropolitan	M
19	South + Northwest + West	S-NW-W
20	Northeast	NE
21	Northwest + Metropolitan + North + South	NW-M-N-S
22	Metropolitan + North + Northwest + Northeast + East	M-N-NW-NE-E
23	East + Northeast + Metropolitan	E-NE-M
24	East + Northeast	E-NE
25	North + Center + West + South + East	N-C-W-S-E
26	North + Northwest	N-NW
27	North + Metropolitan + Northeast + Northwest	N-M-NE-NW
28	Northwest + Metropolitan	NW-M
29	South + North + Metropolitan	S-N-M
30	Northwest + West + North + Metropolitan + South	NW-W-N-M-S
31	North + Metropolitan + Northeast	N-M-NE

ID	NODE	ABBREVIATION
32	South + East + West + North + Metropolitan	S-E-W-N-M
33	Metropolitan + East	M-E
34	South + West	S-W
35	South + East + West + Northwest + Metropolitan	S-E-W-NW-M
36	East + South + Metropolitan + Northeast	E-S-M-NE
37	South + East + Northwest + West + North + Metropolitan	S-E-NW-W-N-M
38	Northwest + West	NW-W
39	Metropolitan + West	M-W
40	Northwest + East	NW-E
41	South + East	S-E
42	Metropolitan + Northwest + East + South	M-NW-E-S
43	North + Northwest + East + South	N-NW-E-S
44	Metropolitan + South + East + Center	M-S-E-C
45	Metropolitan + Center	M-C
46	Metropolitan + North + Northwest + East	M-N-NW-E
47	Metropolitan + Northeast + North + East + South + Northwest	M-NE-N-E-S-NW
48	West + East	W-E
49	West + East + Metropolitan + North + Northeast	W-E-M-N-NE
50	West	W
51	Center	C
52	Others	O

After classifying the information for each event according to the table of definitions (Table 7), the following table of data was obtained for processing with the algorithm (Table 8):

Table 8. Classification of the Data Extracted From the Historical Record According to the Table 7 of Definitions to be Probabilistically Analyzed.

Origin	Outcome	Hazards	Impact	Start_date	End_date
3	0	0	0	18/11/1909	27/11/1909
7	0	1	1	09/06/1798	15/09/1798
0	0	2	2	05/05/1706	13/06/1706
4	0	3	3	02/02/1705	27/03/1705
4	0	3	3	31/12/1704	16/01/1705
14	1	4	4	28/02/1969	28/02/1969
14	1	4	5	15/11/1911	15/11/1911
14	1	4	6	31/03/1761	31/03/1761
14	1	4	7	01/11/1755	01/11/1755
9	2	6	8	16/07/2020	16/07/2020
8	2	7	9	18/01/2019	18/01/2019
10	2	5	10	10/10/2017	10/10/2017
8	2	5	4	30/10/2016	30/10/2016
10	2	5	5	06/11/2015	06/11/2015
13	2	5	11	13/03/2014	13/03/2014
9	2	5	11	17/03/2013	17/03/2013

Origin	Outcome	Hazards	Impact	Start_date	End_date
13	2	5	11	17/12/2012	17/12/2012
9	2	7	12	18/08/2012	18/08/2012
12	2	5	11	05/02/2010	05/02/2010
9	2	5	11	13/06/2009	13/06/2009
9	2	5	11	10/03/2009	10/03/2009
8	2	5	4	13/05/2008	13/05/2008
9	2	5	11	22/11/2005	22/11/2005
8	2	5	11	17/07/2004	17/08/2004
8	2	5	11	13/02/1998	13/02/1998
8	2	5	11	13/04/1995	13/04/1995
8	2	5	11	03/10/1992	03/10/1992
9	2	5	11	20/05/1990	20/05/1990
9	2	5	13	08/01/1990	08/01/1990
8	2	7	3	09/05/1989	09/05/1989
8	2	5	11	22/04/1981	22/04/1981
8	2	5	11	31/10/1979	31/10/1979
8	2	5	14	03/11/1977	03/11/1977
8	2	5	15	18/07/1977	18/07/1977
0	2	5	16	05/01/1971	05/01/1971
8	2	5	10	28/05/1966	28/05/1966
8	2	8	17	22/05/1964	22/05/1964
6	2	5	18	06/12/1962	06/12/1962
8	2	7	18	23/02/1950	23/02/1950
8	2	5	11	07/05/1947	07/05/1947
8	2	8	18	23/01/1947	23/01/1947
3	2	5	11	07/07/1937	07/07/1937
9	2	9	2	21/06/1937	21/06/1937
8	2	5	11	07/12/1935	07/12/1935
8	2	5	11	13/11/1935	13/11/1935
4	2	7	11	11/12/1930	11/12/1930
8	2	5	18	15/05/1927	15/05/1927
4	2	5	11	16/08/1926	16/08/1926
4	2	5	11	03/06/1926	03/06/1926
8	2	5	15	22/12/1911	22/12/1911
8	2	5	11	12/01/1909	12/01/1909
8	2	10	5	05/01/1909	05/01/1909
8	2	5	5	05/01/1909	05/01/1909
8	2	5	12	04/01/1909	04/01/1909
1	2	10	1	18/11/1908	18/11/1908
1	2	10	5	27/07/1908	27/07/1908
0	2	5	5	02/09/1900	02/09/1900
14	2	5	11	01/09/1730	01/09/1730
6	3	12	18	03/12/2020	03/12/2020
6	3	12	18	26/11/2020	26/11/2020
16	3	20	21	20/10/2020	20/10/2020

Origin	Outcome	Hazards	Impact	Start_date	End_date
16	3	20	21	18/11/2018	18/11/2018
17	3	13	4	04/11/2016	05/11/2016
18	3	13	22	19/02/2016	19/02/2016
6	3	11	18	19/10/2015	24/10/2015
19	3	14	23	19/10/2014	19/10/2014
21	3	20	12	09/01/2014	09/01/2014
23	3	15	24	09/12/2013	11/12/2013
4	3	12	14	02/12/2013	02/12/2013
5	3	20	10	03/11/2013	03/11/2013
25	3	20	25	03/03/2013	05/03/2013
20	3	12	26	24/12/2012	25/12/2012
27	3	15	27	02/11/2012	07/11/2012
29	3	20	28	09/10/2010	10/10/2010
31	3	20	29	17/02/2010	18/02/2010
3	3	15	7	01/02/2010	02/02/2010
29	3	20	28	22/12/2009	23/12/2009
35	3	15	30	16/11/2009	17/11/2009
37	3	16	31	18/03/2007	19/03/2007
39	3	11	32	01/11/2006	01/11/2006
40	3	11	33	24/01/2006	24/01/2006
42	3	20	34	19/12/2005	20/12/2005
40	3	20	33	28/11/2005	28/11/2005
5	3	20	10	17/08/2005	18/08/2005
44	3	20	17	14/12/2004	14/12/2004
5	3	20	10	19/02/2004	20/02/2004
16	3	20	21	12/04/2003	15/04/2003
0	3	20	5	10/04/2002	11/04/2002
46	3	11	35	16/12/2002	18/12/2002
46	3	11	35	12/12/2002	13/12/2002
48	3	12	36	31/03/2002	31/03/2002
49	3	20	37	20/11/2001	21/11/2001
31	3	20	29	11/11/2000	11/11/2000
50	3	20	38	06/04/2000	07/04/2000
49	3	12	37	01/01/1999	10/01/1999
17	3	12	4	10/03/1996	12/03/1996
29	3	20	28	10/12/1995	15/12/1995
5	3	20	10	28/10/1993	28/10/1993
44	3	20	17	17/03/1993	17/03/1993
37	3	20	31	04/12/1991	04/12/1991
5	3	20	10	06/11/1990	06/11/1990
47	3	20	39	24/11/1989	28/12/1989
0	3	20	5	01/11/1988	01/11/1988
37	3	20	31	24/02/1988	27/02/1988
45	3	20	40	23/10/1987	23/10/1987
43	3	20	41	11/04/1987	13/04/1987

Origin	Outcome	Hazards	Impact	Start_date	End_date
1	3	20	2	13/01/1987	13/01/1987
21	3	20	12	06/01/1979	23/01/1979
41	3	16	42	10/04/1977	11/04/1977
38	3	12	15	12/02/1971	13/02/1971
6	3	20	18	00/12/1968	00/12/1968
21	3	20	12	22/11/1968	25/11/1968
31	3	20	29	05/12/1957	05/12/1957
36	3	20	43	15/01/1953	15/01/1953
34	3	20	44	08/11/1950	11/11/1950
21	3	20	12	29/11/1946	02/12/1946
2	3	20	20	22/10/1944	22/10/1944
17	3	17	4	04/05/1944	04/05/1944
32	3	20	45	15/01/1926	17/01/1926
17	3	18	4	29/11/1922	01/12/1922
30	3	15	46	02/03/1920	04/03/1920
28	3	11	47	03/01/1918	05/01/1918
17	3	20	4	22/11/1914	22/11/2014
0	3	20	5	05/02/1912	08/02/1912
2	3	20	20	01/11/1904	02/11/1904
26	3	11	13	10/04/1901	14/04/1901
24	3	20	48	00/00/1901	00/00/1901
22	3	20	49	22/12/1899	26/12/1899
2	3	20	20	28/10/1898	28/10/1898
14	3	20	11	00/00/1895	00/00/1895
2	3	20	20	06/03/1894	06/03/1894
2	3	20	20	30/10/1893	30/10/1893
4	3	20	14	18/12/1880	21/12/1880
6	3	20	18	00/10/1879	00/12/1879
21	3	20	12	07/03/1867	17/05/1927
2	3	20	20	00/11/1865	00/11/1865
6	3	20	18	12/12/1859	12/12/1859
1	3	20	2	06/01/1856	07/01/1856
6	3	20	18	00/00/1853	00/00/1853
6	3	20	18	00/00/1849	00/00/1849
6	3	20	18	08/03/1837	08/03/1837
6	3	20	18	00/11/1829	00/11/1829
15	3	19	3	06/11/1826	08/11/1826
20	3	20	26	00/11/1821	00/11/1821
6	3	20	18	05/11/1820	05/11/1820
0	3	20	5	00/00/1815	00/00/1815
14	3	20	11	21/02/1781	21/02/1781
1	3	20	2	27/12/1773	27/12/1773
6	3	20	18	00/00/1773	00/00/1773
2	3	20	20	00/00/1769	00/00/1769
6	3	20	18	00/00/1759	00/00/1759

Origin	Outcome	Hazards	Impact	Start_date	End_date
6	3	20	18	00/00/1752	00/00/1752
6	3	20	18	00/00/1750	00/00/1750
6	3	20	18	01/11/1749	01/11/1749
1	3	20	2	27/12/1733	27/12/1733
17	3	20	4	25/10/1722	25/10/1722
1	3	20	2	19/04/1719	19/04/1719
6	3	20	18	24/01/1713	27/01/1713
15	3	20	3	00/00/1649	00/00/1649
1	3	18	2	11/12/1645	11/12/1645
6	3	18	18	00/00/1594	00/00/1594
6	3	18	18	00/00/1590	00/00/1590
6	3	20	18	00/00/1550	00/00/1550
6	3	6	18	05/12/2020	05/12/2020
2	3	6	20	05/12/2020	05/12/2020
2	3	6	20	05/12/2020	05/12/2020
2	3	6	20	25/11/2020	25/11/2020
4	3	6	14	17/11/2020	17/11/2020
2	3	6	20	16/05/2020	16/05/2020
1	3	6	2	07/05/2020	07/05/2020
1	3	6	2	06/05/2020	06/05/2020
6	3	6	18	06/04/2020	06/04/2020
6	3	6	18	04/04/2020	04/04/2020
1	3	6	2	19/02/2020	19/02/2020
2	3	6	20	05/12/2019	05/12/2019
2	3	6	20	05/12/2019	05/12/2019
6	3	6	18	05/12/2019	05/12/2019
2	3	6	20	05/12/2019	05/12/2019
1	3	6	2	28/10/2019	28/10/2019
1	3	6	2	28/10/2019	28/10/2019
5	3	6	10	26/10/2019	26/10/2019
1	3	6	2	06/04/2019	06/04/2019
0	3	6	5	16/02/2019	16/02/2019
1	3	6	2	01/01/2019	01/01/2019
2	3	6	20	23/11/2018	23/11/2018
2	3	6	20	23/11/2018	23/11/2018
2	3	6	20	23/11/2018	23/11/2018
1	3	6	2	23/11/2018	23/11/2018
1	3	6	2	18/09/2018	18/09/2018
6	3	6	18	24/08/2018	24/08/2018
1	3	6	2	18/02/2018	18/02/2018
6	3	6	18	29/11/2017	29/11/2017
4	3	6	14	19/10/2017	19/10/2017
1	3	6	2	15/08/2017	15/08/2017
1	3	6	2	29/07/2017	29/07/2017
0	3	6	5	02/12/2016	02/12/2016

Origin	Outcome	Hazards	Impact	Start_date	End_date
7	3	6	51	14/11/2016	14/11/2016
0	3	6	5	27/10/2016	27/10/2016
1	3	6	2	19/10/2016	19/10/2016
2	3	6	20	25/07/2016	25/07/2016
3	3	6	50	12/07/2016	12/07/2016
2	3	6	20	06/03/2016	06/03/2016
1	3	6	2	24/02/2016	24/02/2016
1	3	6	2	22/02/2016	22/02/2016
1	3	6	2	21/02/2016	21/02/2016
1	3	6	2	21/02/2016	21/02/2016
0	3	6	5	21/02/2016	21/02/2016
4	3	6	14	21/02/2016	21/02/2016
6	3	6	18	21/02/2016	21/02/2016
0	3	6	5	20/02/2016	20/02/2016
7	3	6	51	18/02/2016	18/02/2016
7	3	6	51	18/02/2016	18/02/2016
7	3	6	51	18/02/2016	18/02/2016
5	3	6	10	14/02/2016	14/02/2016
6	3	6	18	14/02/2016	14/02/2016
4	3	6	14	11/01/2016	11/01/2016
6	3	6	18	11/01/2016	11/01/2016
4	3	6	14	09/12/2015	09/12/2015
2	3	6	20	01/11/2015	01/11/2015
2	3	6	20	31/10/2015	31/10/2015
2	3	6	20	31/10/2015	31/10/2015
3	3	6	50	30/10/2015	30/10/2015
6	3	6	18	30/10/2015	30/10/2015
6	3	6	18	30/10/2015	30/10/2015
5	3	6	10	26/10/2015	26/10/2015
6	3	6	18	16/10/2015	16/10/2015
6	3	6	18	10/10/2015	10/10/2015
6	3	6	18	02/06/2015	02/06/2015
0	3	6	5	13/05/2015	13/05/2015
6	3	6	18	10/03/2015	10/03/2015
1	3	6	2	30/11/2014	30/11/2014
1	3	6	2	23/11/2014	23/11/2014
2	3	6	20	19/11/2014	19/11/2014
1	3	6	2	10/10/2014	10/10/2014
3	3	6	50	17/02/2014	17/02/2014
6	3	6	18	29/01/2014	29/01/2014
7	3	6	51	16/12/2013	16/12/2013
3	3	6	50	12/12/2013	12/12/2013
4	3	6	14	03/12/2013	03/12/2013
2	3	6	20	03/12/2013	03/12/2013
7	3	6	51	03/12/2013	03/12/2013

Origin	Outcome	Hazards	Impact	Start_date	End_date
0	3	6	5	00/00/2013	00/00/2013
1	3	6	2	14/11/2012	14/11/2012
1	3	6	2	07/11/2012	07/11/2012
1	3	6	2	07/11/2012	07/11/2012
1	3	6	2	07/11/2012	07/11/2012
1	3	6	2	07/11/2012	07/11/2012
6	3	6	18	31/10/2012	31/10/2012
1	3	6	2	02/06/2012	02/06/2012
1	3	6	2	09/04/2012	09/04/2012
1	3	6	2	28/02/2012	28/02/2012
1	3	6	2	11/10/2011	11/10/2011
0	3	6	5	08/09/2011	08/09/2011
0	3	6	5	21/08/2011	21/08/2011
1	3	6	2	04/07/2011	04/07/2011
4	3	6	14	05/06/2011	05/06/2011
1	3	6	2	03/06/2011	03/06/2011
1	3	6	2	30/05/2011	30/05/2011
1	3	6	2	23/04/2011	23/04/2011
1	3	6	2	09/04/2011	09/04/2011
1	3	6	2	20/03/2011	20/03/2011
6	3	6	18	15/03/2011	15/03/2011
1	3	6	2	09/02/2011	09/02/2011
2	3	6	20	31/01/2011	31/01/2011
2	3	6	20	31/01/2011	31/01/2011
4	3	6	14	31/01/2011	31/01/2011
2	3	6	20	31/01/2011	31/01/2011
0	3	6	5	31/01/2011	31/01/2011
6	3	6	18	31/01/2011	31/01/2011
1	3	6	2	31/01/2011	31/01/2011
1	3	6	2	29/11/2010	29/11/2010
4	3	6	14	28/04/2010	28/04/2010
7	3	6	51	09/02/2010	09/02/2010
7	3	6	51	09/02/2010	09/02/2010
3	3	6	50	01/11/2009	01/11/2009
3	3	6	50	07/10/2009	07/10/2009
5	3	6	10	00/08/2009	00/08/2009
2	3	6	20	27/01/2007	27/01/2007
3	3	6	50	06/08/2006	06/08/2006
5	3	6	10	23/12/2001	23/12/2001
1	3	6	2	26/01/1996	26/01/1996
6	3	6	18	00/12/1987	00/12/1987
6	3	6	18	00/11/1987	00/11/1987
6	3	6	18	27/01/1947	27/01/1947
6	3	21	18	07/07/1941	07/07/1941
2	3	6	20	00/00/0000	00/00/0000

Origin	Outcome	Hazards	Impact	Start_date	End_date
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
0	3	6	5	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
2	3	6	20	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000

Origin	Outcome	Hazards	Impact	Start_date	End_date
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000
6	3	6	18	00/00/0000	00/00/0000

As can be seen, the total number of events shown in Table 8 is lower than the number of events shown in Table 17 of Annex 4. This is due to the fact that many of them were grouped according to a series of assumptions and recommendations that we have already announced in previous paragraphs. These were, for example, the grouping of those earthquakes considered as foreshocks and aftershocks of a mainshock, so that the "outcome" would be the mainshock and the related foreshocks and aftershocks would be considered as its "hazards". Similarly, those earthquakes that were clearly associated with a volcanic eruption, therefore, with volcanic and not tectonic origin, were classified as hazards of volcanic eruptions. And likewise, those landslides that were clearly associated with some of the floods recorded, would be considered together with these as part of the hazards produced by the outcomes considered as "other" (remember that for both floods and landslides, since their cause was not clear or, in the case of floods, not all the rainfall episodes that occurred on the island were recorded, it was decided to give them the branch of "other" in the outcome node, thus also making the node exhaustive). As for the eruptions, those of Fasnia and Siete Fuentes were considered a single event, according to

Sobradelo et al. (2011), because they were very close in time and had similar compositions. All this together means that the final record of events contains fewer records.

3.3. Long-term multi-hazard assessment for an extreme geohazard on Tenerife (Canary Islands)

To conduct the multi-hazard assessment corresponding to a hypothetical repetition today of the same succession of events that took place on Tenerife about 0.18 Ma, it is necessary to simulate scenarios that reproduce all the succession of volcanic and associated hazards that occurred during the caldera-forming eruption of El Abrigo. This will help predict which areas could be affected by each of these processes in case they occur today. The objective was to combine freely available models and commercial software with Geographic Information Systems (GIS) to model and analyze the various potential hazards and so identify their current potential extent and impact. According to the succession of events deduced from the geological record and, in particular, from the inland stratigraphy (Martí, 2019), the following hazards needed to be simulated: pyroclastic density currents (PDCs), seismicity, landslide and tsunami. Ash fallout has not been identified on Tenerife in association with El Abrigo eruption (Pittari, 2004), although it is likely that a considerable co-ignimbrite ash cloud developed during the emplacement of the El Abrigo ignimbrite. Nevertheless, no data exist to indicate its size or extent and so this hazard was not modeled.

PDC simulations were conducted using VORIS 2.0.1. (Felpeto et al., 2007, available at http://www.gvb-csic.es/GVB/VORIS/VORIS.htm), a GIS-based tool for volcanic hazard assessment that includes several simulation models. The PDC simulation model used is based on the Energy Cone model (Malin & Sheridan, 1982; Sheridan & Malin, 1983) and the modification by Toyos et al. (2007), and is able to calculate the runout, velocity and dynamic pressure of pyroclastic flows. Simulations of the Peak Ground Acceleration (PGA) caused by seismicity induced by caldera collapse were performed automatically using a plugin developed by Núñez (2017) implemented in the Geographic Information System QGIS, 2.14 version. Landslide simulations were conducted using the commercial software SLIDE, developed by Rocscience Inc. (Rocscience Inc., 2020, https://www.rocscience.com/software/slope-stability) for slope stability analyses. Finally, the tsunami was simulated using VolcFlow (Kelfoun & Druitt, 2005)

As input parameters for all these simulations, the current topography of Tenerife consisting of a 50-m resolution Digital Elevation Model provided by the National Geographic Institute (IGN, www.ign.es) was used, in combination with the digital bathymetry around the Canary Islands at the same resolution generated by the Spanish Institute of Oceanography (IEO, www.ieo.es).

Given that one of the objectives was to reproduce the extent of the ignimbrite deposited after El Abrigo that nearly buried the whole island of Tenerife (Pittari, 2004; Pittari et al., 2008), up to seven different collapse equivalent angles (a_c) (4° — for base surge explosions —, 7°, 11°, 15°, 19°, 23° and 27° — for column collapse phases —) (Sheridan & Malin, 1983), and a collapse equivalent height (H_c) of 2,000 and 3,000 m, respectively, were considered in a trial and error application of the PDC simulation model. All the simulations were conducted assuming a single eruptive area located in the current crater of Mt Teide.

We replied the methodology used by Núñez (2017) to elaborate the seismic amplification map of Tenerife, necessary as input file for the PGA model used in this study. Using the Geographic Information System QGIS, 2.14 version, we grouped the 220 geological units of the geological map GEODE 1:25000 from Tenerife (Bellido-Mulas et al., 2014), introduced as a shapefile, into the 6 synthesis classes (Table 9) proposed by Borcherdt (1994). The geological classification was already done by Núñez (2017), and it can be consulted in Table 3.39 of his work, but no seismic amplification map of Tenerife was elaborated then. This new map is shown in Fig. S1 of Annex 5. In the legend of this map, the color of each synthesis class is shown, together with the equivalent amplification factor for short periods (Fa) (see Núñez, 2017 for more details about the methodology). Once obtained, the seismic amplification map was introduced into the PGA model implemented in QGIS 2.14.

Table 9. Synthetic Classification of Soils and Rocks According to Their Amplification Capacity. Source: Núñez (2017).

Type of emplacement		**Geotechnical properties**					
Nº	**Borcherdt (1994)**	**Geotechnical description**	**Vs30 (m/s)**	$\bar{N}$ **(blows/foot)**	$\bar{s}_u$ **(kPa)**	**Minimum thickness (m)**	F_a
1	SC-Ia	Hard rocks	Vs30 > 1500				0.86
2	SC-Ib	Medium-resistant rocks	760 < Vs30 ≤ 1500				0.97
3	SC-II	Very dense soils Soft to firm rocks	360 < Vs30 ≤ 760	$\bar{N} > 50$	$\bar{s}_u > 100$	10	1.50
4	SC-III	Hard soils Consistent clays	180 ≤ Vs30 ≤ 360	$15 \leq \bar{N} \leq 50$	$50 \leq \bar{s}_u \leq 100$	5	2.42
5	SC-IVa	Medium-consistent soils	Vs30 < 180	$\bar{N} < 15$	$\bar{s}_u < 50$	3	3.40
		Soils with more than 3 m of soft clay defined as a soil with PI > 20, w ≥ 40 % and s_u < 25 kPa					

Type of emplacement		Geotechnical properties		
6	SC-IVb	Soft soils Soils that require specific geotechnical investigation in situ: 1. Soils prone to liquefaction 2. Quick and highly sensitive clays 3. Highly organic clays 4. Clays with very high plasticity, with H > 8 m and PI > 75 5. Clays with soft-to-medium-hard consistency, with H > 36 m and $\bar{s}_u$ < 50 kPa	3	2.08

**Note. Vs30 is the average shear wave speed to a depth of 30 m, $\bar{N}$ the average resistance according to the SPT (Standard Penetration Test) to a depth of 30 m, PI the Plasticity Index, w the moisture content, s_u the shear and undrained resistance, $\bar{s}_u$ the average shear and undrained resistance to a depth of 30 m, H the power of the soil and Fa the amplification factor for short periods (Núñez, 2017).*

Then we assumed that the seismic shocks triggered by a caldera collapse had their hypocenters along the ring faults that control the vertical movement of the block that is collapsing. It is also well known that the position and extent of a collapse caldera are limited by the position and extent of the associated magma chamber (Martí, Ablay, et al., 1994; Martí, Geyer, Folch, et al., 2008; Folch & Martí, 2009). For this reason, the position of the hypothetical magma chamber in the case simulated here will determine the position of the ring faults and hence the position of the possible hypocenters and/or epicenters. The magma chamber at the time of El Abrigo eruption was assumed to have had a total volume of at least 20 km^3 (this is the minimum erupted volume; Martí, Mitjavila, et al., 1994; Pittari, 2004), to have been about 5 km in diameter given the size of the resulting depression (Martí, Mitjavila, et al., 1994; Coppo et al., 2008), and to have been located about 4 km below surface at the time of the eruption (Andújar et al., 2008). Two positions for the magma chamber were assumed in our simulations (Fig. 19, a and b, respectively) and three hypocenters were considered for each epicenter given current topography and the depth of the magma chamber, which thus give rise to a total of six possible locations for the seismic focuses. For each focus, three moment magnitudes (Mw) were used (Mw = 5, 6, and 7), values that are within the observed common range for these type of eruptive seismic shocks (Hürlimann et al., 2000). Finally, the simulation of the seismic scenarios was performed by applying three attenuation laws following our geotechnical classification of materials. All of the input parameters are shown in Table 10.

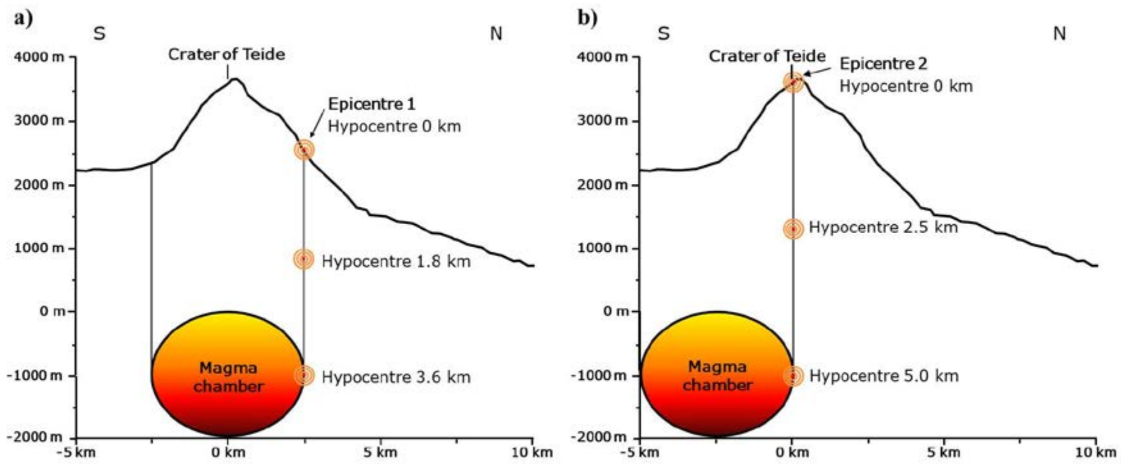

Figure 19. Simplified cross section of Mt Teide (S–N) showing the two presumed positions of the magma chamber (>20 km^3, 5-km wide, 4-km deep) and their respective epicenters and hypocenters proposed for the earthquake simulations: (a) a magma chamber located just below the crater of Mt Teide and (b) a magma chamber displaced to the south whose the northern limit would be below the crater. Source: own elaboration based on the information provided by Martí, Mitjavila, et al. (1994), Andújar et al. (2008), Coppo et al., (2008).

**Note: The line corresponding to this cross-section is part of the red line I-I' shown in Fig. 5.*

Table 10. Input Parameters for Peak Ground Acceleration Simulations.

Epicenter 1		Epicenter 2		Mw	Attenuation laws*
Location	Hypocenters	Location	Hypocenters		
lat = 28.294332º lon = -16.650575º	0 km 1.8 km 3.6 km	lat = 28.272319º lon = -16.642437º	0 km 2.5 km 5 km	5 6 7	Pétursson and Vogfjörd (2009) Ágústsson et al. (2008) Beauducel et al. (2004)

**Note: Núñez (2017) states that the most accurate attenuation laws for Canary Islands are those given by Beauducel et al. (2004), Ágústsson et al. (2008), and Pétursson and Vogfjörd (2009) since they were built using accelerations observed in Iceland and on the island of Guadalupe, which are also volcanic environments.*

By taking into account the estimated earthquake magnitudes that could have triggered the Icod landslide (Hürlimann et al., 2000), slope stability simulations were carried out considering the current topography, stratigraphy and geotechnical properties. We used SLIDE (Rocscience Inc., 2020), a 2D limit equilibrium slope stability program, to evaluate the Factor of Safety (FS) or probability of failure, of circular or non-circular failure surfaces on soil or rock slopes. This program uses different limit equilibrium methods designed to investigate the equilibrium of a soil or a rock mass tending to slide down under the influence of gravity. These methods compare forces, moments, or stresses resisting movement of the mass for a given geotechnical configuration, with disturbing forces, such as those produced by an earthquake. As a result, the program calculates the FS of the slope and reveals the most probable slip surfaces. Two simplified contrasting models (Model 1, Fig. 20a and Model 2, Fig. 20b) based on the cross-sections drawn by Carracedo et al. (2007), Marrero (2010) and Martí (2019) were designed to evaluate the stability of the northern slope of Tenerife according to the geotechnical classification of volcanic materials in Del Potro and Hürlimann (2008).

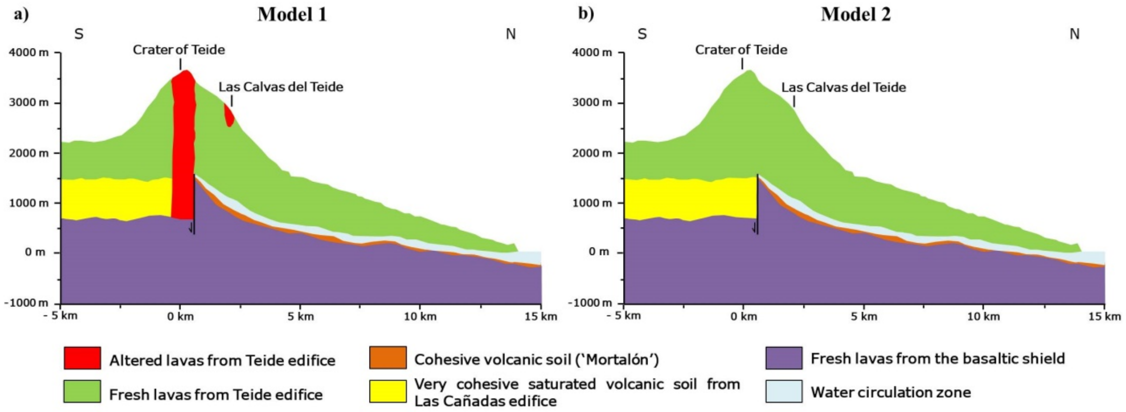

Figure 20. Simplified geotechnical S–N cross-sections in the north of Tenerife proposed for the slope stability analysis. (a) Model 1 considers alteration zones shown in red; (b) Model 2 does not consider alteration zones. Source: own elaboration based on Carracedo et al. (2007), Marrero (2010) and Martí (2019).

**Note: See red line I–I' in Fig. 5 for the line of the S–N cross-section.*

In order to simplify the model, infinite strength was assumed for fresh lavas from the basaltic shield as there was no landslide after the formation of the Las Cañadas edifice. Thus, these lavas represent a slip surface "exclusion zone" through which slip surfaces cannot penetrate. The Drained-Undrained option of SLIDE was used for both the "Mortalón" and the Las Cañadas edifice intracaldera materials, as it defines a soil strength envelope that considers both drained and undrained Mohr-Coulomb strength parameters, that is, effective and total parameters, for materials whose response to a seismic shock is unknown. For the rest of units considered as "rocks" (including the altered lavas from Mt Teide, which were characterized as an intermediate material between rock and soil based on their geotechnical characteristics), the Generalized Hoek-Brown strength criterion was applied, which works well for most rock masses of reasonable or low quality in which the rock mass strength is controlled by tightly interlocking angular rock pieces (Rocscience Inc., 2020). All inputs of geotechnical parameters are shown in Table 11.

Table 11. Input Parameters for SLIDE Software.

Parameter	Geotechnical units					
	Fresh lavas from the basaltic shield	**Las Cañadas collapsed material**	**Mortalón**	**Water circulation zone**	**Fresh lavas from Mt Teide**	**Altered lavas from Mt Teide**
Type	Rock	Soil	Soil	Rock	Rock	Rock/Soil
Strength criterion	Infinite strength	Drained-Undrained	Drained-Undrained	Gen. Hoek-Brown	Gen. Hoek-Brown	Gen. Hoek-Brown

Parameter	Geotechnical units					
	Fresh lavas from the basaltic shield	**Las Cañadas collapsed material**	**Mortalón**	**Water circulation zone**	**Fresh lavas from Mt Teide**	**Altered lavas from Mt Teide**
Unit weight (kN/m^3)	24.6 ± 2.3[a]	14.9[a]	17.1 ± 2[a]	22.6[b]	24.6 ± 2.3[a]	22.2 ± 3[a]
Saturated unit weight (kN/m^3)	-	16.9[c]	21[c]	24.6[c]	24.6[c]	23.6[c]
Effective angle of internal friction (ϕ) (°)	-	35[d]	20[d]	-	-	-
Undrained cohesion (Cu) (kg/cm^2)	-	0.1[c]	0.7[e]	-	-	-
Effective cohesion (c’) (kg/cm^2)	-	0.01[f]	0.13[g]	-	-	-
Uniaxial Compressive Strength (UCS) (MPa)	-	-	-	55[h]	65[j]	30[d]
Geological Strength Index (GSI)	-	-	-	25[i]	35[i]	20[i]
m_i	-	-	-	15[i]	15[i]	14[i]
m_b	-	-	-	1.03[i]	1.472[i]	0.804[i]
s	-	-	-	0.00024[i]	0.00073[i]	0.00013[i]
a	-	-	-	0.313[i]	0.5159[i]	0.5437[i]

**Note. Error margins were ignored during simulations to simplify calculations. m_i is a material constant for intact rocks. m_b, s and a are rock mass material constants.*

[a] *Del Potro and Hürlimann (2008).*

[b] *Assumed using geological-geotechnical criteria.*

[c] *Assumed using geological-geotechnical criteria based on the geological description in Del Potro and Hürlimann (2008).*

[d] *Considering conservative values from Hernández-Gutiérrez and Santamarta (2015) and assumed using geological-geotechnical criteria.*

[e] *Weighted average from values provided by Uriel and Serrano (1975).*

[f] *c'/Cu ratio = 0.1 (Rocscience Inc., 2020).*

[g] *c'/Cu ratio = 0.186 (Rocscience Inc., 2020).*

[h] *Conservative values from those recommended by González de Vallejo et al. (2002) for intact rock from this type of material.*

[i] *Recalculated with RocData software (Rocscience Inc., 2020) under geological-geotechnical criteria.*

[j] *Arithmetic mean of the mean values of the simple compression tests corresponding to the basaltic type lithotypes from Hernández-Gutiérrez and Santamarta (2015), from a conservative perspective in terms of risk.*

The SLIDE software package enables different methods of vertical slice limit equilibrium analysis to be applied. These methods discretize the soil or rock mass above the assumed failure surface into vertical slices or columns with equal widths. In each column, force and moment equilibrium are held, at the same time that internal forces due to the interaction between the slices are considered. For this study, only three methods were used since Rocscience Inc. recommends that the others do not fit the reality of our case of study: Bishop's simplified method, which satisfies only moment equilibrium and considers interslice shear forces as zero (Bishop, 1955); Janbu's Generalised method, which satisfies only force equilibrium but also considers interslice shear forces as zero (Janbu, 1973); and Morgenstern-Price method, which satisfies both moment and force equilibrium and considers variable interslice shear forces (Morgenstern & Price, 1965).

A static analysis was performed for both contrasting geotechnical models by applying the previous analytic methods to obtain the FS prior to an earthquake. Then, a pseudo-static analysis was performed for both models using the same methodology to analyze slope stability under seismic conditions. Since we were unable to simulate the whole caldera collapse process to determine how the seismicity produced by friction along the ring fault affects the Icod valley at each moment, we simulated the two extreme stages: at the beginning of the collapse, when the edifice is practically intact but some friction is occurring and so some seismic shocks are being generated, and at the end, when the collapse is almost over and so the seismicity generated by the friction is about to end. Nevertheless, we are aware that the landslide could have occurred at any time during the collapse process and, although we do not know exactly when, we know from the stratigraphy that it occurred after the ignimbrite was emplaced. Hence, a third pseudo-static analysis was performed for Model 1 excluding the central part of the Mt Teide volcanic edifice. This considered a collapse of that sector into the magma chamber during the formation of the caldera to test the slope stability of the Icod valley at the end of the collapse process. To do so, we used Model 1 as an input file for SLIDE software, but renamed it as “Model 1 Bis”, and assumed the existence of a magma chamber located just below the crater of Mt Teide corresponding to the configuration shown in Fig. 19a. To achieve this, we moved one of the limits of the calculation zone considered by SLIDE 2.5 km to the north of the crater and restricted the calculation of the FS to the portion corresponding only to the Icod valley since it would not have any mass behind its head zone.

A total of 10 different maximum values of acceleration of gravity (g) were taken from the results obtained from the PGA simulations, and three formulas—those of Marcuson (1981) (1), Noda and Uwave (1976) (2) and Saragoni (1993) (3)—were applied to each PGA value to obtain 22 different horizontal seismic coefficient (k_h) values used in the SLIDE pseudo-static analysis.

$$k_h = \frac{0.33 * a_{max}}{g} \qquad (1)$$

$$k_h = \frac{a_{max}}{g} \qquad If a_{max} \leq 2m/s^2$$

$$k_h = 0.33 * \left(\frac{a_{max}}{g}\right)^{0.33} \qquad If a_{max} > 2m/s^2 \qquad (2)$$

$$k_h = 0.3 * \frac{a_{max}}{g} \qquad If a_{max} \leq 6.6m/s^2$$

$$k_h = 0.22 * \left(\frac{a_{max}}{g}\right)^{0.33} \qquad If a_{max} > 6.6m/s^2 \qquad (3)$$

where a_{max} is the PGA as a fraction of the acceleration of gravity on Earth (g), and g = 1 in these formulas (Gutiérrez, 2017).

These 10 PGA values (shown in Table 12) were selected after filtering the results from previous seismicity simulations (Tables 19 and 20 from Annex 4); the variable "depth" was eliminated as PGA values did not vary with depth, as were all results for Mw = 7 since this magnitude is outside the range of applicability of the three attenuation laws, but it was tested as an upper limit. Repeated values were selected only once. The input seismic values for simulations are shown in Table 12. An extra value of k_h = 0.13 for Model 1 was included after a trial and error analysis to search for the limit at which all three methods of analysis show slope instability. This was not necessary for either Model 2 or Model 1 Bis since the limit was found at k_h = 0.15 and k_h = 0.29, respectively, which were two of the previously selected values from PGA results. According to Eurocode 7 (AENOR, 2016) and the Basic Document on Structural Safety (DB-SE) of the Technical Building Code (CTE) (Ministerio de Fomento, 2006), a minimum FS of 1.5 is required for slope stability in static and permanent conditions, and 1.1 for seismic and permanent conditions. Below these values, the slope is considered unstable. However, a lower FS limit is known to be sometimes more suitable for big landslides/slopes or for slope stability analysis different than those made for building security. Thus, we determined unstable conditions when FS < 1, and short-term stable conditions when FS values were 1–1.5 after considering the geotechnical configuration of the sector of the island selected and the possible margin of error in our parameter selection.

Table 12. k_h Values for the Selected Accelerations of Gravity According to the Pseudo-Static Analysis Criteria.

Acceleration of gravity values (g)	k_h		
	Noda and Uwave (1976)	Marcuson (1981)	Saragoni (1993)
0.1	0.1	0.03	0.03
0.20	0.20	0.07	0.06
0.67	0.29	0.22	0.19
3.35	0.49	1.11	0.33
0.12	0.12	0.04	0.04
0.49	0.49	0.16	0.15
0.19	0.19	0.06	0.06
0.61	0.28	0.20	0.18
3.04	0.48	1.00	0.32
0.48	0.26	0.16	0.14
Extra value of k_h		0.13	

**Note. PGA values in bold text were obtained from PGA simulations using Epicenter 1 (Fig. 19a); underlined values in bold were obtained using Epicenter 2 (Fig. 19b); the remaining values coincided with both epicenters.*

According to the geological record, the powerful tsunami was the final event of the chain of cascading multi-hazards in this case study. A simulation of the tsunami was generated with the two-fluid version of VolcFlow (Kelfoun et al., 2010), which can simulate both an avalanche and an associated tsunami. VolcFlow is a finite difference Eulerian code based on a depth-averaged approach. It runs inside MATLAB and solves depth-averaged equations of mass and momentum using a topography-linked coordinate system in time and space. First, the area covered by the landslide was drawn using Surfer software, keeping approximately the limits of the sliding mass obtained with SLIDE, and then entered as a numerical code in a TIF file, along with the bathymetry file in a Surfer Grid format. A maximum thickness of 500 m for the sliding block was considered, since it is approximately the thickness of the sliding mass obtained with SLIDE during the simulation of the landslide in this study. This thickness coincides with the average thickness of the current fill of the Icod valley from the surface to the "Mortalón" layer (Fig. 20), which is taken to be the décollement surface of the last mega-landslide (Bravo, 1962). Following Kelfoun et al. (2010), the rheology of the sliding material was defined by a density of the avalanche block of 2,500 kg/m^3 (Del Potro & Hürlimann, 2008). This approximately coincides with the one used for the geotechnical unit of the fresh lavas from Teide, which occupies most of the sliding mass, as it was seen during the landslide simulation. Two different values were also used for the constant retarding stress that is equivalent to the cohesion of rocks or to yield strength: 50,000 Pa and 100,000 Pa, reasonable values determined by Kelfoun & Druitt (2005), and Kelfoun et al. (2010). This rheology was obtained by comparing the results of the model with natural deposits (Kelfoun & Druitt, 2005; Kelfoun et al., 2010). A dynamic viscosity of water of 0.001137 Pa · s and a density of water of 1,025 kg/m^3 were also assumed.

3.4. A Comprehensive examination of Iceland's risk management system

Within the framework of a complementary mobility grant for beneficiaries of the University Teacher Training Program (FPU), a three-month stay was carried out at the Institute of Earth Sciences of the University of Iceland (Reykjavík, Iceland). The stay took place from September 2 to December 1, 2022. The objective of this stay was to learn first-hand how the risk management system works in Iceland, assuming that it is a country with sufficient experience in natural disaster risk mitigation and reduction given the occurrence of multiple hazards with local, regional and even global consequences in its historical record. This objective responds to a larger one, part of this doctoral project, which is to be able to provide solutions to the existing problems in Tenerife, taking as a guide a country with more experience in natural hazards, especially volcanic-related hazards.

To this end, a series of interviews were conducted with representatives of various public security institutions involved in the management of natural risks and emergencies in the country. In addition, we worked with personnel from the Institute of Earth Sciences itself, where several volcanic hazard assessment projects and other related hazards are being carried out.

We wanted to obtain a view from different perspectives of risk management. For that reason, we sought to interview people/institutions involved in different stages and/or levels of disaster risk mitigation, with different roles and tasks, and different legal structures. Accordingly, the list of people interviewed and their institutions were as follows (all under previous authorization):

- Ásgrímur L. Ásgrímsson, Chief of Operations at the Icelandic Coast Guard.
- Sigrún Karlsdóttir, Director of Natural Hazards Services at the Icelandic Meteorological Office (IMO).
- Sara Barsotti, volcanic hazards coordinator at the Icelandic Meteorological Office (IMO).
- Elín Björk Jónasdóttir, head of Department of Forecasting and Natural Hazard Monitoring at the Icelandic Meteorological Office (IMO).
- Hafsteinn Pálsson and Elisabet Palmadottir, retired civil engineer and Head of Division, respectively, at Ministry for the Environment and Natural Resources.

- Birgir Vilhelm Óskarsson, researcher at the Icelandic Institute of Natural History
- Árni Guðbrandsson, senior ATM expert at Isavia (national airport and air navigation service provider of Iceland).
- Friðfinnur Freyr Guðmundsson and Elva Tryggvadóttir, project managers for Isavia Crisis and Emergency Coordination.
- Aðalheiður Jónsdóttir, team coordinator for disaster services at the Icelandic Red Cross.
- Guðný Björk Eydal, professor of social work at the University of Iceland.
- Guðrún Pétursdóttir, retired director of the Institute for Sustainability Studies of the University of Iceland.
- Úlfar Lúðvíksson and Gunnar Ó. Schram, Chief of Police and Chief Superintendent, respectively, in Suðurnes district.
- Guðbrandur Arnarson, project manager for search and rescue in Iceland (ICE-SAR).
- Hulda Árnadóttir and Jón Örvar Bjarnason, CEO and responsible for the insurance part, respectively, at the Natural Catastrophe Insurance of Iceland.
- Thor Thordarson, professor of volcanology and petrology at the Institute of Earth Sciences of the University of Iceland.
- William Michael Moreland, Adjunct Lecturer at the Institute of Earth Sciences of the University of Iceland.

In general, the same questions were asked to all of them, so that their answers and points of view could be contrasted. However, some of them were adapted according to the institution to which they belonged or the work they performed. Some questions were also deleted or added during the interview according to how the conversation developed and what the interviewee wished to explain. In general, the interviews began with a set of questions to get to know the interviewee and his/her institution. Subsequently, we went on to ask about the relations of that institution with the others also involved in risk management and with which they could possibly have collaborated. The role of the institution was also discussed during the prevention stage, emergency response and subsequent recovery after a disaster, as well as the experience with past events. Finally, questions of a more subjective nature were posed in which the interviewee was asked to describe the strengths and weaknesses of his/her institution's performance in disaster risk reduction and, globally, of the risk management carried out jointly in Iceland. These interviews were transcribed and collected, with permission, in Annex 6 "Supplementary Material 3: Interviews" (some were omitted because they contained very similar information already collected with other interviews and to speed up their analysis, so they are not attached in the Annex 6; however, this information has been kept in case further studies are required).

As previously indicated, although the methodology used to carry out this work is presented in this section of the report, the information gathered and extracted from these interviews is not presented as part of the results of this project. However, the data and knowledge derived from these interviews was used to discuss the current problems in Tenerife and to propose risk mitigation strategies in this region based on how they do it in Iceland.

CHAPTER 4

RESULTS

4.1. Non-extreme event multi-hazard assessment for Tenerife (Canary Islands)

4.1.1. Qualitative analysis

From 1496 to 2020, a total of 6 eruptions occurred in Tenerife (2 of which could be considered as the same eruption, resulting in a total of 5 events of this type), along with 96 seismic events recorded with a magnitude greater than 3.5 (13 of which, whether seismic swarms or individual earthquakes, were considered of volcanic origin due to their association with previous eruptions). Additionally, there were 104 floods and 5 tsunamis (most of which were caused by distal earthquakes, except for one caused by a landslide on the coast of Tenerife). As for landslides/rock falls, the period for which records are available is much shorter, so only up to 198 events were accounted for (with the date unknown for 71 of them) for the period from 1941 to 2020. Although landslides/rock falls could be considered the most frequent event, followed by floods, it's worth noting that only earthquakes with a magnitude greater than 3.5 were considered due to their potential impact on the population. If earthquakes had not been filtered according to their magnitude, this type of event would probably have been much more frequent, potentially surpassing floods and/or landslides in frequency. However, since the purpose of this analysis was to identify events that have a potential impact on the population, landslides/rock falls would already occupy the position of the most frequent events.

It can be observed that the majority of these landslides/rock falls, for the period under study, occur on the sides of roads, closely related to human activities such as road cuts that leave slopes with high gradients. Another common location is on the cliffs of some beaches or in ravines on the island. If we look at the dates, in addition to seeing that up to 22 events of this type occur in the same year, they generally occur more frequently in the months of February and November, followed by January, October and December. However, many others occur throughout the rest of the months. These events are quite fast, lasting from a few seconds to a few minutes; sometimes the instability lasts for hours or days but the falling is instantaneous. In general, although their cause is difficult to determine, they are produced by a previous triggering event or set of conditioning events. However, most of these events don't lead to subsequent hazards, except for the landslide that occurred on July 7, 1941, caused by the impact of a wind wave that triggered the detachment of part of the cliff into the sea, generating a tsunami that inundated the coast of Santa Cruz de Tenerife. The number of deaths due to landslides/rock falls between 1941 and 2020 amounts to 16 (most of them on beaches or in ravines, such as the one in the Infierno ravine, which is a popular hiking route, or in houses near slopes), with a minimum of 10 injuries. Generally, they don't require evacuating the population. Furthermore, these events usually don't cause significant economic losses, and the cleanup and recovery work in the area is relatively quick and straightforward, returning to normality on the same day or the following days.

Regarding floods, throughout the analyzed period, they are concentrated in the months of November and December, with less frequency in October and January, followed by February-March-April. However, while autumn-winter floods remain constant, focusing on November-December, those occurring in spring show a slight tendency in recent years to become more frequent from January to March and increasingly occur in later months, towards April-May, and even some in August. This distribution throughout the year coincide with the Atlantic storms described in subsection 2.2.2. "Climatology and hydrology," with the main periods of rainfall occurring in autumn and spring. They usually last between one and three days, although some events extend to a week. Most floods occur in the "Northwest," "North," "Metropolitan," and "Northeast" zones shown in Fig. 18, which also align with the areas of the highest precipitation shown in Fig. 7. Similar to landslides/rock falls, floods are often triggered by a preceding event. However, unlike landslides/rock falls, floods themselves can cause chains of events. These multi-hazard scenarios are typically defined by intense rainfall leading to flash floods, which overflow through ravines and inundate population centers in areas with lower slopes, especially near the coast. Additionally, these floods are usually accompanied by a significant load of sediment. Although to a lesser extent, it is also common for these floods to occur due to wave action during storm episodes with strong winds. On the other hand, these events are also responsible for significant economic and human losses. Of the recorded events, around 800 people lost their lives due to floods throughout the study period (which is likely to be higher based on historical accounts), in addition to multiple injuries and evacuations. Moreover, the accumulated and recorded economic losses from 2000 to 2020 alone exceeded 37 billion euros. Typically, these economic losses result from the destruction and damage to houses and buildings, as well as damage to infrastructure and municipal elements. It's worth noting that with technological development, inflation, and urban expansion, these economic losses have greater value towards the end of the study period. Additionally, this type of event complicates emergency management and the recovery of the affected area compared to other events. While in the early centuries of recording, emergency management was mainly handled by mayors and local government authorities of each affected locality, as well as the Insular Council, and a significant portion of recovery work was carried out by workers and strong citizen participation, in recent centuries, these tasks now fall under the previously mentioned Spanish risk management system. This includes authorities such as the Police, Civil Protection, and the military, among other first responders. Furthermore, in the early centuries, funds came from anonymous or known donors in the community and region, in addition to those from the municipality and/or government. In the recent decades, these funds mainly come from the Compensation Consortium of Insurance and the insular and Spanish governments. However, with this change in the compensation system, accompanied by a political process of approval of aid through special legal norms such as Royal Decrees, there is an observed increase in the time required for recovery or the provision of aid to return the region to normalcy. It is also interesting to highlight that the El Cabo Bridge, located in the Santos ravine, one of the most frequently overflowing ravines, has been reconstructed around seven times throughout the study period. On the other hand, with urban development, many ravines were paved and converted into streets for circulation.

Tectonic earthquakes affecting Tenerife, which are also quite frequent, usually have their epicenter in the sea surrounding the island. Most of these earthquakes occur mainly in the Tenerife Gran Canaria Atlantic Zone determined in Fig. 18 and described in Fig. 6. However, on land, many have their epicenter in the Icod Valley or the Orotava Valley. As for the areas where the population perceives these earthquakes, they are mainly concentrated in the Northern zone of Fig. 18, and to a lesser extent in the Metropolitan zone, the Northwest zone, the East zone, and the South zone. They usually last a few seconds or minutes, although foreshocks and aftershocks may occur during several days before and/or after the mainshock. These events, in the case of Tenerife and the period studied, usually don't trigger other hazards, and it's common for them to have no effects, at least immediately. Occasionally, they have caused landslides/rock falls. During the study period, no deaths were recorded, either because they didn't occur or because they weren't documented, and there were few injuries and a low number of evacuations, sometimes only causing panic among the population. As these earthquakes have no effects, there is no record of significant damage or resulting economic losses. The highest magnitude recorded is 6.3; however, most of the selected events (those exceeding a magnitude of 3.5) range between 3.5 and approximately 5. The highest calculated epicentral intensity was 7.3. Volcanic earthquakes tend to have higher epicentral intensities, as well as magnitudes exceeding 6. Due to their characteristics, this type of event didn’t require significant management measures or recovery efforts in the affected areas.

Volcanic eruptions, for the period studied, are the least frequent events. The first eruption for which there is a written record and that has been corroborated with geological data is that of Siete Fuentes - Fasnia, which began on December 31, 1704. Only 17 days after the end of the latter, the Arafo eruption began in a nearby area in the Güímar Valley. However, 404 days passed after the end of the latter, until the Garachico or Arenas Negras eruption started. And between the end of the latter and the beginning of that of Chahorra or Narices del Teide (1798), 33,599 days (91 years, 11 months, and 25 days) elapsed. The last eruption experienced by the island is that of Chinyero, from November 18 to 27, 1909, 40,605 days (111 years, 2 months, and 3 days) after the end of the previous one. As for the zone where they occurred, all of them took place in rift zones, originating those of Siete Fuentes-Arafo and Fasnia, in the Dorsal Rift Zone, those of Arenas Negras and Chinyero in the Santiago Rift Zone, and that of Narices del Teide on the SW flank of Pico Viejo, being still not very clear if it is also an eruption of the Santiago Rift Zone. All of them gave rise to multiple associated hazards, such as seismicity before, during and after the eruption, explosions, ash fall and ejection of pyroclasts, lava flows, and landslides. The area affected by these hazards was quite variable. The seismicity could be felt in areas far from the vents, around the island, and the ash also affected large areas of Tenerife and even other islands, while the lava flows had a more limited effect, except for the eruption of Garachico, which reached the sea, devastating the town of the same name located on the coast. In general, no direct deaths were reported as a result of these events, with the exception of the Siete Fuentes-Fasnia-Arafo eruption, where 17 people are believed to have died due to the panic caused by the eruption and the poor living conditions during the associated seismicity. However, there are reports of injuries and evacuations. The associated seismicity was perhaps the hazard that caused the most damage and economic losses, due to its high magnitude, as mentioned above, compared to earthquakes of tectonic origin. The local authorities of the time were in charge of the management, which consisted of sending people to explore the area where the phenomenon was occurring and return with descriptions of the same, evict people in vulnerable houses and relocate them in safer places, especially places donated by the church or other donors, but above all, much of the actions revolved around faith and religion, organizing processions and prayers in altars built provisionally to pray for their lives and pray for the cessation of such events. Generally there is not much information about the recovery work in the area, but it is known that for example, 35 years after the Garachico/Arenas Negras eruption, in 1741, the Cabildo met in an assembly in which the representatives of Garachico demanded money to fix the town destroyed by the lava flows. Although some religious buildings, such as parishes and convents, were previously rebuilt, it was then when several works of recovery of the town were carried out, which continued in 1798. It should be noted that these historical eruptions in Tenerife were of the Strombolian type, with VEIs between 2 and 3, and lava flow volumes between 0.004 km^3 and 0.035 km^3.

Finally, there are only written records of what could be 5 tsunamis. The first one, of which it is said that the sea retreated and then a wave flooded some towns, especially on the north coast of the island, is that of November 1, 1755, almost certainly caused by the Lisbon earthquake. The next one would come 5 years, 4 months, and 30 days later, and another one 150 years, 7 months, and 10 days later. All were produced with certainty by distal earthquakes, for this reason they were given the branch "other" as the zone of origin, as they were outside the map of the zones established for Tenerife in Fig. 18. The last one produced by a distal earthquake and corresponding to the last one recorded in Tenerife occurred on February 28, 1969. However, prior to this, a landslide caused by the impact of a wave on a cliff near Santa Cruz de Tenerife, caused a tsunami wave that flooded part of the port of the capital of Tenerife. In general, the areas most affected by this type of event are the coasts of the north of Tenerife, and the coasts of Santa Cruz de Tenerife and San Andrés (northeastern coast). In no did case they caused fatalities, and only some people were injured or evacuated. The effects are similar to those of floods, but with less extension and less intensity, being the flooding of some buildings and houses and some damage to municipal elements in coastal areas.

In summary, the possible scenarios that can be found in Tenerife given its historical record are as follows (Table 13):

Table 13. Possible Natural Hazard Scenarios for Tenerife According to its Historical Record (1496-2020).

Outcome	Primary/direct hazards	Secondary/indirect hazards
Volcanic eruption	Seismicity	-
		Rock falls
	Gases	-
	Explosions	-
	Lava flows	-
		Wildfires
	Fallout	-
Earthquake	Seismic foreshocks	-
	Seismic aftershocks	-
	Rock falls	-
	Landslides	-
	No effects	-
Distal earthquake	Tsunami	Flooding
	No effects	-
Others (storms, human action, unknown)	Rock falls	-
	Landslides	-
	Flooding	-
		Debris flow
		Erosion
		Electrocution
		Wildfire
		Famine
	No effects	

4.1.2. Long-term multi-hazard assessment for non-extreme events on Tenerife (Canary Islands)

From the probabilistic analysis of the historical record of non-extreme events occurring in Tenerife between 1496 and 2020, classified according to Table 8, the probabilities shown in Fig. 21 were obtained.

Figure 21. Probabilities of occurrence of each branch separated by node obtained from a probabilistic analysis of an Event tree structure with Bayesian inference, for a year after the period analyzed (1496 - 2020).

For better visualization, Fig. 22 shows the circular diagrams for each node. In addition, this interface also allows obtaining the most probable scenarios; in our case, we displayed 4 of them. It is important to clarify that the probabilities shown in both Fig. 21 and the circular diagrams in Figs. 22, 24-27 are the probabilities for each branch within each node. On the other hand, the probabilities shown at the bottom of Figs. 22, 24-27 in the “Most Probable Scenarios” section are global probabilities for each scenario resulting from the combination of one branch from each node. Therefore, throughout this subsection, the probabilities of each branch will be explained separately, and then a brief summary will be provided for the most probable combinations based on the results, which may coincide.

Figure 22. Visualization of probabilistic analysis results using the VOLCANBOX tool.

As we can see in Fig. 21 and Fig. 22, from the "origin" node, the branch with the highest probability is "Metropolitan", with a value of 0.2917. The next branch with the highest probability is "Atlantic Zone Tenerife Gran Canaria", with a value of 0.1250, followed by

"Northeast" and "North", both with values of 0.1146. The branches with the lowest probability are the "Atlantic Zone West Tenerife", “Atlantic Zone East Tenerife”, and “Atlantic Zone Northeast Tenerife”. Although the probability appears as 0 for these branches, it is not an absolute 0, but rather it is so small that it is displayed as 0 in the interface. This means that the areas most likely to host some type of event in the future are the Metropolitan zone (Fig. 18), followed by the Atlantic Zone Tenerife Gran Canaria. On the other hand, the area where a future event is least likely to occur is the Atlantic Zone West, East and Northeast of Tenerife.

For the "outcome" node, the "others" branch has the highest probability, with a value of 0.6923, followed by the "earthquake" branch (0.2404) (Fig. 21 and Fig. 22). With probabilities of 0.0385 and 0.0288, volcanic eruptions and distal earthquakes, respectively, would be the events with the lowest probability of occurrence in the future affecting the island. It should be noted that in the case of distal earthquakes, we measure the probability of this type of event occurring and having an impact on Tenerife. Therefore, according to these probabilities, in the future it is more likely that events other than eruptions and earthquakes will occur, which could correspond to storms with heavy rainfall, wind and/or waves, human actions, or any other type of those mentioned in this branch.

As for the "hazards" node, those branches with the highest probability are, in this order, "Flooding" (0.6082), "No effects" (0.1753), "Rock falls" (0.0928), while the branches with the lowest probability, being its probability so small that, as mentioned above, it is displayed as 0 even though it is slightly greater than 0, are “Seismicity”, “Gases”, “Explosions”, “Lava flows”, “Fallout”, “Wildfires”, “Electrocution, “Erosion”, “Famine” (Fig. 21 and Fig. 22). In this case, since there are no other types of events not described in any of the previous branches, the probability of the "Others" branch is an absolute zero. This means that in the future, the most probable derived hazard is flooding.

Finally, with a value of 0.3267, the "Metropolitan" branch is the one with the highest probability from the “impact” node, followed by the "North" branch (0.1287) (Fig. 21 and Fig. 22). The branches with the lowest probability for this node are "West" and "Center", with values of 0.0297 and 0.0198, respectively. Again, having no other types of events not described in any of the preceding branches, the probability of the "Others" branch in our case is an absolute zero. This means that the areas with the highest probability of being affected by any of the hazards described above are the Metropolitan zone and the Northern zone, while the center of the island presents a lower probability of being impacted by any of the hazards registered (Fig. 23).

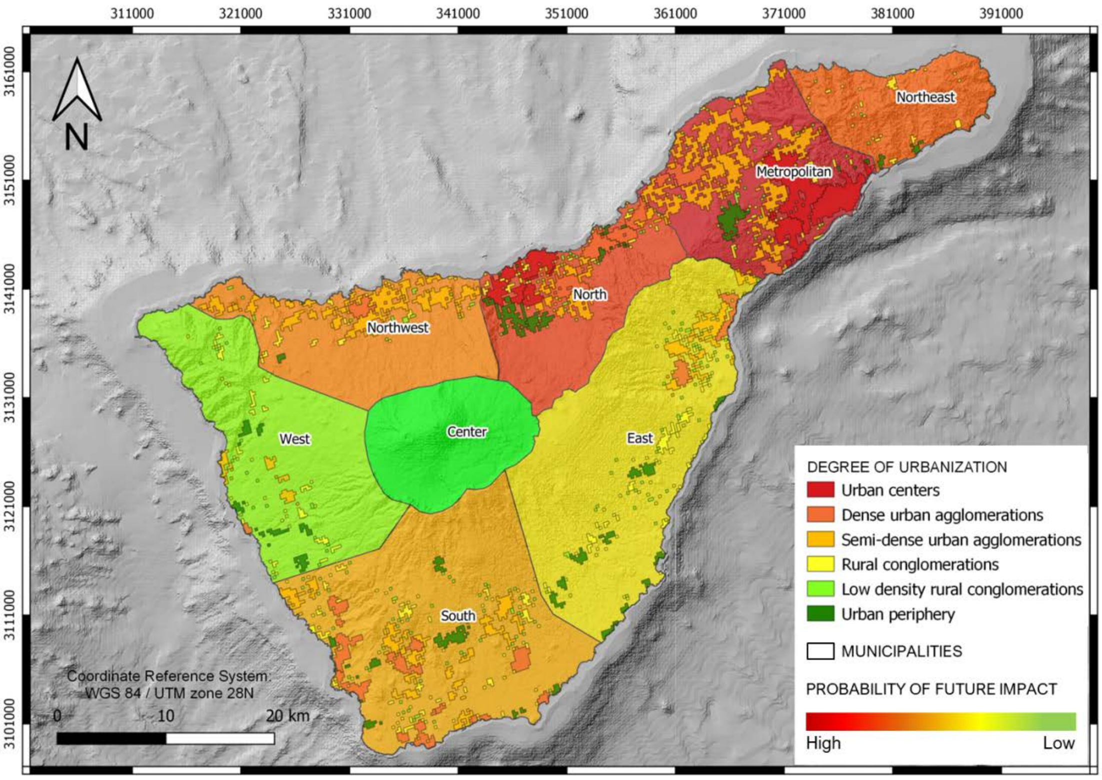

Figure 23. Map of probability of future impact by some type of natural hazard for the different areas of Tenerife, according to their historical record of events from 1496 to 2020.

As seen in the bottom part of Fig. 22, the most probable scenarios would be the following:

1) With a probability of 0.03386, an indeterminate event from the "other" category would occur, which could potentially be a storm and/or rainfall, human action, waves, or other triggering hazards originating in the metropolitan area, causing a flood in the same area.
2) With a probability of 0.01396, similarly, an indeterminate event from the "other" category would occur, which could potentially be a storm and/or rainfall, human action, waves, or other triggering hazards originating in the metropolitan area, causing a flood in the North area.
3) With a probability of 0.01370, an indeterminate event from the "other" category would occur, which could potentially be a storm and/or rainfall, human action, waves, or other triggering hazards originating in the metropolitan area, causing a flood in the Northeast area.
4) With a probability of 0.01300, an indeterminate event from the "other" category would occur, which could potentially be a storm and/or rainfall, human action, waves, or other triggering hazards originating in the Northeast area, causing a flood in the Metropolitan area.

However, if we look at Table 8, which classifies our data by branches based on nodes, we can see that scenarios 2, 3, and 4 are not possible since there is no record of an event classified as "other" originating in one area causing a flood in a different area. This is because most of these scenarios refer to rainfall originating in an area and flooding that same area. For this reason, as will be discussed in Chapter 5 "Discussion", the tool/methodology has some limitations, such as showing scenarios that are not real or possible within our registry by taking each node independently and looking to combine those branches with higher probabilities. This, in turn, means that these global probabilities, although fairly accurate and providing a good understanding of reality, are not exact or precise, as they are calculated taking into account scenarios that have occurred and scenarios that have not. Additionally, due to the significantly different frequencies of different types of events, the temporal window adjustment may underestimate the probability of some events (e.g., volcanic eruptions) compared to others that occur almost every year or even multiple times within a year (e.g., floods). These are some of the limitations of the current tool/methodology used, which we discuss, along with other identified limitations, later in subsection 5.5. "A roadmap for further investigation". However, to provide the reader with results that are more accurate to reality, a temporary solution was sought. This involved repeating the probabilistic analysis by applying the code to each branch of the "outcome" node separately, thus eliminating the scenarios that are not possible and obtaining real probabilities for each scenario created by each triggering event. These results are shown below, where it can be observed that in the "outcome" node, the circular diagram appears completely colored according to the displayed branch. This is because it is a single-hazard analysis in this case, where only the results of one branch of that node are shown.

If we filter the records according to the branch of the “outcome” node, for the “volcanic eruption” branch (Fig. 24), we find that the most probable source area is the “East” zone. The most probable associated hazards are seismic activity, fallout, and gas emissions. The most likely impacted area by one or more of these hazards is the “Northwest” zone, followed by the “North” and “Center” zones. According to the most probable scenarios, they all coincide in the occurrence of an eruption in the east, with the derived hazards affecting the northwest area (probability of 0.02201).

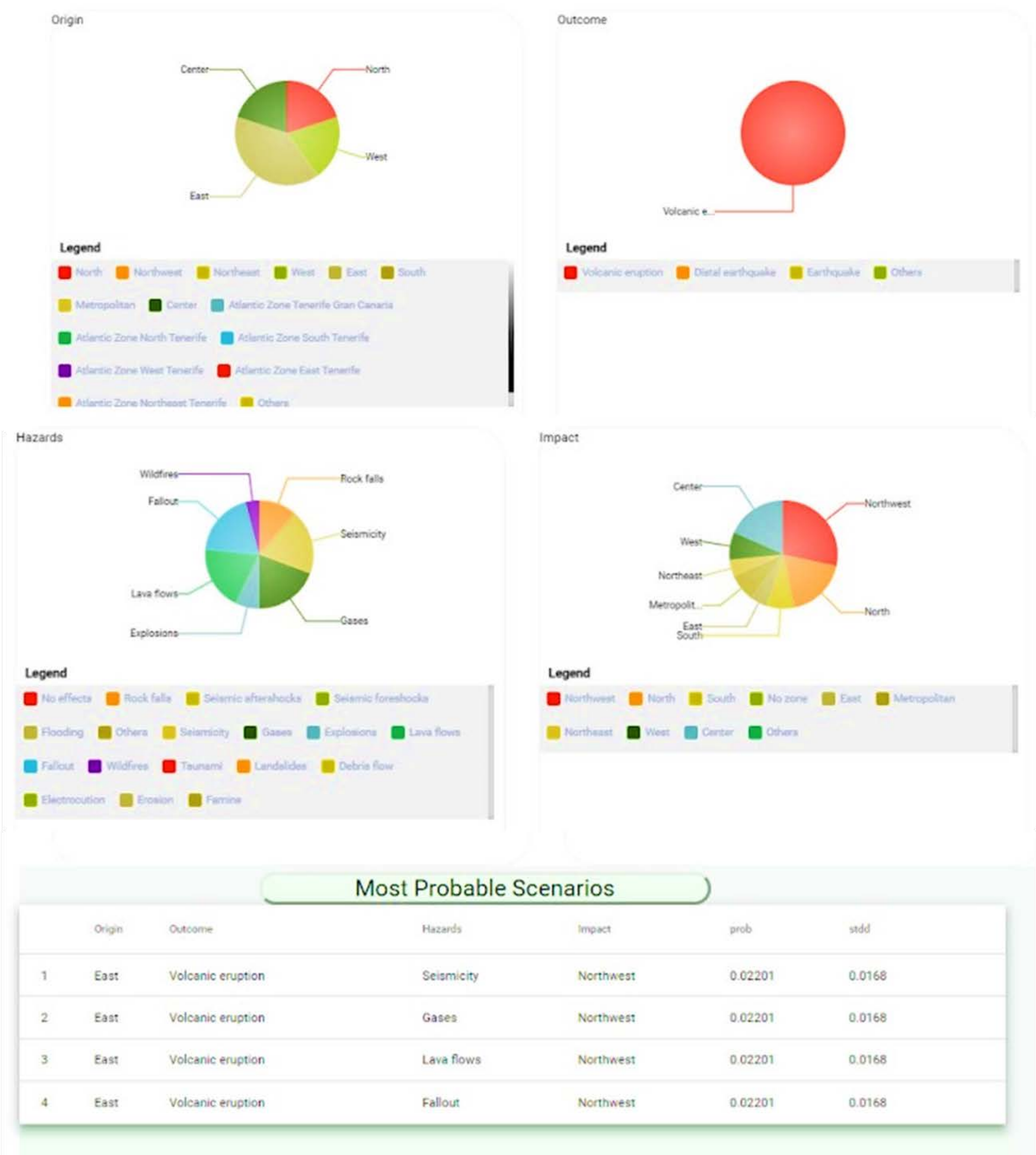

Figure 24. Visualization of probabilistic analysis results for the branch “volcanic eruption” from the node “outcome” using the VOLCANBOX tool.

In the case of “distal earthquake” (Fig. 25), the most probable source area is “Other” (i.e., areas not shown in the map of Fig. 18). The probability of triggering a tsunami and flooding is the same for this event, and the zones with the highest probability of being affected are the “North” zone, followed by the “Metropolitan” and “Northeast” zones. This aligns with the most probable global scenarios for this event, which involve a distal earthquake occurring in an area outside the map of Fig. 18, resulting in both a tsunami and flooding impacting the “North” zone (0.16834), followed by the same scenarios but with impact on the “Metropolitan” zone (0.10553).

Figure 25. Visualization of probabilistic analysis results for the branch “distal earthquake” from the node “outcome” using the VOLCANBOX tool.

Earthquakes with their epicenter within the zone shown in Fig. 18 have a higher probability of being originated in the Tenerife Gran Canaria Atlantic zone and not causing any effects on inland areas (Fig. 26). Therefore, the most probable scenarios are earthquakes originating in this zone without any effects (0.19783).

	Origin	Outcome	Hazards	Impact	prob	stdd
1	Atlantic Zone Tenerife Gran Canaria	Earthquake	No effects	No zone	0.19783	0.0846
2	Atlantic Zone Tenerife Gran Canaria	Earthquake	No effects	Metropolitan	0.07363	0.0538
3	Atlantic Zone Tenerife Gran Canaria	Earthquake	No effects	North	0.05753	0.0478
4	Atlantic Zone North Tenerife	Earthquake	No effects	No zone	0.05206	0.0381

Figure 26. Visualization of probabilistic analysis results for the branch “earthquake” from the node “outcome” using the VOLCANBOX tool.

Lastly, for the “other” branch (Fig. 27), the most probable source area is the “Metropolitan” zone. The most probable derived hazard, by far, is flooding, and the most probable impacted area is also the “Metropolitan” zone. Therefore, the most probable combined scenarios are indeterminate events originating in the “Metropolitan” zone resulting in flooding in the same zone (0.10465). This scenario aligns with the most probable global scenario, considering all branches of the “outcome” node, which encompasses the entire dataset. Following this scenario, we have the same scenario but with impacts in the “Northeast” zone (0.04073), followed by the “Northwest” (0.03695) and “North” (0.03347) zones.

Most Probable Scenarios

	Origin	Outcome	Hazards	Impact	prob	stdd
1	Metropolitan	Others	Flooding	Metropolitan	0.10465	0.0573
2	Metropolitan	Others	Flooding	Northeast	0.04073	0.0346
3	Metropolitan	Others	Flooding	Northwest	0.03695	0.0329
4	Metropolitan	Others	Flooding	North	0.03347	0.0313

Figure 27. Visualization of probabilistic analysis results for the branch “others” from the node “outcome” using the VOLCANBOX tool.

It can be seen that in these single-hazard analyses, the issue of obtaining unrealistic scenarios resulting from the combination of the most probable branches of each node still persists. This is the case of earthquakes that do not affect any zone, yet the analysis still indicates a scenario with a probability different from zero of impact on a certain zone. Another example is the same one we mentioned in the initial multi-hazard analysis, where scenarios, in the case of the branch “others”, indicate the occurrence of indeterminate events, which could be rainfall, human-induced events, storms, heavy swell, etc., resulting in flooding in areas different from the origin zone. Although this is a possible scenario in the real world and even in Tenerife, it is not within the record of events that we collected after applying our assumptions. This limitation is discussed in detail, as previously mentioned, in subsection 5.5. “A roadmap for further investigation". On the other hand, these probabilities appear very small because they are expressed over the total of all possibilities, which are numerous. For the most probable scenarios, the algorithm should recalculate among them, resulting in higher probabilities for the scenarios that are indeed more likely.

4.2. Long-term multi-hazard assessment for extreme events on Tenerife (Canary Islands)

In all, 277 different eruptive scenarios were obtained from the simulations performed for the four extreme hazards selected for this study, and maps are all included in Supplementary Material 2 (Annex 5).

4.2.1. PDC scenarios

In all, 14 scenarios were obtained by combining up to seven different values for a_c and two different values for H_c. Numerical results and implications are summarized in Table 18 attached in Annex 4. The PDC map scenarios are shown in Figs. S2–S15 attached in Annex 5, and an example is shown as well in Fig. 28.

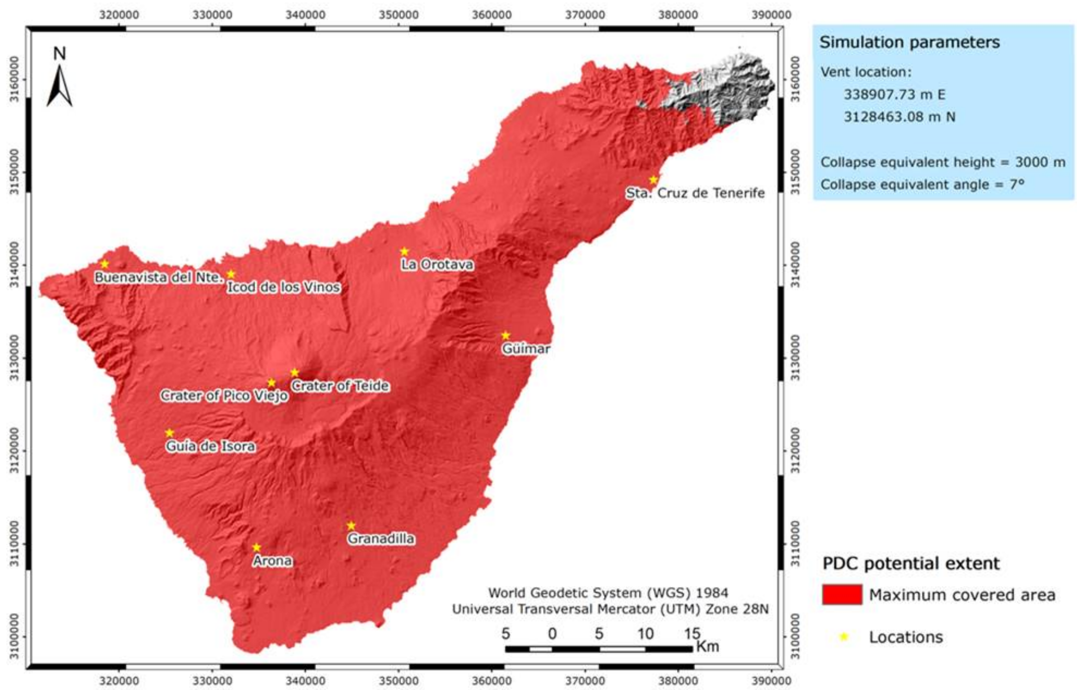

Figure 28. Pyroclastic Density Current map scenario considering H_c = 3,000 m and a_c = 7°, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

Results show that as the a_c decreases, the surface area covered by PDC deposits increases. PDCs scenarios obtained here go from the whole affectation of the island of Tenerife, produced by an a_c of 4°, regardless the H_c, to a minimum affected area of almost 200 km^2 and just over 300 km^2 concentrated around the vent, corresponding to the area of Las Cañadas caldera and surroundings, produced by an a_c of 27° and an H_c of 2,000 m. Between these two extremes, there is a wide range of results in terms of surface area covered and municipalities affected by ignimbrite that deserves to be taken into account (see Table 18 from Annex 4). Changes in two or three degrees of a_c, or in 1,000 meters of H_c, result in a variation of some hundreds of square kilometers affected.

It is observed that the Las Cañadas wall, a natural barrier for some volcanic hazards, such as lava flows, would stop the PDCs produced by a column collapse with an a_c equal or higher than 27° and an H_c of 2,000 m or less. In case an H_c of 3,000 m occurred, an a_c above 27° should occur so that the PDC would not exceed the limits of the central caldera. As there is no caldera wall towards the north, the most affected area after the Las Cañadas caldera is the Icod Valley. Beyond this central topography, other topographic features, such as valleys, other cones, lava walls, basaltic shield remnants, could channel or act as barriers for pyroclastic flows, but this is observed in few more distal areas.

4.2.2. PGA scenarios

In all, 54 scenarios were obtained combining three moment magnitudes (Mw), two different epicenters, each with three different hypocenters, and three attenuation laws. Tables 19 and 20 attached in Annex 4 summarize all the results. The maps of the expected PGA values are shown in Figs. S16–S69 attached in Annex 5, along with an example in the main text (Fig. 29).

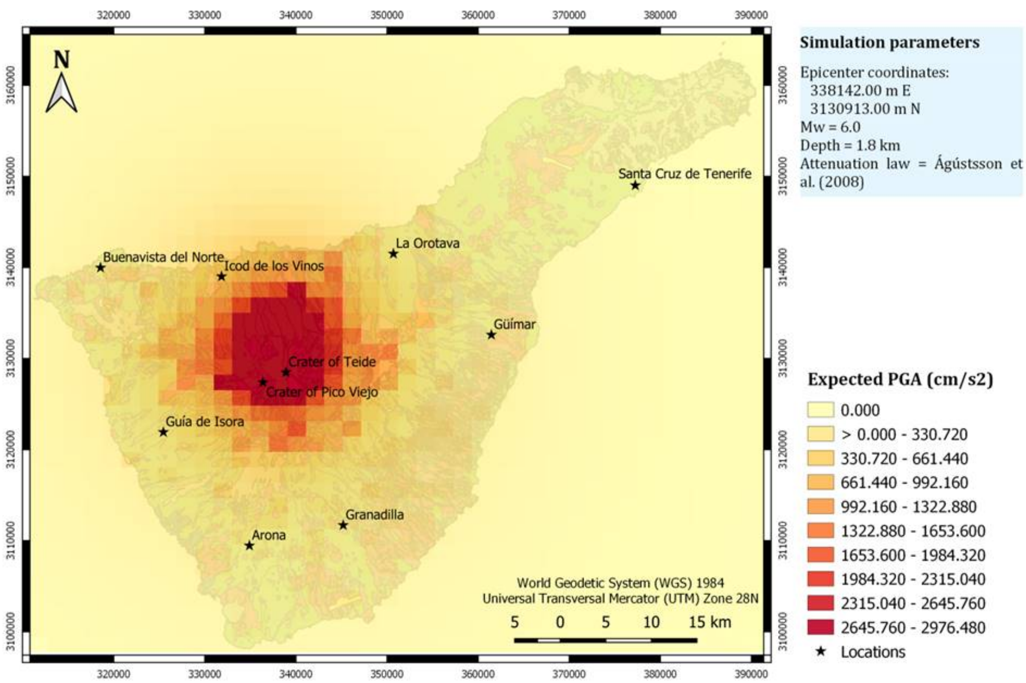

Figure 29. Expected Peak Ground Acceleration values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Ágústsson et al. (2008) attenuation law.

Both epicenters give similar gravity acceleration values, even coinciding in some cases. Likewise, the modification of the hypocenter does not imply any change in these values. Only a slight increase in the expected PGA in cm/s^2 is observed as the hypocenter depth increases when applying the Beauducel et al. (2004) attenuation law, but these minor differences are eliminated when transforming the values into acceleration of gravity (g) units. The main differences in the expected PGA results are due to the Mw of the earthquake, but also to the chosen attenuation law.

Considering that a lower Mw would give a lower PGA, the lowest expected PGA values were obtained by applying the Pétursson and Vogfjörd (2009) attenuation law. In this case, PGA values go from 0.10 g (in case of both epicenters) to 0.29 g (in case of epicenter 1). At the other extreme, the highest expected PGA values, keeping all other parameters unchanged, were obtained after applying the Ágústsson et al. (2008) attenuation law. Thus, the lowest PGA value is 0.61 g (in case of epicenter 1), while the highest is 13.21 g (in case of epicenter 2). Therefore, the choice of one attenuation law or another, and of one epicenter or another, can vary the expected PGA value for the same Mw by up to 12.93 units.

Between these mentioned extremes, there is also a wide range of scenarios, not only in terms of maximum expected PGA values (Tables 19 and 20 from Annex 4), but also in terms of ground response distribution (see Figs. S16–S69 from Annex 5). Deleting the depth variable, which has no influence on the results in this case, a total of 9 different scenarios were obtained per epicenter by combining only three Mw with the selected three attenuation laws. In case we could remove the attenuation law variable, if we would be able to know which one best suits the terrain of Tenerife, results would be reduced to one possibility per Mw and per epicenter. However, despite having selected only three different Mw for this study, the proposed range was between 5 and 7, a range that already includes multiple options and associated scenarios.

Apart from these results, the scenarios reveal that the areas most affected by the different earthquakes generated in this study are, in this order, the Las Cañadas caldera and its walls, the Icod valley, the NW and NE rift zones, and the area corresponding to Bandas del Sur, in the southeast of the island.

4.2.3. Landslide scenarios

A total of 207 simulations was performed, six using a static analysis and 201 with a pseudo-static analysis, by applying the input parameters introduced previously (Tables 10, 11 and 12) to the three considered geotechnical models (Model 1, Model 2 and Model 1 Bis). The results of the slope stability analysis are shown in Figs. S70–S276 attached in Annex 5, and an example is given here in Fig. 30; the FS values are summarized in Tables 21–25 from Annex 4.

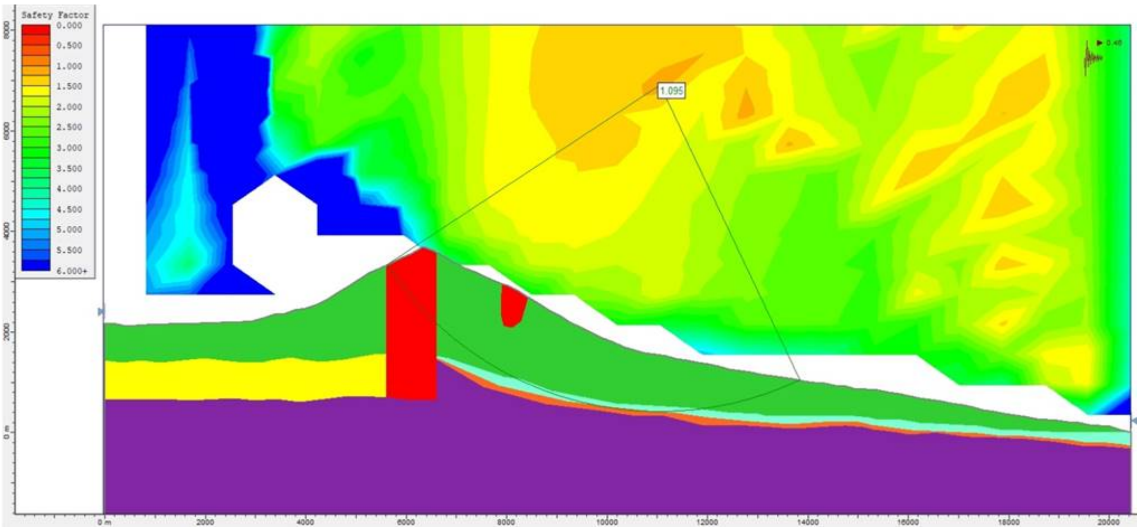

Figure 30. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Fig. 20a) using the Morgenstern-Price method and a k_h of 0.13.

**Note: x axis corresponds to the distance in meters, with the 0 located at southern limit of the cross section represented in line I-I' shown in Fig. 5, and y axis shows the altitude. The colors shown in the cross section correspond to the geotechnical units used for Model 1 and coincide with those represented in Fig. 20. Colors appearing above the cross section correspond to the Factor of Safety (FS) for each area of the diagram, shown as a mirror of it. The semi-circular shape corresponds to the most probable slip surface and its FS is shown in the box, which in this case is 0.996.*

All static analyses carried out for both geotechnical models give FS above 1 but below 1.5 (see Tables 21 and 22 in Annex 4), what means that both geotechnical configurations can be considered stable under steady state conditions, that is, no earthquake. However, FS values are lower for Model 1, which has alteration zones compared to Model 2. This also holds true during pseudo-static analyses, which means that under both steady state and seismic conditions, Model 1 is slightly more unstable than Model 2 due to the presence of altered materials, which increases the instability of the area.

Under seismic conditions, the pseudo-static analyses show that Model 1 becomes unstable (FS < 1) at a minimum k_h of 0.1, while a minimum k_h of 0.12 and 0.28 is required for Model 2 and Model 1 Bis, respectively. This is true in case the Janbu Generalised method is applied (also Bishop simplified in case of Model 1 Bis, see Table 25 in Annex 4), but from the results obtained it is clear that this value, which would mark the minimum required to generate instability (FS < 1) in the studied slope, varies from one method to another, requiring a higher k_h and, thus, a higher Mw, in case the other methods are applied to each model. This fact means that, in this study, at least three different seismic scenarios of minimum k_h required to generate instability could exist for each model. Knowing which method and which geotechnical configuration best fits the portion of the studied island, these seismic scenarios would be reduced to one. However, even with a single minimum k_h value, there are still multiple earthquakes that could give this value. This is because if we undo the formulas of Noda and Uwave (1976), Marcuson (1981), and Saragoni (1993), applied before, to know the PGA capable of giving that value of k_h and, in turn, compare which Mw could generate that PGA, we find multiple possible seismic scenarios (see Table 14, where the minimum values of k_h discussed above were taken as an example). This is also influenced by the location of the epicenter, as we can see in Table 14 for a PGA of 0.61 g in case of Model 1 Bis.

Table 14. Equivalences Between the Minimum Instability Values of Horizontal Acceleration (k_h) for Each Geotechnical Model and the Corresponding Peak Ground Acceleration and Mw Values.

	Model 1	
k_h	**PGA**	**Mw**
0.1	0.1 g (Noda & Uwave, 1976)	5.0 (Pétursson & Vogfjörd, 2009) < 5.0 (Ágústsson et al., 2008) < 5.0 (Beauducel et al., 2004)
	0.3 g (Marcuson, 1981) 0.33 g (Saragoni, 1993)	> 7.0 (Pétursson & Vogfjörd, 2009) < 5.0 (Ágústsson et al., 2008) > 5.0 and < 6.0 (Beauducel et al., 2004)
	Model 2	
k_h	**PGA**	**Mw**
0.12	0.12 g (Noda & Uwave, 1976)	> 5.0 and < 6.0 (Pétursson & Vogfjörd, 2009) < 5.0 (Ágústsson et al., 2008) 5.0 (Beauducel et al., 2004)
	0.36 g (Marcuson, 1981) 0.4 g (Saragoni, 1993)	> 7.0 (Pétursson & Vogfjörd, 2009) < 5.0 (Ágústsson et al., 2008) > 5.0 and < 6.0 (Beauducel et al., 2004)
	Model 1 Bis	
k_h	**PGA**	**Mw**
0.28	0.61 g (Noda & Uwave, 1976)	> 7.0 (Pétursson & Vogfjörd, 2009) 5.0 (< 5.0 for an epicenter located on the crater) (Ágústsson et al., 2008) > 5.0 and < 6.0 (Beauducel et al., 2004)
	0.85 g (Marcuson, 1981)	> 7.0 (Pétursson & Vogfjörd, 2009) > 5.0 and < 6.0 (Ágústsson et al., 2008) > 6.0 and < 7.0 (Beauducel et al., 2004)
	2.08 g (Saragoni, 1993)	> 7.0 (Pétursson & Vogfjörd, 2009) > 5.0 and < 6.0 (Ágústsson et al., 2008) > 7.0 (Beauducel et al., 2004)

**Note. These equivalences are made with the minimum value of horizontal acceleration (k_h) at which each geotechnical model showed instability (FS < 1) after the analysis with SLIDE. Also shown are the PGA and Mw values after reversing the three previously applied formulas (Noda & Uwave, 1976; Marcuson, 1981; Saragoni, 1993) to each k_h and checking the possible ranges of the Mw causing these values.*

The generated scenarios also show the most probable failure surfaces as semicircular lines affecting the slope, with the associated FS in a box (see Fig. 30). These slip surfaces show a rotational movement of the sliding block, the head of which is located south of the crater of Mt Teide in Model 1 (Fig. 30 and Figs. S76-S144 from Annex 5) and Model 2 (see Figs. S145-S210 from Annex 5). For Model 1 Bis (Figs. S211-S276 from Annex 5), the head of the sliding block is located north of the Las Calvas del Teide alteration zone. For higher values of k_h these semicircular sliding surfaces become more open and wider and the head of the landslide moves northwards (see Fig. S70–S276 in Annex 5). All the slip surfaces generally reach the depth of the limit between the water circulation zone unit and the “Mortalón”, the latter being unaffected or only slightly affected by the potential landslide. The average maximum thickness of the potential sliding block for all models is around 500 m, but it is reduced to 300 m in case of Model 1 Bis for high k_h values.

4.2.4. Tsunami scenarios

Two simulations were obtained by combining two different values for the constant retarding stress or yield strength. Tsunami simulations are shown in AVI Movies “ms01” and “ms02” (which can be found at the following link, https://drive.google.com/drive/folders/1y5w0drCTsd98ZUxz93_3TVZ9hwKAxmaW?usp=sharing, attached as digital Supplementary Material 4: Movies, Annex 7), which correspond to a simulation made with a yield strength of the sliding block of 50,000 Pa and 100,000 Pa, respectively. Four different stages of the tsunami propagation are shown in Fig. 31.

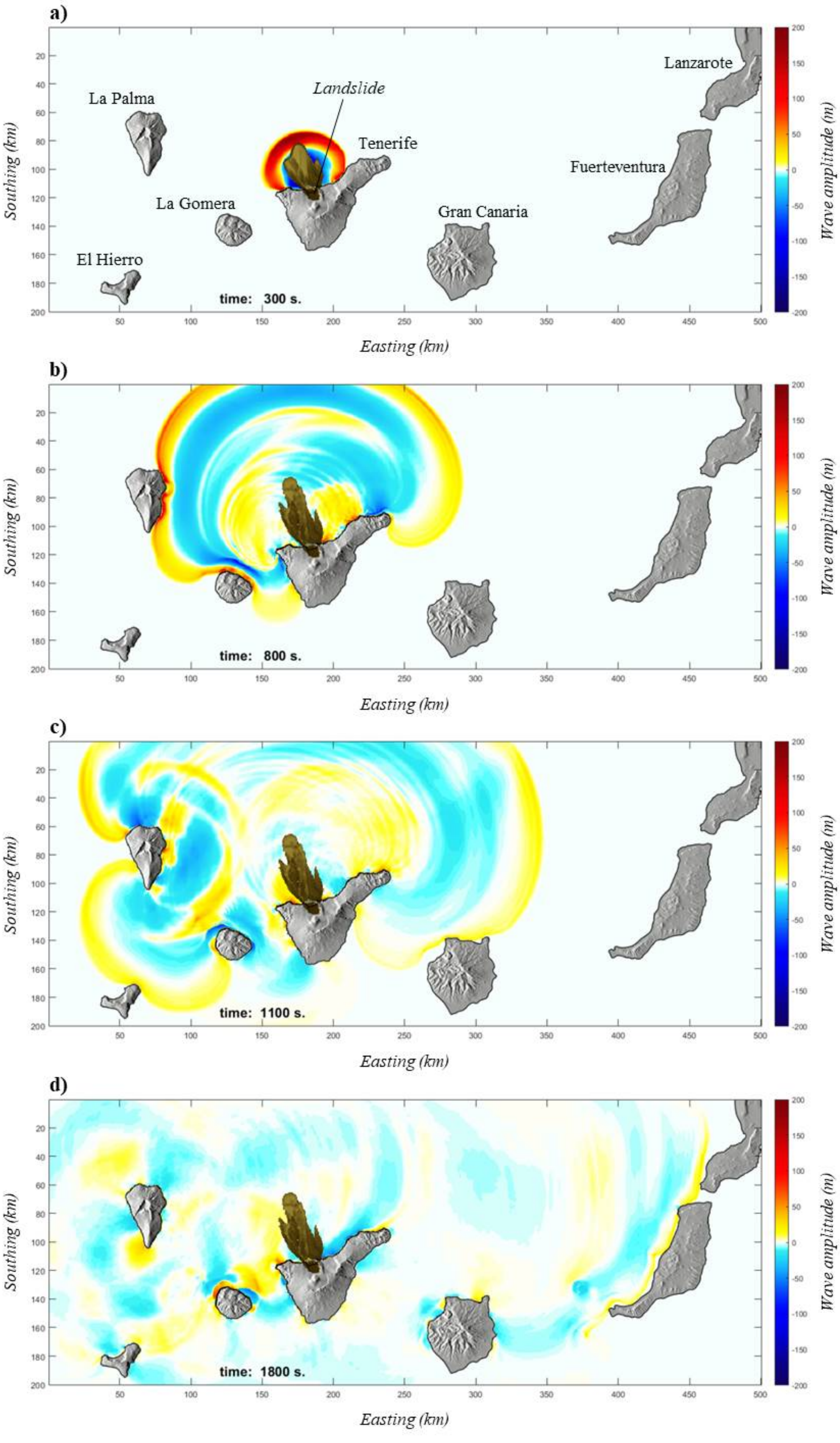

Figure 31. Simulation of the propagation of the tsunami caused by the impact of a landslide originating in the Icod valley on the ocean, with a yield strength of the sliding block of 50,000 Pa.

Both simulations give a first tsunami wave of about 200 m in height traveling northwards (Fig. 31a). However, the amplitudes obtained along the affected coasts outside the impact zone are higher and slightly faster for the 100,000 Pa than for 50,000 Pa simulation. Therefore, the choice of one yield strength for the sliding block or another would vary the arrival time of the waves by about 10 s and the maximum amplitude recorded on the affected coasts by up to 50 m. In both cases, the northern and western coasts of Tenerife, the eastern coasts of La Palma and the northern coasts of La Gomera are the most affected areas of the archipelago (see Fig. 4 for location of the islands).

Considering the simulation made with 50,000 Pa, we observe that the northern coast of Tenerife is wholly affected within 580 s with a maximum amplitude of around 100 m; the exception is the municipality of Los Silos, where waves reach almost 200 m in height (see Fig. 10 for location of municipalities). This coast is hit up to nine times by waves originating from the impact of the sliding block on the ocean and by reflected waves originating after the initial impact on the eastern coast of La Palma. The western and the eastern coasts of Tenerife are completely affected after 840 s and 1,300 s. The western coast registers a maximum amplitude of 50 m, which decreases towards the south, while the eastern coast registers around 20 m. Waves coming from both sides of the island are inhibited after meeting along the southern coasts. The southern municipality of Granadilla, on the opposite coast to the landslide site, is affected after 1,070 s by the tsunami originating from the western side of the island, with maximum amplitude of 10–15 m.

After 700 s, the north of La Gomera is the first site of the other islands of the archipelago to be hit by up to seven waves from around 80–100 m. These waves come both from the impact zone and from other islands after their reflection, especially from La Palma. The last affected island is Lanzarote, which is first hit by waves of about 25 m along its south-west coast after 1,790 s.

After 3,600 s, the ocean is still agitated around the Canary Islands and there are still maximum wave amplitudes of up to 40 m in some places. The least affected areas are the south of Gran Canaria and the eastern coasts of Fuerteventura and Lanzarote.

CHAPTER 5

DISCUSSION

5.1. Key considerations for risk management in volcanic islands: insights and best practices from a geoethical perspective

5.1.1. Critical scenarios for future risk management in Tenerife: from likely to catastrophic impacts

As has been announced throughout this project, conducting a long-term multi-hazard assessment for a territory based on the knowledge of its geological record, but mainly its historical record, represents an example of the methodology to be applied in addressing the risk management problem in active volcanic areas such as volcanic islands. By testing the efficiency and applicability of this methodology in a territory like Tenerife, we have been able to gain a better understanding of the issues, contextualize them for the future, and propose recommendations that are more closely aligned with the reality faced by the island. Evidence of the effectiveness of this methodology is the adjustment of the most probable and catastrophic scenarios for the island, which we will now present.

The island of Tenerife has been the scene of both extreme and non-extreme events throughout its evolution. Its natural characteristics, seen by its topography (steep slopes and significant elevations, especially in the central part, reaching 3,718 m at the peak of Teide), its geology (varying volcanic terrains such as lava flows, pyroclastic products such as ash and pumice fallout deposits, pyroclastic flow deposits, etc., as well as other sedimentary rocks), or its geographic location, make it an area susceptible to different natural processes that not only modify its morphology, but can also seriously affect its society. However, the overexploitation of resources, massive tourism, and the expanding overpopulation that the island suffers from can exacerbate the consequences of such phenomena. Meteorological phenomena, geological processes, and anthropogenic actions all work to modify the relief and give rise on numerous occasions to interrelated natural disasters.

Knowing all the multi-hazard scenarios that have occurred in a place, either through the geological and/or historical study of the area, will allow us to answer questions such as those presented in section 3.1. "General overview" of Chapter 3 "Methodology". And the fact is that only with the collection of data from the historical record of events in Tenerife for the period 1496 - 2020 we have been able to elaborate a catalog with all the possible multi-hazard scenarios that the island has experienced in the last 524 years. Therefore, at the outset, any of these events has a probability greater than 0 of occurring in the future. And although these are not all the possible scenarios for the island, since some with much longer recurrence periods, such as large eruptions, could have occurred prior to the period analyzed, all the scenarios listed here will have, to a greater or lesser extent, a higher probability of occurring in the future than any possible scenario that is not in Table 13. It should be said that the period studied could have been shorter and sufficient to carry out the study, but given the influence that natural and social factors have on the occurrence of these phenomena, which in turn have changed over the years, a shorter period would have given more inaccurate results, in addition to being able to ignore some possible scenarios as we have already mentioned.

The results of the probabilistic analysis indicate that events such as rainfall occurring in the metropolitan area (see map in Fig. 18), causing only floods (i.e. without derived hazards) in that same area, is the most likely scenario for Tenerife. The tool also tells us that the area with the highest probability of occurrence and impact of any event is the Metropolitan area. In this way, we would be addressing the second and third questions posed in Section 3.1., "General overview." However, with the current tool we cannot give a precise answer to the question of which scenario is more likely for each area of the map nor which area is the most likely for each type of scenario, so at present we could not yet answer questions 4 and 5 of section 3.1. (see section 5.5. "A road map for further investigation" for next steps in the development of this tool and its future capabilities).

However, according to the records, these floods would most likely occur in the autumn-winter seasons, with the most probable months being November to January. However, trends suggest that they could also extend or occur in the winter-spring period, from January to May. It is expected that rainfall would be the most probable cause of these scenarios since it has the same distribution through the year. The subtropical climate of the island, influenced, among other factors, by Atlantic storms, generates these storms during these periods of the year. According to Fig. 7, these storms enter from the ocean towards the land from the north, resulting in the heaviest precipitation in the northern and northwestern parts of the island.

Furthermore, it is also expected that, given the steep slopes characteristic of volcanic islands like Tenerife, heavy rain produce flash floods, which pose a common danger, with the main risk being the overflow of ravines. They usually overflow when they reach flatter areas or areas modified by human activity, either by channeling, bridges and narrowings, changes along the course of the flow, or due to paving. The most affected cities are usually Santa Cruz de Tenerife, San Cristóbal de La Laguna, Garachico (especially by waves), San Andrés, the La Orotava Valley, Güímar, Puerto de la Cruz, Los Realejos, Icod de los Vinos, among other municipalities. In addition, these torrential floods drag large quantities of sediment along the ravines which, added to the landslides caused, lead to the occurrence of debris flows and the deposition of mud and large rocks in the overflow areas, thus increasing their impact and making cleanup and repair tasks more difficult.

In general, the frequency of this phenomenon has remained more or less constant throughout the period studied, although a quantitative analysis was not carried out because it was beyond the scope of this doctoral thesis. Perhaps a slight increase in frequency was observed in recent years. However, its impact has increased, with the flooding of the metropolitan area and coastal populations becoming more frequent. Given the record so far and the high probability of this event, we can determine for the sixth question posed in section 3.1. that this scenario causes the most damage and has the potential to do as much or more in the future. If we look at the location of these population centers, in addition to being in areas with high rainfall, most of them are situated on or around major ravines. Many of these ravines have been paved and converted into passable streets, while others have undergone modifications and constructions, some of which hinder their drainage towards the sea. It should be noted that water will always seek its original course, so measures aimed at avoiding danger rather than mitigating associated risks are likely to have a greater economic and social impact. In that case, some of the mitigation measures that should be implemented include: (1) cleaning of ravines to reduce solid load during torrential floods; (2) creation of water retention areas, such as allocating gardens, parks, or other open and permeable areas for controlled overflow of watercourses; (3) reforestation of the headwaters and areas where precipitation is concentrated (and consequently reducing the risk of fires through greater control of negligence and intentional actions, as well as clearing forests of combustible material); (4) permeabilization of the channel beds, for example, avoiding paved channelization; (5) increasing the height of bridges crossing the ravines; (6) facilitating drainage to the sea, cleaning and enlarging the sewage system, as well as opening its outlet to the beach, protecting it from sand blockage during storms and increasing the slope towards the sea to prevent waves from entering, taking into account the sea level rise forecasts shown in Fig. 13, for example; (7) respecting the natural alignment of the ravines and conducting land planning accordingly. All these measures, and more, should be designed based on more detailed flood hazard mapping, taking into account the hazards that may arise from them.

Another common phenomenon in Tenerife is rock falls and small-scale landslides. These typically occur in road cuts or in the ravines themselves, with only a few of them being frequented by tourists. That is why they generally do not result in fatalities, injuries, significant damage, or high costs. However, it is worth mentioning the landslide that occurred in the Barranco del Infierno on October 26, 2015, which resulted in one fatality and four injuries, as well as the landslide on November 1, 2009, on the cliff of Los Gigantes, causing the deaths of two people who were on the beach of Santiago del Teide. Another significant landslide took place on January 27, 1947, in Tacoronte, resulting in five fatalities (Instituto Geológico y Minero de España, 2016). However, it should be mentioned that there has been an underestimation of this type of events due to having a much shorter registration period compared to other typologies. This limitation could not be overcome as no assumptions could be made since we cannot assume that the frequency in other years is the same, as several factors influence it. For example, the creation of kilometers of roads may increase the number of slope failures, as well as variations in rainfall and other conditioning factors. However, it cannot be assumed that the frequency was much lower either. Nevertheless, it is observed that although these phenomena have been very frequent in recent years, they do not cause significant economic or social losses, so they may not pose an alarming situation if they occur in the future. However, certain consequences cannot be ignored, such as road closures or the risk they pose to people.

Despite the uncertainty in the data, and although the cause of almost all of these events is unknown, records indicate that many of them do not have a direct triggering event but rather result from various influencing factors such as temperature changes, rainfall, or earthquakes acting on the slope of the rock and the force of gravity. In some cases, they occur immediately after a period of rain, earthquakes, floods, strong winds, or intense waves. This could coincide with the periods following heavy rains and floods, as will be explained below. However, their distribution throughout the year is broader than that of floods, so it is not possible to establish an exact triggering cause. Additionally, prior to some of these events, earthquakes have also occurred, which could have prepared the ground to trigger these landslides together with the rains in the following days. Knowing this, it is essential to be prepared for this type of phenomena, especially after periods of rain and earthquakes. Some of the measures can be the cutting of roads and trails susceptible to suffer this type of events days after rains or earthquakes, as well as the installation of meshing, bolting, and other structures to retain landslides. It is also possible to opt for the cleaning of slopes with those blocks susceptible to fall, in addition to adequate and accurate geological and geotechnical studies for the creation of road cuts. Whenever possible, the relief and geomorphology of the site should be respected, and the creation of large slopes with steep gradients should be avoided. This is complicated in volcanic terrain, but sometimes the easiest solution can have more costly long-term consequences.

Earthquakes felt in Tenerife usually have two origins: tectonic or magmatic. Earthquakes with a tectonic origin are usually associated with the transform fault that runs through the channel between the islands of Gran Canaria and Tenerife. In this area, which hosts the highest seismic activity in the Canary Islands, there are usually between 400 and 500 earthquakes per year below 2.5 magnitude, with only a little less than a dozen exceeding this limit (Instituto Greográfico Nacional, 2022). The earthquakes felt in Tenerife since records have been gathered have had intensities between I and VI on the MSK-64 scale (Medvedev & Sponheuer, 1964), and do not usually cause any damage. Some exceptional cases are the earthquake of May 9, 1989, with a magnitude of 5.0 and an epicentral intensity of 6.7, which caused some breakage of windows and displaced furniture in houses (Mezcua et al., 1992). As for earthquakes of magmatic origin, they can occur in isolation or in seismic swarms, i.e., groups of numerous earthquakes of low to intermediate magnitude in the same place, related to the movement of magma or fluids.

Other hazards that occur on Tenerife are the haze, coming from the Sahara, which, in addition to respiratory problems, has sometimes been accompanied by plagues of locusts, as happened in 2004; forest fires caused by heat waves and / or human action (such as in 2007, which burned 15,000 ha) or are aggravated by the haze; or tsunamis, which are somewhat less common, having a record of a tsunami on March 31, 1761, although some of these data are not so solid. However, there can be no doubt that being an island in the middle of the Atlantic Ocean, it can easily be affected by any tsunami that runs through this area.

On the other hand, during the construction of the Las Cañadas edifice, Tenerife experienced several cascading extreme events. This is the case of the La Orotava and Icod valleys, on the northern flank of Tenerife, two large sector collapses, which coincided in time with the occurrence of caldera-forming episodes. They are coeval with the formation of the central (Guajara, 0.56 Ma) and eastern (Diego Hernández, 0.17 Ma) sectors of the caldera of Las Cañadas, respectively (Martí, 2019; López-Saavedra et al., 2021). These sector collapses also generated large-scale tsunamis (Paris et al., 2017). Caldera eruptions ranged in size from 12 to more than 20 km^3 of phonolitic magma, mostly in the form of pyroclastic material that had been deposited on the island and offshore (Martí, Mitjavila, et al., 1994; Bryan et al., 1998). The Icod and La Orotava landslides moved volumes of 240 – 264 km^3, including subaerial and submarine materials (Hunt et al., 2018). The resulting tsunami left deposits that are preserved in thicknesses of 0.4 – 3 m on the northwestern flanks of Tenerife at altitudes up to 132 m a.s.l. (Paris et al., 2017). Since the succession of events described here is a process that has repeated several times in the past, it is not inconsistent to consider that it might occur again in the future (López-Saavedra et al., 2021). Therefore, this would be the worst-case scenario for Tenerife.

For this reason, in order to develop more comprehensive risk management plans for the region, a past extreme event in Tenerife, whose cascading sequence of hazards is known from the geology and stratigraphy of the island, was identified and quantified. This allowed us to know what would be the most catastrophic scenario that the island could experience in the future. What we did is to look for the most probable multi-hazard scenarios in case this extreme event would be repeated today. However, multi-hazard assessments considering cascading effects of an extreme event are more difficult to perform due to the complex relationships that can be established between different hazards and their magnitudes of occurrence and impact. In addition, this is an event that lacks direct observers and, therefore, a written historical record describing how it occurred, so the margin of error is much greater as it is based solely on observations from the geologic record. This is a problem we had to face during this study. The lack of information and data regarding the magnitude and characteristics of each of the studied hazards (e.g., the collapse height of the PDCs, the magnitude of the seismic shocks, etc.) means that we had to work with wide ranges of input parameters. For that reason, the 277 scenarios obtained in this study were analyzed to identify those combinations of parameters for each event, and those combinations of hazard scenarios, whose results best fit what happened during the El Abrigo eruption. Out of this context, all the obtained scenarios could be possible, but only few combinations of them adjust to what we observe in the geological record of the island corresponding to the El Abrigo eruption. These scenarios are discussed here.

Given that the ignimbrite resulting from the El Abrigo eruption covered nearly the whole island, the closest PDC scenario would be a collapse of the eruptive column from a height of between 2,000 and 3,000 m, with a collapse equivalent angle around 7°. In this case, nearly all the island would be hit by PDCs, and only its northeast corner would be unaffected. At the same time, or just after the emplacement of the PDCs, the caldera collapse process would begin. The resulting high magnitude seismicity would severely affect the central part of the island, corresponding to the caldera of Las Cañadas and its walls, the Icod Valley, the NE and NW rifts, and Bandas del Sur in the southeast. From a conservative point of view, and considering both the results from Hürlimann et al. (2000) and our stability analysis, if at the beginning of the collapse seismic shocks produce a PGA of around 0.3–0.33 g, an unstable state of the Icod Valley slope could be reached. Over that range of PGA, a landslide is very probable to be produced in the Icod Valley area. However, if these values of PGA are not reached at the very beginning of the collapse, but they are achieved when the process is more advanced, instability is less likely to occur, as a higher PGA is required. In this case, being conservative, a landslide could be produced if a PGA between 0.61 and 0.85 g is reached during the final stages of the caldera collapse process.

The head of the landslide would be located at some point in the northern slope of Mt Teide, depending on the position of the magma chamber, as it controls the extent of the caldera collapse, and would affect an area similar to the last Icod landslide, involving a maximum thickness of 500 m. According to what is observed from the original Icod landslide deposits (Ablay & Hürlimann, 2000; Watts & Masson, 2001), the sliding material would behave as a cohesive avalanche with mega-blocks, whose translational movement towards the sea would produce a 200 m-high tsunami wave in the impact area. The northern coast of Tenerife would be devastated in less than 10 min by waves with heights of around 100–150 m (even 200 m in some places), and the rest of the islands of the Archipelago would be hit by tsunami waves up to

120 m in less than 30 min. These results are in good agreement with the geological evidence represented by the presence of tsunami deposits on the north of the island of Tenerife, at 132 m a.s.l (Paris et al., 2017). This is a reasonable approximation for the 50,000 Pa simulation, which reached 100–150 m on Tenerife. Moreover, the simulation presented also suggests that the propagation of the tsunami waves could progress beyond the limits of the Canary Islands, being potential for the impacts of such an event to be felt far from the source. However, geologic evidence has not yet identified any such distal impacts from past events, so any attempt to identify the distal limits of such tsunami remains speculative by now.

At present, the Tenerife volcanic system is not in a situation similar to that of the last caldera eruption. In fact, reaching the conditions for a caldera-forming eruption may take thousands to hundreds of thousands of years, as it requires generating a sufficient amount of eruptible phonolitic magma, and all the phonolitic eruptions occurred on Tenerife during the Holocene are too small in terms of erupted volume (Martí, Geyer, Folch, et al., 2008). At the current stage, the Teide and Pico Viejo complex seems still too young to reach these conditions. However, it is following a very similar evolution than the previous phonolitic cycles, and the succession of events described here is a process that has repeated several times in the past, so it is not inconsistent to consider it might occur again in the future. The occurrence of such a succession of catastrophic events does not define a scenario that can be easily managed, but identifies a possible scenario in which efforts must be invested in forecasting and prevention well in advance. In this sense, increasing the monitoring network and applying high resolution geophysical imaging methods (e.g., magnetotellurics, gravimetry, seismic tomography, etc.) of the interior of the island, able to identify and quantify the presence of fresh magma, would be potential actions to be undertaken.

Through the identification and quantification of the main processes and characteristics of this type of extreme hazards, the uncertainty is reduced when making decisions in case we encounter a similar event in the future. For this reason, we believe that this comprehensive multi-hazard assessment could help to suggest guidelines for management, monitoring and urban planning, and should be taken into account by emergency management plans designed for the Canary Islands. Despite the difficulties and the simplicity of the simulation models used, our analysis does provide significant clues that should serve to increase awareness of the potential occurrence and consequences of such large-scale events. Although our analysis could be thought of as a purely academic exercise that merely aims to increase our fund of knowledge, we believe that it will in fact help improving the current emergency management plans by detailing appropriate hazard scenarios and optimizing mitigating actions well before any emergency caused by such extreme multi-hazard events ever occurs.

5.1.2. Capacities of Tenerife's risk management system: is Iceland's approach a model to emulate?

Iceland, known as the "Land of Fire and Ice," is a Nordic island country located in the North Atlantic Ocean. It is situated northwest of mainland Europe and has a unique geographical and geological context that sets it apart. Despite being both populated active volcanic islands, with multiple natural disasters experienced, Tenerife and Iceland differ both geologically and geographically (and therefore meteorologically), as well as socio-economically and politically. However, the task of introducing modifications to our current system in order to adopt efficient strategies from another model system should not be given up. On the contrary, if we want to adopt exemplary measures from one territory to another, we must take into account both contexts and their differences, in order to be able to carry out a customized implementation that meets the particular needs of each area. The extrapolation of such strategies must go through a process of adaptation to the system of each region, but without losing the strengths that make it an efficient measure. It is necessary to analyze why these measures are successful in the system of origin, which of them can be implemented in the target system, how they can be integrated and/or adapted, and which others cannot be adopted. But first we must know the differences and similarities between the two countries at all levels. However, since this is not the main objective of this thesis project, only a simplified and generalized comparison is presented in the text. Thus, although an extensive analysis and description of Tenerife was made, only the most important characteristics of Iceland are detailed below for comparison.

Geologically, Tenerife and Iceland differ in their tectonic settings. Iceland is located on the Mid-Atlantic Ridge, where the North American and Eurasian tectonic plates meet, making it a hotspot for volcanic and geothermal activity. This geologic activity has shaped the island with dramatic volcanic mountains, vast lava fields, geysers, hot springs, and majestic glaciers, such as Vatnajökull, the largest ice cap in Europe. In terms of natural hazards, both islands have experienced similar types of events. Iceland experiences frequent earthquakes and volcanic eruptions. Volcanic hazards, including lava flows, ash clouds, and gas emissions, pose challenges to both the population and infrastructure. Notable volcanic eruptions in recent history include the 2010 Eyjafjallajökull eruption, which caused significant disruptions to air travel across Europe. In addition to volcanic hazards, Iceland is prone to other natural hazards such as glacial floods (jökulhlaups), avalanches, and coastal erosion. The country's rugged terrain and active geological processes require constant monitoring and preparedness to mitigate the potential risks. On the contrary, the frequency of eruptions in Tenerife is much lower, as mentioned in previous sections, but it also experiences both tectonic and volcanic earthquakes. However, since it is not covered by ice or experiences prolonged snowy periods, there is no risk of avalanches or jökulhlaups. Nonetheless, flash floods and storm-induced flooding are much more frequent. Both islands have also experienced landslides and rockslides, as well as severe rainstorms, strong winds, and snow on numerous occasions in the case of Iceland and with much less frequency in Tenerife. Additionally, in the past, both have had episodes of landslides associated with volcanic structures and the generation of tsunamis (e.g., the 2014 Lake Askja rockslide-induced tsunami).

Socio-economically, Tenerife and Iceland have also distinct profiles. Let us recall that the surface area of Tenerife is 2,034 km^2, with a population of 927,993 (2021), whereas the surface area of Iceland is 103,000 km^2, with a population of 372,520 (2021). These figures give rise to significant disparities in population densities between the two regions, with approximately 456.24 inhabitants/km^2 in Tenerife, as opposed to 3.62 inhabitants/km^2 in Iceland. On the other hand, Tenerife is a popular tourist destination, attracting around 4.5 millions of visitors each year. For that reason, its economy is heavily reliant on tourism, with a developed infrastructure to accommodate travelers. Tenerife benefits from a mild climate, stunning beaches, and a variety of attractions, including theme parks and natural wonders. Additionally, agriculture, primarily focused on banana plantations, plays a significant role in the local economy. Iceland, on the other hand, receives about 2 million tourists each year and its economy is more diversified. While tourism has grown in importance, particularly after the financial crisis of 2008, Iceland's economy also relies on fishing, renewable energy, and high-tech industries. It is known for its high standard of living, strong social welfare system, and a small, tightly-knit population. The country has abundant geothermal and hydroelectric resources, which contribute to its energy self-sufficiency and sustainability efforts, in contrast to Tenerife, which is largely dependent on external sources. One of the main resources that Tenerife depends on from the outside is water, which is abundant in Iceland.

Politically, as we mentioned, Tenerife is a part of Spain and follows the political framework of the Spanish government. It is one of the autonomous communities within the Canary Islands. The Canary Islands have a regional government that handles specific local affairs, including tourism, agriculture, and economic development. Iceland, on the other hand, is an independent country with its own political system. It operates as a parliamentary republic, with a multi-party system and regular elections. Iceland has a strong tradition of democracy, and its government places an emphasis on environmental conservation and sustainable practices. Icelanders have a strong sense of national identity and cultural heritage, often influenced by Norse mythology and sagas.

In summary, Iceland's unique geographical and geological context, natural hazards, socio-economic stability, and environmental consciousness make it a captivating and resilient nation.

Its breathtaking landscapes and harmonious blend of nature and modernity continue to attract visitors from around the world.

The differences in their geological, geographical, cultural, socio-economic, and political characteristics, among others, make their risk management systems also distinct (Table 15). Risk management in Tenerife and Iceland follows different approaches but shares the goal of safeguarding public security. As we mentioned before, in Tenerife, civil protection is organized and implemented by various public administrations and entities involved in risk management. The Ministry of Interior holds the highest authority, and the Directorate General of Civil Protection and Emergencies (DGPCE) plays a pivotal role at the national level. The National Civil Protection System (NCPS) ensures coordination, cohesion, and efficiency in civil protection policies. Emergency situations require the mobilization of resources from public administrations, institutions, private entities, and citizens. Autonomous communities are responsible for directing and coordinating emergencies within their territories, while cooperation among entities at national and supranational levels is crucial for joint prevention, planning, and disaster response. The Tenerife's civil protection system is built upon a comprehensive legal framework, coordinating bodies, and robust planning and training activities.

In Iceland, civil protection is overseen by the Minister of Justice, who serves as the supreme authority in the field. The Civil Protection and Security Council, chaired by the Prime Minister, formulates government policies for civil protection and security in three-year periods. The council includes government ministers, representatives from local authorities, critical infrastructure sectors, volunteer organizations, and civil protection entities. The government's policy accounts for the current situation, prospects, prevention measures, response plans, recovery, and infrastructure function necessary for national survival during disasters. The National Commissioner of the Icelandic Police/Department of Civil Protection and Emergency Management (NCIP/DCPEM) implements measures aligned with the government's policies. Icelandic Search and Rescue (ICE-SAR) and the Red Cross play vital roles in Iceland's civil protection efforts.

Table 15. Risk Management System Comparison Between Iceland and Spain. Source: own elaboration based on the information extracted from the interviews and European Commission (2019a,b).

Risk management aspects	Iceland	Spain
Responsible	The National Commissioner of the Icelandic Police (NCIP) of which the Department of Civil Protection and Emergency Management (DCPEM) is member, which belong to the Ministry of Interior.	Ministry for Ecological Transition and the Demographic Challenge (MITECO), Ministry of the Interior, of which the Directorate General of Civil Protection and Emergencies (DGCPE) is member, and the autonomous community and local institutions.

Risk management aspects		Iceland	Spain
Approach		Centralized with coordination at the national level.	Decentralized with the participation of the Autonomous Communities and local entities.
Prevention	**Overview**	All-hazard approach and collaboration among different stakeholders.	Sectorial approach with various authorities responsible for specific prevention plans.
		Priority to prevention through policies, risk assessments and collaboration with relevant entities.	
	Research and monitoring	A single official body, the Icelandic Meteorological Office (IMO), in collaboration with other entities.	Multiple institutions/organizations specialized according to the type of natural event.
	Risk assessments	Primarily focused on volcanic activity, earthquakes, flooding, and avalanches.	Primarily focused forest fires, and flooding, along with other natural and man-made risks.
		Recognition of the importance of conducting risk assessments to understand and address the hazards they face. Shared commitment to preparedness and effective response to potential disasters through collaboration among countries and international entities in risk assessment.	
	Risk management planning	Local and national coordination, with clear activation phases and crisis centers at various levels. The NCIP/DCPEM implements measures based on the national risk assessment and the government's Civil Protection and Security Policy. Mitigation measures are implemented for known risks, and response plans are prepared for identified high-risk scenarios. The National Crisis and Coordination Centre, operated by the NCIP, coordinates and assists local crisis centers during crises.	Multiple levels of administration and specialized civil protection plans for different individual hazards. The state plan establishes the direction and coordination of all public administrations during emergencies of national interest. Territorial plans focus on emergencies affecting autonomous communities or municipalities, for pre-identified key risks. Additionally, self-protection plans are established to prevent and control risks associated with hazardous activities in specific industries.
		Comprehensive approach taking into account various levels of administration and coordination. Priority to risk management planning for preparedness and effective response.	
Preparedness	**Training and exercises**	Response plans regularly updated and implemented, with each civil protection district collaborating with the NCIP/ DCPEM.	National exercises regularly conducted by the DGCPE to test response plans and emergency management strategies at the local, regional, and state levels.
		Regular training and exercises to enhance preparedness and response capabilities in dealing with natural risks.	
	Monitoring	The IMO is the official monitoring organization for natural hazards, including early warning systems. Daily communication between the NCIP/ DCPEM and the IMO, together with other monitoring organizations. The Civil Protection Scientific Advisory Board (SAB) convenes when necessary, comprising specialists from various agencies and institutes, including the IMO, the Institute of Earth Sciences from the University of Iceland, the Environmental Agency, the Medical Directorate of Health, the Occupational Safety and Health Agency, and the Food and Veterinary Agency.	The National Meteorological Agency (AEMET) issues warning bulletins for meteorological hazards such as rain, storms, wind, and snow. The National Water Office and river basin offices collect hydrological data. The National Seismic Network plays a vital role in detecting and monitoring seismic and volcanic risks, with real-time data connection to a central data center at the National Geographic Institute. Oceanographic Institute, Geological Institute, and National Seaport Management Authority, collaborate to establish a national tsunami warning center. All information collected is shared in near real-time with the National Emergency Centre (CENEM) at the DGCPE.
		Real-time information exchange and close coordination between monitoring organizations and civil protection authorities to effectively respond to natural hazards.	
Emergency response	**Coordination**	The NCIP operates the National Crisis and Coordination Centre for Civil Protection. The NCIP, in consultation with the relevant regional police commissioner, has the authority to declare an emergency and determine alert levels. The Minister of Justice is then informed of this decision. Three levels of activation exist: the uncertainty phase, the alert/hazard phase, and the emergency/distress phase. At the operational level, response efforts are managed through on-scene command, area command at the local level, and the National Crisis Coordination Centre at the national level.	Structured based on the severity and scale of the situation. At the local level (level one emergency situation), when an emergency occurs, the corresponding territorial plan is activated, and local resources are utilized. If the emergency escalates and exceeds the capacity of the local response, the autonomous community civil protection (CP) plan is activated (level two emergency situation), and the responsibility for emergency management is transferred to the autonomous community's CP authority, which also provides its own resources. However, if the situation surpasses the capabilities of the autonomous community, affects multiple autonomous communities, or involves nuclear emergencies or war situations (level three emergency situation), the Minister of Interior may declare a national emergency and assume overall coordination of the activities.
		Mechanisms for international assistance when needed, highlighting the importance of effective coordination and cooperation in managing emergencies.	

<table>
<tr><th>Risk management aspects</th><th>Iceland</th><th>Spain</th></tr>
<tr><td>Search and rescue</td><td>Collaboration between the Icelandic Search and Rescue organization (ICE-SAR), the Coast Guard, the Police and Civil Protection.</td><td>Collaboration between different units of Police, Civil Protection and the Army together with the Military Emergency Unit (UME).</td></tr>
<tr><td>Humanitarian assistance</td><td colspan="2">Red Cross action.</td></tr>
<tr><td>Financial risk-sharing</td><td>Iceland's Natural Catastrophe Insurance (NTI) is a compulsory, state-run insurance scheme that covers damage caused by certain types of natural disasters and is financed by premiums paid by homeowners and building owners.</td><td>Ordinary insurance policies would cover the imperfections. In the event of a catastrophe or exceptional event, in which insurers are unable to cover material losses, policyholders have access to aid sponsored by the Insurance Compensation Consortium, which will act in cases of extreme virulence. The compensation granted by the Consortium is processed according to the contracted capital, and to be able to access it is necessary to have a contracted policy. If you do not have a policy, the only possibility is to wait until the area is indicated as a catastrophic zone, in which case you will receive compensation from the public administrations, although lower.</td></tr>
<tr><td rowspan="2">Cross-border, European and international cooperation</td><td>Cooperation within the Nordic region through the NORDRED agreement, established between Denmark, Finland, Norway, Sweden, and Iceland in 1989. International collaborations include partnerships with HAGA, the Council of the Baltic States, NATO, and the UN</td><td>Active participation in cross-border cooperation by being a member of the Iberoamerican Association of governmental bodies for civil protection and civil defense. Bilateral agreements on civil protection assistance and cooperation with Algeria, France, Morocco, Russia, Portugal, and Tunisia. The DGCPE serves as the point of contact for the European Civil Protection Mechanism.</td></tr>
<tr><td colspan="2">Active cross-border and international cooperation in addressing emergencies and ensuring effective response and support across different jurisdictions.</td></tr>
</table>

Both systems prioritize preparedness, response planning, and cooperation, but with different institutional structures and approaches to achieving their objectives. While Tenerife emphasizes the coordination and integration of various organizations, including public and private entities, Iceland focuses on government-led policy formulation and implementation. This is the main difference between the two risk management systems. However, the duplication of administrations as it occurs in Spain, can pose several challenges for natural risk management in areas such as Tenerife. Having multiple management bodies at different levels (national, regional, insular, municipal) can result in a lack of coordination and effective collaboration between these entities. Some of the problems that may arise are as follows:

1. Poor coordination: The existence of multiple administrations can hinder coordination and the ability to make quick and efficient decisions. There may be a lack of communication and collaboration between different levels of government, making it difficult to implement coherent risk management strategies.
2. Allocation of responsibilities: With multiple management bodies, there can be overlapping roles and responsibilities. This can lead to a lack of clarity regarding who is responsible for which aspects of natural risk management. Moreover, the duplication of efforts and the lack of clear resource allocation can negatively impact the overall effectiveness of risk management.
3. Inconsistency in policies: Each level of administration may have its own policies, regulations, and approaches to natural risk management. This can result in

inconsistencies and conflicts in the implemented strategies and actions. The lack of a comprehensive and harmonized vision of risk management can weaken the responsiveness and effectiveness in emergency situations.

On the other hand, in the case of Iceland, where there is no such duplication of administrations, there may be a more streamlined and centralized risk management structure. This can facilitate coordination, decision-making, and the implementation of more coherent and efficient strategies.

However, it's important to note that each country or region has its own political, geographical, and administrative context, so there is no one-size-fits-all approach. While the duplication of administrations may present challenges in risk management, there are also ways to overcome them through increased coordination, collaboration, and policy harmonization among different levels of government.

Many interviewees agree that part of the effectiveness of risk management in Iceland is due to “the small and interconnected nature of the country” (e.g. personal communication from Sigrún Karlsdóttir, Director of Natural Hazards Services at IMO; see the full transcript of her interview in Annex 6). Even though both the Chief of Police, Úlfar Lúðvíksson, and the Chief Superintendent, Gunnar Ó. Schram, in Suðurnes district, also believe that “being part of a small community […] allows for close-knit cooperation and effective communication channels”, they highlight the lack of manpower derived from this fact (see the full transcript of her interview in Annex 6). This sentiment is also shared by the majority.

However, many recognize the great work and manpower provided by the ICE-SAR, with approximately 7,500 volunteers, and the Icelandic Red Cross. Despite being two organizations of volunteers, for search and rescue and humanitarian assistance, respectively, there is an agreement with both organizations so that after the initial 72 hours in a life-threatening situation, the units involved in the rescue operations are compensated. This compensation is provided by the government to the organization rather than individual members. Then the teams have the responsibility to remain in the field for the entire duration. This can be exhausting, both physically and mentally. For that reason, Chief of Police Úlfar Lúðvíksson, and Chief Superintendent Gunnar Ó. Schram, ask for a professional response team. Still, Guðbrandur Arnarson, project manager at ICE-SAR, stresses that his team's efficiency lies in its "Bras" mentality, understood as the willingness to perform physically and mentally exhausting tasks, finding enjoyment and satisfaction in overcoming challenges. He himself recognizes that this may involve taking unnecessary risks (see the full transcript of her interview in Annex 6).

According to Ásgrímur L. Ásgrímsson, Chief of Operations at the Icelandic Coast Guard, the same deep commitment to the mission fuels their dedication and drives them to perform their tasks efficiently and effectively. The Coast Guard, like ICE-SAR, has a motivated and committed workforce that is always ready to respond and adapt to rapidly changing circumstances. However, the desires for improvement of both may conflict. For while Ásgrímur L. Ásgrímsson is calling for discipline and respectful procedures, with a more organized and coordinated approach, and clear communication and coordination regarding deployment and response procedures, Guðbrandur Arnarson seek empowerment from other institutions, i.e. “to have the freedom to operate in our own way”.

There are two opposing opinions regarding coordination between the actors involved. On the one hand, for Sigrún Karlsdóttir “the close interaction and collaboration between different institutes involved in risk management make communication and information exchange easier.” According to her, their daily meetings with other stakeholders to discuss natural hazards and their situation have been instrumental in improving coordination and response efforts. This idea is shared by Aðalheiður Jónsdóttir, team coordinator for disaster services in the Icelandic Red Cross. According to her, one of the key characteristics of their organization is the close and effective cooperation with other responders.

On the contrary, the requests of Ásgrímur L. Ásgrímsson are joined by those of Thor Thordarson, professor in Volcanology and Petrology at the Faculty of Earth Sciences of the University of Iceland, and Árni Guðbrandsson, senior ATM expert at Isavia. Thor Thordarson calls for a comprehensive re-evaluation and restructuring when it comes to the structure of monitoring, risk assessment, and related activities. He adds that the Department of Civil Protection and Emergency Management “should be established as a separate entity rather than being part of the police department”, in order to establish a clearer separation between management and mitigation activities and crisis research. In the same way, “those involved in management and mitigation should not be leading the research, although their participation is valuable. Similarly, the responsibility of monitoring should not overlap with risk assessment.” His argument is that “when a single entity handles both monitoring and risk assessment, there is a risk of prioritizing personal or institutional benefits over impartial evaluation.” When an eruption occurs, everyone would know their roles and responsibilities, collect necessary data efficiently, and provide timely information to relevant parties. He uses volcanic eruptions as an example, for which he highlights the need for everyone to know their respective roles and responsibilities, collect the necessary data efficiently, and provide the relevant parties with timely information. This would be very much in line with the principles of geoethics. And this is essential for Árni Guðbrandsson, who “would request is better communication and coordination with meteorological agencies and volcanic monitoring organizations to receive more timely and comprehensive information” (see the full transcript of her interview in Annex 6). He stresses that having more time to prepare and assess the situation can mitigate risks, improve response capabilities, and reduce losses. For this reason, one of his requests is for a risk assessments conducted on various volcanic areas to provide a solid foundation for decision-making and resource allocation. This is also recognized by Sigrún Karlsdóttir, along with other interviewees.

However, despite Iceland being a country with a strong economy, the government-dependent institutions in charge of research also suffer from the obstacle of funding. So says Birgir Vilhelm Óskarsson, a researcher at the Icelandic Institute of Natural History, who shares the frustration of encountering limited financial resources and having to rely on research grants to support his projects. Or Thor Thordarson, who expresses his dissatisfaction that many areas with a potential risk have yet to be studied in depth. However, despite economic constraints, Iceland offers certain facilities for the investigation of many of these natural phenomena compared to other regions, such as Tenerife. In the case of volcanoes, according to Thor Thordarson, one of the primary advantages of conducting research in volcanology in Iceland is the easy accessibility to numerous eruptions and eruption sites. This accessibility is a result of two factors: the abundance of volcanoes in Iceland and their widespread distribution across the country. Thor Thordarson said “Many of our eruptions are often of low intensity, allowing researchers to get close to them without significant obstacles. Another advantage of conducting research in Iceland is the frequency of eruptions. We experience eruptions every three to five years, which provides researchers with ample opportunities for observation and study.”

This is what happened during the Eyjafjallajökull eruption in 2010. All interviewees who were somehow involved in the eruption agree that it was a learning period and a turning point in the way of proceeding both at the level of each institution and at the level of relationships and cooperation. Similarly, the COVID-19 pandemic, despite bringing several logistical difficulties, also brought positive aspects, such as communication and meetings by video call and other telematic means.

Although many interviewees have noted a slight increase in the frequency and magnitude of events such as landslides, as Sigrún Karlsdóttir points out, the impact of many of these events in recent years has been greater. There are several reasons they have highlighted. On the one hand, the massive arrival of tourists, who have no previous experience in this type of events and underestimate the natural phenomena in Iceland. This has made the work of the police especially difficult, as pointed out by Úlfar Lúðvíksson and Gunnar Ó. Schram. On the other hand, the increase in the immigrant population, who similarly have no experience of such events and no related training in their home countries. But this is not something that occurs exclusively among the tourist or immigrant population, although it is more noticeable here. The respondents' sense of the Icelandic population's perception of risk highlights a need for improvement in natural hazards education in the country. According to Sigrún Karlsdóttir, although “some individuals, especially those with long experience or who have lived in areas prone to natural hazards, are highly aware of the risks and collaborate effectively with the measures put in place, […] in some cases, there may be limited awareness or even denial of the potential risks associated with natural hazards”. This could be due to a lack of personal experience, misinformation, or a general sense of complacency.

For this reason, although the majority of interviewees commented that their institutions carry out education and training programs for both their employees and the population, some demanded to increase joint training exercises and collaborative efforts to invest more in prevention and preparedness. This includes “raising awareness and providing training to communities, especially those in isolated areas or towns that may experience temporary road closures due to adverse weather conditions” (e.g. Aðalheiður Jónsdóttir, Icelandic Red Cross). Because, according to Guðrún Pétursdóttir, retired director of the Institute for Sustainability Studies of the University of Iceland (see the full transcript of her interview in Annex 6), “the participation of individuals in exercises or drills, such as simulated evacuations in the south, have contributed to increased awareness.” Another difficulty noted by many of the interviewees when carrying out their tasks during emergencies is the excessive media pressure.

Another reason for this increasing trend in the impact of some events is spatial planning. Although Iceland is a rather unpopulated country, with its population mostly concentrated in the capital, Reykjavík, population growth and urban expansion are forcing the conquest of areas increasingly exposed to the impact of these events. Last but not least, climate change is melting Iceland's glaciers, increasing the severity of many events and leading to unexpected consequences. When asked whether each of them applies the multi-hazard perspective in one way or another to cope with these changing scenarios, there are two clearly differentiated groups. Those people belonging to research and monitoring, i.e., who would be placed in the prevention and recovery stage, believe it necessary to introduce this new perspective in their procedures and actions, and some are even already doing it today directly or indirectly, i.e., applying it without realizing that they were doing it with a multi-hazard approach. However, those actors responsible for emergency response, whose tasks are more action-oriented, mostly first responders, agree with the idea but do not see it as fundamental to their operations.

Despite all the pros and cons, there is one thing that is also quite unique to this territory, and that contributes to the economic stability of the area in the face of natural disasters. This is the steady influx of money into a fund earmarked for compensation for any buildings destroyed during a catastrophe. In the words of Hulda Ragnheiður Árnadóttir, CEO of Iceland's Natural Catastrophe Insurance (NTI), and Jón Örvar Bjarnason, head of the insurance side at NTI (see the full transcript of her interview in Annex 6), “It is vital for Iceland that everyone is insured and pays the same percentage of their property's value. […] People don't really feel the impact of paying it individually, but when everyone contributes, it feels more like a collective responsibility, similar to a tax.” However, they also note the lack of personnel in their institution, which forces them to resort to contractors for major catastrophes and to invest in automated processes. They also stress that some delicate situations such as the loss of electricity in hospitals, or the rescue of businesses affected by the natural disaster, are not covered by any entity.

In summary, from the interviews conducted, the key success points of risk management in Iceland are as follows:

- ✓ Small community.
- ✓ Close collaboration and coordination.
- ✓ Mandatory and constant compensation system through Natural Catastrophe Insurance.
- ✓ Multiple training exercises in prevention and response to natural events.
- ✓ Experience in natural disasters.
- ✓ Accessibility to study areas.
- ✓ Availability of professional and volunteer groups with a high sense of duty.

Although with common problems of:

- Lack of manpower.
- Lack of financing.
- Centralization of tasks and responsibilities.
- High weight on voluntary groups.
- Lack of hazard assessments for many potential risk areas.
- Shortcomings in communication to certain stakeholders.
- Conflicts in some professional relationships.

But from the experience in Iceland and from the personal communications received by the above-mentioned individuals, a key factor that plays in favor of the success of Iceland's risk management is evident. Some described it as "luck", others as "chance". However, in our opinion, the fact that the main urban settlements are away from volcanoes and other areas with other potential hazards such as jökulhlaups, is not due to chance. But to a passive territorial planning for historical, economic and/or social reasons that has led to the fact that, unlike other regions such as Guatemala, Colombia, Nicaragua, Indonesia, Tenerife (Canary Islands), Stromboli (Aeolian Islands), among many others, in Iceland volcanoes are not so close to cities or towns. And this makes the impact of their effects less. They have brought this "luck" on themselves, although this could change in the coming years.

From the comparison between both risk management systems and geographic, geological, socio-economic and political contexts, the following key characteristics stand out to be taken into account when analyzing the feasibility of implementing certain strategies to any region:

- Area of the region.
- Size and density of the population.
- Size and diversification of the economy.
- Sovereignty.
- Urban and infrastructure distribution.
- Management responsibility.
- Hierarchy and centralization/decentralization.
- Quantity of manpower.
- Number and size of institutions involved.
- Types of natural hazards experienced.
- Geographical location and proximity to other countries.
- Established international relations and agreements.
- Education and training systems.
- Experiences.
- Geographic, geologic, and climatic diversity.

Taking into account these key aspects on which we believe the success of some model measures or strategies may depend, we proceed to discuss the feasibility of implementing the strengths of the Icelandic risk system into the Tenerife's or the Spanish system.

It is true that the centralization of risk management can allow for a more efficient and coherent coordination of risk management policies, strategies and actions throughout the country, allowing for faster and more uniform decision making throughout the territory. In addition, by concentrating financial, technical and human resources in a single entity, greater efficiency can be achieved in the allocation of resources and in the execution of risk management actions. However, this may have advantages for countries with a smaller population, such as Iceland, where decentralization could lead to fragmentation and dispersion of limited resources. Spain being a country with greater geographic and climatic diversity, larger land area and larger population, decentralization may better meet its needs. Decentralization allows local authorities to have greater knowledge and capacity to manage risks specific to their areas, as they are more familiar with local characteristics and community needs. Local authorities, being close to the affected population, can mobilize the necessary resources more immediately and coordinate evacuation, rescue and victim care actions more effectively. In addition, decentralizing decision making promotes the development of local leadership and empowers communities to take an active role in protecting their own lives and property.

But even though we are comparing a country (Iceland), with a part (Tenerife) of an Autonomous Community belonging to a larger state, we can scale the analysis. If we focus on the management that is done locally in Tenerife, this could be compared with Iceland, being equivalent the national coordination of the Nordic country with the insular coordination of the Canary Islands region. However, without forgetting that the latter belongs to a more complex hierarchical and decentralized system, which can even support it in events that exceed its capacity. That is why in Tenerife the problem of lack of manpower, as well as the availability of professional action teams and the non-reliance of responsibility on volunteer groups, is overcome.

The advantages of Icelandic centralization could benefit Tenerife, since it is a smaller community. However, the higher population density of Tenerife compared to Iceland, its reduced space, and the greater proximity of its urban centers to the areas of potential risk, make it difficult to achieve an urban planning model similar to the Icelandic one, with the main cities far from the areas of greatest risk. On the other hand, the frequency of experienced events also influences the risk perception of the population of Tenerife, having lived through multiple floods, fewer felt earthquakes, and no volcanic eruptions in current generations. This lack of experience lowers the alertness. However, the eruption of La Palma, although in another island, served as a test of the current volcanic risk management system (PEVOLCA) for which many things could be learned. But the risk in Tenerife is different. The current protocols for the Autonomous Community of the Canary Islands do not contemplate multi-hazard scenarios, nor extreme events such as a caldera-forming eruption. And despite the fact that there is plenty of experience in flooding, the damage has not been reduced over the years, quite the contrary. This denotes a lack of knowledge of the historical record of events, a lack of geological and environmental knowledge of the areas, a lack of investment in knowledge and technology, a greater value of economic and political interests, and all this results in a lack of territorial planning according to risk areas.

So, at the island level we believe that we should improve those points where the Icelandic system is efficient, and according to the characteristics of Tenerife. In the short term these are: (1) greater coordination and closeness between small communities, thus improving the effectiveness of communication; (2) greater investment in technology and knowledge for disaster risk prevention and mitigation; (3) greater investment in multi-hazard early warning systems; (4) the establishment of research and monitoring protocols to make the most of each natural event that occurs as an opportunity for learning and improvement; (5) better coordination and communication between the different entities in charge of investigating and monitoring events, which would imply conflict resolution, sharing of tasks and responsibilities to avoid their repetition, or, on the contrary, centralization of resources in a single entity in charge of these tasks; (6) direct and exclusive communication between the Scientific Advisory Committees and the First Responders, and the latter with the media for truthful, direct information adapted to all audiences; (7) development of protocols or plans for the recovery of the area after the disaster, thus incorporating social services and the tasks developed by voluntary organizations such as NGOs; (8) the implementation of some kind of mandatory minimum fixed fee for a common compensation fund in case of natural disasters or the obligation to have an insurance policy and a greater control of the fulfillment of this duty.

In the long term, it would be necessary to: (1) a diversification of the economy and a commitment to nature-based solutions; (2) territorial planning in line with risk management based on long-term multi-hazard assessment; (3) a multi-hazard approach in risk prevention and mitigation policies, with development of management plans with a multi-hazard character but with action plans for first-responders focused on clear actions for each hazard or result of the interrelation of hazards; (4) an increase in education and training in natural hazards for citizens and tourism; (5) a change of mentality, especially in the political spheres, towards a preventive culture with proactive strategies, for which (6) an improvement in the community's communication skills is needed to get the message across that prevention will always bring greater economic benefits than reaction.

In spite of this, as we have seen, the Spanish risk management system, and specifically that of the island of Tenerife, already has its own advantages. However, here we could speak of "luck", the "luck" of not yet having experienced a natural event of great dimensions. Although the cumulative impact of these non-extreme events that we have collected, could be equated to one of these extreme events. But the fable goes, a frog jumped into a pot of boiling water and immediately jumped out to escape and save himself, however, when one day he found himself swimming in a pot of cold water and it gradually warmed up, the frog continued swimming in it, getting used to the heat, until he died. In Tenerife we can continue trying to adapt with temporary and immediate solutions to temporary and immediate problems. But we must not forget that climate change will bring a greater severity of these events, which will require us to jump from those disaster reduction policies that try to adapt step by step, event by event, to bet on a series of long-term strategies adapted to future scenarios, as we will show in the following sections. This is the path to the resilience of a society.

5.1.3. Challenges and considerations in conducting multi-hazard assessments: a focus on volcanic islands

The experience gained from developing and applying a multi-hazard perspective methodology to a real case study such as the volcanic island of Tenerife has allowed us to understand and learn firsthand the opportunities and limitations of long-term multi-hazard assessments for these types of regions, which can be extrapolated to regions with similar issues and contexts. We hope that the discussion presented here will serve as a reflection on how to apply and enhance this approach in the future should a similar problem arise in a similar region.

Hazard assessment is an essential step in risk reduction (UNDP, 2004; Stein & Stein, 2013a; Ward et al., 2020). Here we can distinguish between long-term and short-term hazard assessment, depending on when and why each hazard assessment is conducted. Long-term hazard assessment is based on past data (e.g., past monitoring data sets, historical, geological data) and is principally used for territorial planning and for defining emergency plans and long-term mitigation actions (e.g., Alcántara-Ayala, 2002; Martí, 2017). It analyses past phenomena and aims to determine the physical parameters of past events such as to model possible hazards and scenarios that may repeat in the future. Long-term hazard assessment (Fig. 16) calculates the spatial and temporal probabilities that a new event or group or events will take place and characterizes its possible resulting impacts, as we did for non-extreme and extreme events in Tenerife. Long-term hazard assessment is usually delivered as hazard maps, which may be similar to those obtained and shown in Fig. 23 and/or in Annex 5, and will represent an essential tool for land planning and design of emergency procedures, as well as for conducting risk analysis and to identify communities exposed to the greatest risks (e.g., Tarolli & Cavalli, 2013; Calder et al., 2015; Lindell, 2020). Nowadays, a hazard map is a dynamic concept that differs from the classical long-term static maps that were drawn under the assumption that no changes will occur over long periods of time. A hazard map may change as new information becomes available, as the accuracies of simulation models improve, due to revisions of cartographic and geographic data, or as new events occur. Hazard maps are usually probabilistic and may be constructed for just a single hazard, for groups of hazards, or for all the hazards, may be qualitative or quantitative, and forecasted for a particular area and over a particular time window. By contrast, short-term hazard assessment concentrates on the time windows for which precursory signals of an upcoming event are shown, and should be used to modify the long-term assessment, for which these signals should help to making it more precise, by providing information on location, intensity and occurrence of the new event(s). For this reason, having long-term hazard assessments available first is essential to be able to incorporate this information into the short-term assessments and make the latter much more accurate and realistic. Short-term should help to forecast with sufficient time the most probable imminent scenarios, despite this is not always possible. Hazards like those derived from meteorological extreme events, volcanic eruptions, landslides, or tsunamis may be anticipated with a variable time, but sufficient to effectively react in most cases. However, other hazards such as earthquakes, or even volcanic eruptions without precursors, are, unfortunately, still hard to be anticipated with sufficient time to apply any short-term mitigation action. This is why long-term hazard assessment is so important, because even in these cases the application of long-term mitigation actions may reduce hazard impacts also when they may occur in an unexpected way.

The uncertainty associated with natural hazard assessment (long-term) and forecast (short-term) is unavoidable and should not be removed from the decision process (Aspinall, 2010). By definition, uncertainty is used to refer to something that is doubtful or unknown, so it is used to indicate the lack of confidence about something (e.g., Cox, 2012; Stein & Stain, 2013a,b; Sobradelo & Martí. 2017). Hence, it is directly related to the amount of knowledge we have about a process. Hazard assessment, both long and short-term, in the form of a probability estimate is an attempt to quantify this uncertainty and support decision-making. In particular, when conducting short-term hazard assessment to forecast potential outcomes of natural processes usually implies high levels of scientific uncertainty. Anticipating how a natural process (e.g., flank instability, volcanic unrest, stormy weather, etc.) may evolve and end requires scientific knowledge of how such processes have behaved in the past, and scientific interpretation of precursory signals. Whilst this may be less challenging for processes that occur very often (e.g., meteorological hazards) and for which there are abundant observation data, it may become very difficult or nearly impossible in those cases with longer recurrences, lack of observational data and/or lack or precursory signals (e.g., volcanic eruptions, earthquakes, large scale landslides). This is one of the drawbacks we have experienced throughout our study. Therefore, it is important to find objective ways to calculate and communicate this uncertainty when delivering the results of any hazard assessment. From there, the temporary solutions that have been proposed to our methodology arise.

Hazard assessment requires that scientists follow a geoethical procedure to reduce uncertainty (Peppoloni & Di Cappua, 2021; Peppoloni, 2023). This applies both to the methodology used to assess the hazard of an area and to the process of communicating the results to other scientists and decision-makers and, subsequently, to society. Regarding the former, the key lies in the way in which the hazard assessment is carried out. Strategies to reduce as much as possible this uncertainty associated with natural hazard assessments and, in particular, multi-hazard scenarios, should be based on basic principles. These are: (1) basic but thorough scientific knowledge of the study area and the phenomenon; (2) application of the most up-to-date resources available for each region; (3) objective data collection using the scientific method; (4)

objective treatment of uncertainties; (5) consideration of all possible scenarios regardless of experience or subjective perception; (6) avoidance of biases, and interests; (7) development of recommendations based on scientific data and not on political or socio-economic interests. Once these initial premises are clear, scientists must consider the scenario they are in, whether it is an emergency or crisis situation, or a situation of normality. With this, they will be able to distinguish between applying a long-term or short-term hazard assessment. The result of conducting an investigation taking into account all these ingredients will be the availability of real, possible, exhaustive, faithful, objective, serious and more precise and accurate data. Once this is achieved, the resulting uncertainty will be lower and easier to transmit to the next actors in the risk management chain.

Volcanic islands are particular environments exposed to a large variety of natural hazards (e.g., landslides, earthquakes, volcanic eruptions, forest fires, water floods, etc.), with high potential of permanently harming their socio-economic and environmental systems. Moreover, volcanic islands are the environments that will experience the strongest impact from the current Climate Change (e.g., sea level rise and an increase in extreme meteorological events), which may even increase the threat represented by their intrinsic natural hazards. Most of these hazards may occur as compound events and the risks related to their interactions and cascades/simultaneous effects on these highly vulnerable and threatened socio-economic settings and ecosystems can therefore be disastrous. This is why risk reduction programs for such regions need to incorporate the multi-hazard approach, rather than considering individual hazards and risks. And another need arises: to link the Sendai Framework goals with the Sustainable Development Goals and the Paris Agreement on climate change.

A second aspect that needs to be reinforced such as to face multi-hazards on or near volcanic islands is, as we have already mentioned, effective education at all levels of society. A society that is well-educated and trained on the surrounding natural hazards is less vulnerable and more resilient to their associated impacts. In the case of a hazard or multiple hazard risk scenario, the community will understand and react more efficiently to early warnings and alert systems, and may recover better from the eventual effects. However, the intermittent nature of most natural hazards and the complexity in foreseeing their interactions, as may happen with infrequent volcanic hazards, make it difficult to maintain a high level of public risk awareness. Ignoring potential hazards that may impact our society implies that no related mitigation action will be taken, eventually leading to an increased risk; moreover, it makes it much more difficult to react and recover after such disastrous events.

Therefore, a necessary condition for the success of a given risk reduction program in such complex and vulnerable scenarios is to undertake a multidisciplinary and integrative approach involving from the beginning all essential actors in hazard assessment, risk and crisis management, decision-making, and mitigation actions. These are: scientists and technicians working in volcano observatories and research centers, authorities, population, civil protection, educators, media, First Aid organizations, and UNISDR platforms. All actors need to know what the others can do and what each of them actually need from the others. Together, all these actors should understand the most likely scenarios, recognizing the hazards involved, their order of occurrence and cascading effects, extent and potential impacts, the vulnerability of the possible elements impacted, and the mitigation measures that should be considered in each case. Public engagement will play a key role in increasing multi-hazard risk management capacities and efficient response strategies. Only with this multidisciplinary and coordinated effort will it be possible to effectively prepare for and manage a complex multi-hazard crisis and to develop knowledge-based resilience planning.

In summary, volcanic islands offer one of the most risk-prone and vulnerable environments for being impacted by multi-hazard scenarios. Having a scientific-based detailed knowledge of the potential occurrence of natural hazards and their possible interactions—as well as the implementation of real-time monitoring networks and early warning systems, together with the development of educational programs at all levels of the society including adequate management plans—is mandatory to effectively reduce risk there. It is also important to conduct precise vulnerability and risk analyses including an inventory of elements at risk (e.g., populations, properties, infrastructures, cultural heritage, etc.). This should facilitate assessment of the physical, economic, and environmental impacts as cumulative damage on exposed elements produced by possible sequences of hazards and to identify the main technological (e.g., building retrofitting, infrastructure protection) and non-technological (e.g., investments in education and communication) mitigation options and adaptation strategies at territorial and building scales that should be implemented in each case. Finally, we should also considered knowledge-based resilience planning that should promote and implement resilience strategies that account for cascading and large-scale events that may affect such highly vulnerable environments.

In the case of Tenerife, the current demographic growth, together with urban expansion and the island's colonial history, means that today we find buildings and settlements within hazardous areas. This is a common fact among many volcanic islands. But it is also true that the level of management and the availability of preventive material for the different natural hazards common to Tenerife are very uneven. For some hazards such as forest fires or floods, management and emergency plans as well as hazard and risk maps, are available. However, for other hazards such as volcanic eruptions or landslides, the resources available are scarce, insufficient or unequal between the different islands of the archipelago. For the case of earthquakes, the maps are more oriented towards civil works and there is a lack of research at a more local level.

Furthermore, in Tenerife there is insufficiently developed public alert systems for some hazards (e.g., tsunamis). This is a common trend in many countries. Other challenges that this area must face, as is very often the case in the rest of Europe, for example, are the vaguely defined institutional responsibilities for warnings, public warning in cross-border disasters, targeting warnings to a delimited geographical area at risk, dealing with social media in emergencies, assessing the effectiveness of Early Warning Systems (EWS), etc. These challenges reveal the weaknesses of the risk management system and, specifically, the MHEWS of the region of the Canary Islands (e.g. during El Hierro 2011–2012 eruption), which fortunately were improved before the 2021 La Palma eruption.

By combining the irregular and scarce knowledge of the multi-hazardous nature of the island of Tenerife, together with the territorial fragmentation, urban expansion and demographic increase, we find multiple houses and infrastructures located in hazardous areas. If we add to this the fact that many homes lack home insurance, risk management in the post-emergency stage and the recovery process of the area becomes much more complicated, such as what happened after the eruption of September 19th, 2021 in La Palma. In this case, despite the successful management of the eruptive crisis, which only caused material losses, the local government is faced with a scenario that is difficult to prevent. Most of the population of La Palma is located in the most active volcanic area of the island, with a monogenetic volcanism (that is even more difficult to predict) having registered up to 9 eruptions in historical times (the last 600 years); there are no hazard and/or volcanic risk maps for La Palma; and around 50% of the houses on this island are not insured. One of the strategies to prevent the risk derived from incorrect land use planning is the creation of protected areas. Even if the existing ones have been created for biological or ecological conservation reasons, rather than for geological reasons, something is better than nothing. However, the creation of protected areas for geological reasons, focused on hazards, may better prevent the risks derived from them. And this must go hand-in-hand with the introduction of improvements in disaster risk reduction policies from a multi-hazard perspective that has not been realized to date.

5.1.4. From scientific knowledge to decision making

In this second stage of the process of managing risk, despite being able to previously reduce uncertainty with an ethical scientific methodology, the uncertainty of our results may be increased during the debate between scientists and decision makers. If this occurs, some of the gains achieved with previous efficient research, such as the reduction of uncertainty, may be lost or rendered useless. This is why it is not enough to do good research, but also to know how to transmit the results well. Some scientists are reluctant to express their opinion in terms other than using a highly specialized language, which makes the communication and understanding of uncertainties certainly difficult. Also, it is common and even desirable that members of scientific advisory committees have different opinions according to the data they have and their particular knowledge on the process(es) under debate. Here, it is important that no opinion is propagated to the exterior before a consensus is reached on the current situation. The public diffusion of contrasted or opposed scientific opinions in front of a crisis, or even when dealing with the application of a long-term hazard assessment, is probably one of the worst situations that may happen. This provokes confusion among the receivers of this information and, more importantly, the discredit of the scientific community. Faced with uncertainty, decision-makers, but also the general population, invariably seek agreement or unambiguous consensus from experts, so it is important to quantify uncertainty, not to remove it from the decision process, even when the situation is so complex that a total consensus among the scientists involved in the advisory process is difficult to be reached (Aspinall, 2010).

As we have already announced in the previous section, the next problem after conducting any multi-hazard analysis is the seamlessly integration of the derived outcomes into the existing risk management system (López-Saavedra et al., 2023). As explained before, multi-hazard assessment should not only be used to address those actions necessary to cope with an imminent natural-derived crisis but also those mitigation actions aimed at reducing risk in the area in the long-term. Among others, these should include structural measures (e.g., vulnerability analysis and engineering solutions), emergency management actions, and land-use planning. Land-use planning should be based on the long-term hazard assessment and should consider the most appropriate measures to guarantee the security of citizens and obtaining the maximum resources that the land can provide, and restricting land-use when necessary (López-Saavedra et al., 2023). However, this is not an easy task, and a number of challenges appear when dealing with land-use planning considering multi-hazard scenarios. The uncertainty over the timing, magnitude and impact of future events constitutes the main obstacle. This is because policy makers tend to be reluctant to make decisions over the long term, particularly when these are based on scientific assumptions that are not exempt of high uncertainties and may have inconvenient or disruptive political or economic implications (consequences) to their interests. This is why it is important for scientists to convince policy makers of the fact that prevention and preparation is always preferable to reaction, particularly when dealing with multi-hazard scenarios in the climate change context (López-Saavedra et al., 2023). Natural hazards may have significant negative consequences on human populations, their economies, and the environment, which may then require long psychologically, physically, and economically difficult periods of recovery (Blong, 2000; Sheets, 2015; Torrence, 2016). Thus, despite their potentially high cost, investment in risk-reduction programs is always preferable to merely reacting once disasters have struck (Blong, 2000). The cost of prevention and mitigation actions is always lower than the cost of recovery, particularly when a catastrophic event hits a place that has not invested in risk reduction (e.g., Cutter et al., 2015; UNDRR, 2022). This is the main message that needs to be transmitted to policy makers. Moreover, there is the fact that a safe area is much more attractive than a dangerous one.

Sometimes, scientists impose restrictions when they are unable to satisfactorily explain to the population and policy makers about hazards and risks, nor about the convenience and (long-term) benefits of adequate land-use and risk mitigation planning. Therefore, risk management is a task that needs to involve all stakeholders of an affected society. A society must collectively aim to understand and accept their risks and potential consequences, taking a proactive stance going forward. Scientific uncertainty in forecasting natural events is not a sufficient excuse for inaction, and even less so when it is a question of when, not if, a phenomenon will occur.

The geoethical procedure to reduce uncertainty during the transmission of information should be based on five main principles: 1) scientists involved in hazard assessment should be sure that they are free from compromises and (or) conflicts of interest, 2) sharing all available data; 3) assuming the opinions from the other scientists; 4) reaching consensus on which are the most probable processes to occur; and 5) reaching consensus on how to explain in the most objective way the current situation to the rest of the society. As already indicated by Bobrowsky et al. (2018) scientists are not always free from compromises and (or) conflicts of interest, including political, social and psychological pressures. If this is the case, their opinions could be biased by these external influences and not be impartial or objective enough to guaranty the objectivity required by any hazard assessment. Sharing all available data among scientists involved in hazard assessment is essential to reduce this fact. Unfortunately, the sense of property that some scientists have on their data, even when these have been obtained with public funds, makes the fulfillment of this requirement not always easy. Also, it is not uncommon that scientists may consider themselves better than the others and, so, may believe that they are right and the others are wrong. This attitude may leave to important misinterpretations when analyzing the available data. The study of natural hazards is a complex world that requires a multidisciplinary approach and all the available expertise, so all opinions should initially be taken into account, although later some can be discarded depending on the precise knowledge necessary to evaluate each situation and how the analysis and interpretation of the available data progresses. When the situation that scientists are dealing with becomes clearer it is important to reach consensus on what it is known and what it is not known, and how this can be communicated to the exterior. This communication needs to be not ambiguous and done using a plain language understandable by any receiver, even when the message is that we do not know what may happen. In predicting the future, scientists should not be afraid to acknowledge that sometimes there is insufficient information to make an accurate prediction. This is better than providing an opinion based on serious doubts or inconsistent information.

There are different ways in which probabilities (and uncertainties) can be described (Martí, 2015). These include words, numbers, or graphics. The use of words to explain probabilities seeks to offer a language that appeals to people's intuition and emotions (Lipkus, 2007). However, it usually lacks precision as it tends to introduce significant ambiguity by the use of words such as “probable”, “likely”, “doubtful”, etc., which lack precision or clear definitions. Probabilities are defined mathematically (e.g., Pshenichny, 2004), but such descriptions may fail when the audience has a low numeracy. In the last years it has been increasingly common to use graphics to represent probabilities in natural hazards (Kunz et al., 2011; Spiegelhalter et al., 2011; Stein & Geller, 2012). That is why our probabilistic numerical results were accompanied by pie charts that facilitate visualization and, therefore, the interpretation and understanding of the values. The advantage of communicating uncertainties (or probabilities) visually is that we are everyday better prepared and trained to use and understand infographics. A graphic can be adapted to the aims of the communicator, stressing the importance of the context of the communication exercise and the needs and capabilities of the audience (Spiegelhalter et al., 2011). Scientists working on natural hazards can adapt these modern methodologies to their needs, in order to make assessments and forecasts and their intrinsic uncertainties clear enough to any potential receptor of this information. Also, it is very important to consider the educational level of each particular society that should receive information on natural hazards. The cultural diversity of societies facing natural threats determines that some communication approaches may work in one country or culture but not in another. Therefore, it is important to analyze and understand the particular cultural aspects of each society in order to define the best communication procedures and languages in each case. Anyway, regardless of the way used to communicate probabilities (and uncertainties) is to communicate exactly what is known.

Consequently, hazard assessment based on scientific knowledge should always be considered in decision-making processes, with no interests behind other than the protection of people and of their environment. Does this mean that scientist should take part in the decision-making processes? The answer to this essential question may be controversial depending on who is responding, as there is a diversity of opinions among the proper members of scientific community. While some scientist highlight some of the complexities and challenges involved in involving scientists in decision-making, (e.g., Wynne, 2006; Jasanoff, 2011; Macnaghten & Chilvers, 2014), other assume that scientists can and should be part of the decision-making process, especially when the decisions being made are related to scientific fields such as public health, climate change, or environmental protection (e.g., Cash et al., 2003; Oreskes, 2004; Pielke, 2007; Sarewitz & Pielke, 2007; NRC, 2011; EEA, 2019; NASEM, 2019). For most scientists it is obvious that scientific knowledge and expertise can help inform decision-making by providing accurate and reliable information, identifying potential risks and benefits, and highlighting uncertainties and knowledge gaps. Scientists can also provide insight into the likely consequences of different courses of action, and help to develop strategies for mitigating or adapting to potential risks. However, it is important to note that scientific knowledge is just one of many factors that should be considered in decision-making. Decisions often involve trade-offs between different values, interests, and priorities, and require input from a range of stakeholders, including policymakers, industry representatives, and members of the public. In the case of decision-making process with regard to natural hazards, the main aim should be to guaranty the security of people by ensuring that any impact caused by a hazard or group of hazards can be minimized through the application of an adequate risk reduction program. Therefore, the involvement of scientist in the decision-making process should be mainly to provide scientific evidence and research. This should help policymakers and other stakeholders involved in the decision-making process to acquire sufficient data-driven perspectives on the potential impacts of different hazards and help them to weigh the pros and cons of different choices in the decision-making.

5.1.5. Limitations of a multi-hazard perspective in the context of risk management: implications for basic structural frameworks

So far, we have provided an ethical guide for addressing multi-hazard scenario management, through clarifications and recommendations for the stage of scientific knowledge development and its transmission to decision-makers, as well as its integration into the multi-risk management system. However, we must not ignore that there are still many obstacles that hinder the implementation of the multi-hazard perspective in disaster risk reduction policies. Natural hazards embrace a large variety of phenomena that have different origins (geological, meteorological), recurrences, predictability, impact intensities, and cause/effect relationships among them. The physical factors controlling natural hazards may significantly differ from ones to the others, so our understanding on how they occur and behave may be quite different. However their assessment and forecast share several principles that make the methodologies used for such purpose coincident in certain conceptual aspects. In all cases, assessment and forecast of natural hazard pretend to identify when, where and how a new hazard or groups of hazard may occur, being this the basic information we need to anticipate them and to try to minimize their potential impacts. Obviously, not all hazards can be anticipated, but if this is the case, it will depend principally on the nature of each hazard, the availability of observational data, and on whether or not the occurrence of a particular hazard is preceded by clear precursory signals. In essence, forecasting natural hazards is a difficult task always subjected to a significant uncertainty derived from the intrinsic stochastic behavior of natural processes (aleatoric uncertainty) and on the degree of knowledge we have about them (epistemic uncertainty). This implies, therefore, that communicating hazard assessment and forecast implies communicating in an understandable and unambiguous way what is known and what is not known.

Under the climate change context people have learned that natural hazards are increasing in frequency and magnitude and that it is altering the interrelationships between events, making cascading effects more frequent and complex. This is why today hazard assessment is looking at being conducted as a multi-hazard approach rather than considering isolated hazards (e.g., May, 2007; Gill & Malamud, 2014; De Angeli et al., 2022). However, this is still a new concept and multi-hazard scenarios where several hazardous phenomena may occur in a simultaneous or consecutive way have not yet been well constrained (see López-Saavedra & Martí, 2023 for a review). We are still far from a full understanding of the potential interrelations (cause/effect) between different hazards and their related cascading effects and potential impacts. Also, we have not yet developed or implemented effective combined monitoring and early warning systems, as well as complete vulnerability and risk analysis to confront multi-hazard cascading effects (López-Saavedra & Martí, 2023). In consequence, the uncertainty associated with multi-hazard assessment is higher than that arising from the evaluation of a single hazard, but we must be aware of the need to identify and quantify as much as possible the potential multi-hazard scenarios that may derive from future events in order to be effective in reducing risk. Despite this, the multi-hazard perspective is becoming commonplace in risk reduction plans in contrast to the classical approach of considering each hazard and its potential impacts separately.

Unfortunately, when considering a multi-hazard scenario, the fragmentary understanding of interrelations among the different hazards (cause/effect) and their cascading effects has hampered the development of robust procedures to perform hazard assessments, and thus to implement effective combined monitoring and early warning systems. Therefore, an initial aspect that needs to be addressed when considering a multi-hazard environment is to conduct a dynamic multi-hazard assessment (López-Saavedra & Martí, 2023). In this context, knowing the time scales at which the different hazards may impact is of primary importance. On some occasions, the recurrence of natural hazards may be so infrequent that the possibility of being impacted by such phenomena is not regarded as a serious present threat; nevertheless, many other hazards, in particular those directly or indirectly related to global change, may severely impact many parts of the World with increasing frequency. As a result, knowing what may occur and with which frequency and potential combinations of events, is fundamental for developing adequate land and emergency planning in order to minimize risk. And, in the short term, to anticipate probable hazard scenarios, thus giving sufficient time to react in front of them.

Based on the compilation of all the observations made throughout this doctoral thesis project, implementing the lessons learned from the Tenerife case study, the experience gained in Iceland, and all the reflections developed in the previous sections, we provide the following basic framework for multi-hazard management in a region. An overall risk reduction plan should include several essential programs (Fig. 32): (1) a scientific program aimed at improving knowledge of the process and its potential impacts (i.e., hazard assessment); (2) a monitoring program for determining the current state of activity of the process; (3) an educational program to educate the population about the potential hazards and risks that threaten them; and (4) a management program for designing customized emergency plans and resilience strategies for specific locations.

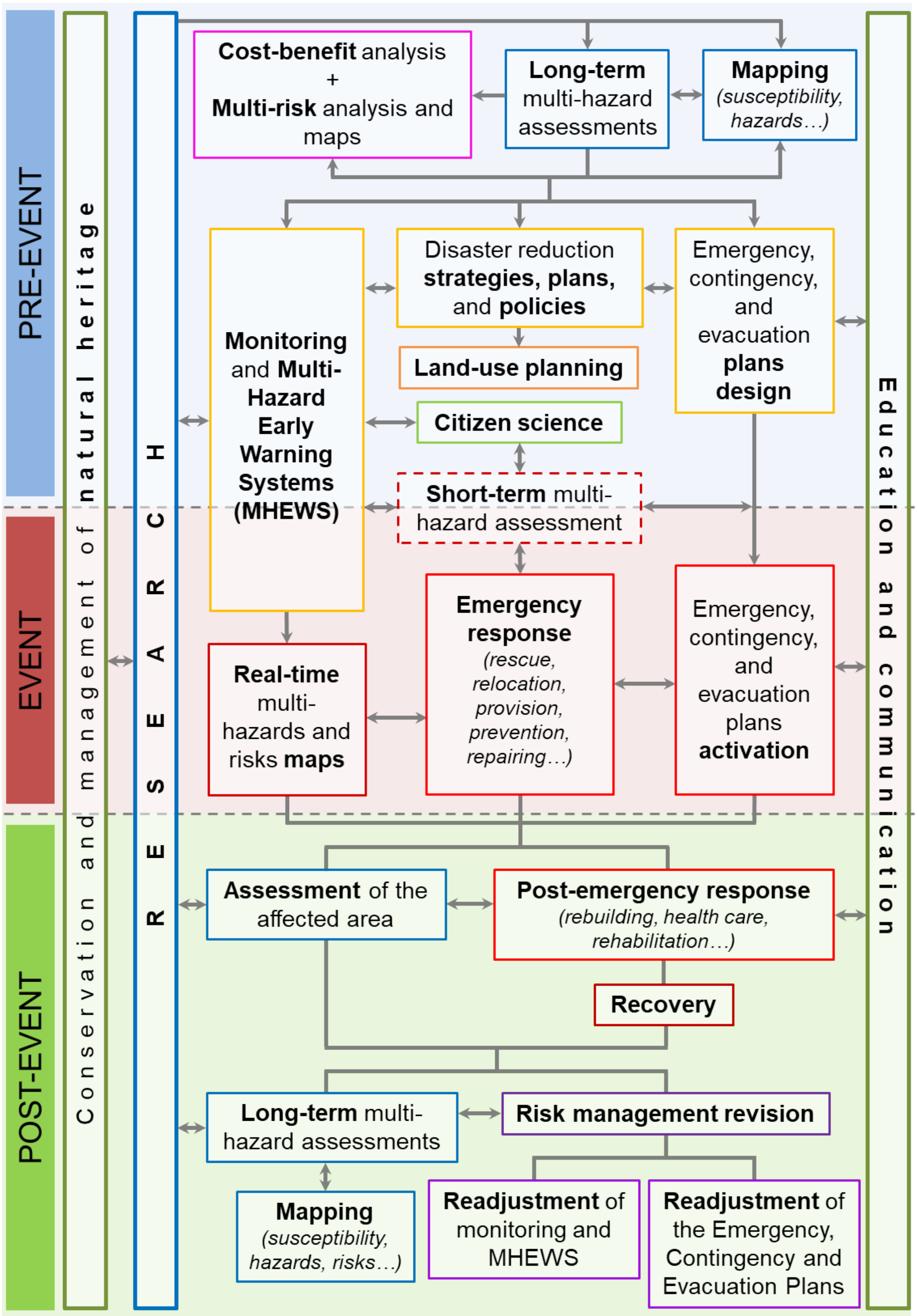

Figure 32. Standard diagram for the design of a risk management system in a region, from a multi-hazard approach. Source: López-Saavedra and Martí (2023) (CC BY-NC-ND 4.0).

A robust risk management structure must be underpinned by three essential pillars: research, conservation, and education and communication. Long-term hazard assessment based on geological but also historical data is the first task that a society threatened by volcanoes needs to undertake if it aims to live with volcanoes and take advantage of what they offer (majestic landscapes, productive soils, mineral and energy resources, etc.). The impact of disasters caused by natural hazards significantly increases when societies are not prepared to cope with natural threats—or they simply ignore them. Erroneous land planning, a lack of emergency plans, and poor knowledge of natural hazards and risks—not only amongst the general population, but also amongst decision makers and even scientists—may convert a natural event into a disaster (Martí, 2017). For those reasons, multi-hazard and people-based research is the foundation for the characterization and the study of a region, in order to obtain robust risk data, and the identification of the problems and the aspects of improvement for risk reduction. The conservation and management of natural heritage make possible this research by protecting the natural record from the study area. Last but not least, education and impact plus action-based communication enables the transmission of knowledge and provides the population with tools both to make efficient self-protection decisions at the time of an emergency and to train society in risk mitigation. No matter how well-developed the other sectors are, if any of these pillars fail, disaster management is destabilized, resulting in major economic or, unfortunately, human losses.

However, the reductionist tendency to work on each sector separately must be abandoned and a holistic perception of the system must be adopted. The result is full transdisciplinarity, and the method, geoethics. Dealing with the ethical, social, and cultural ramifications of geological research and practice, geoethics serves as a meeting point for geosciences, sociology, and philosophy (Moores, 1997; Bosi et al., 2008; Peppoloni and Di Capua, 2012; Peppoloni, 2012a, 2012b). By facilitating research and contemplation on fundamental values, it establishes a foundation for responsible conduct and behavior in areas where human activities intersect with the geosphere (IAPG, 2012; Peppoloni & Di Capua, 2012). In addition, geoethics seeks to enhance the connections among the scientific community, decision-makers, mass media, and the general public (Höppner et al., 2012). It emphasizes the societal role carried by geoscientists and the obligations they bear, as their decisions can have ethical, cultural, and economic consequences on society (Peppoloni and Di Capua, 2012; Bickford, 2013).

As we mentioned before, some actions have been taken after the impact of a big disaster, such as the 2004 tsunami or Hurricane Katrina in 2005. Ideally, we should not have to wait for the consequences of an extreme event before taking certain measures. These experiences strongly suggest the need to start taking action at the pre-event stage. In this stage, researchers should elaborate and combine long-term multi-hazard assessments, understood as the analysis of some specific future events expected to occur in a region, deduced from what has happened in the past by studying the natural record (see e.g., Martí, 2017), as we did for the case of Tenerife, and developing susceptibility maps, hazard maps, hazard scenarios, etc., with cost-benefit and multi-risk analyses. All these analyses should consider the interrelationships between hazards and their possible cascading effects. At the same time, they should consider the variations derived from climate change. The combined outcomes must be the basis for the design of effective monitoring and MHEWS, proper disaster reduction policies, and suitable emergency, contingency, and evacuation plans.

According to the WMO (2018), MHEWS should address:

1. Disaster Risk Knowledge.
2. Detection, Monitoring, Analysis & Forecasting of Hazards and Possible Consequences.
3. Warning Dissemination and Communication.
4. Preparedness and Response Capabilities.

All these strategies, shown in yellow in Fig. 32, must be coordinated and always intercommunicated to establish a strong social, political, and economic risk reduction framework that enables the prediction, anticipation and preparation for natural disasters; in addition it must always be accompanied with a quality education and communication to society. It is worth mentioning the importance of initiating work on land-use planning in this context of anticipation, because it is sometimes the main cause of major damage, by not taking into account the hazard maps and studies of the area, which at the same time are usually ignored by these policies. Also, citizen science has proven on numerous occasions to be essential and helpful in the monitoring of geological hazards by scientists and technicians, as well as a key factor in the realization of short-term scenarios for risk mitigation. Needless to say, this citizen participation is made possible by extensive and solid training and efficient communication.

Whenever possible, when we have indications that a natural event is imminent due to detection by monitoring and MHEWS, it is essential to elaborate short-term hazard assessments. This element has been marked with a dashed line in Fig. 32 because not all geohazards allow for this short-term analysis, as some of them lack precursors. These assessments help forecast where and when the event will take place and the most likely hazard scenarios. This forecasting, in addition to forecasting the impacts, will allow during the event phase, together with the activation of the emergency plans, and in continuous coordination with real-time monitoring data and maps and communication, to take proper decisions to ensure maximum security for the population, and to organize the available resources (human and non-human) to give an efficient response to the emergency. This should be accompanied by the integration of vulnerable groups' needs and providing warnings in transboundary and cross-border disasters.

Once the event is over, emergency response must continue in order to achieve the maximum possible recovery. However, there should be an exhaustive and accurate study to assess the affected area, such as not only to redirect the efforts for a proper final recovery, but also to get an overview of what happened during and after the emergency. Evaluating the extent of the damage and the state of the recovery will enable the conduct of a risk management revision that makes it possible to identify the strengths and weaknesses of the management that has been done at all stages: pre-event, event, and post-event, in order to make improvements and readjustments in the monitoring and MHEWS and to the emergency plans in order to better face inevitable future hazards. This revision will be fed by new long-term multi-hazard studies of the affected area that will incorporate the lived scenario, which will force the renewal or readjustment of existing maps.

Two main ideas emerge from this framework, which should serve as principles for the proper functioning of the system. On the one hand, there is the importance of collaboration between specialists from different disciplines, especially in a multi-hazard context, always bearing in mind our role of service to the society. On the other hand, we need to continually renew or readjust each element of this structure in a cyclical manner as new events occur in the territory. For this reason, it is also essential to know the history of events that a territory has experienced and to carry out an inventory similar to the one conducted in our study, since the fact of not having experienced a disaster by the population alive at the time sometimes works against a society's management capacity. However, nowadays we have sufficient resources to be able to know the events that have occurred in a place and to be able to thus improve our preparedness, as if it were a drill.

Having all or almost all of these aspects covered allows us not to have to start all over again, wasting time and resources every time a disaster occurs, a common trend in all communities. The multi-hazard approach allows the number of unexpected events to be reduced, thus reducing the uncertainty of the final damage. We are aware that not all countries have the necessary resources to be able to establish a solid and complete structure such as the one we are proposing here, but we are also aware that many of these countries are precisely the ones that make the greatest efforts to achieve it. And it is unacceptable for those who have sufficient resources to ignore certain aspects of risk management because they are unaware of them or because their interests lie elsewhere, when it is the lives of many people and the economic resources of a country that are at stake.

Strengthening this risk management framework in volcanic islands could be more complicated due to their socio-economic situation, but for that reason they are the sites where it is most necessary but, currently, less developed. This need will increase due to the worrying futures posed by climate change. In addition, their multi-hazard intrinsic nature makes these areas the best candidates to implement a multi-hazard risk management system.

5.1.6. Nature-based solutions for sustainable development

As we have seen in previous sections, the level of risk imposed by the occurrence of natural hazards on Tenerife is high, something that is repeated in many other volcanic islands and even active volcanic areas on the mainland. Regarding the type of hazards, their frequency is very variable, as is the affected area and the degree of impact. Some hazards, such as forest fires, floods, torrential avenues, droughts, coastal erosion, and hazes, are directly dependent on climate change and should be expected to increase in frequency and severity in the coming years. Concerning volcanic activity, Tenerife has not shown an increase in its frequency or intensity during the Holocene, but the fact that the last eruptions from Teide and from the basaltic system occurred about 1,000 and 100 years ago, respectively, indicates that the probability of new eruptions from either of the 2 systems is not negligible (Sobradelo et al., 2011). Furthermore, according to the risk cartographies collected in the Island Territorial Emergency Plan (PEIN) (available directly at https://transparencia.tenerife.es/archivos/110/documento-plan-39-16-03-2020-analisis-de-riesgos-1502.pdf, accessed on 27 December 2022) and the map shown in Fig. 12, many of the high-risk areas for any of the phenomena mentioned are densely populated. This is, for example, the case of the valleys of Icod and La Orotava, with high volcanic risk due to eruptions that can originate from Teide and the two rifts zones, as well as forest fires, which also pose a high risk to the cities of San Cristóbal de La Laguna and Santa Cruz de Tenerife. The latter two also have a high risk of flooding.

With this section, we aim to go one step further in the management of multi-hazard events in regions like Tenerife, with the goal of not conveying a negative or discouraging message to the population, but rather providing long-term solutions that enable the sustainable development of this island in harmony with the geological and climatic processes that occur here. These solutions can be similarly applied to other regions with similar potential after conducting an analysis of the risks and opportunities that each region presents.

To ensure that hazard assessment and vulnerability analysis are adequately addressed within policy statements and plans, one way to make risk reduction plans understandable and acceptable in active volcanic areas is by proposing nature-based solutions—for example, in the case of deciding whether new developments should be permitted in areas identified as high risk. While the authorization of new permanent constructions may be questionable, it could be that the development of certain activities that facilitate observation of the natural environment (even the temporary use of the land) should always depend on the degree of volcanic and non-volcanic activity, as well as the expediency of emergency plans, in case of unforeseen activity. Further, we recommend to undertake planning for other land use recovery aspects by considering what the effects of a natural event might be, how land use could be improved after an event, and what steps might be taken before an event to ensure such improvements can be made (Becker et al., 2006). In fact, volcanism and other phenomena do not need to be incompatible with certain types of activities and land uses if these are based on precise knowledge of the risk in each case. In this sense, geoethics actively promotes the concept of geoeducation, with the primary objective of designing and implementing effective educational resources (Bezzi, 1999). It strives to cultivate awareness, values, and a sense of responsibility, particularly among young individuals. Additionally, geoethics encourages the establishment of geoparks (Eder, 2004; Zouros, 2004; McKeever, 2013) and the development of geo-tourism (Newsome & Dowling, 2010; Dowling, 2011), with the aim of generating appreciation for a region's geological heritage (Brocx & Semeniuk, 2007; Gray, 2008) and the importance of preserving geodiversity (Osborne, 2000).

The application of nature-based solutions to the sustainable development of volcanic areas (especially to volcanic islands) is sufficiently broad to involve numerous contributions. The list of possible nature-based solutions may include: (1) the sustainable use of raw materials, (2) geothermal energy production, (3) sustainable soil management for agriculture, (4) ranching, (5) for use in construction, (6) landscape solutions that are resilient to climate change (e.g., reducing flood risk, erosion, etc.), and (7) the promotion of safe and sustainable nature-based tourism, among others. However, the number of these potential solutions that have already been applied in volcanic areas is still low and rather unequal, depending on the characteristics of each area (e.g., local economy, social development, political system, risk perception, etc.).

In most active volcanoes and volcanic areas, it is common to find protected natural spaces (Casadevall, Tormey, Roberts, 2019; Casadevall, Tormey, Van Sistine, 2019), either because of the rich soils that generate high biodiversity, because of their scenic beauty, or because of their geological heritage. For example, of the 100 sites that have been declared as having geological interest by the IUGS (International Union of Geophysical Sciences), 27 are active volcanic areas or are related to volcanism. These protected natural spaces, if they are well-managed, generate social and economic improvement (Planagumà & Martí, 2020), as well as awareness and knowledge of geology, for both the local population and their visitors. In addition, the promotion of volcanic geoheritage is an efficient way to enhance the development of poor and rural regions by educating their inhabitants on its geological richness and how to benefit from preserving it and exhibiting it to others. This nature-based solution is important in two senses. It will help local residents value their area and, hence, see the need for preserving this value, and it will lead them to organize new businesses around rural tourism. In addition, such a solution will help create a community conscience around the need for preserving their geological values and related ecosystems, and to be aware of potential risks that may affect their area.

The possible problems that Tenerife has in relation to land use planning are diverse and include aspects derived from the extraction and use of natural resources (water, rock materials, and soils), landscape, ecosystems, and geological heritage conservation, in addition to those derived from natural risks that may affect the island—some of these will be aggravated due to climate change. For example, the scarcity of drinking water is already a problem on the island, with an evident annual decrease in natural water resources and the increasing demand from the permanent population and tourism (Braojos-Ruiz et al., 2006). A similar situation is observed with the extraction of natural material for construction, as currently there is only one legally authorized quarry for aggregate extraction (Medina, 2021). Forest fires, floods, torrential avenues, rockslides, and small landslides are recurrent problems that also require attention. These destructive processes affect soil and landscape stability and their related ecosystems. The main zones affected by soil erosion correspond to the landslide valleys of Icod and La Orotava at the northern side of the island and the Guímar Valley in the southeast, as well as the older corners of Teno and Anaga. The application of nature-based solutions, such as soil–vegetation solutions that enhance soil function and soil resilience (e.g., better infiltration, soil stability, and soil roughness, etc.) and landscape solutions, considering hillslope morphology, runoff pathways, topographic humidity, and water and sediment sinks, would be effective approaches to determine the potential for water and sediment transport, and to evaluate and reduce soil and landscape degradation (Keesstra et al., 2018). These solutions should be applied in land use planning in these areas of Tenerife to preserve the health of soils and landscapes.

For volcanic hazards, as we mentioned before, the problem changes due to the lack of risk perception by most inhabitants of the island and its visitors. Even though the Canary Islands is an active volcanic region that has suffered two volcanic eruptions in recent years (El Hierro in 2011–2012 and La Palma in 2021), the possibility of having an eruption on Tenerife is regarded as less probable, in part due to the long eruption frequency of its volcanoes. However, the likelihood of having a new eruption cannot be neglected, especially when we consider the time that has passed since previous eruptions. In addition, the presence of the Teide–Pico Viejo complex, a high-risk volcanic system (Martí et al., 2012) able to produce explosive eruptions of considerable size, should be a matter of serious concern for local authorities and must, therefore, be considered in the land use and emergency planning for the island. However, at the time of writing, there is no comprehensive volcanic risk reduction plan for Tenerife based on a long-term hazard assessment, so existing land use planning does not consider potential volcanic hazards. What does exist is a monitoring plan of volcanic activity, run by IGN and duplicated to a certain extent by other institutions (CSIC, ITER), and the consideration of Teide–Pico Viejo as an effusive volcano in the emergency plan to be applied to manage a volcanic crisis (PEVOLCA). However, land use planning for Tenerife (Fig. 11) only considers land classification according to its level of environmental and economic protection and its potential use in development. Obviously, this is not the best way to address land use planning in an area threatened by active volcanoes.

If we consider, for example, the Icod Valley (Fig. 5), where there are more than 50,000 inhabitants, and which constitutes an important economic and touristic area of Tenerife, we observe that most products from the latest eruptions of Teide–Pico Viejo have been emplaced there (Ablay & Martí, 2000; Martí et al., 2012), in addition to the products from some historical eruptions, such as those of Garachico (1706) and Chinyero (1909), which had a significant impact on the area (Romero, 1991). The demographic and economic development in this area, also affected by other natural hazards (Perez, 2016; Arroyo, 2019), make it of higher risk if we take into consideration the potential impact of volcanic hazards. With the degree of development already achieved in this area, it is difficult now to carry out reasonable land use planning to preserve it, but there is still time to apply some nature-based solutions to reduce risk and to provide simultaneous benefits to society, the economy, and nature. The most urgent actions should include: (1) a long-term development plan based on hazard assessment and risk management (these long-term development plans should be based on long-term risk assessment, which will come from the historical record of events, to find out the frequency, type of events and interrelationships, susceptibility, hazard, and others, as well as risk simulations, monitoring, and short-term analysis); (2) rationalization of construction and demographic expansion according to the potential volcanic and associated hazards that may impact the zone—those places not suitable for construction (e.g., recreation parks, tracking areas, etc.) and that can still provide some benefits to society could be utilized non-permanently; and (3) the mobility, energy, and water supply networks should be revised and, if necessary, redesigned to ensure their functionality, even in the case of severe impacts on the area. Additionally, coastal management should be implemented to mitigate the effects of climate change, as well as the restoration of floodplains, to reduce the risk of downstream flooding. In summary, these solutions would contribute to the sustainability and security of the area by maintaining or enhancing its economic development, with clear benefits for the environment and human health.

Another important aspect that we need to consider in the case of Tenerife, one of the most visited places in the world, is the role of tourism. Tourism is the main source of employment and income for local inhabitants and is also an important component of regional development, while also contributing to the preservation of natural and cultural heritage as a source of income (Pigram & Wahab, 1997; Buckley, 2011; Azam et al., 2018; Brtnický et al., 2020). However, tourism in Tenerife demands better rationalization and planning if it is expected to become a sustainable solution for the economy of the island. As for the rest of the Canary Islands, tourism in Tenerife started in the 1960s as mass tourism and has continued in this way until the present. It has not been until very recently that rural tourism, which is more interested in natural aspects and is much more respectful to the environment, has started to mature. This is probably the reason why, despite the existence in Tenerife of many protected areas and it having of one of the main national parks in Europe, the amount of scientific information and outreach material to be distributed among visitors remains scarce.

Geotourism is fast becoming a new way of generating income, and so it is important to foster it and ensure that it is as sustainable as possible. Examples of how to make geotourism sustainable and a valuable element in the development of a particular area or region have been documented elsewhere, e.g., Planagumà and Martí (2018). However, these examples also reveal how demanding this type of tourism is. For this reason, it requires information that is based on rigorous scientific knowledge and employs properly trained communicators who can transmit natural values to visitors. At the same time, geotourism needs to be included in land use planning in order to determine the best and most informative places to be visited and the routes to reach them. This same land use planning based on risk analysis should include not only the main attractions and activities that add value to geotourism, but also the accessible infrastructure, accommodation, and facilities, so that these are also located in safe areas, with a lower environmental impact, and facilitate sustainable tourism. Otherwise, massive tourism may become a source of negative environmental impacts, including heavy metal pollution of soils due to an excess of oil-dependent transport, degradation of the landscape and the geoheritage, and the perturbation of ecosystem equilibrium (e.g., Brtnický et al., 2020).

In this sense, the presence of a growing tourism industry may require having adequate infrastructure and services, as well as territorial planning, in accordance with the increase in mechanical transport and the presence of people in places that are not necessarily suitable for it. Moreover, security is one of the most important aspects for tourism development (Ritchie & Jiang, 2019). In volcanic areas, the main attraction is to observe active volcanoes or their products and forms from past eruptions, in addition to the ecosystems that have developed around them. In Tenerife, where there is no active volcanism, the main touristic interest is geoheritage. Therefore, ensuring the presence of tourism means ensuring the preservation of the volcanic heritage and safety in the area. This requires effective territorial planning and risk management to prevent possible impacts due to the occurrence of various natural phenomena typical of the island and the degradation of its natural heritage—but also due to the presence of tourism itself. Warnings in multiple languages; recommendations designed for a transient population, not just for local people or scientists; guides trained by geologists with experience in disaster management; recognition of the hazards of each area and indications for visitors in case of emergency; and knowledge of the health problems that can occur in areas with some geological risk, as well as how to detect their symptoms in order to call for immediate help, are some of the safety measures that need to be improved in many of the cases (Heggie, 2009; Erfurt-Cooper, 2011). Even in the event of an eruption, depending on its size and conditions, it may have positive aspects by attracting tourism and generating income when it is well-managed and the safety of visitors is guaranteed, despite the potential damage it may cause. However, it may also become a disaster when the eruption exceeds the management capabilities in the affected area. This all depends, of course, on the size and style of the eruption—but also on the degree of prevention and preparedness carried out as part of the risk management program that should be implemented in any active volcanic area.

Finally, it is worth mentioning the relevance of protected natural spaces in a volcanic island like Tenerife. Well-managed protected natural spaces may represent an important social and economic improvement, but they also may raise awareness and knowledge of geology, for both the local population and the visitors (Planagumà & Martí, 2020). Responsible management implies a correct definition of geosites of geological interest, interpretation guides, training of geotourism guides, etc., but also good planning of the routes to and within these spaces—in addition to having adequate services and an adequate risk management plan based on a long-term hazard assessment. The different programs of the protected natural space entail better participation of the communities that live inside them, and therefore, this predisposes them to appreciate the richness of these areas. Consequently, a well-informed populace facilitates policy makers to design thorough risk mitigation policies. Protected natural areas also facilitate the zoning and management of the territory, which entails better planning and adequate infrastructure, research, monitoring, alert levels, response plans, including evacuation routes, etc., alongside effective communication. Tongariro (New Zealand), Hawaii (USA), and Iceland are good examples of where there are participation spaces where both authorities and the local population participate according to their decision level, making it much easier to involve the public in emergency planning and response. The development and implementation of environmental education programs of the protected natural spaces is a great tool to develop capacities and awareness, and in places like Tenerife, it would contribute to volcanic risk reduction. In this sense, one of the tools to disseminate volcanological knowledge and security perception when visiting these protected areas is geotourism. The equipment and guides that partake in geotourism are the key actors to improve the knowledge of both the local population and the visitors about the geological and volcanological characteristics of the area, while at the same time being active participants in the definition of volcanic risk management plans. The high number of protected natural spaces in Tenerife (more than 50% of the island has some type of protection) should be sufficient reason to undertake these types of policies, thus making the island much safer and more sustainable. The information shown in Table 2 should be presented to visitors and should help to raise awareness about geological risks on the island.

5.2. A roadmap for further investigation

The present study represents a significant milestone in the understanding and management of multi-hazard scenarios on volcanic islands, particularly in the context of Tenerife. Through rigorous research and analysis, we have achieved several key accomplishments, including the clarification of multi-hazard approach issues and the development of a comprehensive methodology to address these challenges specifically in the unique setting of Tenerife. Despite the significant achievements and advancements made thus far, there remains important work to be done in further exploring and addressing the complexities of multi-hazard assessment and risk management in active volcanic areas like Tenerife.

Firstly, to further advance our understanding and improve the precision and accuracy of the data used in this study, it is crucial to conduct additional fieldwork and incorporate citizen science initiatives. This roadmap outlines the need for comprehensive geological studies through field campaigns in Tenerife and emphasizes the importance of investing in earth sciences and fundamental scientific knowledge, particularly in the field of physical geology.

Fieldwork plays a vital role in scientific research, particularly in the context of geological studies. By directly observing and collecting data from the field, we can gather crucial information about the geological processes and phenomena occurring in a specific region. In the case of Tenerife, conducting field campaigns will provide invaluable insights into the island's geological characteristics, including its volcanic activity, tectonic processes, and hazard-prone areas. By augmenting our dataset with new field observations, we can refine our understanding of the local geology and enhance the accuracy of our analyses.

Additionally, incorporating citizen science initiatives can greatly contribute to the collection of valuable data. Citizen science involves engaging the public in scientific research, allowing individuals from various backgrounds to actively participate in data collection and analysis. In Tenerife and other regions, citizen scientists can contribute by reporting observations, sharing photographs, and providing local knowledge about geological events and processes. By involving the community, we can gather a broader range of data points, improve spatial coverage, and enhance our understanding of the region's geological dynamics.

To effectively implement citizen science initiatives, it is essential to establish collaborative platforms and communication channels between scientists and the public. These platforms can facilitate data sharing, provide guidance for data collection protocols, and ensure the accuracy and reliability of the collected information. Engaging citizens in the scientific process not only expands the available data but also promotes public awareness and understanding of geological hazards and their potential impacts.

Moreover, the need for investing in earth sciences and fundamental scientific knowledge cannot be overstated. While experimental studies are valuable, they should be complemented by a solid foundation in physical geology. Understanding the fundamental principles and processes that govern the Earth's geological dynamics is crucial for accurate hazard assessments, modeling, and prediction. By supporting research and education in earth sciences, we can foster a deeper understanding of our planet's geological intricacies and better inform decision-making processes related to risk mitigation and preparedness.

The development of the tool for quantitative probabilistic analysis presented in this study was tailored to the case of Tenerife. However, in the future, it would be valuable to expand this tool's applicability to any situation by increasing the number of branches per node. Currently, the tool provides global probabilities for all branches, but these probabilities are not precise as they take into account non-realistic scenarios. To obtain more accurate probabilities, the system eliminates the non-realistic scenarios and recalculates the probabilities for each separate branch. This process currently requires manual intervention by the user. However, the problem still persists for each branch, as it presents other probable but unrealistic scenarios. The ultimate goal is for the tool to no longer calculate global probabilities based on non-realistic scenarios, but instead provide global probabilities for only possible scenarios, as well as recalculating probabilities for each specific branch of interest. It should also be noted that in the calculation of probabilities, the years in which no event occurs have not been taken into account. Therefore, the probabilities are being obtained assuming that an event has occurred. To obtain the actual probabilities, the result of each scenario should be multiplied by the number of occurrences of that event and divided by the total number of windows. That is something we are also working on to automate the process.

On the other hand, when we have events of different nature with widely disparate occurrence frequencies, this methodology only provides valuable information for each cause if we adjust the size of the time window to the least frequent event. In our case, since we wanted to estimate the annual probability and there are some causes with much higher frequencies, such as volcanic eruptions, they appear with an almost negligible probability. This happens because the methodology does not take into account the time that has elapsed since the last occurrence of a specific event. As mentioned before, this would not happen if we had estimated using a much larger time window; however, this solution would result in a loss of resolution for more frequent events. To address this, we propose implementing a weighting factor for each event in future work, which adjusts the probabilistic results, taking into account the time that has passed since the last occurrence. Since this new method is not developed at the time of writing this text, we have chosen to perform an additional single-risk analysis by filtering the records based on their cause. This allows us to have an idea of the most probable scenarios at the multi-risk and single-risk levels to evaluate them in parallel. In this way, with the availability of the original records, we can obtain the most probable scenario for each cause and assess the real possibility of that scenario given the time elapsed since the last occurrence of a similar event.

One important aspect is to adapt the tool to be able to answer questions as they are presented. For example, if the question is about the natural risks that may occur in Tenerife in the next 10 years, the tool should provide total global probabilities. However, if the question is about the probability of an eruption of Mount Teide with ash fall, it is necessary to eliminate other scenarios and focus solely on volcanic scenarios that involve ash fall. Furthermore, intermediate questions could explore the probability of such a scenario occurring along with others, such as earthquakes.

Regarding the simulation of the impact of future events, as we did for the El Abrigo caldera-forming eruption in case it happens again, it is necessary to develop a tool that allows the incorporation of different software or simulation models that feed back to each other. This means that once the simulation of the first event is started, on which the rest of the cascading hazards may depend, the tool will be able to incorporate and modify the input parameters automatically to simulate the whole chain of events without requiring user intervention, as we did for our study. Another option is to work further on the development of software that incorporates the simulation of more than one interrelated event, such as VolcFlow's code for two fluids, although progress is already being made in this area. The ideal would be to understand as much as possible how these interrelationships work in order to eliminate as much as possible the subjectivity of the process. However, in addition to numerical models, it is necessary to develop models based on knowledge of the historical record, whenever possible. So far, a lot of effort is being put into developing software with a complex and immense mathematical framework. But sometimes the reality is different, and experience tells us that the observation of what has happened repeatedly in the past is more accurate than any numerical model.

The objective is to develop tools that objectively depict reality based on data and expertise. While decision-making should be left to others, as scientists, it is essential to provide objective results and information. The tool's objectivity must be evident throughout the process.

Considering the limitation of epistemic uncertainty, it is crucial to acknowledge the uncertainty surrounding data collection methods. Additionally, it is worth exploring the correlation index to understand how the obtained probabilities could be affected by the increasing frequency of other events. Understanding the correlation index of certain events helps assess how they contribute to event cascades in the context of climate change. These efforts are crucial for anticipating the occurrence of specific events.

On the other hand, in this study, we employed various e-tools to simulate different hazards that occur in a cascading sequence. However, the manual integration of these simulation models required expert judgment and consideration of the consequences of one hazard scenario on the input parameters of the subsequent hazard scenario. While we were able to achieve this integration using an expertise-based approach and drawing insights from past events, our aim now is to develop an automated simulation tool that can encompass the entire cascading sequence while accounting for the modification of input parameters based on the outcomes of previous events. Additionally, we seek to incorporate climate change modifications or alterations into the consequences of these events.

The need for such an automated simulation model arises from the realization that hazard events in a cascading sequence are interconnected, and the outcomes of one event can significantly influence the characteristics and impacts of subsequent events. Manual integration, as we have done in this study, can be time-consuming and reliant on expert judgment. By developing an automated simulation model, we can streamline the process and enhance the accuracy and efficiency of the analysis.

The automated simulation model we envision would allow for the simulation of the entire cascading sequence in a concatenated manner. It would consider the dynamic modification of input parameters for each event in the sequence based on the outcomes of previous events. This feature is crucial as it captures the complex interdependencies and feedback mechanisms that exist within cascading hazard scenarios.

Furthermore, the simulation model should incorporate climate change considerations. Climate change has the potential to alter the consequences and characteristics of hazard events, making it essential to account for these modifications in our analysis. By integrating climate change factors into the simulation tool, we can assess how changing climatic conditions may influence the outcomes and impacts of the cascading hazard sequence.

Developing such an automated simulation model requires the collaboration of experts in various fields, including hazard modeling, climate science, and simulation tool development. The model should be designed to handle a wide range of hazard scenarios and enable flexibility in incorporating new data and research findings. The automation of the simulation process will not only enhance the accuracy of our analyses but also facilitate faster and more comprehensive assessments of cascading hazard scenarios under varying conditions.

By creating an automated simulation model that combines the simulation models applied in this study, we can advance our understanding of the interconnectedness and cascading effects of hazards. This model will contribute to more informed decision-making processes, enabling better preparedness and risk mitigation strategies in the face of complex hazard scenarios influenced by climate change. It is important to highlight that we already have a foundational VOLCANBOX tool, which works for volcanoes. However, our aim is to further develop it for multi-hazard purposes and this contribution is the first step towards this goal.

In conclusion, the next steps in research entail amplifying scientific knowledge and advancing the development of more automated and objective multi-hazard assessment tools for both prediction and simulation of impacts. This includes incorporating the processes of climate change into these tools to provide a comprehensive understanding of the evolving risks. Furthermore, it is crucial to effectively transmit and implement this valuable information into the current risk management system. Educational programs, aimed at both the general population and authorities, will play a pivotal role in ensuring the widespread dissemination and practical application of this knowledge. By embracing these next steps, we can foster a stronger and more resilient society, better equipped to mitigate and adapt to the multi-hazard challenges faced by volcanic islands such as Tenerife.

CHAPTER 6

CONCLUDING REMARKS

6.1. Key findings and implications

This study examined the development of the multi-hazard concept and its application in current policies for reducing disaster risks. Specifically focusing on volcanic islands and taking Tenerife in the Canary Islands as a case study, we analyzed their multiple hazards by studying actual disasters and how they are managed. We found the following conclusions from our analysis: (1) There is a gradual adoption of the multi-hazard approach in national and international risk management policies, although progress is still being slow. (2) Many countries have implemented projects and strategies with a multi-hazard perspective in line with the objectives set during the Conferences on Disaster Risk Reduction, despite the non-binding nature of the Sendai Framework. (3) Collaborative efforts among countries have led to regional projects that build upon existing individual systems for monitoring and early warning of hazards. (4) Volcanic islands face significant vulnerabilities due to their multi-hazard nature, social and economic contexts, political factors, and climate change. Therefore, it is crucial to establish effective multi-risk management systems in these territories. (5) To achieve this, research, conservation, and education should be prioritized to develop scientific knowledge for real-time monitoring, early warning systems, educational programs, and management plans at all societal levels.

Climate change not only directly affects the population through rising global temperatures, extreme weather events, and sea-level rise but also amplifies the magnitude and frequency of natural hazards while altering their interconnections. In the context of climate change, where hazards will intensify and population growth will increase exposure to natural disasters, reducing risk cannot solely rely on technological advancements. Following the Sendai Framework, disaster risk reduction policies should adopt a cross-sectoral, climate change-focused, socially inclusive, and multi-risk management system. This system should be based on scientific knowledge and connected to critical societal solutions. Active volcanic islands are highly susceptible to various natural hazards, which will worsen due to climate change. To ensure a safe society, we must create and implement appropriate plans to mitigate these risks. These islands are also popular tourist destinations and have experienced significant population growth, increasing the exposure of people to natural hazards. Thus, it is crucial to focus on developing long-term risk mitigation strategies based on hazard assessments and transforming these areas into sources of nature-based solutions. Nature-based solutions play a vital role in adapting to climate change and the impacts of natural hazards, enhancing society's resilience and sustainability.

Furthermore, volcanic islands provide ideal settings for exploring multi-risk scenarios, an emerging concept under the Sendai Framework. These islands have clear boundaries and already boast protected natural areas, such as Tenerife. However, these boundaries also present challenges, such as limited space for population expansion and resource utilization, which come with associated risks.

In the case of Tenerife, as well as many other volcanic islands and volcanic areas in general, one of the primary challenges is demographic growth and increasing tourism. This necessitates changes in land use, which often do not align with effective risk reduction solutions. In Tenerife, tourism is the main source of income, leading local policies to prioritize construction and service-related land uses for tourism. Unfortunately, there is a lack of well-established land use planning policies that effectively incorporate scientific information on natural hazards. This results in reactive rather than proactive emergency plans, addressing specific hazards without considering a multi-hazard approach. To enhance the effectiveness of risk reduction plans, it is essential to integrate hazard and vulnerability information into land use planning, reducing exposure to natural hazards for people, critical infrastructure, and valuable assets.

Moreover, during emergencies and crisis situations triggered by volcanic eruptions, landslides, earthquakes, and more, uncertainty, pressure, and chaos prevail. Precursors to such events are often unclear or absent. In an ideal world, with comprehensive knowledge of natural processes and access to advanced technology, uncertainty could be minimized. However, the reality is different, and climate change further complicates these physical processes and their interconnections, resulting in increasing uncertainties. Technological advances can improve research and monitoring, but they sometimes distance us from reality-based science. While long-term multi-hazard assessments based on existing records can help prevent disasters, short-term assessments during crises require globalization and transdisciplinarity. Nevertheless, the human factor remains crucial. This factor introduces additional uncertainties or increases existing uncertainties, even when methodology and knowledge are near perfect. Personal interests, lack of objectivity, ambition, limited awareness and responsibility, difficulties in effective communication, and a lack of long-term vision contribute to these uncertainties. To overcome these challenges, the implementation of science in the political process, with a multi-risk perspective guided by geoethics, is essential. Geoethics ensures ethical human interactions with the Earth system, thus promoting societal resilience.

Through our rigorous study focused on multi-hazard assessment and risk management in volcanic islands, specifically Tenerife, we have made significant strides in clarifying the complexities associated with the multi-hazard approach. Our research has not only shed light on these issues but has also led to the development of a comprehensive methodology aimed at addressing and resolving these challenges. A major accomplishment of our study has been the successful execution of a long-term multi-hazard assessment specifically tailored for Tenerife.

To achieve this, we adapted and applied a well-established methodology that had already demonstrated effectiveness in volcanic hazard assessment. The utilization of the Event tree structure with Bayesian inference, through an adapted version of the HASSET tool, provided a robust framework for systematically evaluating and quantifying the probabilities associated with various hazard scenarios. This allowed us to verify that in the future, Tenerife will face a higher probability of phenomena such as storms that will produce floods, and with less probability, debris flows, whose already significant and severe impacts can be further exacerbated by the effects of climate change and poor land management. Furthermore, the areas where these rainfall events that cause floods occur the most are in the north and northeast of the island, particularly affecting the Metropolitan area where major population centers such as San Cristóbal de La Laguna or the island's capital, Santa Cruz de Tenerife, are located. Other highly probable future scenarios include the occurrence of landslides near roads, which have a close relationship with precipitation and earthquake events.

We performed a long-term multi-hazard assessment of Tenerife to predict the potential extent and impact of extreme events occurring in cascade during a caldera-forming eruption. By considering multiple hazards simultaneously, we captured the intricate interdependencies and cascading effects that can arise during complex hazard scenarios. The resulting scenarios show how large areas could be covered by PDCs (and probably associated ash fall) that would affect the main urban centers and possible evacuation routes. Furthermore, seismicity focused on the central part of the island during a caldera collapse event–that in itself could have catastrophic effects on several parts of the island–could trigger a devastating landslide in the Icod valley and produce a tsunami that would probably have a severe impact not only to the northern and western coasts of Tenerife but also to other coasts of the archipelago. This is probably the most hazardous scenario that can be envisaged for Tenerife. Fortunately, despite being possible, such scenarios only need to be anticipated with recurrences on a geological timescale; however, they should not be ignored. Over the past 1 Ma, Tenerife has experienced a cascading succession of disastrous events several times and the persistence today of the same geophysical conditions that caused them in the past means that their occurrence in the future cannot be ruled out. Therefore, improving current knowledge of the causes and mechanisms of such processes should form part of the emergency plans that are being developed to confront volcanic phenomena in the Canary Islands and other regions with similar potential problems.

In addition to our fieldwork and analysis, we drew upon our experiences in Iceland, where we conducted interviews to gain insights into their risk management system. Leveraging this valuable knowledge, we were able to propose improved measures and strategies for risk mitigation specific to the context of Tenerife. By incorporating lessons learned from other volcanic regions, we aimed to enhance the resilience of Tenerife and its communities to various hazards.

Furthermore, our study emphasized the identification of nature-based solutions that contribute to the sustainable development of the island. Recognizing the intrinsic value of ecosystems and their services, we identified strategies that integrate nature-based measures within the overall risk management framework. These nature-based solutions offer sustainable and effective approaches for mitigating hazards while preserving the island's natural heritage.

Having achieved these significant milestones in our study, it is now crucial to outline a roadmap for further investigation. This roadmap will guide future research endeavors and build upon the foundations we have established. By expanding our knowledge, refining methodologies, and incorporating additional data and perspectives, we aim to further enhance our understanding of multi-hazard scenarios in volcanic islands, ultimately promoting effective risk management and sustainable development.

6.2. Tailored conclusions: strategic recommendations to enhance risk management in Tenerife

Tenerife's risk management system focuses on coordinating and integrating various organizations, both public and private, while Iceland emphasizes government-led policy formulation and implementation. However, the duplication of administrations in Tenerife, as seen in Spain, can pose challenges for natural risk management. Multiple management bodies at different levels (national, regional, insular, municipal) can lead to poor coordination, overlapping responsibilities, and inconsistency in policies. These issues hinder effective collaboration and decision-making in risk management.

In contrast, Iceland's centralized risk management structure offers streamlined coordination and coherent strategies. Centralization allows for efficient allocation of resources and decision-making throughout the country. However, decentralization can be advantageous for countries like Spain, with its diverse geography, larger population, and the need for local authorities' knowledge and capacity to manage specific risks. Although the advantages of Icelandic centralization could benefit Tenerife due to its smaller community compared to the whole of Spain, challenges such as population density, limited space, and proximity to high-risk areas make it difficult to replicate Iceland's urban planning model. Tenerife's risk perception is also influenced by the frequency and types of past events, which can affect preparedness.

Improvements needed at the island level include greater coordination between small communities, increased investment in technology and knowledge for risk prevention, multi-hazard early warning systems, research and monitoring protocols, and better communication between entities involved in investigating and monitoring events. Additionally, protocols for recovery and incorporating social services and voluntary organizations are essential. Long-term measures involve diversifying the economy, territorial planning aligned with risk management, multi-hazard approaches, education and training for citizens and tourism, and a proactive preventive culture.

In the last decades, Tenerife has not experienced a major natural event, but they may occur in the near future. So, it is necessary to emphasize the need for proactive, long-term strategies to adapt to future potential scenarios and climate change. Achieving resilience requires transitioning from incremental adaptation to comprehensive strategies. Tenerife may face high risks from various natural hazards. Climate change is expected to increase the frequency and severity of hazards such as forest fires, floods, droughts, coastal erosion, and haze. Mitigation measures include cleaning ravines, creating water retention areas, reforestation, and proper land planning.

While volcanic activity on Tenerife has not shown an increase, the possibility of new eruptions, including eruptions from Teide and Pico Viejo stratovolcanoes, cannot be ignored. Many high-risk areas are densely populated, including the valleys of Icod and La Orotava, which are at risk from volcanic eruptions and forest fires, and the cities of San Cristóbal de La Laguna and Santa Cruz de Tenerife, which are at risk of flooding. To address risk reduction in volcanic areas, nature-based solutions are proposed, particularly in land use planning. These solutions aim to balance the need for observation of the natural environment with the degree of volcanic activity and the effectiveness of emergency plans. Geoethics promotes geoeducation and the establishment of geoparks and geo-tourism to generate appreciation for geological heritage and the importance of preserving it.

Nature-based solutions can be applied to the sustainable development of the island, including the sustainable use of raw materials, geothermal energy production, sustainable soil management for agriculture and construction, resilient landscape solutions, and safe and sustainable nature-based tourism. However, land use planning in Tenerife faces diverse challenges related to the extraction and use of natural resources, landscape and ecosystem conservation, and natural hazards. Scarcity of drinking water and limited quarry access for construction materials are existing problems. Soil erosion, forest fires, floods, rockslides, and landslides also require attention to preserve soil and landscape stability. Comprehensive volcanic risk reduction plans based on long-term hazard assessment are lacking, and current land use planning does not consider potential interrelated hazards adequately.

For areas like the Icod Valley with high population and economic development, it is challenging to implement reasonable land use planning, but nature-based solutions can still be applied to reduce risk and provide benefits to society, its economy, and the environment. Long-term development plans based on hazard assessment and risk management, rationalization of construction and demographic expansion, and revision of infrastructure networks are urgent actions needed. Coastal management and floodplain restoration are also essential for mitigating climate change impacts, especially in the metropolitan area.

Tourism is the most important aspect of Tenerife's economy, but it requires better planning and rationalization for sustainability. Geotourism, which focuses on natural aspects and environmental preservation, is gaining importance but lacks sufficient scientific information and outreach material for visitors. Geotourism should be included in land use planning to identify informative places and routes, along with suitable infrastructure and facilities. Failure to plan for sustainable tourism can lead to negative environmental impacts. In volcanic areas, tourism revolves around observing active volcanoes, their products, and the surrounding ecosystems. In Tenerife, where there is no active volcanism, the preservation of geoheritage is crucial for tourism. Effective territorial planning and risk management are necessary to prevent impacts from natural phenomena and degradation of natural heritage. Safety measures for tourists should be improved, including multilingual warnings, trained guides, hazard recognition, and knowledge of health issues related to geological risks.

In conclusion, land management based on prior assessment of the Tenerife’s hazards is the key to strengthening the island’s current risk mitigation plans. This will allow for a two-way relationship between the exploitation of sustainable tourism and the education of its population, both oriented toward the conservation of its geological heritage, and will promote the sustainable use of the energy and material resources currently being exploited.

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PART II

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Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Reviewing the multi-hazard concept. Application to volcanic islands

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ARTICLE INFO

Keywords:
Multi-hazard
Geohazard
Risk management
Early warning system
Resilience
Disaster risk reduction

ABSTRACT

Because of their social, economic and political contexts, and their intrinsic multi-hazard nature, volcanic islands are one of the most vulnerable environments, where natural hazards (volcanic and non-volcanic) tend to occur in a simultaneous way causing cascading effects. To date, most of the scientific knowledge, as well as hazard assessment and risk management protocols focus on individual hazards and risks, while it remains a challenge to correctly predict the outcomes and impacts of a multi-hazard scenario where several hazardous phenomena may interact in simultaneous or consecutive ways. The multi-hazard concept originated in the 1990s in the international political context precisely to respond to this need. After its first appearance, different–and often, contradictory–usage perspectives of the multi-hazard concept have been increasingly put forward, thus making it difficult for this new approach to be fully implemented into disaster reduction policies. The present study assesses the current status of the application of the multi-hazard approach in existing risk management systems, and proposes future improvements to disaster risk reduction. It also presents the multi-hazards to which volcanic islands are exposed and analyses their potential impacts, taking the Canary Islands as a case study. In doing so, it emphasizes the need to establish a cross-sectoral, climate change-oriented, socially-inclusive, multi-risk management system, based on scientific knowledge and linked to critical societal demands and solutions.

1. Introduction

Many different communities around the World are yearly struck by natural hazards of diverse typology (e.g., landslides, earthquakes, floods, volcanic eruptions, wildfires, etc.), potentially leading to important economic losses, fatalities, and the destruction of vital infrastructure. Our increasing globalization and technological progress can contribute to a better response to natural disasters through the sharing of resources and knowledge. However, this increased global connectedness, coupled with an increase in our technological dependence and the continuous demographic expansion, makes modern global society progressively more vulnerable in front of such natural destructive phenomena. In consequence, relatively small events, which in other times would have had mainly a local impact, have caused economic losses and, indirectly, impacts on other sectors of the population, both regionally and globally. An example of this is the eruption of Eyjafjallajökull volcano in Iceland in 2010, which caused a major impact on air traffic on a global scale with consequent significant economic losses. In the case of extreme events, the consequences can be catastrophic, as had occurred in the seismogenic tsunamis of Sumatra (Indonesia, 2004) and Tohoku (Japan, 2011). This is even more worrying when it is considered within the context of the current global climate change, for which there is clear evidence of the progressive increase in the occurrence of extreme events and of their interactions (IPCC, 2022), which will increasingly cause severe damage to our society.

According to Munich Re (2022), natural disasters have produced economic losses of US$ 5200 trillion USD since 1980, with >70% of this total being uninsured. This trend, which continues today, shows a lack of preventive culture even in the 21st century, with several cases of major disasters already behind us. During all this time, it is true that the frequency of some types of events, especially weather-related ones, has increased due to Climate Change. However, other types of non-climate related events, such as earthquakes and volcanic eruptions, have not increased in frequency, but the impact of both types of events has shown an increasing trend (Munich Re, 2022). The reason for this is, on the one hand, the increased exposure, complexity and, as a consequence, vulnerability of society, and, on the other hand, the increased magnitude, frequency and impact of the interrelationships between hazards in multi-hazard scenarios. In 2021 alone, natural disasters caused overall

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https://doi.org/10.1016/j.earscirev.2022.104286
Received 5 August 2022; Received in revised form 30 November 2022; Accepted 4 December 2022
Available online 6 December 2022
0012-8252/

losses of 280bn USD, of which roughly 120bn USD were insured, the second-costliest ever for the insurance sector (record year 2017: 146bn USD, inflation-adjusted), and almost 10,000 people have lost their lives (Munich Re, 2022).

Natural hazards are inherently complex phenomena. To date, most of the scientific knowledge and hazard assessment and risk management protocols focus on individual hazards and risks. Multi-hazard scenarios where several hazardous phenomena may occur in a simultaneous or consecutive way have not yet been well constrained. We are still far from a full understanding of the potential inter-relations (cause/effect) between different hazards and their related cascading effects and potential impacts. Also, we have not yet developed or implemented effective combined monitoring and early warning systems, as well as complete vulnerability and risk analysis to confront multi-hazard cascading effects.

Of special concern are volcanic islands, probably one of the most vulnerable environments on Earth, where multiple natural hazards tend to occur simultaneously, causing cascading effects. Due to their natural isolation and strong dependence on external supply chains, volcanic islands tend to be fragile economic systems with highly vulnerable communities, who concentrate their main monetary incomes in the tourism industry and minor local economic activities such as fishing or agriculture. Volcanic islands, created by the growth of volcanoes in the sea, and modified by geologic, environmental, biological, and human activity are subjected to the impact of multiple natural hazards (volcanic eruptions, earthquakes, landslides, tsunamis, forest fires, etc.), which can even be triggered, amplified, or supported by processes derived from Climate Change (e.g., sea level rise, glacial melting) (Fig. 1). In fact, the continuous demographic expansion of many volcanic islands, caused mainly by the massive arrival of tourism, is a critical factor that exponentially increases the risk in such environments. Also, according to the Intergovernmental Panel on Climate Change (IPCC) Fifth assessment report (IPCC, 2014), the existing climatic models for this century forecast increases in the number and intensity of storms and hurricanes, as well as a significant rise of sea level. These phenomena will contribute to increasing the vulnerability of coastal areas, including volcanic islands. Moreover, in these environments, natural hazards can often act simultaneously or in a concatenated way leading to unpredictable cascading effects. Such events may not only affect the island's natural ecosystems, but they may also temporarily suspend the touristic and local activities in the area (e.g., fishing) leading to a serious, and in some cases, irreversible contraction of its economy (e.g., Monserrat Island, Caribbean). As a consequence, predicting, preparing for, and recovering from natural disasters is clearly a pressing cause of concern for volcanic islands. The COVID pandemic has proven to be yet another factor that can contribute to complicating emergency management, thus requiring additional protocols and resources.

This contribution aims to offer an integrated approach to better understand multi-hazards on volcanic islands. To accomplish this objective, first we review the concept of multi-hazards, a relatively new term that is rapidly becoming familiar, despite it not being exempt from certain confusion over its meaning and significance with respect to hazard assessment. Herein, we analyse the evolution of the concept from its first appearances to its current status in national and international policies, and highlight conflicts in terminology and applications. Then, we attempt to integrate the multi-hazard concept into a multi-risk management approach in order to resolve some of the conflicts raised above. Multi-hazards at volcanic islands are discussed and analysed in order to expose the main issue, which is the focus of this review. Finally, the specific case of the Canary Islands is used as a case study to illustrate how everything explained so far has been applied.

2. The 'multi-hazard' concept: evolution and applicability

The term "multi-hazard" has its origins in international policy and was primarily used in the context of risk reduction. The first reference appears in the United Nations' Agenda 21 for sustainable development (UNEP, 1992), where a "complete multi-hazard research into risk and vulnerability of human settlements and settlement infrastructure […]" was called in order to aid pre-disaster planning of human settlement in disaster-prone areas. The term reappears in the United States' National Mitigation Strategy (FEMA, 1995), which expresses the "need for coordinated, multi-hazard approaches" for natural disaster reduction, especially with regard to "the design and construction of buildings", for which the establishment of a National Multi-Hazard Mitigation Council within two years, and the incorporation of national multi-hazard standards into building codes for all new structures were proposed. These first appearances are framed by the International Decade for Natural

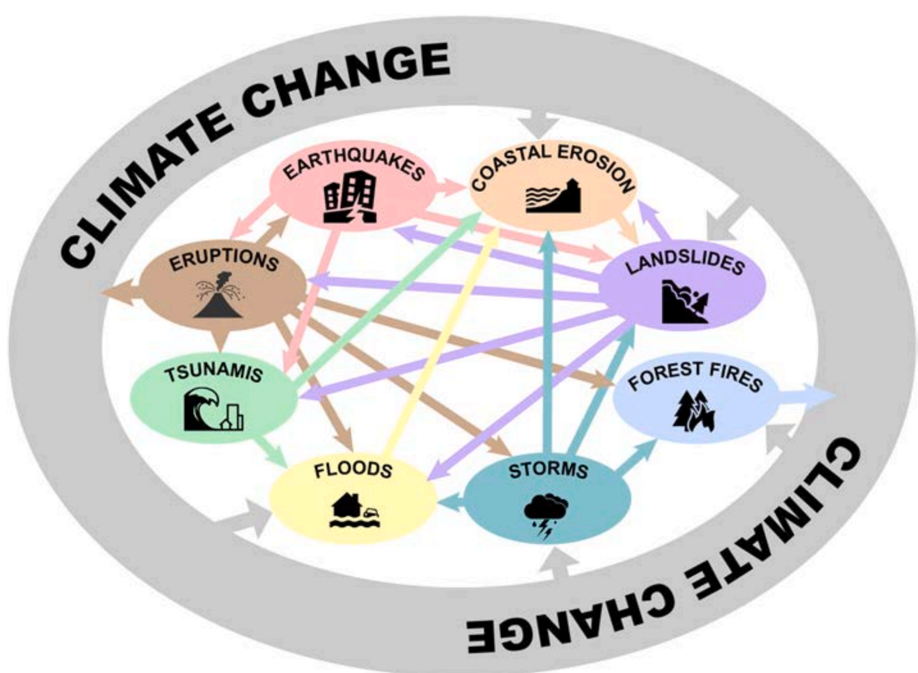

Fig. 1. Example of possible interactions (cause/effect) among some of the most important natural hazards.

Disaster Reduction 1990–2000, with the subsequent creation of the United Nations International Strategy for Disaster Reduction (UNISDR) in 1999 (later renamed United Nations Office for Disaster Risk Reduction, UNDRR).

Later, the Johannesburg Plan (UN, 2002), expressed that "[a]n integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery, is an essential element of a safer world in the twenty-first century". In this context and along the lines of the Johannesburg Plan, some initiatives with a multi-risk perspective at global and regional levels began to emerge. In 2002, the Munich Reinsurance Company developed a comprehensive risk assessment method to evaluate the disaster losses suffered by the World's 50 largest cities (Munich Re, 2002). Since then, it has drafted several annual reviews of natural catastrophes and statistics from around the world (e.g., Munich Re, 2005; Munich Re, 2010). In 2004, the Federal Emergency Management Agency (www.fema.gov) launched a multi-hazard risk assessment software package (HAZUS-MH) for the comprehensive assessment of multiple individual disaster risks at all regional administrative levels of the USA (FEMA, 2004). A year later, the Joint Research Center of the European Commission presented a multi-hazard assessment method and conducted comprehensive risk assessments and mapping of weather disasters in 10 European countries (Lavalle et al., 2005). In parallel, the European Spatial Planning Observation Network (ESPON) conducted, from December 2002 to March 2005, the thematic project called "The spatial effects and management of natural and technological hazards in general and in relation to climate change", which developed an initial integrated hazard and risk assessment of natural and technological disasters on the European territory (Schmidt-Thomé et al., 2005). Between 2004 and 2006, GNS Science (www.gns.cri.nz) and NIWA (www.niwa.co.nz) developed and launched RiskScape software (GNS NIWA, 2010; https://riskscape.org.nz/) for the quantification of direct and indirect losses due to river floods, earthquakes, volcanic activity (ash), tsunamis, and wind storms on people's lives. In 2008, a partnership between the Center for Coordination of Natural Disaster Prevention in Central America (CEPREDENAC), the United Nations International Strategy for Disaster Reduction (UN ISDR), the Inter-American Development Bank (IADB) and The World Bank contributed to developing CAPRA (Probabilistic Risk Assessment: https://ecapra.org/), a software package that facilitates probabilistic analysis and assessment of related losses in the Central America of multiple individual hazards in addition to the secondary hazards arising from the primary (triggering) ones.

The ideas of the Johannesburg Plan were further specified to the risk reduction focus at the Second World Conference of Disaster Risk Reduction (Japan, 2005), with the Hyogo Framework for Action 2005–2015 (UN-ISDR, 2005). The framework included mainstreaming of an integrated and multi-hazard approach into developmental planning and post-disaster or post-conflict phases across relief, rehabilitation, and recovery activities (UN-ISDR, 2005). In line with what was agreed in the Hyogo Framework, some policies, strategies, and frameworks, such as the Internal Security Strategy (SEC 2010, 1626 Final), which evolved into the European Agenda on Security, the EU Community framework on disaster prevention (Regulation 1313/2013/EU), or the European Disaster Risk Reduction Strategy (COM 2008, 130), began to adopt and express the need for an all-hazard/multi-hazard approach. In science, this move towards a multi-hazard perspective would not come until much later, reflected in the creation of the multi-hazard risk subdivision at the European Geosciences Union in 2019 (Ward et al., 2022).

After Hurricane Katrina in 2005 (which caused damages to many bridges due to winds, storm surges, and flooding loads followed by the impact of debris) and the 2011 Tohoku earthquake in Japan (with coastal structures and bridges exposed to the cascading action of the tsunami following the earthquake, resulting in the destruction of >100,000 buildings and the triggering of a nuclear disaster), the scientific and engineering community have paid increasing attention to approaches enabling multi-hazard exposures for the design of structures (Ellingwood, 2010). At the same time, an effort is ongoing to bridge research and policy (Collins et al., 2017). Many studies address performance-based frameworks for buildings and infrastructure design by taking into account all possible simultaneous and/or non-simultaneous events that could potentially cause structural damage (Cao et al., 2016; Cao et al., 2018; Gong et al., 2020; Jalayer et al., 2011; McCullough and Kareem, 2011; Petrini and Palmeri, 2012; Zhao et al., 2020). Li et al. (2012) provide a literature review and the state-of-the-art of multiple hazard assessment, design, and mitigation, while Bruneau et al. (2017) expose a selection of examples that represent the multi-hazard state-of-the-art in engineering, highlighting considerations for improving resilience against multiple hazards in bridges.

However, most of the multi-hazard engineering strategies and assessments take into account each single threat individually, usually addressing only wind, earthquakes and blasts, neglecting complex scenarios with simultaneous and/or cascading hazards (Petrini and Palmeri, 2012). This fact is not something that only occurs in the engineering context. At present, the research into single hazards is mature, but when multiple hazards occur simultaneously, with or even without interrelations, the results of risk analyses are often inaccurate and incomplete, as multi-hazard risk analysis is not simply the sum of single hazard risk examinations (Kappes et al., 2012). The reason why accurate multi-hazard assessments are complicated to carry out lies in the difficulties that Petrini and Palmeri (2012) expose: (1) the different levels of knowledge obtained in different fields; (2) the modeling of hazard interactions with a lack of raw data and the unavailability of concurrent hazards models; (3) the need to consider uniform hazard levels for different types of threats; (4) the need to give similar safety levels to different multi-hazard scenarios; (5) the development of opposing strategies due to different philosophies.

Similarly, Ward et al. (2022) outline the key challenges hindering the movement towards this approach that relate to existing knowledge gaps in multi-(hazard-)risk assessment and management:

1. Diverse language on multi-(hazard-)risk and a lack of overview of existing methods and tools.
2. Lack of a clear framework and guidelines for multi-(hazard-)risk assessment and management.
3. Poor understanding of dynamic feedbacks between hazards, exposure, and vulnerability (Gill and Malamud, 2014, 2016).
4. Focus of many past multi-(hazard-)risk projects and accompanying software on multiple single hazards under current conditions without focusing on multi-(hazard-)risk interactions or future scenarios (Gallina et al., 2016).
5. Assessment of only a few studies on the effectiveness of disaster risk management measures across hazards, sectors, and time horizons.
6. Distinct lack of in-depth case-studies on multi-(hazard-)risk assessment and management.

2.1. *Multi-hazard interactions: terminology conflicts*

Since the first time that the term appeared, different perspectives of the concept have been put forward showing an increasing use of it. However, differing terminology, partly conflicting definitions, and vaguely defined approaches have arisen due to the strict separation of disciplines (Chondol et al., 2020; Kappes et al., 2012; Wang et al., 2020). Even though many hazard assessments refer to "multi-hazard" with respect to the multiple types of hazards to which an area or infrastructure may be exposed (Asprone et al., 2010; Cao et al., 2016; Cao et al., 2018; Gong et al., 2020; Jalayer et al., 2011; Kappes, 2011; Kappes et al., 2012; Marzocchi et al., 2009; McCullough and Kareem, 2011; Petrini and Palmeri, 2012; Sadegh et al., 2018; Wang et al., 2020; Zhao et al., 2020), not all studies on multiple hazards consider all relevant processes of a defined area, but rather they are described as more-than-one-hazard approaches (Kappes et al., 2012), usually without considering the interrelations between hazards and/or the combined impacts.

Nevertheless, associated with the concept of "multi-hazard", understood as the multiple simultaneous or non-simultaneous events that an area can be exposed to, other related terms have emerged together with the evolution of multi-hazard analyses. For example, Sadegh et al. (2018) discuss "compound events", "compound extremes", "compound impacts" or "compound hazards" as those "events with multiple concurrent or consecutive drivers (e.g., oceanic and fluvial flooding, drought, and heatwaves)". They may not necessarily be extreme events individually, but they can nonetheless lead to significant extreme impacts (Leonard et al., 2014; Mehran et al., 2017; Vahedifard et al., 2016; Wahl et al., 2015). In this sense, the multi-hazard scenarios resulting from these compound events are often ignored in many risk assessment and design applications (Sadegh et al., 2018). According to the IPCC (2012), compound events may occur as a result of one of the following situations:

1. Two or more simultaneous or successive extreme events (e.g., simultaneous extreme precipitation and storm surge, Moftakhari et al., 2017),
2. combinations of extreme events with underlying conditions that amplify the impact (e.g., droughts and heatwaves, Mazdiyasni and AghaKouchak, 2015), or,
3. combinations of events that are not by themselves extreme, but which collectively lead to an extreme event or impact (e.g., a moderate coastal flood occurring during or above average tide, Moftakhari et al., 2015).

Even though Marzocchi et al. (2009) use the term "multi-risk" instead of "multi-hazard" to refer to all anthropogenic and natural risks which can affect a territory, behind it lies the idea of a multi-event approach. At this point it is necessary to stress the difference between "multi-hazard" and "multi-risk". "Multi-hazard" refers to the set of physical phenomena, i.e., the occurrence, extent, and intensity of the possible impact of a multi-hazard event. On the other hand, "multi-risk" considers the damages (economic and social) of the impact of a multi-hazard event. For this multi-hazard approach, Marzocchi et al. (2009) distinguish two perspectives: (1) all possible events that can occur in an area during a period of time without any cascading relation, and (2) those sequences of parallel events that are interrelated. All these authors introduce the synergistic (adverse) events as a series-parallel sequence of adverse events generated by different sources that trigger one or more sequential events, in the context of a multi-hazard analysis. In the case of a multi-risk analysis, it would require a previous multi-hazard assessment.

These last terms that have emerged over the years, together with the increasing need to consider a multi-hazard approach in risk reduction management, highlight what has already been presented by Petrini and Palmeri (2012): the complex interactions that can occur between multiple hazards can change significantly the results compared to single-hazard analysis, as they cannot be simply superimposed (Kappes et al., 2012). For that reason, it is crucial to understand the wide variety of possible interrelations between hazards and the consequences of the different multi-hazard scenarios for a correct multi-hazard assessment. However, despite growing awareness of hazard relationships, a multitude of terms remains in use to describe several types of relations between processes, without a uniform conceptual approach or generally used terminology (Kappes, 2011). In the same way as for the term "multi-hazard" defined here, different definitions may exist for the same concept, sometimes overlapping and contradicting one another, while at the same time there may be multiple terms for the same definition. Kappes (2011), Kappes et al. (2012), and Wang et al. (2020) summarize the existing terms and definitions from the literature related to the multiple types of relationships between hazards, shown in Table 1:

Some authors have tried to group this wide variety of concepts into a

Table 1
Terminology and existing definitions for hazard relationships. Modified from Kappes et al. (2012).

Term(s)	Existing definitions	References
Cascades, cascading effects, cascading failures, cascade events, cascading disasters, cascading hazard	1. The triggering of one hazard by another, eventually leading to subsequent hazard events. 2. A failure in a system of interconnected parts, where the service provided depends on the operation of a preceding part, and the failure of a preceding part can trigger the failure of successive parts. 3. Hazards occurring as a direct or indirect result of an initial hazard. 4. Effects following the main one. 5. The triggering and transmission process of events. 6. Extreme events, in which cascading effects progressively increase over time and generate unexpected impactful secondary events. 7. The dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption.	Carpignano et al. *(2009)* Cutter *(2018)* Delmonaco et al. *(2006)* European Commission *(2011)* Pescaroli and Alexander *(2015)* Zuccaro and Leone *(2011)*
Chains, disaster chain	1. Chain reaction of cause and effect in a disaster. The upper level of disasters leads to the subsequent level. It refers to the triggering relationship between natural disasters. 2. One or more disasters (parent disasters) that lead to other disasters (sub-disasters). According to the relationship between parent disasters and sub-disasters, disaster chains can be divided into straight chains, divergent chains, centralized chains, and complex networks.	Erlingsson *(2005)* Guo et al. *(2006)* Shi *(2002)* Shi et al. *(2014)*
Coincidence of hazards in space and time	1. Simultaneous hazards occurring in the same area.	Tarvainen et al. *(2006)*
Coinciding hazards	1. Disasters and accidents that are independent of one another and are not related to one another in cause of formation are referred to as coinciding hazards. They occur in the same time and space only by chance. Occasionally when multiple hazards occur, there may be no obvious correlation or common cause; they occur together only by coincidence. 2. Coinciding hazards can be considered as follow-on events, knock-on effects,	European Commission *(2011)* Wang et al. *(2020)*

(*continued on next page*)

Table 1 (*continued*)

Term(s)	Existing definitions	References
	domino effects, or cascading events.	
Complex	1. Term used to describe the fuzzy relationships between hazards.	Cutter (2018)
Compound hazards, compound disasters, compound events, compound extremes, compound impacts	1. Several elements acting together above their respective damage threshold—for instance, wind, hail, and lightning damage in a severe storm. 2. Two or more (extreme) disaster events that have no genetic relationship but which occur at the same time or in sequence. Even if a single event itself is not extreme, it will cause extreme expansion due to a compound effect. 3. Follow-on sequences of other events that occur as a direct or indirect result of the initial triggering event.	Alexander (2001) Cutter (2018) Hewitt and Burton (1971) Kelly (2009) Liu and He (2017) Saarinen et al. (1973) Sadegh et al. (2018) Shi et al. (2014)
Concurrent hazards	1. When hazards that are not related in origin occur at the same time, their interaction can cause consequences more serious than if the hazards had occurred individually. The interaction between concurrent hazards can be examined from two perspectives: one is that the physical processes of different hazards interact with one another, which may lead to an increase in their intensity or overall impact; the other is that the vulnerability of victims may change due to a certain hazard, and another kind of hazard may have more serious consequences for such victims.	Wang et al. (2020)
Coupled events	1. Term used to describe those related events, to differentiate them from individual events.	Marzocchi et al. (2009)
Cross-hazard effects	1. Interrelation between hazards that includes exacerbating or ameliorating effects.	Greiving (2006)
Domino effects	1. The chain relationship of technological accidents, or the transmission of technological accidents between equipment. 2. An accident in which a primary event propagates to nearby equipment, triggering one or more secondary events and resulting in overall sequences more severe than those of the primary event. 3. It can be associated to the "escalator vector", which means that the final consequence is far more serious than the initial accident. 4. In addition to technological accidents, the domino effect can be also	Chen et al. (2018) Cozzani et al. (2005) Delmonaco et al. (2006) European Commission (2011) Luino (2005) Perles and Cantarero (2010)

Table 1 (*continued*)

Term(s)	Existing definitions	References
	observed in other events (e.g., landslides induced by earthquakes as a domino effect).	
Follow-on events	1. Term used to refer to coinciding hazards, knock-on effects between hazards, or the situation where one hazard causes one or more sequential hazards.	European Commission (2011)
Hazard sets	1. This term refers to the phenomenon in which the relationship between hazards can be disregarded. They may be affected by the same environmental and geographical factors (for natural disasters), or they may be affected by the same hidden dangers and omissions in management or production (for technological accidents). Hazard sets can be divided into natural disaster sets and technological accident sets.	Wang et al. (2020)
Human-induced hazards	1. Human activities (including technological accidents) may trigger natural disasters.	Gill and Malamud (2016) Gill and Malamud (2017) Wang et al. (2020)
Interactions	1. Mutual influence between two processes. 2. Vice versa interactions and interactions during which only one process exhibits a significant influence on the other are distinguished.	De Pippo et al. (2008) Marzocchi et al. (2009) Tarvainen et al. (2006) Zuccaro and Leone (2011)
Interconnections	1. Term used to describe the fuzzy relationships between hazards.	Perles and Cantarero (2010)
Interrelations	1. Term used to describe the fuzzy relationships between hazards.	Delmonaco et al. (2006) Greiving (2006)
Knock-on effects	1. The triggering of one hazard by another. 2. Term used to refer to coinciding hazards, follow-on effects among hazards, or the situation where one hazard causes one or more sequential hazards.	European Commission (2011)
Multiple hazard	1. Quite different types that accidentally coincide, or more often, following one another with damaging force—for instance, floods in the midst of drought, or a hurricane followed by landslides and floods	Hewitt and Burton (1971)
Natech events	1. Natural hazard events that trigger technological emergencies.	Cruz (2012) Showalter and Myers (1994)
Synergic effects, synergistic event	1. A series-parallel sequence of adverse events generated by different sources. For example, an earthquake and a landslide generated by it.	Marzocchi et al. (2009) Tarvainen et al. (2006)
Triggering effects	1. Series-parallel cascade scenario, the triggering of one hazard by another.	Marzocchi et al. (2009)

few main categories, each of which would represent the fundamental process behind each term in order to facilitate the development of multi-hazard risk reduction strategies. Han et al. (2007) classified potential hazard interactions into four hazard chains induced through: spatial and temporal conditions, exogenic geological processes, endogenic geological processes and anthropogenic activities. Kappes et al. (2010) distinguish between two types of hazard relations: (1) those in which one process triggers the next (cascades, domino effects, etc.) and (2) those in which the disposition of one hazard is altered by another, whenever a process modifies the disposition or the frequency and/or magnitude of another process. Gill and Malamud (2016) categorized a possible hazard interactions relationship into three types: triggering, increased-probability, and catalysis/impedance. Tilloy et al. (2019) group hazard interrelations into five types: triggering, change condition, compound, independence, and mutually exclusive. Wang et al. (2020) make a similar distinction to that of Kappes et al. (2010) and distinguish between two main situations of interaction: (1) one hazard is triggered by another, which leads to a series of hazards in a chain or network form, or (2) hazards have complex or vague relationships. In this regard, Wang et al. (2020) divide multi-hazard scenarios into three more general categories, as Fig. 2 shows on the right, in three black boxes with a white background: mutually amplified hazards, mutually exclusive hazards, and non-influential hazards.

In the case of mutually exclusive hazards (Fig. 2), when one event occurs, another cannot occur or its impact is reduced. Regarding the non-influential hazards, there may be a set of hazards or several hazards coinciding in space and/or time, but having no influence on each other.

Finally, one or several hazards may be amplified by the occurrence of others previously or at the same time. In this last category we distinguish mainly between natural disasters (upper part of the figure, in the green box on the left with dashed lines, and the events symbolized by letters A to F in a circle) and technological accidents (at the bottom, in the gray box on the left with the dashed lines, symbolized by numbers 1 to 3 in a circle). In the case of the former, depending on the relationship established, we can distinguish between disaster chains or cascading disasters, which include straight chains, divergent chains, centralized chains and complex networks, and, on the other hand, concurrent hazards. As for technological accidents, the relationships may be the same but are given different names, having the domino effect or the aforementioned concurrent hazards. However, sometimes both types of events, natural and technological, can be related to each other giving rise to cross-category hazards (in the central part, in the blue box with dashed lines). These include natural disasters caused by technological accidents, usually caused by human-induced hazards, and technological accidents caused by natural disasters, called Natech events.

2.2. Global context for multi-hazard policies: evolution during the last decade and current situation

Despite the sometimes-contradicting definitions and terminology, one thing is true: the wide variety of potential interactions in a multi-hazard scenario, regardless of the term used to refer to them, leads to difficulties in prediction and prevention of hazards, making multi-hazard assessment and risk management a complex issue, which

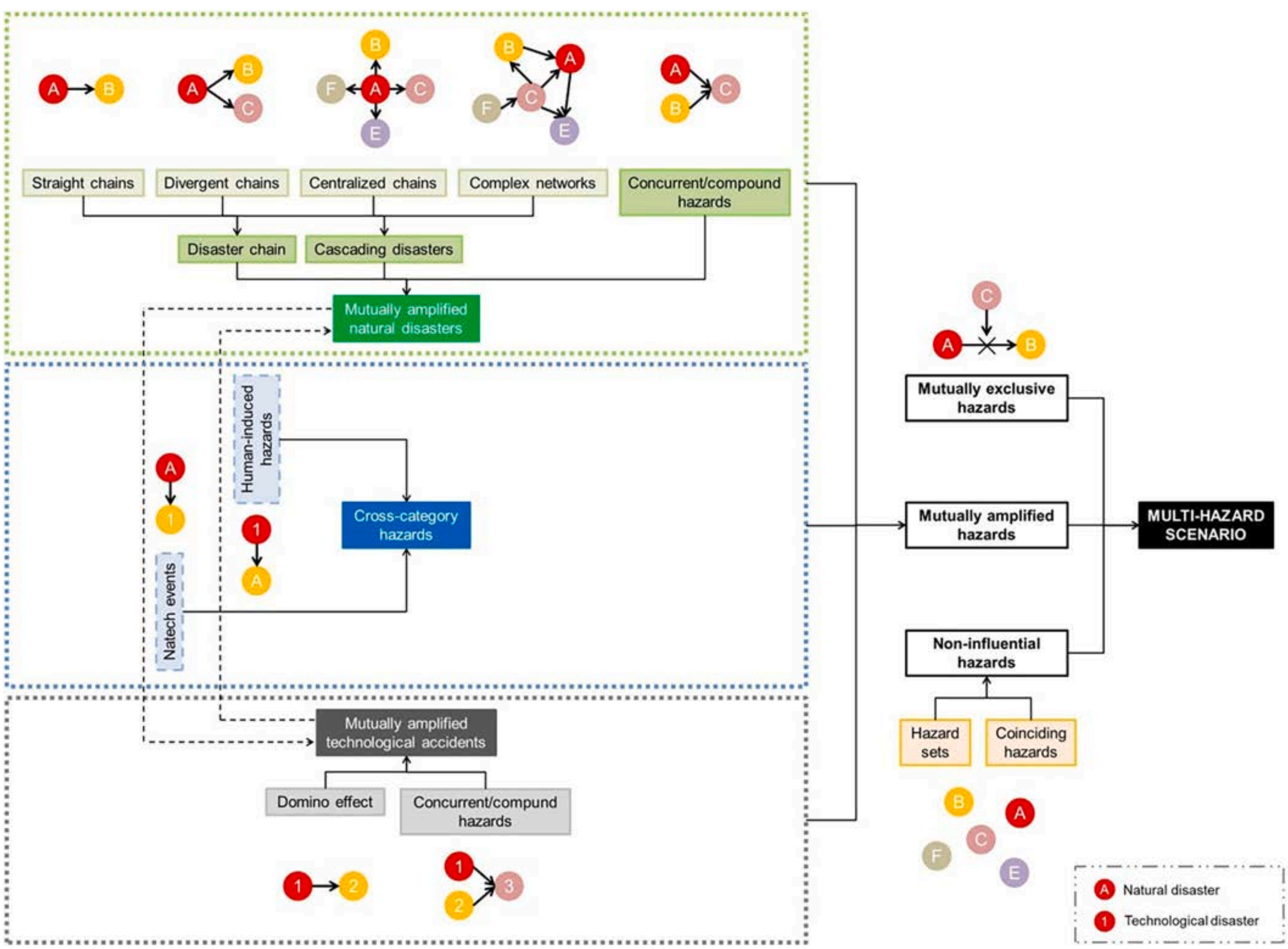

Fig. 2. Classification of the existing terminology for hazard relationships, modified from Wang et al. (2020).

requires an interdisciplinary approach (Wang et al., 2020). Nevertheless, stakeholders, politicians, researchers, and local people are increasingly concerned about the potential loss of victims due to the occurrence of multiple events in a region, such that the understanding of multi-hazard risks has greatly improved and some assessments and strategies are being developed and implemented not only locally, but also internationally.

In the context of growing concern about the effects of Climate Change, many international organizations have begun to adopt a multi-risk approach for the assessment of climate change impacts (e.g., Dilley et al., 2005; IPCC, 2012) at a range of spatial scales, both at global and European scales (European Commission, 2011). However, most analyses consider hazards individually, without taking into account the nature of the interrelationships that can be established between different types of events occurring simultaneously, or at different times but in the same place (e.g., a torrential rainfall triggering a landslide on a slope previously affected by an earthquake, the latter having reduced the slope's cohesion; or a landslide triggering a tsunami).

On a lower scale, many studies have been carried out in some regions using the approach of multi-hazard risk assessment (Chondol et al., 2020). De Pippo et al. (2008) carried out hazard risk assessment and mapping for a coastal region in Italy by investigating the primary hazards in the region and mapping the overall multi-hazard risks by ranking not just the hazards but also their interactions. Neri et al. (2013) estimated the multi-hazard risk associated with the volcano Kanlaon, in the Philippines, using an event tree method that combines probabilistic frequencies of three potential categories of hazardous events, and the secondary hazards associated with them. Kappes et al. (2010) analysed the multi-hazard risk for Barcelonnette Basin, in the Alps, by analyzing the relationship between different types of hazards taking into the account disposition and triggering concerns. The latest multi-hazard assessments that highlight the importance of the study of cascading hazards for future forecasting come from Patrick et al. (2020), which analyses the 2018 Kilauea eruption, and from López-Saavedra et al. (2021), who assess the potential impact of a cascading succession of multiple extreme events similar to the one that occurred in Tenerife 180 ka ago.

The year 2015 marks a step change in multi-hazard risk management with its many global initiatives. The last global agreement on national action for disaster risk reduction came on 18 March 2015, when the UN Third World Conference on Disaster Reduction adopted the Sendai Framework for Disaster Risk Reduction 2015–2030 (UN-ISDR, 2015), the successor instrument of the Hyogo Framework for Action 2005–2015. The Sendai Framework is the first major agreement of the post-2015 development agenda, with seven targets and four priorities for action that advocates for a multi-hazard approach for the management of disaster risk through developmental planning and practices across all the sectors. One of the targets is to substantially increase the availability of and access to Multi-Hazard Early Warning Systems (MHEWS) and disaster risk information and assessments to people by 2030. At the same time, one of the key guiding principles for the implementation of the framework emphasizes promoting multi-hazard and inclusive risk-informed decision-making for the effective reduction and management of disaster risks. To meet the targets of the Sendai Framework, many international, national, and regional initiatives have been developed on multi-hazard forecasting and early warnings in recent years, such as the French Rainfall Flood Vigilance System in France (Hemachandra et al., 2020), or the National Disaster Management Plan of India (Government of India, 2016). Also in2015, the General Assembly began the negotiation process on the post-2015 development agenda. The process culminated in the subsequent adoption of the 2030 Agenda for Sustainable Development—with 17 Sustainable Development Goals (SDG) at its core—at the UN Sustainable Development Summit in September 2015, with the importance of MHEW recognized as the 13th goal. This goal is focused on the strengthening of the resilience and adaptive capacities to address climate-related hazards and disasters in all countries by integrating climate change measures into national policies, strategies, and planning, something that the Paris Agreement supports in order to reduce vulnerabilities and losses due to climate change.

2.2.1. Multi-hazard initiatives in volcanic islands: some examples

In order to illustrate the different views concerning the multi-hazard approach in risk reduction programs, and to emphasize how this relates to the implementation of different initiatives, we now describe some examples of multi-hazard strategies, plans, and mitigation actions around the world. We concentrate this description only on volcanic islands, as this is the purpose of the present study; they constitute the most urgent targets where to apply the multi-hazard concept on risk reduction policies.

In the case of Hawaii, the first approved State Multi-Hazard Mitigation Plan went into effect on October 27, 2004. Wildfires, floods, landslides, volcanoes, earthquakes, and tsunamis are common natural disasters in this region. For that reason, the Plan identifies both the hazards and risks posed by natural and technological disasters and the actions and activities employed to reduce the derived losses, by establishing priorities and a long-term process to implement them (Hawaii Emergency Management Agency, 2018).

The Azores are in a similar situation. Due to its tectonic and volcanic environment, this archipelago is affected also by earthquakes, volcanic eruptions, landslides, floods, costal erosion, etc. The AZORIS Geodatabase acts as the support for multi-hazard analysis, vulnerability assessment, crisis scenarios and alert and warning systems in the Azores region (Gaspar et al., 2011). The data acquired by field monitoring stations, for example, are transmitted to the Emergency Operations Centre (COE) of the Centre for Volcanology and Geological Risk Assessment (CVARG) of the University of the Azores, and stored in AZORIS.

According to Moananu (2019), Vanuatu "is continuously affected by at least one to three cyclones and up to two Magnitude 7 earthquakes with tsunami-triggering potential annually, between 100 to 300 earthquakes per month, and has six permanently active volcanoes which erupt at least once every two years." For that reason, the Vanuatu Meteorology and Geo-hazards Department (VMGD) merged with the Institute of Research for Development (IRD) in Noumea, New Caledonia, to share resources and create a joint volcano and seismic monitoring network. After its recognition by the Intergovernmental Oceanic Commission for the Pacific Tsunami Warning and Mitigation System (PTWS), the Oceania Regional Seismic Network (ORSNET) was created in 2014 through collaboration with other Pacific islands countries that were running their own national seismic networks, particularly Fiji, Papua New Guinea, Samoa, Solomon Islands, and Tonga (Moananu, 2019).

A new MHEWS sub-regional hub for the Pacific in Papua New Guinea was inaugurated at the Third Regional Integrated Multi-hazard Early Warning Systems (RIMES) ministerial conference in Port Moresby on 25 August 2017. It is a significant cornerstone in supporting World Meteorological Organization (WMO) Members and their ongoing and future programs in this region (WMO, 2017).

In the case of Samoa and Tonga islands, their MHEWS are in the process of strengthening through nationally implemented projects as part of the World Bank funded Pacific Resilience Programme (PREP) (Pacific Community, 2019). At the same time, during a technical meeting held in Nadi, Fiji, from 7 to 8 October 2019, senior officials from technical agencies in Samoa and Tonga, representing their respective meteorological, hydrological and disaster management offices met to address the implementation of their MHEWS (Pacific Community, 2019).

The Caribbean region, on the other hand, is also exposed to multiple natural hazards; especially hurricanes and tropical storms, floods, landslides, storm surges, but also earthquakes and tsunamis. Health shocks are also present. For this reason, a project has been carried out titled 'Strengthen integrated early warning systems for more effective disaster risk reduction in the Caribbean through knowledge and tool transfer.' The aim of this Project is to progress in the regional and global framework for disaster risk reduction according to the Sendai Framework goals. On February 1, 2019, the meeting titled "Multi-Hazard Early Warning Systems in the Caribbean: Achievements and Strategic Path Forward" was held on Saint Lucia island to raise awareness among the political directorate on the required support for achieving integrated, fully functional MHEWS (Caribbean Disaster Emergency Management Agency, 2022).

Other volcanic island regions currently have projects underway, such as in Comoros, where the project entitled "Supporting regional cooperation to strengthen seamless operational forecasting and multi-hazard early warning systems at national levels in the South-West Indian Ocean", scheduled for completion in 2025, is underway. Its objective is to enhance the adaptive capacity and climate resilience of communities and economic sectors in five countries of the South-West Indian Ocean

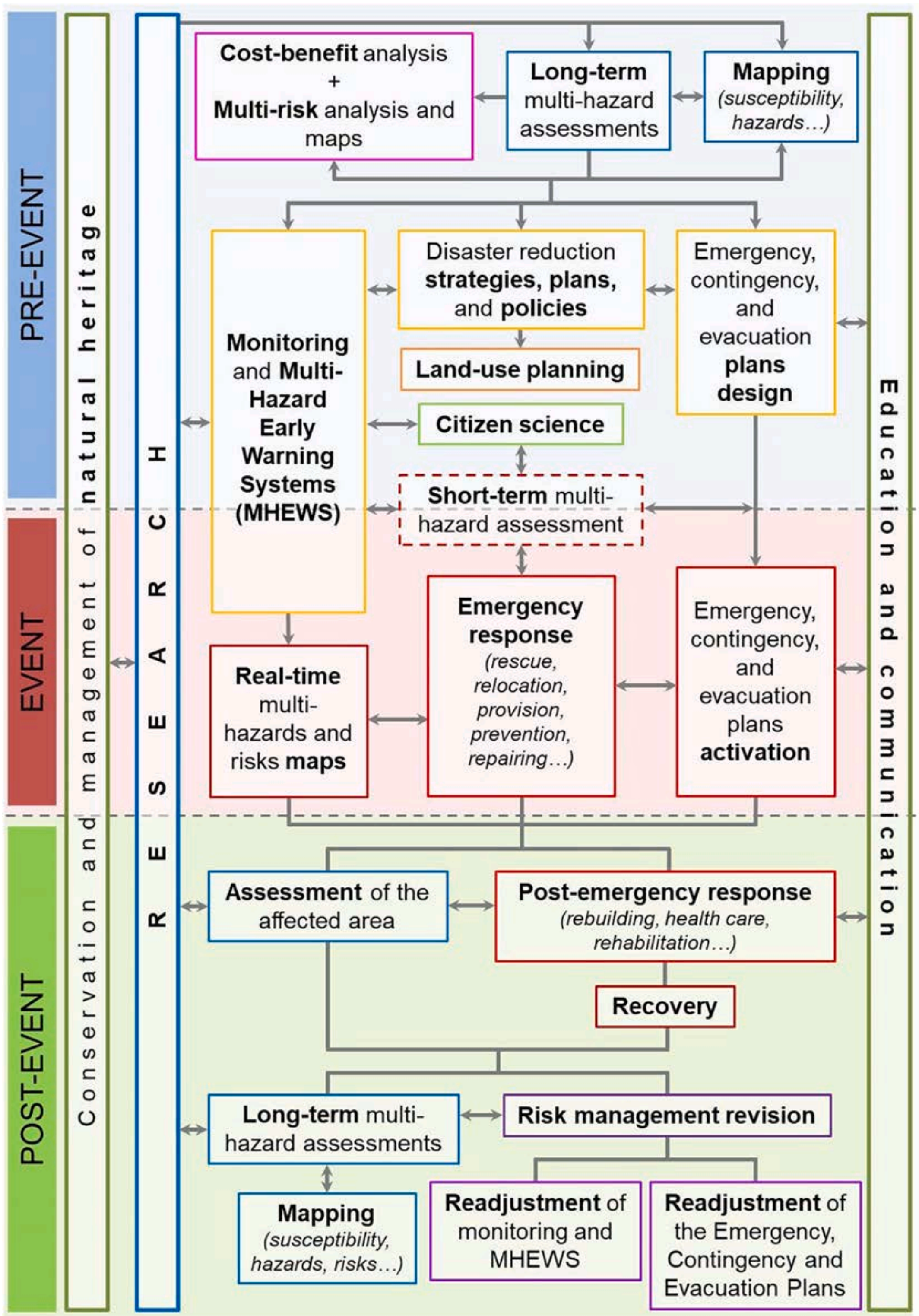

Fig. 3. Standard diagram for the design of the basis of a risk management system in a region, taking into account the multi-hazard approach.

(SWIO) region.

3. Basis for a solid multi-risk management system

At this point, we can see that there has been a hesitant but, at least, growing insertion of the multi-hazard approach into national and international policies. Many countries, especially those with or consisting of volcanic islands, have pursued various initiatives and strategies not only at the local, but also at the regional level through collaboration and pooling of forces and resources. However, the attempts made so far focus only on one or a few aspects of the whole risk management system, in the same way that many countries focus only on climate hazards in a context of climate alarm. As we have seen, some efforts to implement MHEWS in some countries have been made, however, sometimes without prior long-term multi-hazard assessments, such as the few mentioned in the previous section. On other occasions, despite some regions having really effective multi-hazard analyses, plans and maps (e.g., some Pacific islands such as Vanuatu, Fiji, Papua New Guinea, Samoa, Solomon Islands, and Tonga, Moananu, 2019; some countries in Latin America and the Caribbean, e.g., through the CAPRA Probabilistic Risk Assessment Platform, Universidad de los Andes, 2022; Western Peloponnesus, Greece, Skilodimou et al., 2019; Ischia, Italy, Selva et al., 2019; some regions of Iran, Pourghasemi et al., 2020, Yousefi et al., 2020), they unfortunately sometimes do not have the resources to confront and manage a multi-hazard emergency.

These facts reveal the lack of a solid and standardized risk management structure, which makes it even more difficult to implement the multi-hazard approach. The fact that international frameworks for disaster risk reduction, such as the current Sendai framework, issue non-binding proposals and agreements does not facilitate the full insertion of the multi-hazard perspective either.

We believe that the best strategy for any region would be to first create a robust and clear risk management frame, one that can already be created from the outset with a multi-hazard character, provided that the multi-hazard concept is standardized and that the terminology conflict related to interrelationships between hazards is resolved. In addition, it is essential that all actors involved in risk management in that area are clearly identified and their responsibilities and commitments clearly defined, in order to ensure that no aspect or sector is weakened. This is why an interdisciplinary effort is needed. Despite the belief that this should be a basic and obvious principle for disaster mitigation in hazard-prone areas, rarely does a country have all aspects of risk management equally covered. After an arduous search for such a basis, no pattern or plan has been found to date that reflects the above-mentioned structure for proper risk management. This is why we venture to present in Fig. 3 what we believe should be a competent, complete, and useful basic structure for risk management in a particular region. It has been designed from a holistic approach, by reflecting the idea that the different sectors that compose it must be understood as a whole. At the same time, each sector should have a multi-event approach. We encourage researchers, politicians, governors, economists, engineers, citizens, etc., to use it as a pattern for future investments, improvements and implementations.

A robust risk management structure must be underpinned by three essential pillars: research, conservation, and education and communication (Fig. 3). Multi-hazard and people-based research is the foundation for the characterization and the study of a region, in order to obtain robust risk data, and the identification of the problems and the aspects of improvement for risk reduction. The conservation and management of natural heritage make possible this research by protecting the natural record from the study area. Last but not least, education and impact plus action-based communication enables the transmission of knowledge and provides the population with tools both to make efficient self-protection decisions at the time of an emergency and to train society in risk mitigation. No matter how well-developed the other sectors are, if any of these pillars fail, disaster management is destabilised, resulting in major economic or, unfortunately, human losses.

As we mentioned before, some actions have been taken after the impact of a big disaster, such as the 2004 tsunami or Hurricane Katrina in 2005. Ideally, we should not have to wait for the consequences of an extreme event before taking certain measures. These experiences strongly suggest the need to start taking action at the pre-event stage. In this stage, researchers should elaborate and combine long-term multi-hazard assessments, understood as the analysis of some specific future events expected to occur in a region, deduced from what has happened in the past by studying the natural record (see e.g., Martí, 2017), and developing susceptibility maps, hazard maps, hazard scenarios, etc., with cost-benefit and multi-risk analyses. All these analyses should consider the interrelationships between hazards and their possible cascading effects. At the same time, they should consider the variations derived from climate change. The combined outcomes must be the basis for the design of effective monitoring and MHEWS, proper disaster reduction policies, and suitable emergency, contingency, and evacuation plans.

According to the WMO (2018), MHEWS should address:

1. Disaster Risk Knowledge.
2. Detection, Monitoring, Analysis & Forecasting of Hazards and Possible Consequences.
3. Warning Dissemination and Communication.
4. Preparedness and Response Capabilities.

All these strategies, shown in yellow in Fig. 3, must be coordinated and always intercommunicated to establish a strong social, political, and economic risk reduction framework that enables the prediction, anticipation and preparation for natural disasters; in addition it must always be accompanied with a quality education and communication to society. It is worth mentioning the importance of initiating work on land-use planning in this context of anticipation, because it is sometimes the main cause of major damage, by not taking into account the hazard maps and studies of the area, which at the same time are usually ignored by these policies. Also, citizen science has proven on numerous occasions to be essential and helpful in the monitoring of geological hazards by scientists and technicians, as well as a key factor in the realization of short-term scenarios for risk mitigation. Needless to say, this citizen participation is made possible by extensive and solid training and efficient communication.

Whenever possible, when we have indications that a natural event is imminent due to detection by monitoring and MHEWS, it is essential to elaborate short-term hazard assessments. This element has been marked with a dashed line because not all geohazards allow for this short-term analysis, as some of them lack precursors. These assessments help forecast where and when the event will take place and the most likely hazard scenarios. This forecasting, in addition to forecasting the impacts, will allow during the event phase, together with the activation of the emergency plans, and in continuous coordination with real-time monitoring data and maps and communication, to take proper decisions to ensure maximum security for the population, and to organize the available resources (human and non-human) to give an efficient response to the emergency. This should be accompanied by the integration of vulnerable groups' needs and providing warnings in trans-boundary and cross-border disasters.

Once the event is over, emergency response must continue in order to achieve the maximum possible recovery. However, there should be an exhaustive and accurate study to assess the affected area, such as not only to redirect the efforts for a proper final recovery, but also to get an overview of what happened during and after the emergency. Evaluating the extent of the damage and the state of the recovery will enable the conduct of a risk management revision that makes it possible to identify the strengths and weaknesses of the management that has been done at all stages: pre-event, event, and post-event, in order to make improvements and readjustments in the monitoring and MHEWS and to the emergency plans in order to better face inevitable future hazards. This revision will be fed by new long-term multi-hazard studies of the affected area that will incorporate the lived scenario, which will force the renewal or readjustment of existing maps.

Two main ideas emerge from this framework which should serve as principles for the proper functioning of the system. On the one hand, there is the importance of collaboration between specialists from different disciplines, especially in a multi-hazard context, always bearing in mind our role of service to the society. On the other hand, we need to continually renew or readjust each element of this structure in a cyclical manner as new events occur in the territory. For this reason, it is also essential to know the history of events that a territory has experienced and to carry out an inventory, since the fact of not having experienced a disaster sometimes works against a society's management capacity. However, nowadays we have sufficient resources to be able to know the events that have occurred in a place and to be able to thus improve our preparedness, as if it were a drill.

Having all or almost all of these aspects covered allows us not to have to start all over again, wasting time and resources every time a disaster occurs, a common trend in all communities. The multi-hazard approach allows the number of unexpected events to be reduced, thus reducing the uncertainty of the final damage. We are aware that not all countries have the necessary resources to be able to establish a solid and complete structure such as the one we are proposing here, but we are also aware that many of these countries are precisely the ones that make the greatest efforts to achieve it. And it is unacceptable for those who have sufficient resources to ignore certain aspects of risk management because they are unaware of them or because their interests lie elsewhere, when it is the lives of many people and the economic resources of a country that are at stake.

Strengthening this risk management framework in volcanic islands could be more complicated due to their socio-economic situation, but for that reason they are the sites where it is most necessary but, currently, less developed. This need will increase due to the worrying futures posed by climate change. In addition, their multi-hazard intrinsic nature makes these areas the best candidates to implement a multi-hazard risk management system.

4. Natural hazards in volcanic islands and their potential impacts

Dealing with a complex system such as a volcanic island further requires a great commitment to risk management with a multidisciplinary approach that crosses scientific, social, and economic boundaries. These specific systems have: (1) conditioning factors, understood as those that modify the characteristics of the area, favoring or aggravating the occurrence of certain events; and (2) triggering factors, understood as those that trigger the event or chain of events. Both types of factors sometimes do not exist in other non-volcanic regions or they occur less intensely. These hazards may repeat at different frequencies depending on each island, according to their proper magmatic systems and environmental conditions. Considering that these usually isolated regions are created by the growth of volcanoes in the sea and are modified by natural and anthropogenic processes helps us to understand their intrinsically multi-hazard nature. For that reason, when considering the potential hazards that may affect volcanic islands, we must include the proper volcanic and non-volcanic hazards that may act simultaneously or in succession, sometimes with evidence of some that trigger the others (e.g., volcanic eruptions triggering seismicity and avalanches, avalanches triggering tsunamis, etc. (Martí, 2019) (see Fig. 4). Fig. 4, far from pretending to show a simplified and clear summary that allows the reader to follow in detail all the possible derived hazards that may occur along a chain of events, seeks to show the complexity of the interactions, the wide range of possibilities, the aspect that multi-hazard scenarios may acquire, and the same uncertainty that the reader may feel when viewing the figure to predict whether one event or another, or several, will occur. All this complexity is aggravated by human action and climate change, both of which are indicated at the top of the figure as external inputs and frames.

We should also consider its proper environment and ecosystems, from deep sea to the highest peaks, which are dynamic environments responding to the changes in the volcano, the global environment and the local influence of human activity. In the same way it is also important to take into account their social infrastructure, including their greatly varying social, cultural, economic, and demographic distributions, due to their global position, colonial history and the nature of each island. Each site, therefore, presents a different case for resource development and the society of each island will respond differently to changes from hazard impacts.

This makes volcanic island regions where covering all the aspects of the risk management frame proposed in section 3 and, moreover, with a multi-hazard approach, a greater challenge. However, considering that they are highly populated regions—and in some cases, even overpopulated and very touristic areas—risk assessment and management is an unavoidable need. The main natural hazards to which volcanic islands are subjected are described (see Fig. 4, and also Table S1 from Supplemental Material).

4.1. Geohazards

Starting from their complex geology, volcanic islands are by definition volcanic terrains made of magma, solid rock, altered rock, hydrothermal systems, sediments, etc., sometimes deposited over very short periods of time compared to other sedimentation processes unrelated to volcanic eruptions. These conditioning factors lead to more unstable terrains compared to many continental areas. Their steep slopes due to the rapid growth in height favour this instability and can even aggravate or trigger other gravitational events, such as flash floods or rock falls. In addition, they are weak structures affected by intense faulting, alteration, and avalanche structures, which respond to the succession of constructive and destructive processes that account for their entire evolution.

4.1.1. Volcanic geohazards

Volcanic activity is already a multi-hazardous event (e.g., lava flows, gas emissions, seismic activity, PDC emplacements, landslides, lahars, tsunamis, etc., see Fig. 1 and Fig. 4), that may include cascading effects, which may have a severe impact on the population, the infrastructure and the economy of the affected region.

The Soufrière Hills Volcano (Montserrat Island, United Kingdom), offers a good example of such catastrophic events. A period of nearly 18 years of volcanic activity (from 1995 to 2013, but with different phases), mainly represented by lava dome growth, collapse and explosive phases, generated different primary volcanic hazards (dome collapses, ash fall, PDCs, gases, etc.) and other related hazards (lahars, debris flows, tsunamis, etc.) (Herd et al., 2005) (see Table S1). These events have caused roof collapses, impacted spring water sources, and destroyed most of the infrastructure of the island.

Other examples of multi-hazards occurring on volcanic islands are provided by the 2018 eruption of Krakatau, which triggered a sector collapse and, consequently, a tsunami when the sliding flank impacted the sea surface (Walter et al., 2019) (see Table S1 for more information), or the recent eruption at Tonga, that produced a caldera collapse, which triggered a large tsunami (The Prime Minister's Office, 2022). More cases of such types of interactions among natural hazards include lava flows and incandescent tephra fall that cause forest fires, as had occurred during the Gamalama eruption (Ternate Island, Indonesia) in 1980 (Hidayat et al., 2020a, 2020b), and during the Kilauea eruption (Hawaii island, USA) in 2018 (Hawaii Emergency Management Agency, 2020; Hopps, 2018; Klemetti, 2018), or lava flows generating PDCs due to a gravitational collapse of the lava front, as occurred during the Karangetang eruption (Siau Island, Indonesia) in 1992, killing six people

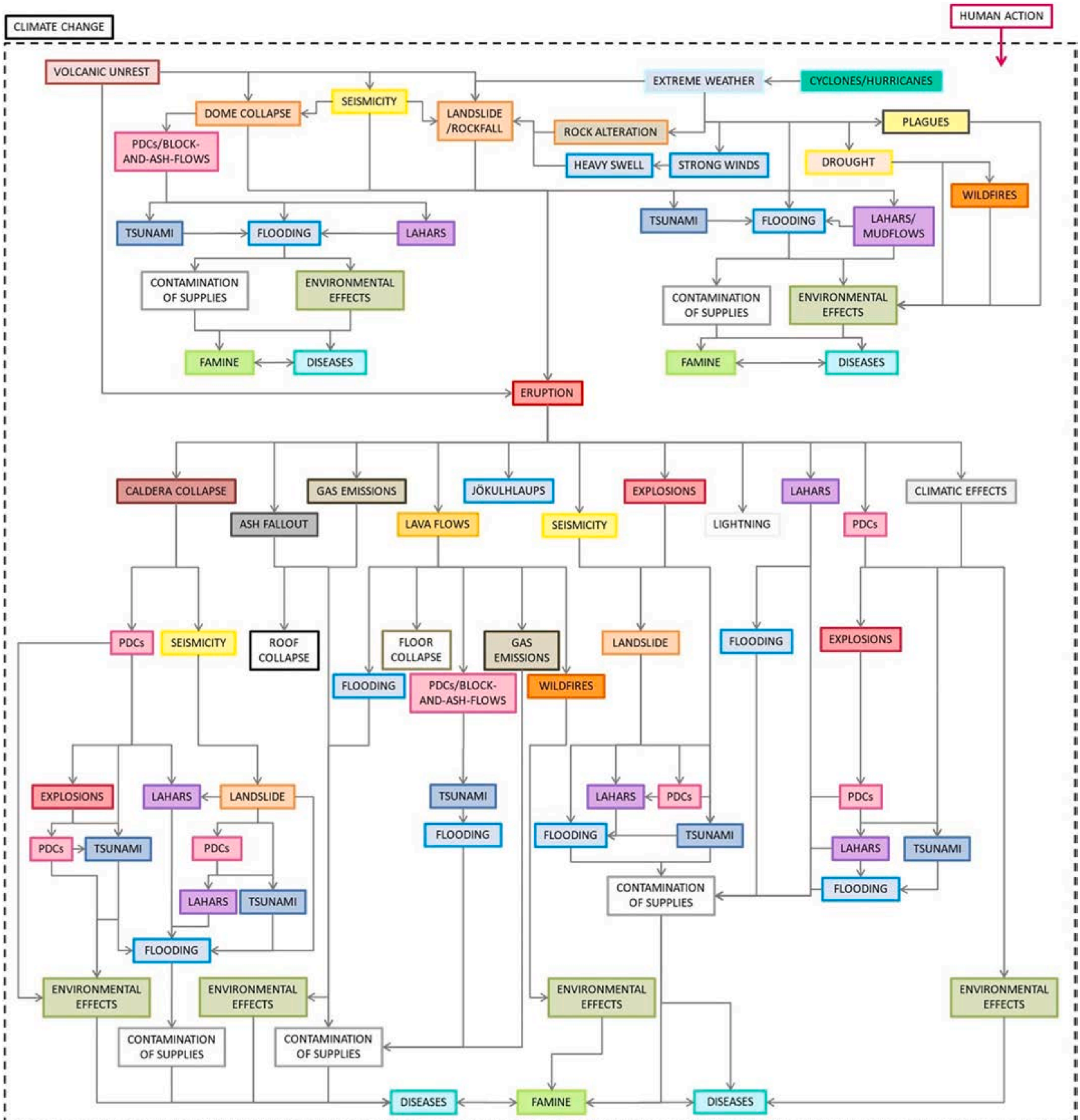

Fig. 4. Diagram of the possible interrelationships and cascading effects of different geohazards that may occur on volcanic islands.
*Note: The diagram in Fig. 4 should normally be read vertically in a downward direction but can also be read horizontally, in order to understand the relationships of events. It should be noted that, although this diagram shows all possible sequences of events and relationships based on real cases, especially those collected in Table S1 from the Supporting Material, not all events shown need to occur, or need not occur simultaneously in space and time. Similarly, some sequences of events can be initiated by any event that is related above or to the side, without necessarily having to be the first in the sequence. Likewise, chains do not necessarily have to be produced complete. Some relationships that affect some repeated boxes have been omitted due to lack of space and so as not to make their visualisation more difficult, as they are already present in another box of the same event, such as the direct relationship between lahars and the contamination of supplies. In the same way, the fact that some boxes are related to one event and others of the same typology are related to other events does not mean that in both cases there are different sequences, but for reasons of space and overlap, it has been more convenient to draw an arrow towards one box in one case and another towards another in the other case, but it means that in case this event occurs, both sequences can occur, as in the case of the relationship of environmental effects with disease and famine.

(Hidayat et al., 2020a). The eruptive column can also cause lightning due to particle friction, as occurred during the Vulcan and Tavurvur eruption (New Britain Island, Papua New Guinea), in 1994, with one person killed due to a lightning strike (International Decade for Natural Disaster Reduction (IDNDR), 1996). Lahars, mudflows, debris flows, and floods are also a common hazard related to ice melting, like during the Eyjafjallajökull eruption (Iceland) in 2010—a small event that caused $4.7 billion USD loss in the global GDP (Carlsen et al., 2012; Ellertsdottir, 2014), and to heavy rainfall or contact with water streams, as had occurred two days after the eruption of Mt. Gamalama (Ternate Island, Indonesia) in 2011 (Smithsonian Institution, 2013). In this last case, the National Disaster Mitigation Agency (Badan Nasional Penanggulangan Bencana, BNPB) allocated $121,000 USD in emergency funds for the residents affected by the eruption. However, a year later, up to 3490 people were still being housed in ten different emergency shelters.

The size of these events and of their impacts may be very variable and may include extreme events, which may even have global effects. A common sequence during large eruptions is the triggering of landslides or flank collapses due to seismicity or explosions, and the associated tsunami produced by the impact of the sliding mass with the ocean. Tsunamis can also be triggered by PDCs impacting the ocean and both are the deadliest hazards in such cascading sequences of events, accounting for between 36,417 and 120,000 deaths in the case of the tsunami during the Krakatau 1883 eruption (Indonesia) (BBC News, 2018), or the more extreme case of Tenerife (Canary Islands), where such a succession of catastrophic events, involving a large explosive eruption, caldera collapse, seismicity, large sector collapse, and tsunami, has occurred at least twice, 560 ka and 170 ka ago, respectively (Hürlimann et al., 2000; López-Saavedra et al., 2021; Martí et al., 1994) (see Table S1 for more information). Or, there is the case of the Thera eruption, in Santorini (Greece), in 1610 BCE ± 14 years, where an explosive caldera eruption triggered a large tsunami severely affecting most of the Mediterranean coasts (Sparks, 1979) (see Table S1 for more information and references).

4.1.2. Non-volcanic geohazards

Due to its unstable terrain and steep slopes, one of the most common phenomena on volcanic islands are landslides. These events can be of variable magnitude and can occur without necessarily being provoked by an eruption. As these environments are completely surrounded by the sea, one of the most frequent hazards during large landslides or rock falls is the generation of tsunamis in the same way as discussed above for those related to eruptive events. An example is the landslide and the subsequent 5–7 m-high tsunami produced on the NW coast of Flores Island (Azores) in 1847, which killed 10 people and injured >100 (Gaspar et al., 2011), or the flank collapse and the related tsunami produced at Ritter Island (Papua New Guinea) in 1888, responsible for several hundreds to 1000 deaths (Ward and Day, 2003). In this last case, the relief effort apparently came from commercial interests instead of concern for the condition of people.

Many of these landslides are caused by earthquakes, other natural phenomena that are common in these places, either of volcanic or tectonic origin. In 1522 in Vila Franca (São Miguel Island, Azores), an earthquake and four aftershocks produced a landslide and a tsunami. In turn, the landslide produced lahars, another commonly associated hazard, which killed between 3000 and 5000 people (Silveira, 2002). Many other landslides are produced in these places due to extreme weather, which can cause heavy rainfall and strong winds. These gravitational collapses, in turn, can clog river channels and cause flooding and mudflows. This was the case for the floods and mudflows that occurred in Madeira (Portugal) in 2010, causing the death of 42 people and having had serious effects on the populations (Lusa, 2010; Pita, 2010). Full restoration of all affected infrastructure may take up to a few years, but most of the island is fully functional (see Table S1 for more details). Landslides on Mt. Pelée (Martinique Island) in the same year, caused serious effects that were also due to the occurrence of lahars, such as the destruction of essential bridges (Aubaud et al., 2013), and in 2013 in the Azores (Portugal), landslides that caused three deaths (La Voz and de Galicia, 2013).

Earthquakes by themselves are very destructive events. Most volcanic islands are concentrated at plate boundaries, especially in subduction zones, where major and frequent earthquakes originate. For this reason, these islands are also subject to earthquakes of a tectonic origin. Many others, although not in this geodynamic context, such as intraplate islands, are also closely related to regional faults or fault systems that give rise to earthquakes. An example is the earthquake produced in 1839 in the west of the subducting St. Lucia Ridge, which affected the east of Martinique Island (Lesser Antilles), killing 700 people due to building destruction and causing $14.5 million USD losses (Nicoletti, 2015). Periods of volcanic unrest, while sometimes not ending with an eruption, also lead to seismic crises, such as the one that occurred in 2005 in the Fogo-Congro seismogenic zone, where >46,000 earthquakes caused landslides and environmental damage due to the incorporation of large amounts of sedimentary load into rivers (Marques et al., 2006).

On the other hand, although volcanic islands can themselves be the source of tsunamis, as we have seen before, the fact that they are located in active tectonic settings make them prone to influence by tsunamis originating from tectonic earthquakes, sometimes far away from their coasts. In addition, their relatively small size, their demographic concentration, especially along the coast where the topography is flatter and more accessible for urbanization, and their location, sometimes in the middle of the ocean unprotected by other pieces of land, make them more vulnerable to tsunamis. A well-known example is the 2004 Indian Ocean tsunami, whose epicentre was located north of the coast of Sumatra, but which devastated every coastline around the Indian Ocean and every island in its path, causing between 230,000 and 260,000 deaths (Inderfurth et al., 2005; Unicef USA, 2020). A case that also deserves attention was the 2011 Tohoku tsunami in Japan, as it passed over the Galapagos Islands, where many animals died, such as the flightless cormorant (which suffered some nest destruction), sea turtles, and marine iguanas. By all accounts the overall natural environment was not drastically disturbed, and critically endangered species, such as the mangrove finch, fortunately were unharmed (UNESCO, 2011).

4.2. Climatic hazards

On the other hand, the topographic relief of volcanic islands, with high natural barriers, deep valleys, and the influence of the sea that surrounds them, means that over a small region, the meteorology is very varied, creating weather contrasts in different parts of the island and sometimes unexpected changes in the same area. Environmental processes make volcanic islands subject to both the development and erosion of soils, due to rainfall, flash floods and flooding, heavy swell, periods of intense drought, rock alteration, or thermal contraction and expansion. Likewise, many volcanic islands are located in the cyclone pathways, so they are also affected by hazards associated with extreme weather events. An example is the flooding that occurred on Martinique Island in 1891 due to the passage of Cyclone San Magin, which caused 700 deaths, brought with it numerous diseases and caused economic losses of between 11.6 and 14.5 million USD (Aubaud et al., 2013; Church, 2014). Another example is Cyclone Pam on its passage through Vanuatu (South Pacific) in 2015, where it left between 11 and 16 deaths, with 132,000 people affected and 33,000 displaced, in addition to losses of 600 million USD (Handmer and Iveson, 2017). On occasions, the development of these soils between layers of volcanic materials from eruptions can act as a conditioning factor for the generation of landslides, as they often correspond to the décollement surface (Boulesteix et al., 2012; Bravo, 1962; Coello, 1973; Iribarren, 2014; Le Friant et al., 2020). The same applies to the deposits created after a landslide that remain in situ with subsequent layers of volcanic materials deposited on top of it.

In addition, these climatic conditions entail a wide range of non-volcanic hazards of different types, such as the occurrence of plagues, forest fires, problems for the refilling of aquifers, landslides caused by floods, such as those mentioned before, damage to coasts due to sea waves, damage to crops both in dry and humid periods, damage to livestock, snowfall, gelifraction, heat waves, etc. A clear example is the Canary Islands (Spain), where many of these hazards have occurred. In 2004 for example, an extreme haze brought a plague of locusts to Lanzarote (Arroyo, 2009). At the same time, a squall formed over the Canary archipelago causing strong gusts of wind and rainfall. On the beach of Maspalomas (Gran Canaria), the waves broke into the dune area and penetrated almost 500 m, causing considerable damage along the coastal area.

On the other hand, global climate change will increase the frequency and severity of many of these events that may impact these vulnerable environments. This is the case for hydrological and coastal hazards, which will increase the flux of material from the subaerial part, extending to the sea through flooding and landslides, producing coastal erosion, thus changing stability of the island slopes and coasts. These effects can get worse in the case of volcanic eruptions, because if there are conditions that favour these processes, the cascade of events following an eruption can become increasingly common and extreme.

4.3. Biological and health hazards

Geohazards of volcanic and non-volcanic origin may cause other hazards since they may relate to the contamination of water and food supplies, worsening hygienic conditions and affecting people's health. Examples of this are the Tambora eruption of 1815 (NOAA, 2020), the Martinique Island floods of 1891 (Aubaud et al., 2013; Church, 2014), the Pinatubo eruption of 1991 (Floret et al., 2006), or the Indonesian tsunami of 2004 (WHO, 2006) (see Table S1 for more details).

4.4. Human-induced hazards

Furthermore, human activities should be also considered, as they may severely alter the natural conditions of each site, a factor that may increase risk considerably. On the one hand, volcanic areas often host significant agricultural activity because they contain very fertile soils, forcing more and more settlements to be established in hazardous areas, increasing the risk due to greater exposure. In addition, the creation of terraced crops, for example, modifies the topography and, in turn, its surface runoff. The change in land use alters its properties and the processes that take place there, so a comprehensive impact study of these types of activities is necessary, not only of those that create crops, but also those that transform natural land into urban land, in order to analyse the consequences of such types of land modifications. Moreover, the lack of space forces companies to build dangerous infrastructure, such as oil refineries, gas depots, power and thermal power plants, and even nuclear power plants, in areas at risk because of the high probable occurrence of the above-mentioned natural events. It is worth recalling the nuclear disaster in Japan following the 2011 Tohoku tsunami.

On the other hand, resources are also limited due to natural space constraints. If we add to this the fact that most of these volcanic islands are popular tourist destinations, overpopulation and a large influx of tourists can endanger reserves and, therefore, supply, often resulting in the overexploitation and degradation of aquifers, the destruction of forests and other green areas for urban expansion, coastal overpopulation, the modification of riverbeds and streams, the destruction of natural heritage, overfishing, increased influx of cruise ships, planes and cars, increased pollution, etc. It also increases the risk exposure of people, who are more vulnerable as they are often unaware of the existing hazards in the area, especially if they come from regions where there is no comprehensive training in natural hazards, and they do not know how to behave in the event of an emergency. In addition, there are a number of irresponsible actions, such as the waste dumping near Truk Island previously mentioned in section 4.3., negligent or intentional fires, access and exposure to dangerous or prohibited areas, etc., among tourists and locals alike. One example were the 2019 fires in the Canary Islands, where arson combined with a heat wave and strong winds resulted in 10,000 ha burned, 84% of which were protected areas, as well as the displacement of 9000 people, the death of some livestock and up to 50 million bees (Minder, 2019; Portillo, 2019).

However, sustainable management of tourism and resource use, and increased awareness and communication, can both reduce risk and boost the economy of these regions by allowing for improvements in disaster reduction strategies.

5. The Canary Islands' case study

The Canary Islands is an active volcanic archipelago belonging to Spain and located in the Atlantic Ocean, off the coast of southern Morocco. All of them have experienced at some point in their history and continue to experience today many of the hazards explained in section 4. In addition, all suffer from enormous human impacts, being highly populated and receiving millions of tourists per year.

5.1. Natural hazards

The Canary Islands have been and continue to be the scene of extreme events, with cascading effects, and non-extreme but more frequent events, which impact the economy and society of this region. Some effects have even crossed borders and have had consequences on a larger scale (Blahůt and Quan Luna, 2021; Copernicus Atmosphere Monitoring Service, 2021; López-Saavedra et al., 2021; Paris et al., 2017).

The island of Tenerife exposes one of the best cases of cascading extreme hazards that have recurred several times in the past and could occur again in the near future. A cascading sequence involving a caldera-forming eruption, high magnitude seismicity, a megalandslide and a tsunami has occurred at least two times during the formation of the central and eastern sectors of Las Cañadas caldera, and the formation of the La Orotava and Icod valleys, respectively (Carracedo et al., 2011; Hunt et al., 2011, 2013a, 2013b, 2018; Ibarrola et al., 1993; Martí, 2019; Martí and Gudmundsson, 2000; Martí et al., 1997). Similar scenarios occurred in La Palma, El Hierro, Gran Canaria, Fuerteventura and Lanzarote islands, as revealed by their morphology and landslide deposits on the seafloor seen in the bathymetry of this region (Ferrer et al., 2021; García-Crespo et al., 2018; Gee et al., 2001; Hunt et al., 2013a; Torrado et al., 2006; Urgeles et al., 1999).

Although the entire archipelago is considered volcanologically active, four of the islands (La Palma, El Hierro, Tenerife, and Lanzarote) have had historical eruptions (since 1341), while the rest, with the exception of La Gomera, have hosted eruptions during the Holocene. Currently, La Palma is the most volcanologically active, with the last eruption having started on September 19th, 2021, and lasting for 85 days.

The seismicity of the Canary Islands is of moderate magnitude, with shallow earthquakes that generally do not exceed the 5.5 degrees of local magnitude. This can be divided into volcanic seismicity and tectonic seismicity (Instituto Geográfico Nacional (IGN), 2022). Regarding the former, seismic series associated with volcanic reactivations usually begin with low magnitude earthquakes, which increase in frequency and size until they are widely felt. Some recent examples are the Tenerife series in 2004 (Domínguez-Cerdeña et al., 2011), the successive reactivations in El Hierro between 2011 and 2014 (Domínguez-Cerdeña et al., 2018) and in La Palma in 2017 and 2018 (López et al., 2018). Regarding those of tectonic origin, earthquakes can reach considerable magnitudes, especially between the islands of Tenerife and Gran Canaria, where the highest magnitudes of the archipelago can be reached, up to M 5.5 (Instituto Geográfico Nacional, 2022). An example is the one that occurred on May 9th, 1989, with a magnitude of 5.2 (Mezcua et al., 1992).

Despite the predominantly temperate climate in the western part of the archipelago, and the warm desert in the east, all islands have significant spatial and temporal climate variability. The numerous microclimates and abrupt changes cause extreme weather episodes to occur on numerous occasions. In turn, the passage of some cyclones or tropical storms through this area of the Atlantic towards Africa, such as the occurrence of DANAs (Isolated Depression at High Levels), (e.g., the Delta storm in 2005), in addition to the associated inland hazards, also causes serious coastal effects due to intense waves and flooding (e.g., the maritime storm in November 2016). All these factors, coupled with the topography of steep slopes with unstable terrain, means that during heavy rainfall events, landslides or rock falls and torrential floods are frequent. On the other hand, during the dry seasons, concentrated in July and August, droughts and heat waves are common. These conditions, together with tourist pressure and illegal activities (burning of areas for land use changes, cheapening of land, burning of pruning, negligence, etc.), and dense forests, combine to create favourable situations for the origin and spread of large forest fires, most of them intentional. One example is the forest fires that hit Gran Canaria and Tenerife in August 2019.

In addition to all these hazards, we must consider demographic expansion, especially in coastal areas and the excessive tourist pressure concentrated in the summer months but also with a significant presence during the rest of the year due to the favourable climate of the region. In 2021 the archipelago received 5.2 million international tourists (Europa Press, 2022). The Canary Islands have serious problems every year in terms of water reserves and supply, both for tourism, which demands more than the resident population, and for agricultural and livestock farming activities. The growing demand for water resources causes a worsening of water quality and a decrease in aquifer reserves. On the other hand, more and more at-risk areas are being developed in order to provide a solution to urban sprawl. This leads to the construction of settlements in areas at risk of flooding, volcanic eruptions, and deforestation, which endangers the microclimatology of the islands. All these impacts are being and will be aggravated in the coming years by the effects of climate change.

5.2. Prevention and monitoring

According to ROYAL DECREE 1476/2004, of June 18th, the Directorate General of the National Geographic Institute (IGN), based in Madrid and in Santa Cruz de Tenerife, is responsible for the observation, monitoring and communication of volcanic activity and seismic movements in Spain and for the determination of the associated risks. For this reason, the IGN operates several monitoring networks. The Volcano Monitoring Network includes a series of seismic stations, geochemical stations, GPS stations, inclinometers, total stations, gravimetric stations, magnetometers, webcams, and tide gauges. In turn, for seismic monitoring there are additional seismic stations and a network of accelerographs, also managed by the IGN. However, there are other entities, such as the Instituto Vulcanológico de Canarias (INVOLCAN) which also has some of these same stations deployed for monitoring and data collection.

Regarding the seismic hazard, on the basis of the seismic hazard cartography produced by the IGN, the Canary Geographic Institute, the Government of the Canary Islands, the Island Councils, and the Municipalities at significant risk will draw up a catalogue of vulnerable elements based on the vulnerable elements according to the characteristics of the constructions.

With regard to adverse meteorological phenomena and flood risk, the State Meteorological Agency (AEMET) must draw up, supply and disseminate meteorological information and forecasts of general interest to the public, as well as the issuing of warnings and forecasts of meteorological phenomena that may affect the safety of people and property. With regard to flood risk, the Island Water Councils are the ones that draw up flood studies of the Areas of Potential Significant Flood Risk (ARPSI's).

Civil Protection is present throughout the risk management process and is responsible for the study and prevention of situations of serious collective risk, catastrophe or public calamity, and for the protection and relief of people and property in cases where such situations occur.

5.3. Response to an emergency and recovery

Territorial Plans exist to deal with an emergency. These Plans, depending on the geographical area where they are established, are limited to the incidence of each emergency. In this sense, at a municipal level, the Municipal Emergency Plan (PEMU) is activated. Likewise, each Island Council must develop its own island plan. Emergencies at the regional level are those that affect more than one island of the Archipelago, or those whose magnitude of the incident requires the use of means outside the affected island. The Territorial Civil Protection Plan of the Autonomous Community of the Canary Islands (PLATECA) is activated when an emergency is declared at the Autonomous Community level. PLATECA includes all the previous territorial plans, in addition to their different Special Plans. These plans are divided into Basic Plans (nuclear and war emergencies, both of which are the responsibility of the State), and Special Plans for other risks (floods, earthquakes, chemicals, transport of dangerous goods, forest fires, volcanic). If we focus on natural hazards, this last category includes the following Special Plans for the Canary Islands:

- Special Plan for Civil Protection and Attention to Emergencies due to volcanic risk in the Autonomous Community of the Canary Islands (PEVOLCA).
- Special Plan for Civil Protection and Emergency Attention due to seismic risk in the Autonomous Community of the Canary Islands (PESICAN).
- Special Plan for Civil Protection and Emergency Attention due to Forest Fires in the Autonomous Community of the Canary Islands (INFOCA).
- Special Plan for Civil Protection and Emergency Attention due to Flood Risk in the Autonomous Community of the Canary Islands (PEINCA).

In addition to these, there is also a Specific Plan for Civil Protection and Emergency Attention of the Autonomous Community of the Canary Islands due to risks of adverse meteorological phenomena (PEFMA).

Some of these hazards also have other types of plans, such as Action Plans, Self-Protection Plans, Awareness and Education Plans, Training Plans, Essential Basic Services Continuity Plans, Emergency Plans for more specific risks within the risk event itself, etc.

The different plans for natural hazards operate in much the same way. However, it is precisely this feature that is in need of reform and improvement. The protocol for dealing with the different types of events is practically the same, with some minor variations, which makes it independent of the phenomenon. These plans lack a multi-hazard perspective from the point of view of the concatenation of events. This sometimes underestimates the potential for cascading effects or other types of interrelationships and, hence, their consequences. It is true that, in the case of PEVOLCA, different types of hazards that may occur during an eruption are considered, but it does so separately, with separate actions for each of them. Furthermore, it does not take into account the fact that the occurrence of a previous independent event can establish favourable conditions for aggravating the impact of another event in the same region but after a period of time (for example, a storm and heavy rainfall in an area where there had previously been a forest fire and soil erosion, or the same rainfall in an area shaken by an earthquake some time ago, reducing the cohesion and stability of the soil and favoring the occurrence of landslides). In a more global sense, these plans also do not take into account the influence of climate change, which could bring about processes and relationships between events that are somewhat different from those observed so far (e.g., soil erosion due to a rise in sea level not only along the coasts, but also at river headwaters as a result of a readjustment of the equilibrium profile of rivers, thus increasing the occurrence of landslides and debris flows).

6. Discussion

Multi-hazard is a new concept that is becoming commonplace in risk reduction plans in contrast to the classical approach of considering each hazard and its potential impacts separately. Volcanic islands are particular environments exposed to a large variety of natural hazards (e.g., landslides, earthquakes, volcanic eruptions, forest fires, water floods, etc.), with high potential of permanently harming their socio-economic and environmental systems. Moreover, volcanic islands are the environments that will experience the strongest impact from the current Climate Change (e.g., sea level rise and an increase in extreme meteorological events), which may even increase the threat represented by their intrinsic natural hazards. Most of these hazards may occur as compound events and the risks related to their interactions and cascades/simultaneous effects on these highly vulnerable and threatened socio-economic settings and ecosystems can therefore be disastrous. This is why risk reduction programs for such regions need to incorporate the multi-hazard approach, rather than considering individual hazards and risks. And another need arises: to link the Sendai Framework goals with the Sustainable Development Goals and the Paris Agreement on climate change.

Unfortunately, when considering a multi-hazard scenario, the fragmentary understanding of inter-relations among the different hazards (cause/effect) and their cascading effects has hampered the development of robust procedures to perform hazard assessments, and thus to implement effective combined monitoring and early warning systems. Therefore, an initial aspect that needs to be addressed when considering a multi-hazard environment is to conduct a dynamic multi-hazard assessment, based on a detailed revision of its past history of multi-hazard impacts in such an environment. In the particular case of volcanic islands, volcano-derived hazards may be the most important ones, but their potential interactions and derivations to other hazards should not be discarded. However, in such a complex multi-hazard context, knowing the time scales at which the different hazards may impact is of primary importance. On some occasions, eruption recurrence may be so infrequent that the possibility of being impacted by volcanic phenomena is not regarded as a serious present threat; nevertheless, many other hazards, in particular those directly or indirectly related to global change, may severely impact these fragile environments with increasing frequency. As a result, knowing what may occur in such an environment, and with which frequency and potential combinations of events, is fundamental for developing adequate land and emergency planning in order to minimize risk.

A second aspect that needs to be reinforced such as to face multi-hazards on or near volcanic islands is effective education at all levels of society. A society that is well-educated and trained on the surrounding natural hazards is less vulnerable and more resilient to their associated impacts. In the case of a hazard or multiple hazard risk scenario, the community will understand and react more efficiently to early warnings and alert systems, and may recover better from the eventual effects. However, the intermittent nature of most natural hazards and the complexity in foreseeing their interactions, as may happen with infrequent volcanic hazards, make it difficult to maintain a high level of public risk awareness. Ignoring potential hazards that may impact our society implies that no related mitigation action will be taken, eventually leading to an increased risk; moreover, it makes it much more difficult to react and recover after such disastrous events.

Therefore, a necessary condition for the success of a given risk reduction program in such complex and vulnerable scenarios is to undertake a multidisciplinary and integrative approach involving from the beginning all essential actors in hazard assessment, risk and crisis management, decision-making, and mitigation actions. These are: scientists and technicians working in volcano observatories and research centers, authorities, population, civil protection, educators, media, First Aid organizations, and UNISDR platforms. All actors need to know what the others can do and what each of them actually need from the others. Together, all these actors should understand the most likely scenarios, recognizing the hazards involved, their order of occurrence and cascading effects, extent and potential impacts, the vulnerability of the possible elements impacted, and the mitigation measures that should be considered in each case. Public engagement will play a key role in increasing multi-hazard risk management capacities and efficient response strategies. Only with this multidisciplinary and coordinated effort will it be possible to effectively prepare for and manage a complex multi-hazard crisis and to develop knowledge-based resilience planning.

In summary, volcanic islands offer one of the most risk-prone and vulnerable environments for being impacted by multi-hazard scenarios. Having a scientific-based detailed knowledge of the potential occurrence of natural hazards and their possible interactions—as well as the implementation of real-time monitoring networks and early warning systems, together with the development of educational programmes at all levels of the society including adequate management plans—is mandatory to effectively reduce risk there. It is also important to conduct precise vulnerability and risk analyses including an inventory of elements at risk (e.g., populations, properties, infrastructures, cultural heritage, etc.). This should facilitate assessment of the physical, economic, and environmental impacts as cumulative damage on exposed elements produced by possible sequences of hazards and to identify the main technological (e.g., building retrofitting, infrastructure protection) and non-technological (e.g., investments in education and communication) mitigation options and adaptation strategies at territorial and building scales that should be implemented in each case. Finally, we should also considered knowledge-based resilience planning that should promote and implement resilience strategies that account for cascading and large-scale events that may affect such highly vulnerable environments.

In the case of the Canary Islands, the current demographic growth, together with urban expansion and the islands' colonial history, means that today we find buildings and settlements within hazardous areas. This is a common fact among many volcanic islands. But it is also true that the level of management and the availability of preventive material for the different natural hazards common to the Canary Islands (discussed in section 5.1) are very uneven. For some hazards such as forest fires or floods, management and emergency plans as well as hazard and risk maps, are available. However, for other hazards such as volcanic eruptions or landslides, the resources available are scarce, insufficient or unequal between the different islands of the archipelago. For the case of earthquakes, the maps are more oriented towards civil works and there is a lack of research at a more local level.

Furthermore, in the Canary Islands there is insufficiently developed public alert systems for some hazards (e.g., tsunamis). This is a common trend in many countries. Other challenges that this area must face, as is very often the case in the rest of Europe, for example, are the vaguely defined institutional responsibilities for warnings, public warning in cross-border disasters, targeting warnings to a delimited geographical area at risk, dealing with social media in emergencies, assessing the effectiveness of Early Warning Systems (EWS), etc. These challenges reveal the weaknesses of the risk management system and, specifically, the MHEWS of this region during El Hierro 2011–2012 eruption, which fortunately were improved before the 2021 La Palma eruption.

By combining the irregular and scarce knowledge of the multi-hazardous nature of the islands, together with the territorial fragmentation, urban expansion and demographic increase, we find multiple houses and infrastructures located in hazardous areas. If we add to this the fact that many homes lack home insurance, risk management in the post-emergency stage and the recovery process of the area becomes much more complicated, such as what happened after the eruption of September 19th, 2021 in La Palma. In this case, despite the successful management of the eruptive crisis, which only caused material losses, the local government is faced with a scenario that is difficult to prevent. Most of the population of La Palma is located in the most active volcanic area of the island, with a monogenetic volcanism (that is even more difficult to predict) having registered up to 9 eruptions in historical times (the last 600 years); there are no hazard and/or volcanic risk maps for La Palma; and around 50% of the houses on this island are not insured. One of the strategies to prevent the risk derived from incorrect land use planning is the creation of protected areas. Even if the existing ones have been created for biological or ecological conservation reasons, rather than for geological reasons, something is better than nothing. However, the creation of protected areas for geological reasons, focused on hazards, may better prevent the risks derived from them. And this must go hand-in-hand with the introduction of improvements in disaster risk reduction policies from a multi-hazard perspective that has not been realized to date.

7. Conclusions

This study has reviewed the evolution of the multi-hazard concept and its implementation in current disaster risk reduction policies. Focusing on the case of volcanic islands, we have analysed their multi-hazards through the contribution of real disaster events and their management, dedicating a section to the case of the Canary Islands and their current state of risk management. The following conclusions emerge from this extensive analysis: (1) there has been a hesitant but growing implementation of the multi-hazard perspective in risk management policies on both national and international scales; (2) despite the fact that the Sendai Framework for Disaster Risk Reduction (2015–2030) includes non-binding agreements, many countries have implemented projects and strategies with a multi-hazard perspective to meet the objectives established during the Conference on Disaster Risk Reduction; (3) many of the initiatives undertaken by various countries have emerged or have given rise to regional projects as a result of a collaborative and interdisciplinary pooling of knowledge and resources, many building on the strengthening of pre-existing individual MHEWS; (4) due to their intrinsic multi-hazard nature, their social, economic and political contexts, as well as climate change, volcanic islands are one of the most vulnerable environments, but they are also precisely one of the territories where a solid and efficient multi-risk management system is most needed; (5) the multi-risk management system must be framed by research, conservation and education, to develop a scientifically based detailed knowledge that will allow the implementation of real-time monitoring networks and early warning systems, educational programmes at all levels of the society, and adequate management plans.

In the context of climate change, with hazards that will increase in magnitude and frequency, and in the context of the present population growth, with increased exposure to natural disasters, risk reduction cannot lie only in technological progress to improve our vulnerability. In line with the Sendai Framework, it is necessary to start acting on the design and implementation of disaster risk reduction policies through a cross-sectoral, climate change-oriented, socially-inclusive, multi-risk management system, based on scientific knowledge and linked to critical societal solutions.

Funding

This work was partially supported by the EG grant EVE (DG ECHO H2020 Ref. 826292) and the CSIC grant MAPCAN (CSIC Ref. 202130E083). Marta López-Saavedra received an FPU PhD grant (FPU19/02413) from the Ministry of Science, Innovation and Universities of the Government of Spain. We warmly thank the Editor Gillian Foulger, and the reviewers (Amiel, and an anonymous referee) for their constructive reviews and comments. English text has been reviewed and revised by Dr. Grant George Bufett of Terranova Scientific (www.terranova.barcelona).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2022.104286.

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ADVANCING EARTH AND SPACE SCIENCE

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RESEARCH ARTICLE

10.1029/2021JB022294

Cascading Effects of Extreme Geohazards on Tenerife (Canary Islands)

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Key Points:

- Tenerife is a good example of where cascading extreme hazards have occurred several times in the past and could occur again in the future
- The modeling of a multi-hazard scenario enables us to predict the potential extent and impact of a caldera-forming eruption on Tenerife
- A long-term multi-hazard assessment of Tenerife shows the impact that a sequence of extreme events could have beyond the Canary Islands

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

López-Saavedra, M., Martí, J., Rubio, J. L., & Kelfoun, K. (2021). Cascading effects of extreme geohazards on Tenerife (Canary Islands). *Journal of Geophysical Research: Solid Earth*, *126*, e2021JB022294. https://doi.org/10.1029/2021JB022294

Received 6 MAY 2021
Accepted 6 SEP 2021

Abstract

Extreme geohazards (volcanic eruptions, earthquakes, landslides, and tsunamis) have the potential to inflict cascading effects whose associated risks are difficult to predict and prepare for. Thus, these events are generally not taken into account in hazard assessment. Anticipating the occurrence of such extreme events is thus key if our life-styles are to remain safe and sustainable. Volcanic islands are often the source of complex successions of disastrous events, as is evident from any examination, for instance, of the geological record of regions such as Hawaii, the Canary Islands, Reunion and Indonesia. The island of Tenerife in the Canary Archipelago is an excellent example of where cascading extreme hazards have occurred several times in the past and could occur again in the future. A cascading sequence involving a caldera-forming eruption, high-magnitude seismicity, mega-landslides and tsunamis occurred at least twice during the construction of this island. In order to understand the possible consequences of such processes if they were to reoccur, we simulated the extent and potential impact of a multiple, extreme geohazard episode similar to the last recorded one that took place on the island of Tenerife around 180 ka. The implications of such a disastrous succession of events are analyzed at local, regional and global scales, and the results obtained are discussed within the framework of disaster risk-reduction policies.

Plain Language Summary

Extreme geohazards are geological events (e.g., volcanic eruptions, earthquakes, landslides, or tsunamis) that pose a serious risk for our globalized and techno-dependent society, and could potentially have a significant impact both locally and globally. Volcanic islands are large volcanoes that have grown out from the seafloor whose tops have emerged above sea level to form islands, on which a chain or succession of disasters (cascading events) could occur. Successions involving large explosive eruptions leading to the collapse of the central part of a volcano into its magma chamber, thereby forming a collapse caldera and provoking high-magnitude earthquakes, mega-landslides and tsunamis, occurred several times during the evolution of Tenerife, the largest volcanic island in the Canary Archipelago, and could occur again in the future. To understand the consequences if such an event occurred today, we modeled the most recent succession of extreme geological events that occurred on Tenerife about 180,000 years ago. The results obtained are analyzed at local, regional and global scales, and are relevant to the emergency plans that need to be developed to confront volcanic and associated risks in the Canary Islands and other similar regions.

1. Introduction

Extreme geohazards (super-eruptions, earthquakes, mega-landslides, and tsunamis) are low-probability high-impact events with the potential to inflict cascading effects, whose associated risks are difficult to predict and prepare for (Lee et al., 2012; Nott, 2006; Plag et al., 2013; Ranke, 2016; Sharma et al., 2012). These types of events are characterized by their short unfolding time but much longer impact time, with the potential to generate global disasters. Thus, they are generally not taken into account in hazard assessment and, consequently, they are usually underestimated in disaster risk-reduction studies and policies (Plag et al., 2013).

However, the eruption of Eyjafjallajökull volcano in Iceland in 2010 showed that today even a small recurrent event could have an impact worldwide due to the greater complexity of our society (Lee et al., 2012; Plag et al., 2013). Modern civilisation's lack of experience in extreme events, together with the rise in population density, has increased our exposure to geohazards since, for instance, many megacities and industries

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are located in hazardous areas. Recent efforts, such as the analysis made by Patrick et al. (2020) on the 2018 Kilauea eruption, have highlighted the importance of the study of cascading hazards for future forecasting, given the magnitude and complexity of their consequences.

Volcanic islands are good examples of fragile economic systems and highly vulnerable communities whose main monetary income is from tourism and local economic activities such as fishing and agriculture. Created by the growth of volcanoes in the sea and modified by natural and anthropogenic processes, volcanic islands are subject to the impact of multiple natural hazards, including extreme geohazards, as well as forests fires, storms and floods. Given their intrinsic multi-hazard nature, volcanic eruptions are the most common extreme geohazards liable to trigger concatenated effects in this type of environment. Tenerife is an excellent example of a site exposed to cascading extreme geohazards that have occurred several times in the past and could occur again in the future, since the geophysical conditions that determine the occurrence of such catastrophic events are still present. A cascading sequence of a caldera-forming eruption, high-magnitude seismicity, a mega-landslide and a tsunami occurred at least twice during the construction of the central and eastern sectors of the caldera of Las Cañadas, and gave rise to the Orotava and Icod valleys. Despite being the most populated island in the archipelago and receiving millions of tourists every year, no detailed multi-hazard assessment has ever been conducted for Tenerife.

In order to fill the gap in the information necessary for correct emergency planning for the island and the rest of the region, we conduct this initial long-term multi-hazard assessment. The aim of this study is to quantify the extent and potential impact of an episode of multiple extreme geohazards similar to the one that occurred on Tenerife around 180 ka if it occurred today. We first review the stratigraphic evidence to determine the temporal succession of events and the relationship of cause and effect. Then, we analyze each of the processes that occurred during the succession separately, but considering the nature and consequences of the possible relationship between the described events. To do this, we describe the main characteristics, magnitude and area of occurrence and impact of each hazard, but we adjust some of these properties depending on the results obtained from the previous event along the cascading simulation. This linkage has been done specially for the seismicity-landslide and landslide-tsunami sequence pairs. We also take into account the current topography of the island and its demographic distribution to assess the potential impact of the multi-hazard scenario. Then, we analyze the overall result of all the simulated scenarios to quantify the potential extent and impact of the occurrence of these multi-hazards today. Finally, we examine the implications of this multi-hazard scenario at local, regional and global scales, and discuss the results obtained within a framework of disaster risk reduction policies.

2. Geological Setting

Tenerife is the largest of the Canary Islands, an intra-plate volcanic archipelago connected to a long-lasting mantle plume whose structure and geodynamic evolution still evoke considerable debate (e.g., Anguita & Hernan, 1975, 2000; Araña & Ortiz, 1991; Carracedo et al., 1998; Fullea et al., 2015; Hernández-Pacheco & Ibarrola, 1973; Hoernle & Schmincke, 1993; Schmincke, 1982). The geological evolution of Tenerife involved the construction of two principal volcanic complexes (Figure 1): a basaltic shield complex (>12 Ma to present, Abdel-Monem et al., 1972; Ancochea et al., 1990; Thirlwall et al., 2000) and a central complex (<4 Ma to present, Ancochea et al., 1990; Araña, 1971; Fuster et al., 1968; Martí, Mitjavila, & Araña, 1994). The basaltic shield complex is mostly submerged and forms about 90% of the volume of the island; its subaerial construction continues at present through two rift zones (Santiago Rift Zone and Dorsal Rift Zone) and in a broad monogenetic volcanic field to the south of the island. The central complex corresponds to Las Cañadas edifice (<4–0.18 Ma), a composite volcano characterized by abundant explosive eruptions of highly evolved phonolitic magmas, and the active Teide-Pico Viejo twin stratovolcanoes (0.18 ka-present). The formation of the caldera of Las Cañadas, of which the Teide-Pico Viejo stratovolcanoes are part (Figure 1c), truncated the edifice of Las Cañadas, which was transformed by several vertical collapses occasionally associated with lateral collapses on the volcano's flanks (Martí & Gudmundsson, 2000; Martí, Mitjavila, & Araña, 1994; Martí et al., 1997).

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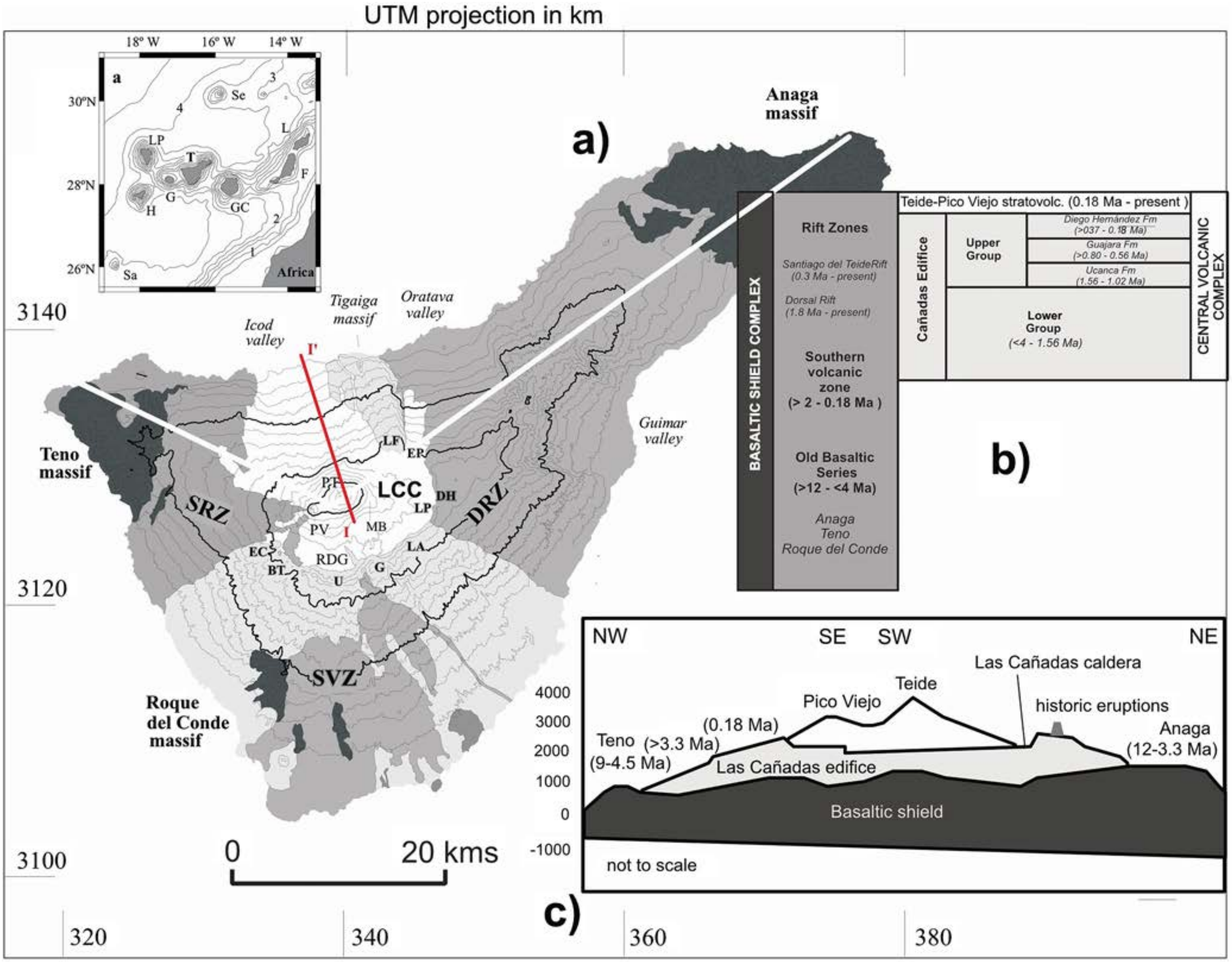

Figure 1. (a) Simplified geological map of Tenerife (modified from Ablay & Martí, 2000), (b) stratigraphy of Tenerife and (c) schematic cross-section of the island. Las Cañadas caldera wall localities: EC-El Cedro; BT-Boca Tauce; U-Ucanca; RDG-Roques de García; G-Guajara; LA-Las Angosturas; LP-Las Pilas; DH-Diego Hernández; EP-El Portillo; LF-La Fortaleza. Main vent systems of the Teide-Pico Viejo formation: PT-Teide volcano; PV-Pico Viejo volcano; MB-Montaña Blanca. Post-shield mafic volcanic zones: SRZ-Santiago rift zone; DRZ-Dorsal rift zone; SVZ-Southern volcanic zone (locally known as Bandas del Sur). Names and locations of landslide valleys are also shown. Contour interval is 200 m. Isotopic ages are from Ancochea et al. (1990) and Martí, Mitjavila, and Araña (1994). Inset map shows the location and distribution of the Canary Islands. Main islands: LP-La Palma; EH-El Hierro; G-La Gomera; T-Tenerife; GC-Gran Canaria; F-Fuerteventura; L-Lanzarote. The white lines correspond to the cross-section of part (c) of this figure, and the red line I–I′ corresponds to the cross-sections in Figures 2 and 3.

2.1. Stratigraphic Relationships Between Extreme Geohazards on Tenerife

A change in the eruptive dynamics of Tenerife between 2 Ma and 1.5 Ma initiated a period consisting of three long-term cycles of phonolitic explosive activity, with volumetrically larger and more extensive eruptions, that constructed Las Cañadas edifice Upper Group and ranges from 1.57 to 0.17–0.18 Ma (Ancochea et al., 1990, 1999; Boulesteix et al., 2012; Brown et al., 2003; Bryan et al., 1998; Edgar et al., 2007; Huertas et al., 2002; Martí, Mitjavila, & Araña, 1994; Mitjavila & Villa, 1993). Each of these phonolitic volcanic cycles terminated with a caldera collapse episode (Martí, 2019; Martí & Gudmundsson, 2000; Martí, Mitjavila, & Araña, 1994).

During the construction of Las Cañadas, several large sector collapses affected parts of the island, at least two of which coincided in time with the occurrence of caldera-forming episodes. This is the case of La Orotava and Icod valleys, on the northern flank of Tenerife, which are coeval with the formation of the central (Guajara, 0.56 Ma) and eastern (Diego Hernández, 0.17 Ma) sectors of the caldera, respectively (Carracedo et al., 2011; Hunt et al., 2011, 2013a, 2013b, 2018; Ibarrola et al., 1993; Martí, 2019; Martí et al., 1997; Martí & Gudmundsson, 2000).

The formation of the Icod valley coincided with the eruption of El Abrigo (Boulesteix et al., 2012; Hunt et al., 2011; Martí, Mitjavila, & Araña, 1994; Martí et al., 1997; Paris et al., 2017), the caldera-forming eruption that culminated the final phonolitic cycle of the Upper Group (0.179 Ma, Martí, Mitjavila, & Araña, 1994). According to Martí (2019), the inland stratigraphy of the related deposits reveals the temporal sequence of these catastrophic events and contrasts with that proposed by other authors (e.g., Hunt et al., 2018; Paris et al., 2017). The lack of El Abrigo deposits in the Icod valley contrasts with their presence throughout the rest of the island in a continuous 2–20 m-thick layer (Pittari, 2004; Pittari et al., 2008), which indicates that this eruption preceded the subaerial landslide. The landslide may have started on the submarine flanks during the unrest period preceding the eruption (Hunt et al., 2011, 2013a, 2013b, 2018), probably as a response to strong continuous seismicity and ground deformation caused by the inflation of the associated magma chamber (Andújar et al., 2008; Martí, 2019). This initial submarine landslide, involving volumes of 240–264 km^3 (Hunt et al., 2011, 2013a, 2013b, 2018), would have continued on land during the caldera collapse episode and led to the removal of approximately 60 km^3 of the northern sector of the volcanic edifice (Iribarren, 2014). The result would have been a multistage retrogressive failure with stages separated by periods of several days (Hunt et al., 2011; Paris et al., 2017).

The subaerial landslide would have caused a tsunami whose deposits are preserved in thicknesses of 0.4–3 m on the north-west flanks of Tenerife at altitudes up to 132 m a.s.l. (Paris et al., 2017). A characteristic of these tsunami deposits found on the northern coast of Tenerife is that they contain pumice clasts from El Abrigo (Paris et al., 2017). This indicates that the tsunami and, consequently, the landslide that originated it, occurred once the eruption had ended or whilst it was still underway and the pumices were already deposited and floating on the surface of the sea.

An avalanche breccia, known as "Mortalón", with an inclination of 9.42° in Icod (Iribarren, 2014) and interpreted by Bravo (1962) and Coello (1973) as an old breccia deposit generated by previous mass wasting processes affecting the basaltic shield and the beginning of the construction of the Las Cañadas edifice, is thought in fact to represent the décollement surface for both La Orotava and Icod landslides.

Hürlimann et al. (2000) proposed adjacent and shallow seismic shocks caused by the seismogenic slip on the ring fault originated by the caldera collapse as the main driving forces triggering the large-scale subaerial slope failure; such shocks are capable of applying faster and more dynamic stress to slopes than other mechanisms such as dike intrusion (e.g., McGuire et al., 1990; Voight & Elsworth, 1997) and the inflation and deflation of the magma chamber (e.g., Lo Giudice & Rasa, 1992). According to stability analyses, an unstable state is reached for a seismic shock with a horizontal acceleration over 0.3 g. Assuming a magnitude of 5.0 for a seismic shock related to the caldera collapse at a distance of 5 km, a maximum horizontal acceleration coefficient (PHAC) of 0.29 would be generated (Hürlimann et al., 2000). Comparing these results with other observational data from some recent calderas (e.g., Abe, 1992; Alvizuri et al., 2020; Filson et al., 1973; Riel et al., 2015), a Mw magnitude of 5–7.2 is required for seismic shocks to have triggered the Icod landslide (Hürlimann et al., 2000).

3. Methodology

To conduct the multi-hazard assessment corresponding to a hypothetical repetition today of the same succession of events that took place on Tenerife about 0.18 Ma, it is necessary to simulate scenarios that reproduce all the volcanic and associated hazards that occurred during the caldera-forming eruption of El Abrigo. This will help predict which areas could be affected by each of these processes. The objective was to combine freely available models and commercial software with Geographic Information Systems (GIS) to model and analyze the various potential hazards and so identify their current potential extent and impact. According to the succession of events deduced from the geological record and, in particular, from the inland stratigraphy (Martí, 2019), the following hazards need to be simulated: pyroclastic density currents (PDC), seismicity, landslide and tsunami. Ash fallout has not been identified on Tenerife in association with El Abrigo eruption (Pittari, 2004), although it is likely that a considerable co-ignimbrite ash cloud developed during the emplacement of the ignimbrite from El Abrigo. Nevertheless, no data exist to indicate its size or extent and so this hazard has not been modeled.

PDC simulations were conducted using VORIS 2.0.1. (Felpeto et al., 2007, available at http://www.gvb-csic.es/GVB/VORIS/VORIS.htm), a GIS-based tool for volcanic hazard assessment that includes several simulation models. The PDC simulation model used is based on the Energy Cone model (Malin & Sheridan, 1982; Sheridan & Malin, 1983) and the modification by Toyos et al. (2007), and is able to calculate the runout, velocity and dynamic pressure of pyroclastic flows. Simulations of the Peak Ground Acceleration (PGA) caused by seismicity induced by caldera collapse were performed automatically using a plugin developed by Núñez (2017) implemented in the Geographic Information System QGIS, 2.14 version. Landslide simulations were conducted using the commercial software SLIDE, developed by Rocscience Inc. (Rocscience Inc., 2020, https://www.rocscience.com/software/slope-stability) for slope stability analyses. Finally, the tsunami was simulated using VolcFlow (Kelfoun & Druitt, 2005)

As input parameters for all these simulations the current topography of Tenerife consisting of a 50-m resolution Digital Elevation Model provided by the National Geographic Institute (IGN, www.ign.es) was used, in combination with the digital bathymetry around the Canary Islands at the same resolution generated by the Spanish Institute of Oceanography (IEO, www.ieo.es). Given that one of the objectives was to reproduce the extent of the ignimbrite deposited after El Abrigo that nearly buried the whole island of Tenerife (Pittari, 2004; Pittari et al., 2008), up to seven different collapse equivalent angles (a_c) (4° — for base surge explosions —, 7°, 11°,15°, 19°, 23° and 27° — for column collapse phases —) (Sheridan & Malin, 1983), and a collapse equivalent height (H_c) of 2,000 and 3,000 m, respectively, were considered in a trial and error application of the PDC simulation model. All the simulations were conducted assuming a single eruptive area located in the current crater of Mt Teide.

Following Núñez (2017), the geological units represented on the geological map GEODE 1:25000 from Tenerife (2913 zone) (Bellido-Mulas et al., 2014) were classified in six groups to elaborate a seismic amplification map of Tenerife (Supporting Information S1), according to the methodology developed by Borcherdt (1994) (more information in Text S1). We assumed that the seismic shocks triggered by a caldera collapse have their hypocenters along the ring faults that control the vertical movement of the block that is collapsing. It is also well known that the position and extent of a collapse caldera are limited by the position and extent of the associated magma chamber (Folch & Martí, 2009; Martí, Ablay, Redshaw, & Sparks, 1994; Martí et al., 2008). For this reason, the position of the hypothetical magma chamber in the case simulated here will determine the position of the ring faults and hence the position of the possible hypocenters and/or epicenters. The magma chamber at the time of El Abrigo eruption is assumed to have had a total volume of at least 20 km^3 (this is the minimum erupted volume; Martí, Mitjavila, & Araña, 1994; Pittari, 2004), to have been about 5 km in diameter given the size of the resulting depression (Coppo et al., 2008; Martí, Mitjavila, & Araña, 1994), and to have been located about 4 km below surface at the time of the eruption (Andújar et al., 2008). Two positions for the magma chamber were assumed in our simulations (Figure 2) and three hypocenters were considered for each epicenter given current topography and the depth of the magma chamber (Figure 2), which thus give rise to a total of six possible locations for the seismic focuses. For each focus, three moment magnitudes (*Mw*) were used (*Mw* = 5, 6, and 7), values that are within the observed common range for these type of eruptive seismic shocks (Hürlimann et al., 2000). Finally, the simulation of the seismic scenarios was performed by applying three attenuation laws following our geotechnical classification of materials. All of the input parameters are shown in Table 1.

By taking into account the estimated earthquake magnitudes that could have triggered the Icod landslide (Hürlimann et al., 2000), slope stability simulations were carried out considering the current topography, stratigraphy and geotechnical properties. We used SLIDE (Rocscience Inc., 2020), a 2D limit equilibrium slope stability program, to evaluate the Factor of Safety (FS) or probability of failure, of circular or non-circular failure surfaces on soil or rock slopes. This program uses different limit equilibrium methods designed to investigate the equilibrium of a soil or a rock mass tending to slide down under the influence of gravity. These methods compare forces, moments, or stresses resisting movement of the mass for a given geotechnical configuration, with disturbing forces, such as those produced by an earthquake. As a result, the program calculates the FS of the slope and reveals the most probable slip surfaces. Two simplified contrasting models (Model 1, Figure 3a and Model 2, Figure 3b) based on the cross-sections drawn by Carracedo et al. (2007),

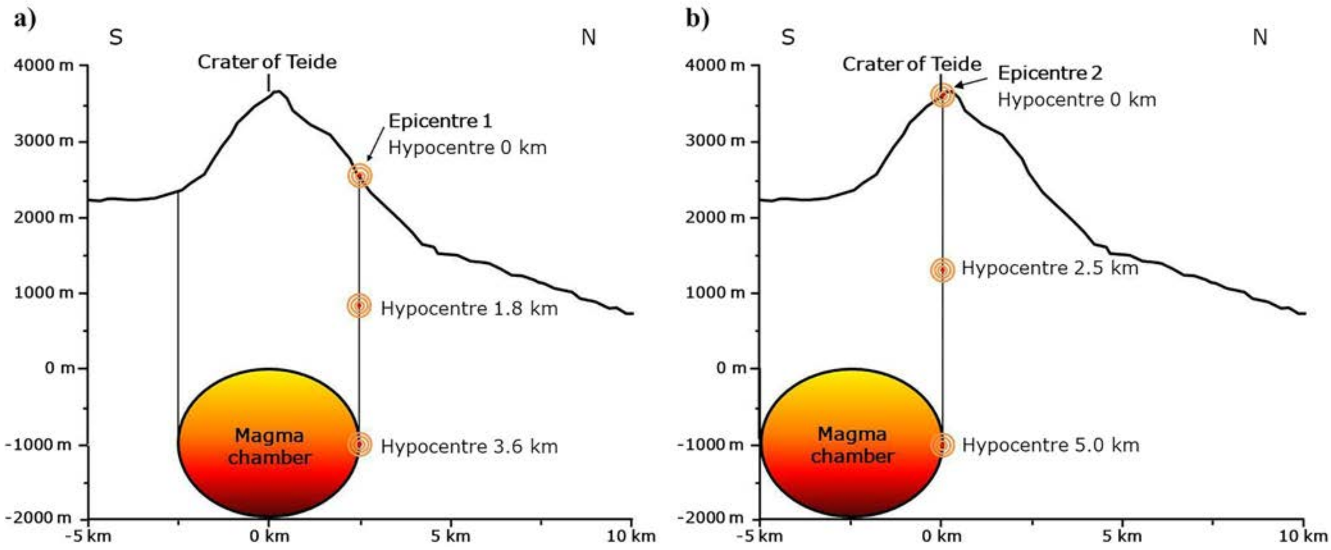

Figure 2. Simplified cross section of Mt Teide (S–N) showing the two presumed positions of the magma chamber (>20 km^3, 5-km wide, 4-km deep) and their respective epicenters and hypocenters proposed for the earthquake simulations: (a) a magma chamber located just below the crater of Mt Teide and (b) a magma chamber displaced to the south whose the northern limit would be below the crater. The line corresponding to this cross-section is part of the red line I-I′ shown in Figure 1.

Marrero (2010) and Martí (2019) were designed to evaluate the stability of the northern slope of Tenerife according to the geotechnical classification of volcanic materials in Del Potro and Hürlimann (2008).

In order to simplify the model, infinite strength was assumed for fresh lavas from the basaltic shield as there was no landslide after the formation of the Las Cañadas edifice. Thus, these lavas represent a slip surface "exclusion zone" through which slip surfaces cannot penetrate. The Drained-Undrained option was used for both the "Mortalón" and the Las Cañadas edifice intracaldera materials, as it defines a soil strength envelope that considers both drained and undrained Mohr-Coulomb strength parameters, that is, effective and total parameters, for materials whose response to a seismic shock is unknown. For the rest of units considered as "rocks" (including the altered lavas from Mt Teide, which were characterized as an intermediate material between rock and soil based on their geotechnical characteristics), the Generalized Hoek-Brown strength criterion was applied, which works well for most rock masses of reasonable or low quality in which the rock mass strength is controlled by tightly interlocking angular rock pieces (Rocscience Inc., 2020). All inputs of geotechnical parameters are shown in Table 2.

The SLIDE software package enables different methods of vertical slice limit equilibrium analysis to be applied. These methods discretize the soil or rock mass above the assumed failure surface into vertical slices or columns with equal widths. In each column, force and moment equilibrium are held, at the same time that internal forces due to the interaction between the slices are considered. For this study, only three methods were used since Rocscience Inc. recommends that the others are not used as they do not fit the reality of our case of study: Bishop's simplified method, which satisfies only moment equilibrium and considers interslice

Table 1
Input Parameters for Peak Ground Acceleration Simulations

Epicenter 1		Epicenter 2			
Location	Hypocenters	Location	Hypocenters	*Mw*	Attenuation laws[a]
lat = 28.294332°	0 km	lat = 28.272319°	0 km	5	Pétursson and Vogfjörd (2009)
lon = −16.650575°	1.8 km	lon = −16.642437°	2.5 km	6	Ágústsson et al. (2008)
	3.6 km		5 km	7	Beauducel et al. (2004)

[a]Núñez (2017) states that the most accurate attenuation laws for Canary Islands are those given by Ágústsson et al. (2008), Beauducel et al. (2004) and Pétursson and Vogfjörd (2009) since they were built using accelerations observed in Iceland and on the island of Guadalupe, which are also volcanic environments.

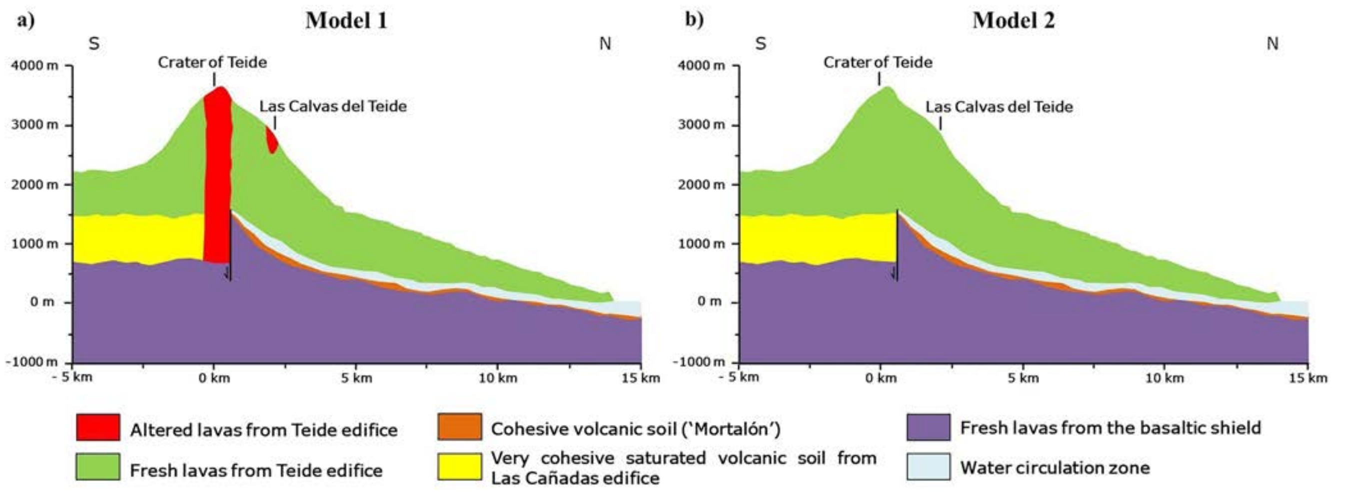

Figure 3. Simplified geotechnical S–N cross-sections in the north of Tenerife proposed for the slope stability analysis. (a) Model 1 considers alteration zones shown in red; (b) Model 2 does not consider alteration zones. See red line I–I' in Figure 1 for the line of the S–N cross-section. Based on Carracedo et al. (2007), Marrero (2010) and Martí (2019).

Table 2
Input Parameters for SLIDE Software

Parameter	Geotechnical units: Fresh lavas from the basaltic shield	Las Cañadas collapsed material	Mortalón	Water circulation zone	Fresh lavas from Mt Teide	Altered lavas from Mt Teide
Type	Rock	Soil	Soil	Rock	Rock	Rock/Soil
Strength criterion	Infinite strength	Drained-Undrained	Drained-Undrained	Gen. Hoek-Brown	Gen. Hoek-Brown	Gen. Hoek-Brown
Unit weight (kN/m^3)	24.6 ± 2.3[a]	14.9[a]	17.1 ± 2[a]	22.6[b]	24.6 ± 2.3[a]	22.2 ± 3[a]
Saturated unit weight (kN/m^3)	-	16.9[c]	21[c]	24.6[c]	24.6[c]	23.6[c]
Effective angle of internal friction (ϕ) (°)	-	35[d]	20[d]	-	-	-
Undrained cohesion (Cu) (kg/cm^2)	-	0.1[c]	0.7[e]	-	-	-
Effective cohesion (c') (kg/cm^2)	-	0.01[f]	0.13[g]	-	-	-
Uniaxial Compressive Strength (UCS) (MPa)	-	-	-	55[h]	65[j]	30[d]
Geological Strength Index (GSI)	-	-	-	25[i]	35[i]	20[i]
m_i	-	-	-	15[i]	15[i]	14[i]
m_b	-	-	-	1.03[i]	1.472[i]	0.804[i]
s	-	-	-	0.00024[i]	0.00073[i]	0.00013[i]
a	-	-	-	0.313[i]	0.5159[i]	0.5437[i]

Note. Error margins were ignored during simulations to simplify calculations. m_i is a material constant for intact rocks. m_b, s and a are rock mass material constants.

[a]Del Potro and Hürlimann (2008). [b]Assumed using geological-geotechnical criteria. [c]Assumed using geological-geotechnical criteria based on the geological description in Del Potro and Hürlimann (2008). [d]Considering conservative values from Hernández-Gutiérrez and Santamarta (2015) and assumed using geological-geotechnical criteria. [e]Weighted average from values provided by Uriel and Serrano (1975). [f]c'/Cu ratio = 0.1 (Rocscience Inc., 2020). [g]c'/Cu ratio = 0.186 (Rocscience Inc., 2020). [h]Conservative values from those recommended by González de Vallejo et al. (2002) for intact rock from this type of material. [i]Recalculated with RocData software (Rocscience Inc., 2020) under geological-geotechnical criteria. [j]Arithmetic mean of the mean values of the simple compression tests corresponding to the basaltic type lithotypes from Hernández-Gutiérrez and Santamarta (2015), from a conservative perspective in terms of risk.

Table 3
k_h Values for the Selected Accelerations of Gravity According to the Pseudo-Static Analysis Criteria

	k_h		
Acceleration of gravity values (g)	Noda and Uwave (1976)	Marcuson (1981)	Saragoni (1993)
0.1	0.1	0.03	0.03
0.20	0.20	0.07	0.06
0.67	0.29	0.22	0.19
3.35	0.49	1.11	0.33
0.12	0.12	0.04	0.04
0.49	0.49	0.16	0.15
0.19	0.19	0.06	0.06
0.61	0.28	0.20	0.18
3.04	0.48	1.00	0.32
0.48	0.26	0.16	0.14
Extra value of k_h	0.13		

Note. PGA values in bold text were obtained from PGA simulations using Epicenter 1 (Figure 2a); underlined values in bold were obtained using Epicenter 2 (Figure 2b); the remaining values coincided with both epicenters.

shear forces as zero (Bishop, 1955); Janbu's Generalised method, which satisfies only force equilibrium but also considers interslice shear forces as zero (Janbu, 1973); and Morgenstern-Price method, which satisfies both moment and force equilibrium and considers variable interslice shear forces (Morgenstern & Price, 1965).

A static analysis was performed for both contrasting geotechnical models by applying the previous analytic methods to obtain the FS prior to an earthquake. Then, a pseudo-static analysis was performed for both models using the same methodology to analyze slope stability under seismic conditions. Since we were unable to simulate the whole caldera collapse process to determine how the seismicity produced by friction along the ring fault affects the Icod valley at each moment, we simulated the two extreme stages: at the beginning of the collapse, when the edifice is practically intact but some friction is occurring and so some seismic shocks are generated, and at the end, when the collapse is almost over and so the seismicity generated by the friction is about to end. Nevertheless, we are aware that the landslide could have occurred at any time during the collapse process and, although we do not know exactly when, we know from the stratigraphy that it occurred after the ignimbrite was emplaced. Hence, a third pseudo-static analysis was performed for Model 1 excluding the central part of the Mt Teide volcanic edifice. This simulated a collapse of that sector into the magma chamber during the formation of the caldera to test the slope stability of the Icod valley at the end of the collapse process. To do so, we used Model 1 as an input file for SLIDE software, but renamed it as "Model 1 Bis", and assumed the existence of a magma chamber located just below the crater of Mt Teide corresponding to the configuration shown in Figure 2a. To achieve this, we moved one of the limits of the calculation zone considered by SLIDE 2.5 km to the north of the crater and restricted the calculation of the FS to the portion corresponding only to the Icod valley since it would not have any mass behind its head zone.

A total of 10 different maximum values of acceleration of gravity (g) were taken from the results obtained from the PGA simulations, and three formulas–those of Marcuson (1981) (1), Noda and Uwave (1976) (2) and Saragoni (1993) (3)—were applied to each PGA value to obtain 22 different horizontal seismic coefficient (k_h) values used in the SLIDE pseudo-static analysis.

$$k_h = \frac{0.33 * a_{\max}}{g} \tag{1}$$

$$\begin{aligned} k_h &= \frac{a_{\max}}{g} && \text{If } a_{\max} \le 2\, m/s^2 \\ k_h &= 0.33 * \left(\frac{a_{\max}}{g}\right)^{0.33} && \text{If } a_{\max} > 2\, m/s^2 \end{aligned} \tag{2}$$

$$\begin{aligned} k_h &= 0.3 * \frac{a_{\max}}{g} && \text{If } a_{\max} \le 6.6\, m/s^2 \\ k_h &= 0.22 * \left(\frac{a_{\max}}{g}\right)^{0.33} && \text{If } a_{\max} > 6.6\, m/s^2 \end{aligned} \tag{3}$$

where $a_{\max}$ is the PGA as a fraction of the acceleration of gravity on Earth (g), and $g = 1$ in these formulas (Gutiérrez, 2017).

These 10 PGA values (Table 3) were selected after filtering the results from previous seismicity simulations (Tables S2 and S3); the variable "depth" was eliminated as PGA values did not vary with depth, as were all results for $Mw = 7$ since this magnitude is outside the range of applicability of the three attenuation laws, but it was tested as an upper limit. Repeated values were selected only once. The input seismic values for simulations are shown in Table 3. An extra value of $k_h = 0.13$ for Model 1 was included after a trial and error analysis to search for the limit at which all three methods of analysis show slope instability. This was not necessary for either Model 2 or Model 1 Bis since the limit was found at $k_h = 0.15$ and $k_h = 0.29$, respectively, which were two of the previously selected values from PGA results. According to Eurocode 7 (AENOR, 2016) and the Basic Document on Structural Safety (DB-SE) of the Technical Building Code (CTE) (Ministerio de Fomento, 2006), a minimum FS of 1.5 is required for slope stability in static and permanent conditions, and 1.1 for seismic and permanent conditions. Below these values, the slope is considered unstable. However, a lower FS limit is known to be sometimes more suitable for big landslides/slopes or for slope stability analysis different than those made for building security. Thus, we determined unstable conditions when FS < 1, and short-term stable conditions when FS values were 1–1.5 after considering the geotechnical configuration of the sector of the island selected and the possible margin of error in our parameter selection.

According to the geological record, the powerful tsunami was the final event of the chain of cascading multi-hazards in this case study. A simulation of the tsunami was generated with the two-fluids version of VolcFlow (Kelfoun et al., 2010), which can simulate both an avalanche and an associated tsunami. VolcFlow is a finite difference Eulerian code based on a depth-averaged approach. It runs inside MATLAB and solves depth-averaged equations of mass and momentum using a topography-linked coordinate system in time and space. First, the area covered by the landslide was drawn using Surfer software, keeping approximately the limits of the sliding mass obtained with SLIDE, and then entered as a numerical code in a TIF file, along with the bathymetry file in a Surfer Grid format. A maximum thickness of 500 m for the sliding block was considered, since it is approximately the thickness of the sliding mass obtained with SLIDE during the simulation of the landslide in this study. This thickness coincides with the average thickness of the current fill of the Icod valley from the surface to the "Mortalón" layer (Figure 3), which is taken to be the decóllement surface of the last mega-landslide (Bravo, 1962). Following Kelfoun et al. (2010), the rheology of the sliding material was defined by a density of the avalanche block of 2,500 kg/m^3 (Del Potro & Hürlimann, 2008). This approximately coincides with the one used for the geotechnical unit of the fresh lavas from Teide, which occupies most of the sliding mass, as it was seen during the landslide simulation. Two different values were also used for the constant retarding stress that is equivalent to the cohesion of rocks or to a yield strength (50,000 Pa and 100,000 Pa, reasonable values determined by Kelfoun & Druitt, 2005, and Kelfoun et al., 2010). This rheology was obtained by comparing the results of the model with natural deposits (Kelfoun & Druitt, 2005; Kelfoun et al., 2010). A dynamic viscosity of water of 0.001137 Pa · s and a density of water of 1,025 kg/m^3 were also assumed.

4. Results

In all, 277 different eruptive scenarios were obtained from the simulations performed for the four extreme hazards selected for this study, and they are all included in Supporting Information S1.

4.1. PDC Scenarios

In all, 14 scenarios were obtained by combining up to seven different values for a_c and two different values for H_c. The PDC map scenarios are shown in Figures S2–S15, and an example is shown as well in Figure 4; numerical results and implications are summarized in Table S1.

Results show that as the a_c decreases, the surface area covered by PDC deposits increases. PDCs scenarios obtained here go from the whole affectation of the island of Tenerife, produced by an a_c of 4°, regardless the H_c, to a minimum affected area of almost 200 km^2 and just over 300 km^2 concentrated around the vent, corresponding to the area of Las Cañadas caldera and surroundings, produced by an a_c of 27° and an H_c of 2,000 m. Between these two extremes, there is a wide range of results in terms of surface area covered and municipalities affected by ignimbrite that deserves to be taken into account (see Table S1). Changes in two or three degrees of a_c, or in 1,000 meters of H_c, result in a variation of some hundreds of square kilometers affected.

It is observed that the Las Cañadas wall, a natural barrier for some volcanic hazards, such as lava flows, would stop the PDCs produced by a column collapse with an a_c equal or higher than 27° and an H_c of 2,000 m or less. In case an H_c of 3,000 m occurred, an a_c above 27° should occur so that the PDC would not

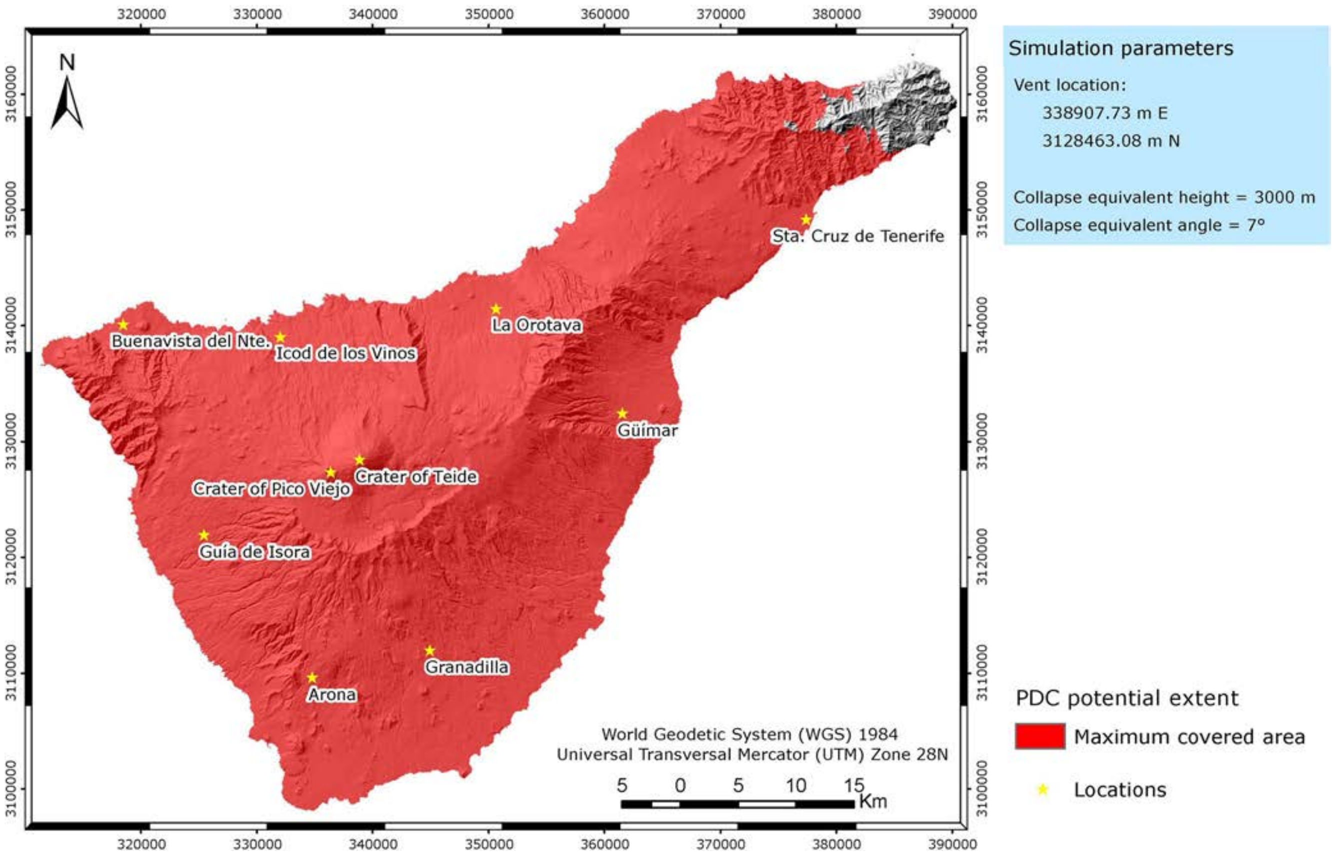

Figure 4. Pyroclastic Density Current map scenario considering H_c = 3,000 m and a_c = 7°, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

exceed the limits of the central caldera. As there is no caldera wall towards the north, the most affected area after the Las Cañadas caldera is the Icod Valley.

Beyond this central topography, other topographic features, such as valleys, other cones, lava walls, basaltic shield remnants, could channel or act as barriers for pyroclastic flows, but this is observed in few more distal areas.

4.2. PGA Scenarios

In all, 54 scenarios were obtained combining three moment magnitudes (*Mw*), two different epicenters, each with three different hypocenters, and three attenuation laws. The maps of the expected PGA values are shown in Figures S16–S69, along with an example in the main text (Figure 5). Tables S2 and S3 summarize all the results.

Both epicenters give similar gravity acceleration values, even coinciding in some cases. Likewise, the modification of the hypocenter does not imply any change in these values. Only a slight increase in the expected PGA in cm/s^2 is observed as the hypocenter depth increases when applying the Beauducel et al. (2004) attenuation law, but these minor differences are eliminated when transforming the values into acceleration of gravity (g) units. The main differences in the expected PGA results are due to the *Mw* of the earthquake, but also to the chosen attenuation law.

Considering that a lower *Mw* would give a lower PGA, the lowest expected PGA values were obtained by applying the Pétursson and Vogfjörd (2009) attenuation law. In this case, PGA values go from 0.10 g (in case of both epicenters) to 0.29 g (in case of epicenter 1). At the other extreme, the highest expected PGA values, keeping all other parameters unchanged, were obtained after applying the Ágústsson et al. (2008)

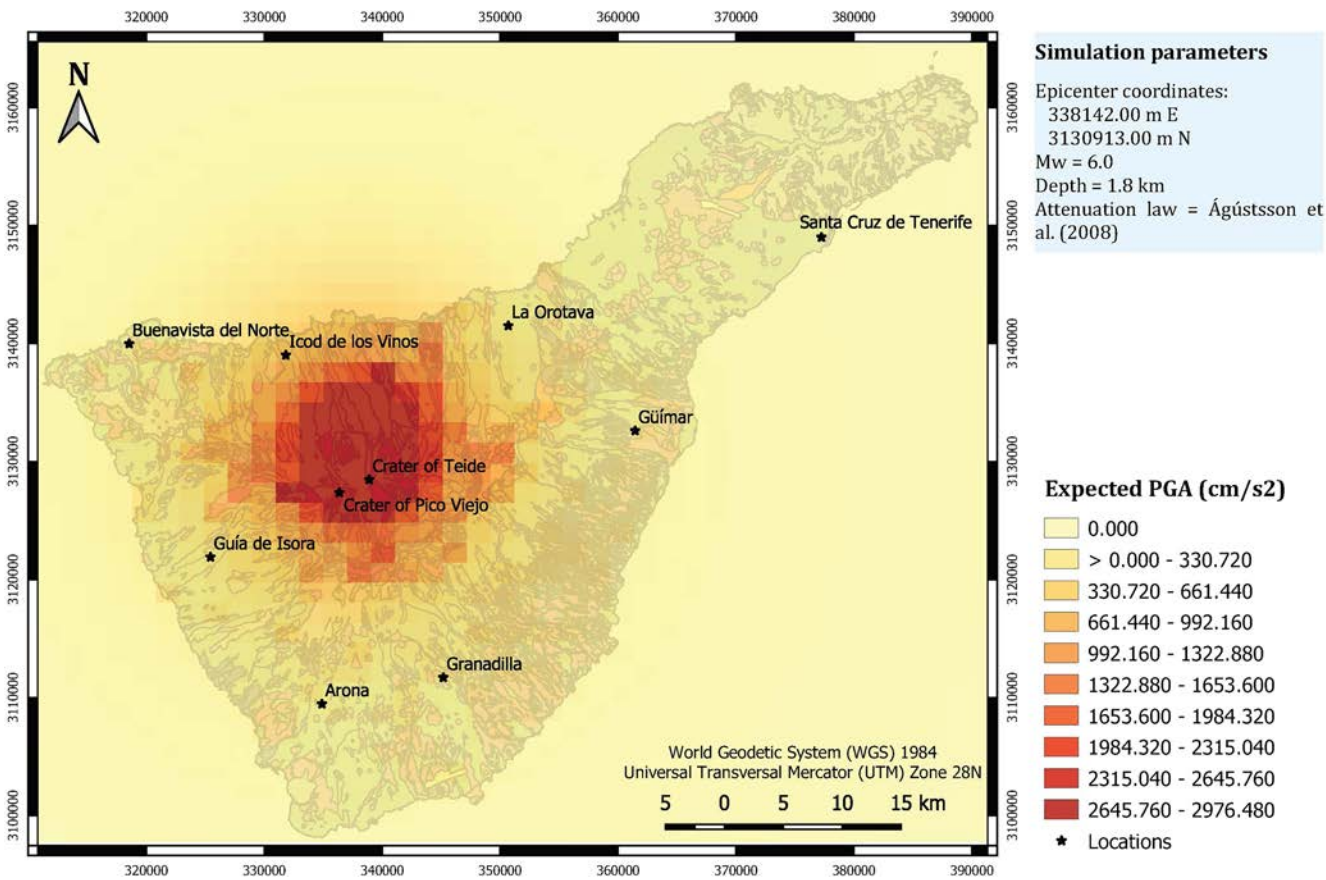

Figure 5. Expected Peak Ground Acceleration values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Ágústsson et al. (2008) attenuation law.

attenuation law. Thus, the lowest PGA value is 0.61 g (in case of epicenter 1), while the highest is 13.21 g (in case of epicenter 2). Therefore, the choice of one attenuation law or another, and of one epicenter or another, can vary the expected PGA value for the same *Mw* by up to 12.93 units.

Between these mentioned extremes, there is also a wide range of scenarios, not only in terms of maximum expected PGA values (Tables S2 and S3), but also in terms of ground response distribution (see Figures S16–S69). Deleting the depth variable, which has no influence on the results in this case, a total of 9 different scenarios were obtained per epicenter by combining only three *Mw* with the selected three attenuation laws. In case we could remove the attenuation law variable, if we would be able to know which one best suits the terrain of Tenerife, results would be reduced to one possibility per *Mw* and per epicenter. However, despite having selected only three different *Mw* for this study, the proposed range was between 5 and 7, a range that already includes multiple options and associated scenarios.

Apart from these results, the scenarios reveal that the areas most affected by the different earthquakes generated in this study are, in this order, the Las Cañadas caldera and its walls, the Icod valley, the NW and NE rift zones, and the area corresponding to Bandas del Sur, in the southeast of the island.

4.3. Landslide Scenarios

A total of 207 simulations was performed, six using a static analysis and 201 with a pseudo-static analysis, by applying the input parameters introduced previously to the three considered geotechnical models. The results of the slope stability analysis are shown in Figures S70–S276, and an example is given here in Figure 6; the FS values are summarized in Tables S3–S8.

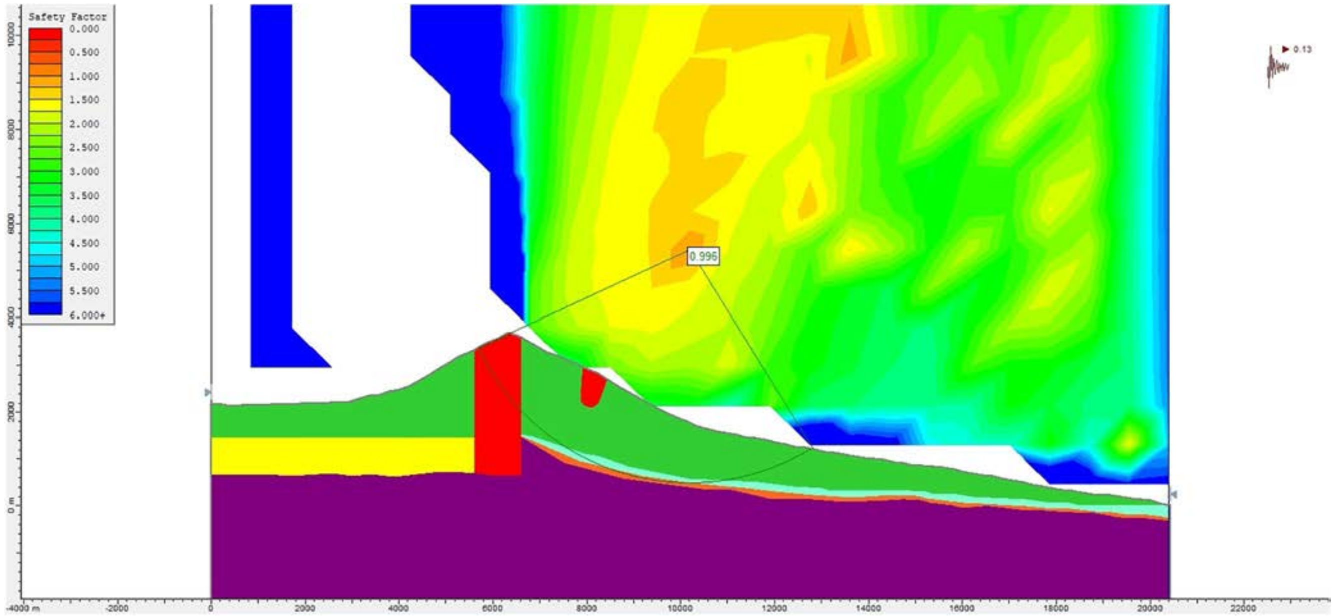

Figure 6. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 3a) using the Morgenstern-Price method and a k_h of 0.13. *x* axis corresponds to the distance in meters, with the 0 located at southern limit of the cross section represented in line I-I′ shown in Figure 1, and *y* axis shows the altitude. The colors shown in the cross section correspond to the geotechnical units used for Model 1 and coincide with those represented in Figure 3. Colors appearing above the cross section correspond to the Factor of Safety (FS) for each area of the diagram, shown as a mirror of it. The semi-circular shape corresponds to the most probable slip surface and its FS is shown in the box, which in this case is 0.996.

All static analyses carried out for both geotechnical models give FS above 1 but below 1.5 (see Tables S4 and S5), what means that both geotechnical configurations can be considered stable under steady state conditions, that is, no earthquake. However, FS values are lower for Model 1, which has alteration zones compared to Model 2. This also holds true during pseudo-static analyses, which means that under both steady state and seismic conditions, Model 1 is slightly more unstable than Model 2 due to the presence of altered materials, which increases the instability of the area.

Under seismic conditions, the pseudo-static analyses show that Model 1 becomes unstable (FS < 1) at a minimum k_h of 0.1, while a minimum k_h of 0.12 and 0.28 is required for Model 2 and Model 1 Bis, respectively. This is true in case the Janbu Generalised method is applied (also Bishop simplified in case of Model 1 Bis, see Table S8), but from the results obtained it is clear that this value, which would mark the minimum required to generate instability (FS < 1) in the studied slope, varies from one method to another, requiring a higher k_h and, thus, a higher *Mw*, in case the other methods are applied to each model. This fact means that, in this study, at least three different seismic scenarios of minimum k_h required to generate instability could exist for each model. Knowing which method and which geotechnical configuration best fits the portion of the studied island, these seismic scenarios would be reduced to one.

However, even with a single minimum k_h value, there are still multiple earthquakes that could give this value. This is because if we undo the formulas of Marcuson (1981), Noda and Uwave (1976) and Saragoni (1993), applied before, to know the PGA capable of giving that value of k_h and, in turn, compare which *Mw* could generate that PGA, we find multiple possible seismic scenarios (see Table 4, where the minimum values of k_h discussed above have been taken as an example). This is also influenced by the location of the epicenter, as we can see in Table 4 for a PGA of 0.61 g in case of Model 1 Bis.

The generated scenarios also show the most probable failure surfaces as semicircular lines affecting the slope, with the associated FS in a box (see Figure 6). These slip surfaces show a rotational movement of the sliding block, the head of which is located south of the crater of Mt Teide in Model 1 (Figure 6) and 2. For Model 1 Bis, the head of the sliding block is located north of the Las Calvas del Teide alteration zone. For higher values of k_h these semicircular sliding surfaces become more open and wider and the head of the landslide moves northwards (see Figure S70–S276).

Table 4
Equivalences Between the Minimum Instability Values of Horizontal Acceleration (k_h) for Each Geotechnical Model and the Corresponding Peak Ground Acceleration and Mw Values

k_h	PGA	M_w
Model 1		
0.1	0.1 g (Noda & Uwave, 1976)	5.0 (Pétursson & Vogfjörd, 2009) <5.0 (Ágústsson et al., 2008) <5.0 (Beauducel et al., 2004)
	0.3 g (Marcuson, 1981) 0.33 g (Saragoni, 1993)	>7.0 (Pétursson & Vogfjörd, 2009) <5.0 (Ágústsson et al., 2008) >5.0 and <6.0 (Beauducel et al., 2004)
Model 2		
0.12	0.12 g (Noda & Uwave, 1976)	>5.0 and <6.0 (Pétursson & Vogfjörd, 2009) <5.0 (Ágústsson et al., 2008) 5.0 (Beauducel et al., 2004)
	0.36 g (Marcuson, 1981) 0.4 g (Saragoni, 1993)	>7.0 (Pétursson & Vogfjörd, 2009) <5.0 (Ágústsson et al., 2008) >5.0 and <6.0 (Beauducel et al., 2004)
Model 1 Bis		
0.28	0.61 g (Noda & Uwave, 1976)	>7.0 (Pétursson & Vogfjörd, 2009) 5.0 (<5.0 for an epicenter located on the crater) (Ágústsson et al., 2008) >5.0 and <6.0 (Beauducel et al., 2004)
	0.85 g (Marcuson, 1981)	>7.0 (Pétursson & Vogfjörd, 2009) >5.0 and <6.0 (Ágústsson et al., 2008) >6.0 and <7.0 (Beauducel et al., 2004)
	2.08 g (Saragoni, 1993)	>7.0 (Pétursson & Vogfjörd, 2009) >5.0 and <6.0 (Ágústsson et al., 2008) >7.0 (Beauducel et al., 2004)

Note. These equivalences are made with the minimum value of horizontal acceleration (k_h) at which each geotechnical model showed instability (FS < 1) after the analysis with SLIDE. Also shown are the PGA and *Mw* values after reversing the three previously applied formulas (Marcuson, 1981; Noda & Uwave, 1976; Saragoni, 1993) to each k_h and checking the possible ranges of the *Mw* causing these values.

All the slip surfaces generally reach the depth of the limit between the water circulation zone unit and the "Mortalón", the latter being unaffected or only slightly affected by the potential landslide. The average maximum thickness of the potential sliding block for all models is around 500 m, but it is reduced to 300 m in case of Model 1 Bis for high k_h values.

4.4. Tsunami Scenarios

Two simulations were obtained by combining two different values for the constant retarding stress or yield strength. Tsunami simulations are shown in Movies S1 and S2, which correspond to a simulation made with a yield strength of the sliding block of 50,000 Pa and 100,000 Pa, respectively. Four different stages of the tsunami propagation are shown in Figure 7.

Both simulations give a first tsunami wave of about 200 m in height traveling northwards (Figure 7a). However, the amplitudes obtained along the affected coasts outside the impact zone are higher and slightly faster for the 100,000 Pa than for 50,000 Pa simulation. Therefore, the choice of one yield strength for the sliding block or another would vary the arrival time of the waves by about 10 s and the maximum amplitude recorded on the affected coasts by up to 50 m. In both cases, the northern and western coasts of Tenerife, the eastern coasts of La Palma and the northern coasts of La Gomera are the most affected areas of the archipelago.

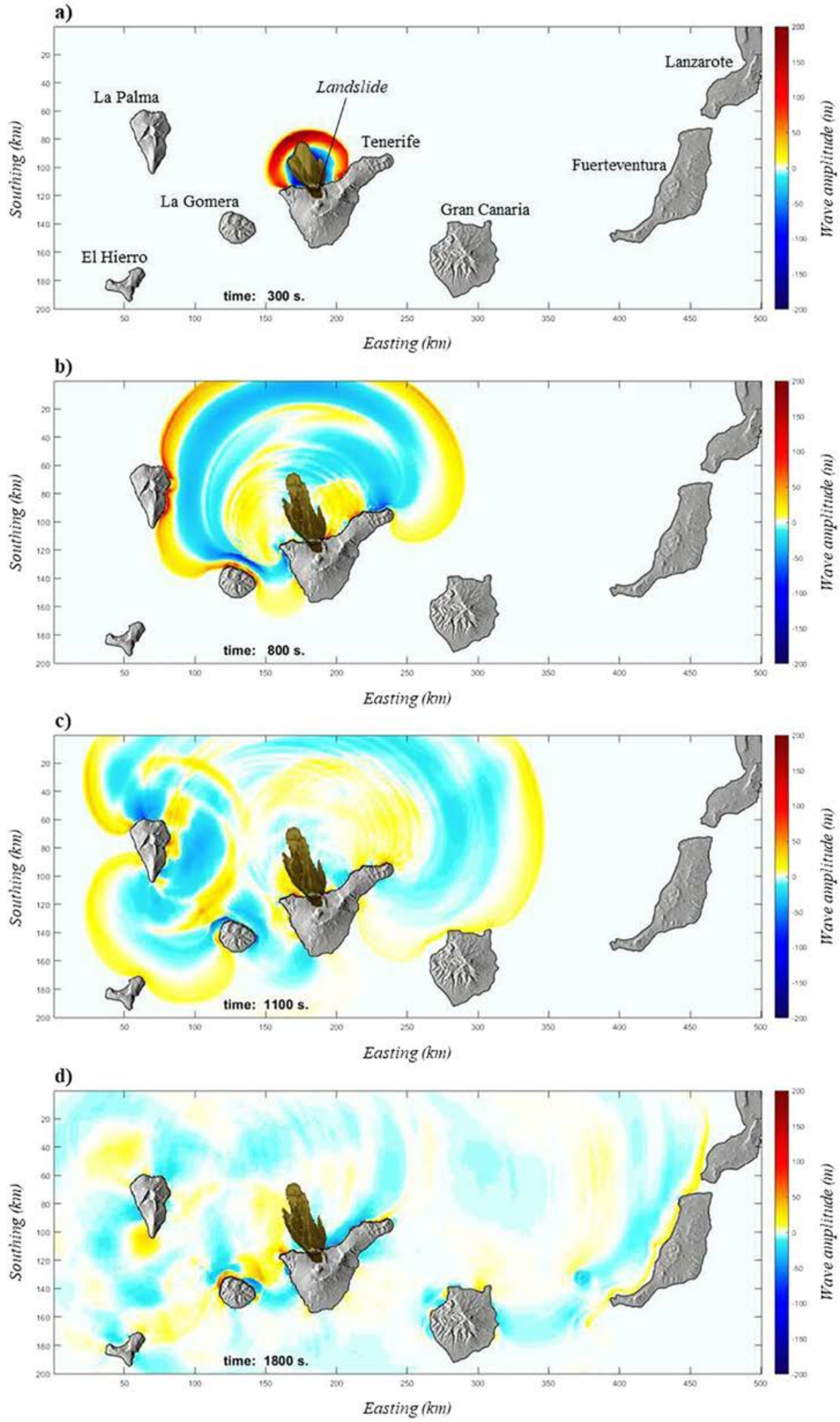

Figure 7. Simulation of the propagation of the tsunami caused by the impact of a landslide originating in the Icod valley on the ocean, with a yield strength of the sliding block of 50,000 Pa.

Considering the simulation made with 50,000 Pa, we observe that the northern coast of Tenerife is wholly affected within 580 s with a maximum amplitude of around 100 m; the exception is the municipality of Los Silos, where waves reach almost 200 m in height. This coast is hit up to nine times by waves originating from the impact of the sliding block on the ocean and by reflected waves originating after the initial impact on the eastern coast of La Palma. The western and the eastern coasts of Tenerife are completely affected after 840 s and 1,300 s. The western coast registers a maximum amplitude of 50 m, which decreases towards the south, while the eastern coast registers around 20 m. Waves coming from both sides of the island are inhibited after meeting along the southern coasts. The southern municipality of Granadilla, on the opposite coast to the landslide site, is affected after 1,070 s by the tsunami originating from the western side of the island, with a maximum amplitude of 10–15 m.

After 700 s, the north of La Gomera is the first site of the other islands of the archipelago to be hit by up to seven waves from around 80–100 m. These waves come both from the impact zone and from other islands after their reflection, especially from La Palma. The last affected island is Lanzarote, which is first hit by waves of about 25 m along its south-west coast after 1,790 s.

After 3,600 s, the ocean is still agitated around the Canary Islands and there are still maximum wave amplitudes of up to 40 m in some places. The least affected areas are the south of Gran Canaria and the eastern coasts of Fuerteventura and Lanzarote.

5. Discussion

Our objective was to identify a past extreme event in Tenerife, whose cascading sequence of hazards is known from the geology and stratigraphy of the island, and to quantify it. What we have done is to look for the most probable scenarios in case this event would be repeated today. However, multi-hazard assessments considering cascading effects are difficult to perform due to the complex relationships that can be established between different hazards, and this is a problem we had to face during this study. The lack of information and data regarding the magnitude and characteristics of each of the studied hazards (e.g., the collapse height of the PDCs, the magnitude of the seismic shocks, etc.) means that we had to work with wide ranges of input parameters. For that reason, the 277 scenarios obtained in this study were statistically analyzed to identify those combinations of parameters for each event, and those combinations of hazard scenarios, whose results best fit what happened during the El Abrigo eruption. Out of this context, all the obtained scenarios could be possible, but only few combinations of them adjust to what we observe in the geological record of the island corresponding to the El Abrigo eruption. These scenarios are discussed here.

Given that the ignimbrite resulting from the El Abrigo eruption covered nearly the whole island, the closest PDC scenario would be a collapse of the eruptive column from a height of between 2,000 and 3,000 m, with a collapse equivalent angle around 7°. In this case, nearly all the island would be hit by PDCs, and only its northeast corner would be unaffected. At the same time, or just after the emplacement of the PDCs, the caldera collapse process would begin. The resulting high magnitude seismicity would severely affect the central part of the island, corresponding to the caldera of Las Cañadas and its walls, the Icod Valley, the NE and NW rifts, and Bandas del Sur in the southeast. From a conservative point of view, and considering both the results from Hürlimann et al. (2000) and our stability analysis, if at the beginning of the collapse seismic shocks produce a PGA of around 0.3–0.33 g, an unstable state of the Icod Valley slope could be reached. Over that range of PGA, a landslide is very probable to be produced in the Icod Valley area. However, if these values of PGA are not reached at the very beginning of the collapse, but they are achieved when the process is more advanced, instability is less likely to occur as a higher PGA is required. In this case, being conservative, a landslide could be produced if a PGA between 0.61 and 0.85 g is reached during the final stages of the caldera collapse process.

The head of the landslide would be located at some point in the northern slope of Mt Teide, depending on the position of the magma chamber, as it controls the extent of the caldera collapse, and would affect an area similar to the last Icod landslide, involving a maximum thickness of 500 m. According to what is observed from the original Icod landslide deposits (Ablay & Hürlimann, 2000; Watts & Masson, 2001), the sliding material would behave as a cohesive avalanche with mega-blocks, whose translational movement towards the sea would produce a 200 m-high tsunami wave in the impact area. The northern coast of Tenerife would be devastated in less than 10 min by waves with heights of around 100–150 m (even 200 m in some places), and the rest of the islands of the Archipelago would be hit by tsunami waves up to 120 m in less than 30 min. These results are in good agreement with the geological evidence represented by the presence of tsunami deposits on the north of the island of Tenerife, at 132 m a.s.l (Paris et al., 2017). This is a reasonable approximation for the 50,000 Pa simulation, which reached 100–150 m on Tenerife. Moreover, the simulation presented also suggests that the propagation of the tsunami waves could progress beyond the limits of the Canary Islands, being potential for the impacts of such an event to be felt far from the source. However, geologic evidence has not yet identified any such distal impacts from past events, so any attempt to identify the distal limits of such tsunami remains speculative by now.

At present, the Tenerife volcanic system is not in a situation similar to that of the last caldera eruption. In fact, reaching the conditions for a caldera-forming eruption may take thousands to hundreds of thousands of years, as it requires generating a sufficient amount of eruptible phonolitic magma, and all the phonolitic eruptions occurred on Tenerife during the Holocene are too small in terms of erupted volume (Martí et al., 2008). At the current stage, the Teide and Pico Viejo complex seems still too young to reach these conditions. However, it is following a very similar evolution than the previous phonolitic cycles, and the succession of events described here is a process that has repeated several times in the past, so it is not inconsistent to consider it might occur again in the future. The occurrence of such a succession of catastrophic events do not define an scenario that can be easily managed, but identifies a possible scenario in which efforts must be invested in forecasting and prevention well in advance. In this sense, increasing the monitoring network and applying high resolution geophysical imaging methods (e.g., magnetotellurics, gravimetry, seismic tomography, etc.) of the interior of the island, able to identify and quantify the presence of fresh magma, would be potential actions to be undertaken.

In this study we have identified and quantified the main processes and characteristics of this type of extreme hazards, which reduces the uncertainty when making decisions in case we encounter a similar event in the future. For this reason, we believe that this multi-hazard assessment could help to suggest guidelines for management, monitoring and urban planning, and should be taken into account by emergency management plans designed for the Canary Islands. Despite the difficulties and the simplicity of the simulation models used, our analysis does provide significant clues that should serve to increase awareness of the potential occurrence and consequences of such large-scale events. Although our analysis could be thought of as a purely academic exercise that merely aims to increase our fund of knowledge, we believe that it will in fact help improving the current emergency management plan (PEVOLCA) by detailing appropriate hazard scenarios and optimizing mitigating actions well before any emergency caused by such extreme multi-hazard events ever occurs.

6. Conclusions

We performed a long-term volcanic multi-hazard assessment of Tenerife to predict the potential extent and impact of extreme events occurring in cascade during a caldera-forming eruption. The resulting scenarios show how large areas could be covered by PDCs (and probably associated ash fall) that would affect the main urban centers and possible evacuation routes. Furthermore, seismicity focused on the central part of the island during a caldera collapse event–that in itself could have catastrophic effects on several parts of the island–could trigger a devastating landslide in the Icod valley and produce a tsunami that would probably have a severe impact not only to the northern and western coasts of Tenerife but also to other coasts of the archipelago. This is probably the most hazardous scenario that can be envisaged for Tenerife. Fortunately, despite being possible, such scenarios only need to be anticipated with recurrences on a geological timescale; however, they should not be ignored. Over the past 1 Ma, Tenerife has experienced a cascading succession of disastrous events several times and the persistence today of the same geophysical conditions that caused them in the past means that their occurrence in the future cannot be ruled out. Therefore, improving current knowledge of the causes and mechanisms of such processes should form part of the emergency plans that are being developed to confront volcanic phenomena in the Canary Islands and other regions with similar potential problems.

Data Availability Statement

Datasets for this research are included in these papers (and their supplementary information files): Andújar et al. (2008), Carracedo et al. (2007), Coppo et al. (2008), Del Potro and Hürlimann (2008), Felpeto et al. (2007), Hernández-Gutiérrez and Santamarta (2015), Hürlimann et al. (2000), Kelfoun and Druitt (2005), Kelfoun et al. (2010), Martí (2019), Martí, Mitjavila, and Araña (1994), Núñez (2017), Pittari (2004), Pittari et al. (2008), Sheridan and Malin (1983).

Acknowledgments
This research was partially funded by the EG grant EVE (DG ECHO H2020 Ref: 826292). Marta López-Saavedra received a CSIC JAE Intro grant (JAEINT 19 01465), and an FPU PhD grant (FPU19/02413). We warmly thank the Editor Isabelle Manighetti, the Associated Editor Michael Poland, and the reviewers (Ricardo Ramalho, and an anonymous referee) for their constructive reviews and comments. We would like to thank Marc Español (CSIC) for his assistance with the computing. The text was reviewed and revised by Michael Lockwood, from Walking Catalonia.

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Article

How Effective Risk Assessment and Management Is the Key to Turning Volcanic Islands into a Source of Nature-Based Solutions

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Abstract: Active volcanic islands are particularly vulnerable to multi-risk natural hazards, many of which are anticipated to become more severe as a result of climate change. It is crucial to create and put into action adequate risk mitigation plans based on comprehensive long-term hazard assessments that include nature-based solutions in order to improve societal safety on these islands. Herein, we study the case of Tenerife. After a compilation and analysis of the potential resources of this island, as well as a study of its main natural hazards and how they are currently managed, we have determined that the most viable solutions are nature-based ones. Land management based on prior assessment of the island's hazards is the key to strengthening Tenerife's current risk mitigation plans. This will allow for a two-way relationship between the exploitation of sustainable tourism and the education of its population, both oriented toward the conservation of its geological heritage, and will promote the sustainable use of the energy and material resources currently being exploited. This contribution thus establishes the pillars from which to exploit the nature-based solutions offered by Tenerife as the only viable option for its sustainable economic development.

Keywords: volcanic islands; multi-hazard risks; risk assessment and management; nature-based solutions; Tenerife

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Citation: López-Saavedra, M.; Martí, J.; Planagumà, L. How Effective Risk Assessment and Management Is the Key to Turning Volcanic Islands into a Source of Nature-Based Solutions. *Land* **2023**, *12*, 686. https://doi.org/10.3390/land12030686

Academic Editors: Thomas Panagopoulos and Vera Ferreira

Received: 15 February 2023
Revised: 10 March 2023
Accepted: 11 March 2023
Published: 15 March 2023

1. Introduction

In modern society, nature-based solutions are necessary to inform policies on biodiversity conservation, climate change adaptation and mitigation strategies, and the sustainable use of natural resources, among other issues [1–4]. They are defined by the European Commission [1] as "actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions, for example, mimicking how non-human organisms and communities cope with environmental extremes". In this sense, they address societal challenges through the protection, sustainable management, and restoration of natural and modified ecosystems, for the benefit of biodiversity and human well-being. They focus on major challenges, such as anthropogenic climate change, disaster risk reduction, food and water security, biodiversity loss, and human health, and are essential for sustainable economic development. Policies such as these should apply to all aspects of society, but they are particularly relevant for volcanic areas, where extreme hazards, natural resources, and socio-economic implications combine.

Active volcanic areas are subjected to the constant threat of eruptions, which may have highly devastating effects. However, they also offer a number of important advantages that have made them so attractive for human settlements throughout history. More than 80 percent of the Earth's surface—including both above and below sea level—is of volcanic origin. Volcanoes are responsible for the magnificent landscapes and fertile soils that provide the essential basis for the development of some of the richest ecosystems on

Earth [5]. Furthermore, they are the source of important energy and mineral resources that remain vital for the development of societies (e.g., [6]). This is even more relevant in our modern globalized society, in which certain technological requirements (e.g., mobile phones, computers, etc.) contain primary elements derived from volcanic products. Volcanoes also offer an unavoidable attraction for nature tourism interested in visiting places where active geological processes can be observed (e.g., [7]). These positive aspects sometimes cause societies living around active volcanos to ignore or underestimate their risks. This disequilibrium between potential economic benefits and the perception of potential risks is often the cause for turning volcanic eruptions into disasters, as the obvious income may reduce the perception of risk to levels at which the necessary prevention and preparedness actions vis-a-vis volcanic threats are simply ignored.

Generally, humans and volcanoes are not incompatible, but living near volcanoes implies knowledge of how they work and, therefore, when they may represent either a risk or a benefit. To minimize the risk from active volcanoes, it is important to first conduct a long-term hazard assessment, which will inform us on the spatial and temporal probabilities of volcanic and associated hazards [8]. This will constitute the basis for correct land use planning in the area toward an adequate risk management plan. It will also permit implementing the necessary mitigation actions and will help those concerned to think about the importance of constraining the potential benefits and their associated risks, prior to a development action plan.

Due to their natural isolation and strong dependence on external supply chains, volcanic islands tend to have fragile economic systems and are thus comprised of highly vulnerable communities, with their main monetary incomes coming from the tourism industry and local economic activities, such as fishing (e.g., El Hierro, Canary Islands, Spain; Iceland) or viticulture (e.g., Pico Island, Azores, Portugal).

Volcanic islands are created by the growth of oceanic volcanoes having evolved and been modified by geological, biological, and human activity. Volcanic islands can be affected by multiple natural hazards; these can be meteorological (e.g., hurricanes or typhoons) or geophysical (volcanic eruptions, earthquakes, landslides, tsunamis, etc.) events, as well as secondary hazards, such as forest fires, droughts, floods, etc., which have been induced by weather and/or volcanic events. In some cases, these can be triggered, amplified, or exacerbated by processes driven by Climate Change (e.g., changes in atmospheric conditions, sea level rise, coastal erosion, glacial melting, etc.). In addition, the continuous demographic expansion of many volcanic islands, caused mainly by the steadily increasing tourism, is a critical factor that exponentially increases the risk in such environments. Moreover, the latest climate models for this century project increases in the number and intensity of storms and hurricanes, as well as significant sea level rise [9]. These phenomena will increase the vulnerability of coastal areas on volcanic islands. These hazards can often act simultaneously or in a concatenated way, leading to unpredictable cascading effects. Such events may not only affect the islands' natural ecosystems, but also may temporarily suspend touristic and local industrial activities in the area (e.g., fishing), leading to serious, and in some cases irreversible, economic contraction.

This contribution explores and determines the potential for establishing nature-based solutions to contribute to disaster risk mitigation strategies and policies that are compatible with economic activities, and which accommodate demographic expansion, future effects of climate change, and sustainable development on volcanic islands. Through the analysis of the volcanic island of Tenerife as a particular case study, we seek alternative solutions for areas with a great geo-conservation and geo-tourism potential. This is especially important for areas that have been abandoned due to their potentially high risk and without considering adequate territorial planning aimed at reducing such risk, while favoring higher economic potential. We propose a series of opportunistic actions for land management, founded on long-term nature-based solutions that will allow increasing resilience against future risk scenarios.

2. Main Geological, Geographic, and Socio-Economic Characteristics of Active Volcanic Islands—Tenerife as a Case Study

Active volcanic islands are located all around the world. Despite the intrinsic direct and indirect hazards associated with them, many volcanic islands are densely populated. This is because of the important benefits associated with volcanoes, which can take the form of rich soils, available energy and mineral resources, and rich landscapes and ecosystems, etc. In recent years, an emerging prosperity associated with active volcanoes has come from tourism, which in many places already represents one of their main incomes. To this end, knowing how volcanoes work and how we can reduce their associated risks is of the utmost importance for preserving the safety of citizens and visitors living near them.

Volcanoes represent the culmination of complex geological processes that involve the generation of magma at depth; its rise, accumulation, and differentiation in shallower reservoirs; and finally, its appearance at the Earth's surface in the form of volcanic eruptions. Eruptions may generate a large diversity of products (lava flows, pyroclastic fragments and deposits, and gases) depending on the characteristics of each eruption (effusive or explosive), and they may also leave signs of its potential future activity in the form of thermal anomalies, fumaroles, hydrothermal alteration, etc. The solid products of volcanism (lavas and pyroclastic deposits) tend to accumulate around volcanic vents, but may also extend to distal regions depending on the magnitude and intensity of the eruption. Depending on the magma composition, most of these products are very rich in chemical components that, when under adequate climate conditions, may transform into fertile soils.

Active volcanic areas—and so, volcanic islands among them—tend to generate very diverse landscapes, which depend on the style of volcanism. These are mostly demonstrated by large and steep stratovolcanoes (composite or polygenetic volcanoes) or relatively flat areas containing a diversity of small volcanic cones and lava fields (monogenetic volcanic fields) [10]. In any case, the landscape is modulated by the presence of this volcanism and subsequent morphological agents (erosion, weathering, sedimentation, etc.), and depending on climate conditions, it will constitute the basis for the development of diverse ecosystems.

Volcanic hazards are inherently complex and, therefore, difficult to predict due to their intrinsic multi-factor nature, in which different volcanic products (lavas flows, fallout, lahars, and pyroclastic flows) and associated hazards (seismic shocks, landslides, tsunamis, and floods) interact or impact together or sequentially [8]. Hence, when evaluating the potential impact of volcanic eruptions, we must identify what direct and indirect hazards can be derived in each case and develop knowledge of their cause–effect relationships. Volcanic eruptions span a broad diversity of hazards that directly derive from the volcanic activity (e.g., lavas flows, fallout, pyroclastic density currents (PDC), lahars, gases, etc.), as well as indirect hazards triggered by the action of the direct hazards (debris flows, rock avalanches, seismicity, tsunamis, etc.). Eruption durations are known to be very variable, ranging from a few hours to several years, with sizes ranging from a few millions of cubic meters to several thousands of cubic kilometers, and may involve very distinct phases, from effusive to highly explosive, generating a variety of products. These products result from different dynamics and emplacement modes and so will generate different potential hazards (e.g., [8,11]). These variations in volcanic eruptions and their products and, consequently, their potential impacts, depend to a large extent on magma composition, which controls its rheology and volatile content. Therefore, the impact of a volcanic eruption will depend on its size, which determines the extent of its erupted products. The impact is also dependent on the type of products generated and the degree of hazard they may represent. In this sense, PDCs, lava flows, and lahars are considered the most destructive products, but fallout and gases may also have important implications in proximal areas [11–13]. The reconstruction of the eruptive history of a volcano, together with a comprehensive understanding of the physics of volcanic processes, allows us to identify eruptive scenarios. This, in turn, allows us to determine which have been the most frequent in the past and, hence, to estimate the probabilities of future eruptions. This is the essence of volcanic hazard assessment [8].

Despite the risks associated with active volcanoes, the richness of volcanic areas has always attracted human settlements, which have evolved and progressed, despite suffering the impact of their eruptions from time to time. Many societies that have developed around volcanoes have demonstrated a high degree of resilience and adaptation, successfully recovering after each volcanic impact (e.g., [14]). The socio-economic development of the different societies around volcanoes is diverse and ranges from very poor societies, where people get just enough to survive on a daily basis, to rich societies, where part of their wealth comes from the extraction of natural resources (energy and minerals) associated with volcanoes. However, in all cases, it is the very existence of volcanoes that determines their socio-economic development. Moreover, in recent years, a direct source of income has emerged: nature tourism, with tourists becoming increasingly interested in visiting active volcanoes, even in remote and underdeveloped areas. This effect has been particularly noticed on volcanic islands (e.g., [15]). Therefore, by mitigating volcanic risks, we transform the effects of volcanoes using nature-based solutions. This approach works to sustainably strengthen and enrich all these societies, which, in one way or another, rely on active volcanoes for their subsistence.

2.1. Tenerife

Tenerife is the largest of the eight islands that make up the Canary Islands (Spain), an active intraplate volcanic archipelago located in the Atlantic Ocean off the coast of northwest Africa (Figure 1). With its more than 8000 m above the sea floor, it is the second largest volcanic structure in the world, after Mauna Loa in Hawaii. Tenerife has experienced several major eruptions in historical times, all corresponding to basaltic volcanism, the last being the Chinyero eruption in 1909. In addition to being a very important tourist destination (it receives an average of 4.5 million tourists per year), it is also the scene of multiple hazards that cause annual economic losses and sometimes even the loss of human life.

2.1.1. Geological Context

The Tenerife basaltic shield started to ascend from the ocean floor at least 12 Ma ago, and its construction has continued until the present, now extending across two rift zones (Santiago Rift Zone and Dorsal Rift Zone), as well as across a broad monogenetic volcanic field to the south of the island (Figure 1) [16–18]. This basaltic shield is mostly submerged and forms about 90% of the volume of the island. After a slowdown in its formation, which was affected by a subsequent significant erosive period (about >3.5 Ma) [17,19], a period of more intensive phonolitic volcanism alternating with basaltic episodes began in the center of the island. This led to the formation of a central complex (Las Cañadas edifice, between 4–0.18 Ma) [17,19–21], a composite volcano mainly formed of the products of explosive eruptions from highly evolved phonolitic magmas. The evolution of Las Cañadas Edifice includes several cycles of phonolitic volcanism that ended with a caldera collapse episode, which together formed the Las Cañadas caldera, in which the active twin stratovolcanoes Teide and Pico Viejo stand [20,22]. Teide and Pico Viejo include a complete series from basanite to phonolite and are mainly characterized by effusive volcanism—but in the last 30 ka, significant explosive activity related to phonolitic magmas has also occurred [23,24].

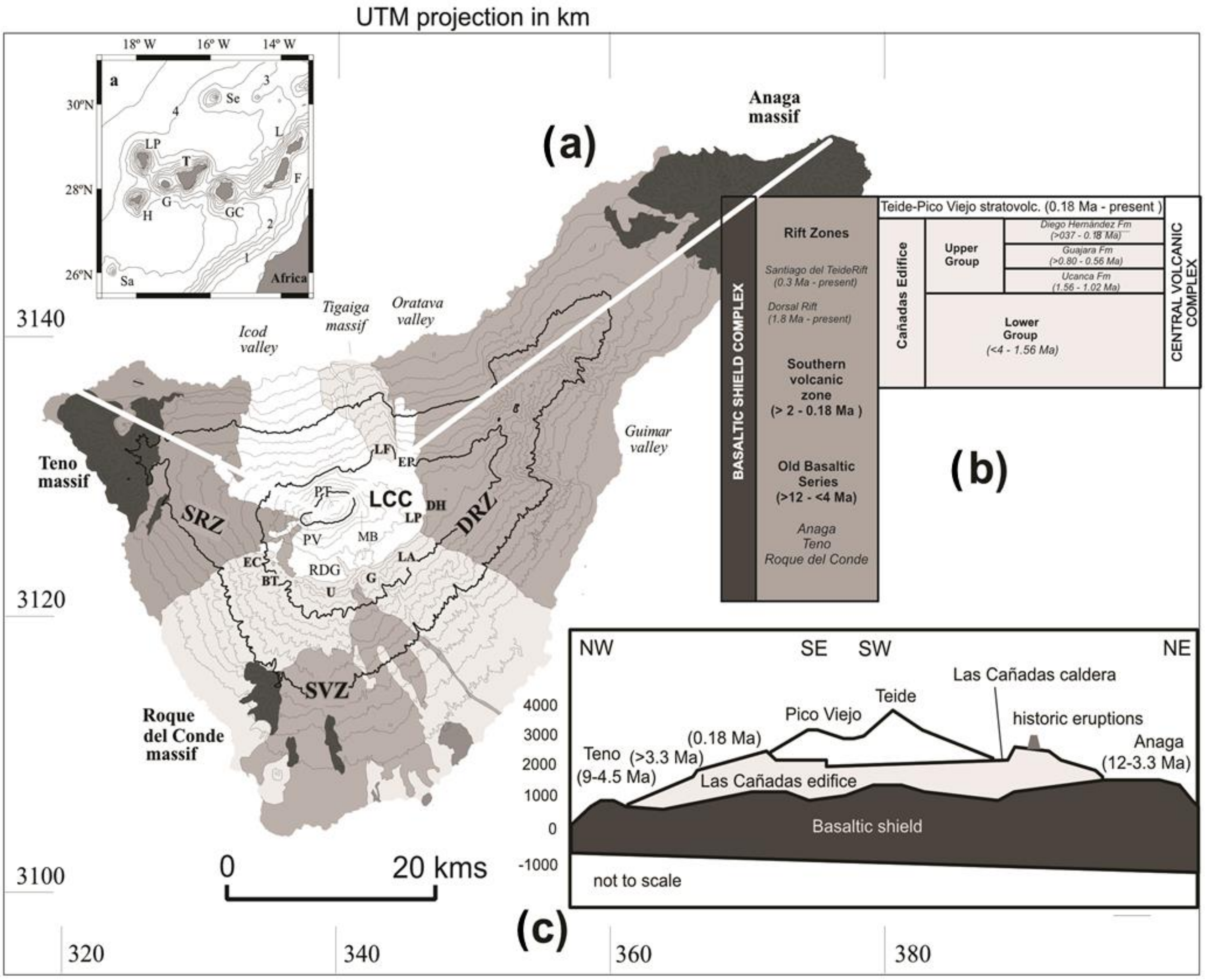

Figure 1. (**a**) Simplified geological map of Tenerife (modified from [23]); (**b**) stratigraphy of Tenerife, and (**c**) schematic cross-section of the island. Las Cañadas caldera wall localities: EC-El Cedro; BT-Boca Tauce; U-Ucanca; RDG-Roques de García; G-Guajara; LA-Las Angosturas; LP-Las Pilas; DH-Diego Hernández; EP-El Portillo; LF-La Fortaleza. Main vent systems of the Teide–Pico Viejo formation: PT-Teide volcano; PV-Pico Viejo volcano; MB-Montaña Blanca. Post-shield mafic volcanic zones: SRZ-Santiago rift zone; DRZ-Dorsal rift zone; SVZ-Southern volcanic zone (locally known as Bandas del Sur). Names and locations of landslide valleys are also shown. Contour interval is 200 m. Isotopic ages are from [17,20]. Inset map shows the location and distribution of the Canary Islands. Main islands: LP-La Palma; EH-El Hierro; G-La Gomera; T-Tenerife; GC-Gran Canaria; F-Fuerteventura; L-Lanzarote. Source: [25] (CC BY-NC-ND 4.0).

As on other volcanic islands, the evolution of Tenerife is characterized by the existence of constructive (accumulation of volcanic materials) and destructive episodes (caldera collapses, sector collapses, and erosion). Large-scale sector collapses and subsequent erosion have modulated three important morphological depressions affecting the northern and southern flanks of the island, the Güímar, La Orotava, and Icod valleys (Figure 1). The products of Teide and Pico Viejo mostly infill the Las Cañadas caldera depression, but also an important part of the Icod and La Orotava valleys. Furthermore, recent basaltic volcanism has contributed to partially infilling these depressions.

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2.1.2. Socio-Economic and Political Context

According to the Instituto Canario de Estadística (ISTAC), Tenerife closed the year 2021 with a population of approximately 927,993 inhabitants, making it the most-inhabited island of the entire archipelago [26]. It has a constrictive population, with a low percentage of young people and, therefore, decreasing birth rates (Figure 2a). However, the general trend has been one of a growing population over the last two decades (Figure 2b).

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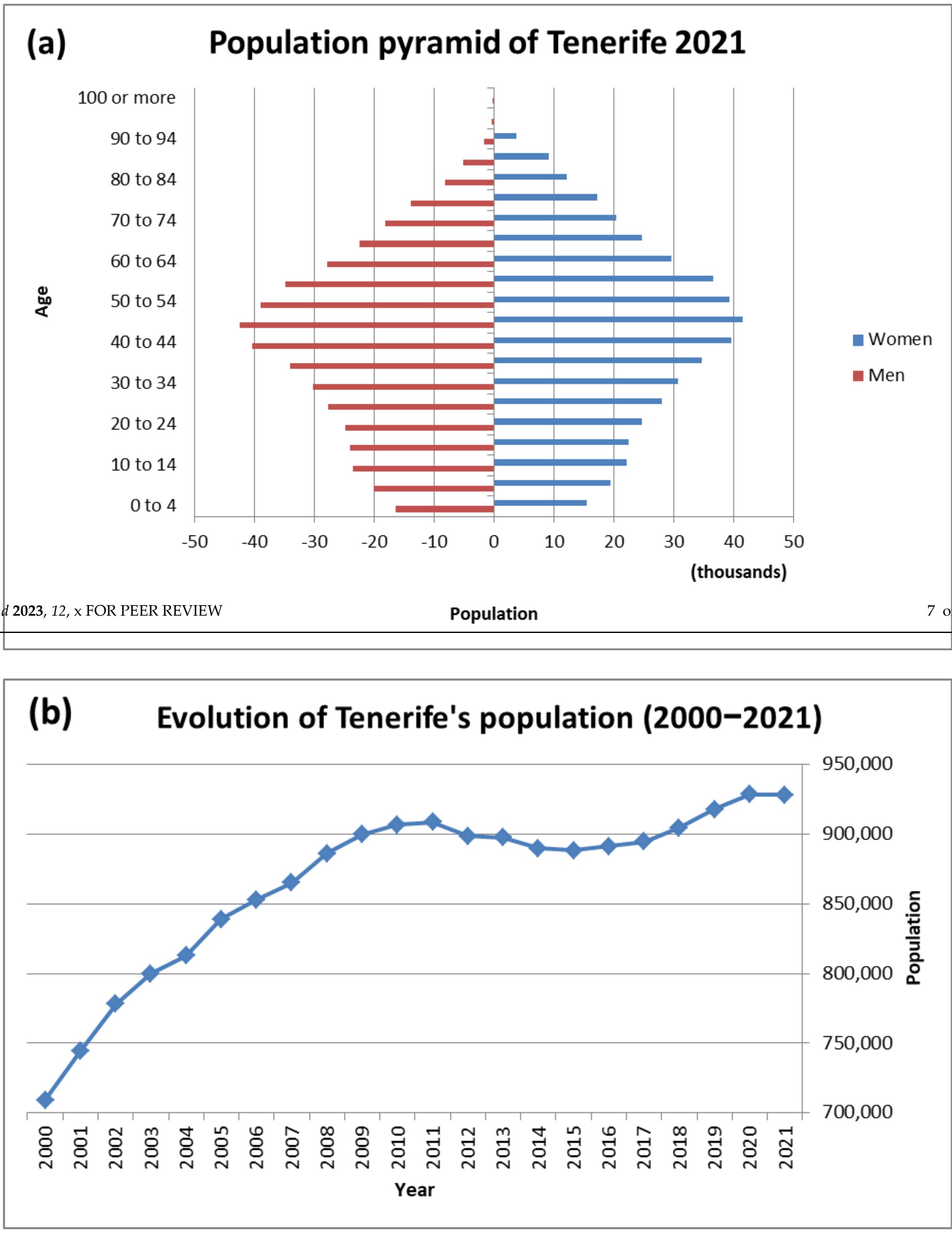

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Figure 2. (**a**) Population pyramid for Tenerife in 2021; (**b**) evolution of the population of Tenerife from 2000 to 2021. Source of data: [26].

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In the island territory, the ISTAC identifies two main urban centers, Santa Cruz de Tenerife-San Cristóbal de La Laguna (northeast) and Puerto de la Cruz-Los Realejos (north) (Figure 3). This category corresponds to a minimum population density of 1500 inhabitants/km² and a minimum population of 50,000 inhabitants. However, the majority of urbanization corresponds to semi-dense urban agglomerations, i.e., with a minimum density of 300 inhabitants/km² and between 5000 and 49,999 inhabitants. The remainder corresponds to dense urban agglomerations (≥1500 inhabitants/km² and between 5000

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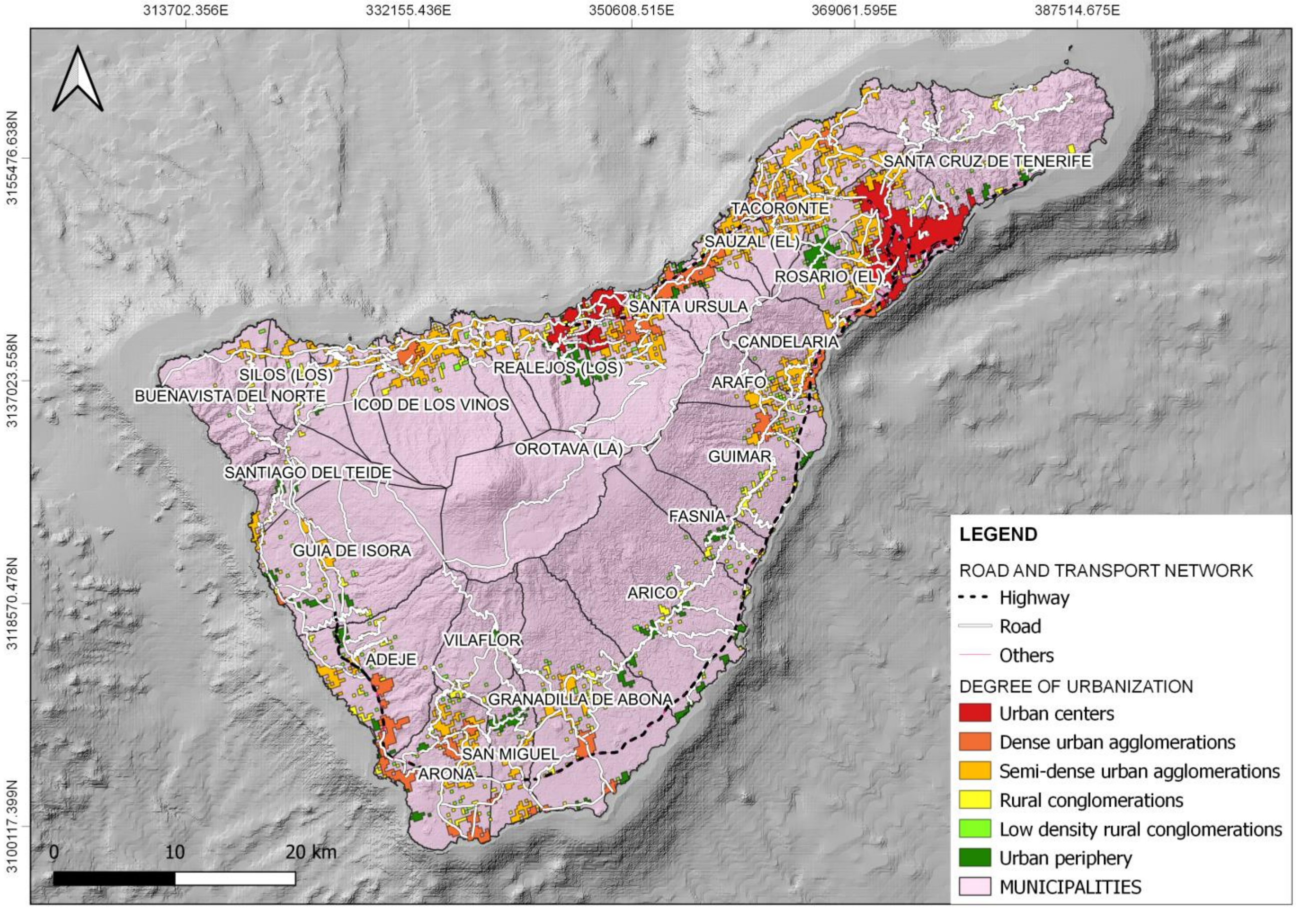

Figure 3. Map of Tenerife showing the municipalities, the road and transport network, and the degree of urbanization according to the ISTAC [26].

To this, we must include a tourism industry that adds between 4 and 4.5 million visitors every year (except in 2020, due to COVID-19 restrictions) over the last decade. This tourism is especially concentrated in July, followed by August, whose overnight stays are focused in the municipality of Adeje (southwest), followed by Puerto de la Cruz (north) [26].

For that reason, and according to the ISTAC [26], Tenerife's economy is mainly based on the Services sector, which contributes nearly 78% of the island's Gross Domestic Product (GDP). Commerce, transportation, lodging, and communications account for 32% of the total GDP of the island, totaling almost EUR 6.5 billion. Construction, on the other hand, contributes nearly 6% of Tenerife's GDP, ahead of industry at 5%. Agricultural activity on the island, with a cultivated surface area of some 16,000 hectares—some 10% of the island's territory—generates 1.7% of the GDP.

3. Methodology

Our aim was to identify the opportunities for volcanic islands to establish nature-based solutions that contribute both to risk mitigation and to their sustainable development. For this, we started by analyzing and outlining the main requirements for

3. Methodology

Our aim was to identify the opportunities for volcanic islands to establish nature-based solutions that contribute both to risk mitigation and to their sustainable development. For this, we started by analyzing and outlining the main requirements for these particular areas, mainly considering risk derived from volcanic hazards, despite many other natural and anthropogenic hazards that may impact these highly vulnerable environments. We first considered what must be known about volcanoes and their eruptions and how they may be characterized in a hazard assessment context. For this purpose, the reader is provided with a summary of this procedure based on a compilation and review, on the basis of expert judgement, of literature from other authors and ourselves. The literature used is based on previous works that have carried out long-term hazard assessment, which also explain as results of these studies how this methodology should be used. From the extraction and summary of the information contained in these works, we defined the actions that need to be undertaken in any active volcanic region before considering land planning and the exploitation of its resources.

Next, we considered how hazard assessment can be implemented into a development plan for these regions, paying special attention to territorial planning, implementation of mitigations measures, and the development of emergency plans. From an extensive revision of the existing bibliography, we extracted the essential elements that a disaster risk reduction program should consider, together with a series of recommendations that are applicable to volcanic regions with similar potential problems.

Next, we consider Tenerife as a case study of a volcanic island with a great potential for implementing nature-based solutions, with the goal of reverting the development policies applied until now by local and regional authorities. We started with a compilation of the main events that the island has experienced in historical time (i.e., since 1492). For this purpose, we consulted historical documents from the Provincial Historical Archive of Santa Cruz de Tenerife and the Municipal Archive of San Cristobal de La Laguna, as well as the landslide database of the Spanish Geological and Mining Institute (IGME) and the seismic catalogue of the National Geographic Institute (IGN). In addition, we revised an extensive bibliography of previously made catalogues, which served as a basis for updating and completing the historical records and for unifying data from different sources. With this, we have summarized the main natural hazards to which Tenerife has been, is presently, or may be exposed to in the future. We place special emphasis on the hazards associated with volcanic eruptions, also considering the extreme events that have occurred over geological time (i.e., prior to the historical record) and which could, therefore, reoccur in the future.

Moreover, we carried out an analysis of the resources of the island. Due to its beneficial climatology and hours of sunshine, tourism and agriculture offer the greatest potential, and in relation to this, we have also compiled a database of energy infrastructure on the island, as well as other economic activities that support the region. Finally, geological heritage, together with biological and cultural heritage, was also considered.

The next step was to study the island's territorial planning and land use. For this purpose, we studied the Tenerife Island Management Plan (available at https://www.tenerife.es/portalcabtfe/es/temas/ordenacion-del-territorio/el-planeamiento-territorial-y-urbanistico/plan-insular-de-ordenacion-de-tenerife/49/800, accessed on 12 December 2022), and we have identified the urban distribution and communications network patterns in relation to topographical and geological elements. In addition, we have summarized and described in detail the protected areas and the variety of landscapes offered by the region, highlighting the geological heritage of the island and its relationship with the tourism sector.

The information derived from protected areas, geological hazards, and geological heritage has been unified and correlated. This allowed for the identification of different places that are under some type of protection, in addition to the sustainably exploitable geological interests they possess and what sensitivity they have to geological hazards. The aim is, thus, to improve the management of the island's geological resources with territorial planning that is focused on risk mitigation customized for each area.

Finally, we explored the risk management mechanisms that Tenerife and its political structure have at the local, regional, and national levels. For this purpose, we consulted the different emergency plans for certain natural disasters, published on the website of the Cabildo de Tenerife (https://www.tenerife.es/portalcabtfe/?lang=es, accessed on 21 December 2022).

This provided a global and general vision of the sustainable development opportunities and fields to be explored, both from an economic and risk mitigation point of view. The understanding of the current state of Tenerife society and the multi-hazardous nature of the island, as well as its future trends, has enabled identification of nature-based solutions that this region can offer in order to cope with demographic expansion and the growing exposure of the population to natural risk. To that end, the text herein offers solutions, alternatives, and strategies to improve the resilience of Tenerife's population.

4. Results

4.1. Volcanic Hazard Assessment and Hazard Map

Long-term volcanic hazard assessment is based on historical and geological data and is principally used for territorial planning and for defining emergency plans. It uses quantitative analysis of past volcanic activity, including its structural and petrological controls, to determine the physical-volcanological parameters of past eruptions, such as to model possible hazards and eruption scenarios that may repeat (Figure 4) [8,27,28]. Long-term volcanic hazard assessment calculates the spatial and temporal probability that a new volcanic event will take place and characterizes its resulting impacts. Therefore, hazard assessment must identify the main physical mechanisms that control the predicted phenomena. In this way it aims to determine a given volcano's extent, potential impact, and destructive capacity, while placing temporal constraints on the framework in which they occur (e.g., [8,13]).

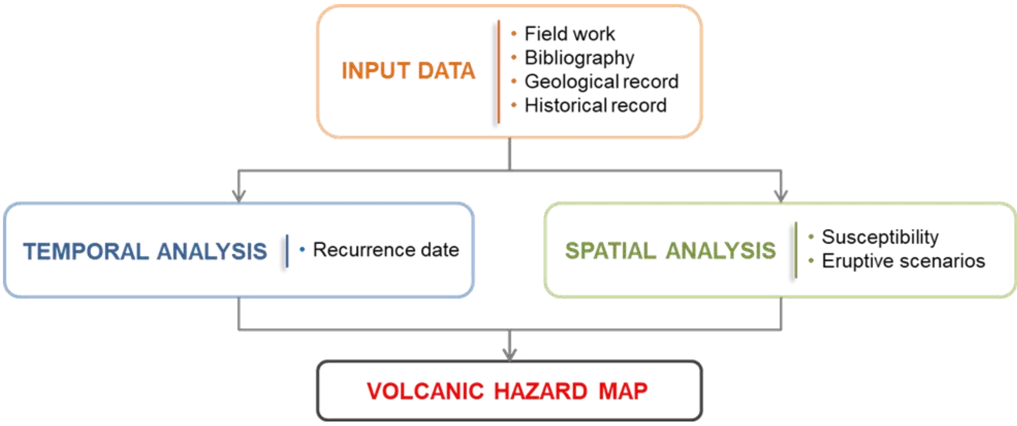

Figure 4. Flow chart for the development of a long-term volcanic hazard assessment.

Spatial analysis aims to determine the position of new vents based on knowledge of past eruptions, the existence of structural controls on vent distribution, the characterization of products from previous eruptions, and their spatial interrelations [29–32]. This information will provide the basis for establishing the vent opening probability (i.e., volcanic susceptibility) and the probability of invasion (i.e., laterally and longitudinally) by new eruptive products. Temporal analysis supports spatial analysis by establishing relative eruption times (volcanic stratigraphy) and, whenever possible, its geochronology by means of radiometric dating. This enables one to identify temporal behavior patterns of the volcanic system, such as clusters of eruptions or episodes of quiescence between eruptions; if absolute ages are available, the eruption frequency or recurrence (i.e., the temporal probability of an eruption) can be estimated as well (e.g., [28]).

As previously mentioned, a volcanic eruption may encompass several phases and pulses, each giving rise to different products. For example, an eruption may produce a Plinian column, which generates units of fallout deposits and then, as it collapses, produces PDCs of differing characteristics. The deposits produced by each phase or pulse will exhibit different lithological, sedimentological, and stratigraphic characteristics, and will be distributed across different sites around the volcano. Plinian fallout deposits will be widely distributed and will tend to blanket the surrounding topography, while PDC

Plinian column, which generates units of fallout deposits and then, as it collapses, produces PDCs of differing characteristics. The deposits produced by each phase or pulse will exhibit different lithological, sedimentological, and stratigraphic characteristics, and will be distributed across different sites around the volcano. Plinian fallout deposits will be widely distributed and will tend to blanket the surrounding topography, while PDC deposits will habitually accumulate in low-lying areas. After deposition, eruptive products may be affected by other geological processes (e.g., erosion, reworking, and resedimentation), forming secondary volcanic deposits. Primary and secondary deposits from a particular eruption that appears in the geological record may exhibit complex stratigraphic relationships that depend on the characteristics of the eruption, in addition to its topography and eruptive environment.

As part of the long-term volcanic hazard assessment, the construction of hazard maps is essential to land planning and emergency procedures, as well as for conducting risk analysis and to identify communities exposed to the greatest risks [33,34]. Nowadays, a hazard map is a dynamic concept that differs from the classical static maps that were drawn under the assumption that no changes will occur over long periods of time. A hazard map may change as new information becomes available, as the accuracies of simulation models improve, due to revisions of cartographic and geographic data, or as new eruptions occur [8,35]. Thus, the methodologies and concepts used to construct hazard maps must bear in mind the fact that a map is a temporary and open-ended product that is continuously evolving [36]. Hazard maps are usually probabilistic (both spatially and temporally) and may be constructed for just a single hazard, for groups of hazards, or for all the hazards forecasted for a particular area and over a particular time window. They may be qualitative or quantitative, and may cover certain restricted areas or a whole volcanic field [34–37]. Previously, hazard maps were constructed using information pertaining to past events, and so the resulting map was basically lithostratigraphic cartography of the products of past eruptions, in which the emphasis was placed on their superficial extent. However, modern hazard maps are constructed using GIS and computational facilities and represent what could happen if similar eruptions to those that have occurred in the past take place again [35,36]. They, therefore, describe areas that may be affected by each hazard, the degree of affectation or impact, and the potential risk. Hazard maps constitute the main tool for illustrating and visualizing how a territory can be classified according to the degree of hazard to which it is exposed; they are, hence, very relevant tools for territorial management. However, they are also highly useful for illustrating and communicating the geological reality to decision makers and the population in general, and they provide an actionable framework in which to respond in the event of an eruption [37].

Another important aspect to be considered when trying to understand the potential risk of an active volcanic area is that volcanoes are intrinsically multi-hazard systems, since they generate different hazards (lavas flows, PDCs, fallout, lahars, debris avalanches, earthquakes, etc.), while they may be the cause or the effect of other hazards (earthquakes, floods, landslides, tsunamis, etc.). This has significant implications when conducting hazard assessment and, consequently, land planning and risk management. Therefore, volcanic hazard maps need to be precise, and they must constitute the basis on which to build possible nature-based solutions for these regions. The application of long-term volcanic hazard assessments to land use planning will permit identification of each area according to its degree of risk and the type of hazards that may impact there. Furthermore, it will facilitate decision making on the types of development activities that could be undertaken there. This must be done in accordance with a risk management plan, which should be a requirement of primary importance for the development of a particular society.

4.2. Risk Management, Risk Mitigation, and Nature-Based Solutions

Volcanoes may have significant negative consequences on human populations, their economies, and the environment, which may then require long psychologically, physically, and economically difficult periods of recovery [13,14,38]. Thus, despite their potentially high cost, investment in risk-reduction programs is always preferable to merely reacting once disasters have struck [13]. The cost of prevention and mitigation actions is always lower than the cost of recovery, particularly when a catastrophic event hits a place that has not invested in risk reduction (e.g., [39,40]). This is the main message that needs to be transmitted to policy makers. Moreover, there is the fact that a safe area is much more attractive than a dangerous one.

An overall risk reduction plan should include several essential programs (Figure 5): (1) a scientific program aimed at improving knowledge of the process and its potential impacts (i.e., hazard assessment); (2) a monitoring program for determining the current state of activity of the process; (3) an educational program to educate the population about the potential hazards and risks that threaten them; and (4) a management program for designing customized emergency plans and resilience strategies for specific locations. Long-term hazard assessment is the first task that a society threatened by volcanoes needs to undertake if it aims to live with volcanoes and take advantage of what they offer (majestic landscapes, productive soils, mineral and energy resources, etc.). The impact of disasters caused by eruptions significantly increases when societies are not prepared to cope with volcanic threats—or they simply ignore them. Erroneous land planning, a lack of emergency plans, and poor knowledge of volcanic hazards and risks—not only amongst the general population, but also amongst decision makers and even scientists—may convert a natural event into a disaster [8].

Volcanic risk management should undertake not only those actions necessary to cope with a volcanic crisis, but also those mitigation actions aimed at reducing risk in the area. Among others, these should include structural measures (e.g., vulnerability analysis and engineering solutions), emergency management actions, and land use planning. Land use planning should be based on the long-term hazard assessment and should consider the most appropriate measures to guarantee the security of citizens and by obtaining the maximum resources that the land can provide, and restricting land use when necessary. However, this is not an easy task, and a number of challenges appear when dealing with land use planning in active volcanic areas. The uncertainty over the timing, magnitude, and impact of future eruptions constitutes the main obstacle. This is because policy makers tend to be reluctant to make decisions over the long term, particularly when these are based on scientific assumptions that are not exempt from high uncertainties and may have inconvenient or disruptive political or economic implications (consequences) to their interests. This is why it is important for scientists to convince policy makers of the fact that prevention and preparation is always preferable to reaction, particularly when dealing with volcanoes, with their complex multi-hazard systems that can be forecasted over the long-term and, increasingly, also in the short-term. Sometimes, restrictions are imposed by scientists when they are unable to sufficiently explain to the population and policy makers about hazards and risks, or about the convenience and (long-term) benefits of adequate land use and risk mitigation planning. Therefore, risk management is a task that needs to involve all stakeholders of an affected society. We must collectively aim to understand and accept their risks and potential consequences, taking a proactive stance going forward. Scientific uncertainty in forecasting volcanic events is not a sufficient excuse for inaction, and even less so when it is a question of when, not if, a volcano will erupt.

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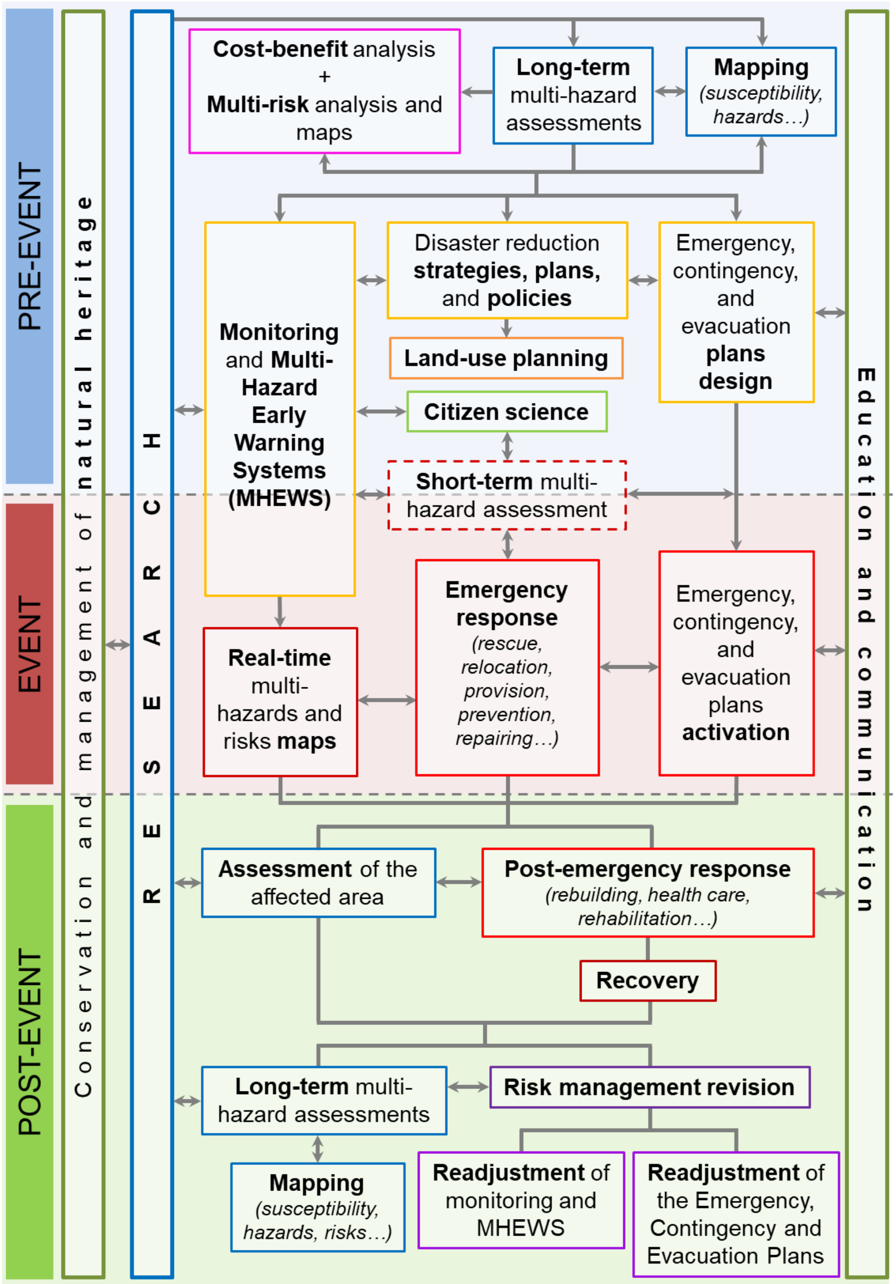

Figure 5. Standard diagram for the design of a risk management system in a region, from a multi-hazard approach. Source: [41] (CC BY-NC-ND 4.0).

In addition, to ensure that hazard assessment and vulnerability analysis are adequately addressed within policy statements and plans, one way to make risk reduction plans understandable and acceptable in active volcanic areas is by proposing nature-based solutions—for example, in the case of deciding whether new developments should be permitted in areas identified as high risk. While the authorization of new permanent constructions may be questionable, it could be that the development of certain activities that facilitate observation of the natural environment (even the temporary use of the land) should always depend on the degree of volcanic activity, as well as the expediency of emergency plans, in case of unforeseen activity. Further, we recommend to undertake planning for other land use recovery aspects by considering what the effects of an eruption might be, how land use could be improved after an event, and what steps might be taken before an event to ensure such improvements can be made [42]. In fact, volcanism does not need to be incompatible with certain types of activities and land uses if these are based on precise knowledge of the risk in each case.

The application of nature-based solutions to the sustainable development of volcanic areas (especially to volcanic islands) is sufficiently broad to involve numerous contributions. The list of possible nature-based solutions may include: (1) the sustainable use of raw materials, (2) geothermal energy production, (3) sustainable soil management for agriculture, (4) ranching, (5) for use in construction, (6) landscape solutions that are resilient to climate change (e.g., reducing flood risk, erosion, etc.), and (7) the promotion of safe and sustainable nature-based tourism, among others. However, the number of these potential solutions that have already been applied in volcanic areas is still low and rather unequal, depending on the characteristics of each area (e.g., local economy, social development, political system, risk perception, etc.).

In most active volcanoes and volcanic areas, it is common to find protected natural spaces [43,44], either because of the rich soils that generate high biodiversity, because of their scenic beauty, or because of their geological heritage. For example, of the 100 sites that have been declared as having geological interest by the IUGS (International Union of Geophysical Sciences), 27 are active volcanic areas or are related to volcanism. These protected natural spaces, if they are well-managed, generate social and economic improvement [45], as well as awareness and knowledge of geology, for both the local population and their visitors. In addition, the promotion of volcanic geoheritage is an efficient way to enhance the development of poor and rural regions by educating their inhabitants on its geological richness and how to benefit from preserving it and exhibiting it to others. This nature-based solution is important in two senses. It will help local residents value their area and, hence, see the need for preserving this value, and it will lead them to organize new businesses around rural tourism. In addition, such a solution will help create a community conscience around the need for preserving their geological values and related ecosystems, and to be aware of potential risks that may affect their area. In the following section, we analyze the case of Tenerife (Canary Islands) and then discuss the possible application of nature-based solutions to solve some of the problems it presents.

4.3. The Case of Tenerife

4.3.1. Volcanic and Other Natural Hazards

The island of Tenerife has been the scene of both extreme and non-extreme events throughout its evolution. Its natural characteristics, seen by its topography (steep slopes and significant elevations, especially in the central part, reaching 3718 m at the peak of Teide), its geology (varying volcanic terrains, such as lava flows; pyroclastic products, such as ash and pumice fallout deposits; pyroclastic flow deposits; etc.; as well as other sedimentary rocks), or its geographic location, make it an area susceptible to different natural processes that not only modify its morphology, but can also seriously affect its society. However, the overexploitation of resources, massive tourism, and the expanding overpopulation that the island suffers from can aggravate the consequences of such phenomena. Meteorological phenomena, geological processes, and anthropogenic actions all work to modify the relief and give rise on numerous occasions to interrelated natural disasters.

Volcanic eruptions have been relatively frequent on Tenerife in recent time, with about 18 phonolitic eruptions during the Holocene from the Teide and Pico Viejo volcanoes [23,24], and more frequent basaltic eruptions, mainly from the rift zones—a total of six in historical times [46,47]. All the historical eruptions of the island, since written records began, which in Tenerife dates back to 1492, have been preceded by earthquakes, which have continued to occur during and after the eruptions [48]. The first eruptions of which there are historical records are those of Arafo (or Arenas), Fasnia, and Siete Fuentes, which occurred between 31 December 1704 and 27 March 1705 [49]. (Previously, Christopher Columbus in 1492, on his way to the Americas through the Canary Islands, described what could have been an eruption in the Boca Cangrejo volcano, but these facts are still being questioned.) On 5 May 1706, the eruption of Garachico or Arenas Negras began and lasted until 13 June of the same year. From 9 June to 15 September, the eruption of Chahorra (or Narices del Teide) took place, and the last eruption that the island experienced was that of Chinyero, from 18 to 27 November to 1909 [49]. As can be seen, these eruptions have not lasted more than three months. However, being events that trigger multiple hazards, the direct and indirect effects are diverse. These eruptions have caused ash falls that have affected crops and water reserves, in addition to the collapse risk of building roofs. The lava flows devastate everything in their path and have sometimes caused fires, in addition to the emission of gases, which are also released from the mouth of the volcano. These eruptions usually have an explosive component, so the projection of different sized pyroclasts (lapilli, bombs, in addition to the ash already mentioned) is common, with the risk of direct impact. Moreover, the associated seismicity can also cause damage to buildings and infrastructure and generate panic among the population.

In addition, during the construction of the Las Cañadas edifice, Tenerife experienced several cascading extreme events. This is the case of the La Orotava and Icod valleys, on the northern flank of Tenerife, two large sector collapses that coincided in time with the occurrence of caldera-forming episodes. They are coeval with the formation of the central (Guajara, 0.56 Ma) and eastern (Diego Hernández, 0.17 Ma) sectors of the caldera of Las Cañadas, respectively [25,50]. These sector collapses also generated large scale tsunamis [51]. Caldera eruptions ranged in size from 12 to more than 20 km^3 of phonolitic magma, mostly in the form of pyroclastic material that had been deposited on the island and offshore [20,52]. The Icod and La Orotava landslides moved volumes of 240–264 km^3, including subaerial and submarine materials [53]. The resulting tsunami left deposits that are preserved in thicknesses of 0.4–3 m on the northwestern flanks of Tenerife at altitudes up to 132 m a.s.l. [51]. Since the succession of events described here is a process that has repeated several times in the past, it is not inconsistent to consider that it might occur again in the future [25].

Furthermore, every year, more moderate natural events occur, which continue to put people and infrastructure on the island at risk. To begin with, there are floods and torrential avenues. These phenomena are usually triggered by storms, with heavy rains and winds, in addition to the effect that the waves have during these episodes in the most coastal areas. These events occur about once or twice a year, from October to December and from February to April. Heavy rains produce torrential floods in ravines bounded by steep slopes and escarpments, which characterize the volcanic terrain of the island. They usually overflow when they reach flatter areas or areas modified by human activity, either by channeling, bridges and narrowings, or changes along the course of the flow, or due to paving. The most affected cities are usually Santa Cruz de Tenerife, San Cristóbal de La Laguna, Garachico (especially by waves), San Andrés, the La Orotava Valley, Güímar, Puerto de la Cruz, Los Realejos, and Icod de los Vinos, among other municipalities [54]. In addition, these torrential floods drag large quantities of sediment along the ravines, which, added to the landslides caused, lead to the deposition of mud and large rocks in the overflow areas, thus increasing their impact and making cleanup and repair tasks more difficult. Some of the worst episodes were the floods of March 2002, which caused 9 deaths and losses estimated at EUR 120 million; the storm of January 1999, without deaths, but with losses of EUR 35 million; or some historical ones, such as the flood of November 1826, which caused around 500 deaths, around 1000 dead animals, and ESP 7,000,000 (i.e., pesetas; currently around EUR 42,000) of economic losses [55].

Other phenomena common in Tenerife are rock falls and small-scale landslides. These usually occur in road cuts or in the ravines themselves, only some of which are frequented by tourists. That is why they do not usually cause deaths or injuries, as well as no major damage or costs; however, it is worth mentioning the landslide that occurred in the Barranco del Infierno on 26 October 2015, causing a single death and four injuries; or the one of 1 November 2009 on the cliff of Los Gigantes, causing the deaths of two people who were on the beach of Santiago del Teide; or the landslide of 27 January 1947 that left five dead in Tacoronte [56]. They are usually caused by heavy rains and winds and/or floods, as described above. Another common cause is earthquakes.

Earthquakes felt in Tenerife usually have two origins: tectonic or magmatic. Earthquakes with a tectonic origin are usually associated with the transform fault that runs through the channel between the islands of Gran Canaria and Tenerife. In this area, which hosts the highest seismic activity in the Canary Islands, there are usually between 400 and 500 earthquakes per year below 2.5 magnitude, with only a little less than a dozen exceeding this limit [57]. The earthquakes felt in Tenerife since records have been gathered have had intensities between I and VI on the MSK-64 scale [58] and do not usually cause any damage. Some exceptional cases are the earthquake of 9 May 1989, with a magnitude of 5.0 and an epicentral intensity of 6.7, which caused some breakage of windows and displaced furniture in houses [59]. As for earthquakes of magmatic origin, they can occur in isolation or in seismic swarms, i.e., groups of numerous earthquakes of low to intermediate magnitude in the same place, related to the movement of magma or fluids.

Other hazards that occur on Tenerife are the haze, coming from the Sahara, which, in addition to respiratory problems, has sometimes been accompanied by plagues of locusts, as happened in 2004; forest fires caused by heat waves and/or human action (such as in 2007, which burned 15,000 ha) or are aggravated by the haze; or tsunamis, which are somewhat less common, having a record of a tsunami on 15 November 1911, although these data are not so solid, such as with the 1755 tsunami caused by the Lisbon earthquake, which is not clear that it had any effect on Tenerife. However, there can be no doubt that, being an island in the middle of the Atlantic Ocean, it can easily be affected by any tsunami that runs through this area.

4.3.2. Resources

Tenerife has a great variety of natural resources, especially because of its great geodiversity and geological heritage, e.g., [60–63]. Its geographical location not only makes it a strategic commercial point in the Atlantic, but also gives it several unique properties. The climate is subtropical oceanic on the coasts (very temperate and sunny during most of the year, with a little rainfall concentrated in the period from October to March, especially in the north–northeast). In the inland areas, the climate varies according to altitude and orientation: on the northeast-facing slopes, there is abundant rainfall, while on the rest of the island, rainfall is scarce (<250 mm/year on the coasts, and often even below 150 mm), giving rise to arid landscapes. Trade winds from the northeast predominate, which make the northern slope more humid, while the heat on the coasts during the summer is more temperate. The average temperature is between 20–25 °C, although with seasonal variations, and the sun is present practically all year round, with many hours of daylight per day.

Thanks to these climatological properties, the island has several photovoltaic parks (i.e., power stations) in the municipality of Arico (southeast) and some in Granadilla de Abona (south), with a total power of more than 300 kW, in addition to several more parks in the process of being approved for the same municipalities and for Arona (southwest) [64]. This same area on the southeast coast of the island has several wind farms and several more planned. On the other hand, the volcanic materials provide the soil with a great variety and quantity of nutrients that are ideal for the crops grown there, especially bananas, as well as tomatoes, potatoes, and grapes. These volcanic materials are also used as building materials in what the island seeks to be sustainable architecture. The main materials exploited are ignimbrites, as ornamental or facing stones, and the main quarries are located at the south of the island, such as Cantera Guama-Arico S.L. (Arico, southeast, Figure 3).

The topography of the island, which causes significant variations in altitude, together with the consequent distribution of rainfall and winds, leads to the existence of a wide variety of ecosystems and unique landscapes in a small area. This has caused the island to have abundant and diverse flora and fauna. This biodiversity, together with the existing geological heritage, turns these natural resources into an important tourist resource that sustains the regional economy.

4.3.3. Land Use Planning

Among the duties of the Council of Tenerife, the administrative body of the island, is the protection of the environment; the management and conservation of protected natural spaces, forestry services, livestock trails, and pastures; the subrogation in the municipal duties to urban planning; and the approval of the Insular Plans of Works and Services elaborated in collaboration with the town councils of each island.

The island's land uses are divided into urban areas, agricultural areas, environmental protection areas, and territorial protection areas (Figure 6) [65]. Regarding the first use, the metropolitan area of Santa Cruz-La Laguna (northeast); the tourist centers of Puerto de La Cruz (north) and Los Cristianos and Las Américas (Arona, southwest); and the industrial and tertiary urban areas of Güímar (east), Granadilla de Abona (south), and Santa Cruz de Tenerife (northeast) are worth mentioning (Figure 3). The entire urbanized area, which would include the categories described in Section 2.1.2 above, is distributed peripherally around the central part of the island, where Teide National Park (TNP) is located, (Figure 6) and, therefore, the central depression of the Caldera de las Cañadas, which houses the Teide–Pico Viejo volcanic complex (Figure 1). The main areas of future growth of the island highlighted by the Tenerife Island Land Management Plan (PIOT) are the metropolitan area of Santa Cruz-La Laguna, the Orotava Valley (north), and the southern zone comprising Las Américas-Los Cristianos (Arona) (Figure 3).

Table 1. Relationship between Tenerife's protected natural areas, their geological heritage, and their main geological hazards. The numbers in brackets are the locations shown in Figure 6 in red circles.

Figure	Site	Geological Heritage	Geological Hazards Sensitivity
National parks	Teide (15)	Volcanism	Volcanic eruption
Strict nature reserves	Ijuana (16)	Erosion	Landslide
	Pijaral (17)	No	No
	Los Roques de Anaga (18)	Erosion	No
	Pinoleris (19)	No	No
Nature reserves	Malpaís de Güímar (20)	Lava flow	Volcanic eruption
	Montaña Roja (21)	Volcanism/Erosion	Volcanic eruption
	Barranco del Infierno (22)	No	Mud Flows/Alluvial Fan
	Chinyero (23)	Volcanism	Volcanic eruption
	Las Palomas (24)	No	No
Natural Parks	La Corona Forestal (25)	No	No
Rural Parks	Anaga (26)	Erosion/Old Volcanism	Landslide
	Teno (27)	No	No
Natural Monuments	Barranco de Fasnia y Güímar (28)	Erosion	Landslide
	La Montaña Centinela (29)	Volcanism	Volcanic eruption
	Los Derriscaderos (30)	Volcanism	Volcanic eruption
	Las Montañas de Ifara y Los Riscos (31)	Volcanism	Volcanic eruption
	Montaña Pelada (32)	Volcanism	Volcanic eruption
	La Montaña Colorada (33)	No	No
	Roque de Jama (34)	Old Volcanism	No
	La Montaña Amarilla (35)	Volcanism	Volcanic eruption
	La Montaña de Guaza (36)	Volcanism	Volcanic eruption
	La Caldera del Rey (37)	Volcanism	Volcanic eruption
	La Montaña de Tejina (38)	No	No
	Teide (15)	Volcanism	Volcanic eruption
	Roque de Garachico (39)	Erosion	Landslide
	La Montaña de Los Frailes (40)	Volcanism	Volcanic eruption

Table 1. *Cont.*

Figure	Site	Geological Heritage	Geological Hazards Sensitivity
Protected Landscapes	La Rambla de Castro (41)	No	Mud Flows/Alluvial Fan
	Las Lagunetas (42)	No	No
	Barranco de Erques (43)	Geomorphology	Mud Flows/Alluvial Fan
	Las Siete Lomas (44)	Volcanism	Volcanic eruption
	Ifonche (45)	No	No
	Los Acantilados de la Culata (46)	Geomorphology	Landslide
	La Resbala (47)	No	No
	Los Campeches, Tigaiga y Ruíz (48)	Geomorphology	Mud Flows/Alluvial Fan
	Costa de Acentejo (49)	Geomorphology	Landslide
Sites of Scientific Interest	Acantilado de La Hondura (50)	Geomorphology	Landslide
	Tabaibal del Porís (51)	No	No
	Los Acantilados de Isorana (52)	Geomorphology	Landslide
	La Caleta (53)	No	No
	Interián (54)	No	No
	Barranco de Ruiz (55)	No	No

January 1954, spanning 18,990 ha, and the surrounding forest crown, the two extreme massifs (Anaga and Teno), and the rest of the Protected Natural Spaces. Finally, the territorial protection areas are those considered to be land reserves for the future, which preserve the vacant territory as a fundamental resource, the main ones being Las Américas and the northern midlands.

The high diversity and uniqueness of its landscapes, ecosystems, and natural resources, among other features, have provided Tenerife with an extensive network of protected natural areas (Figure 6). More than 50% of the island is protected as a natural monument, nature reserve, national park, site of geological interest, protected landscape, rural park, or natural park. In addition, the important geodiversity of volcanic products and the many sites of special geological interest [63,66,67] have endowed the island with a unique geological heritage. Given the wide extension of protected areas and the fact that some of the reasons for their protection or conservation interest are due to elements formed from volcanic and/or geological processes of other origin, it is to be expected that in many of these areas, a natural hazard will prevail. This is shown in Table 1.

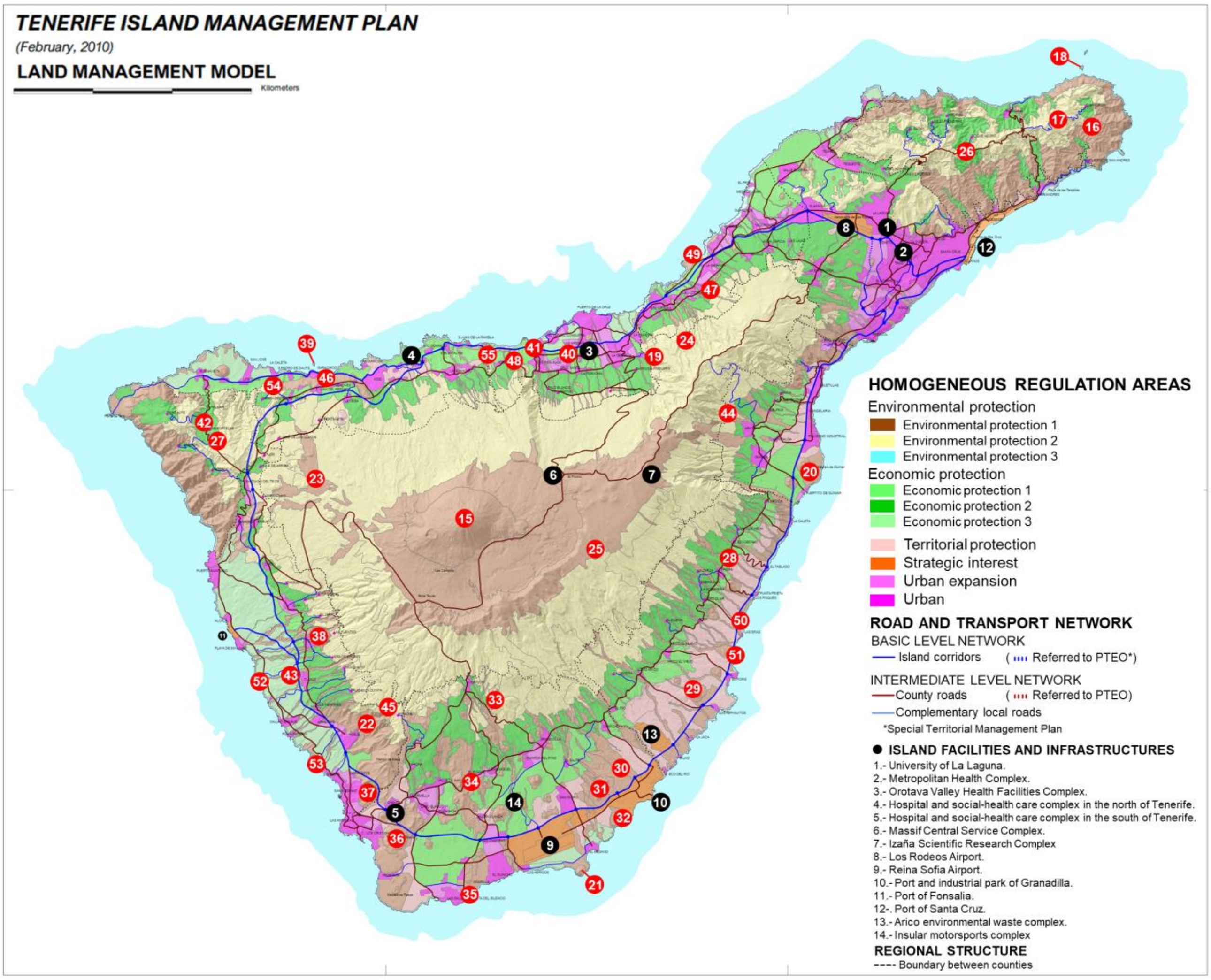

Figure 6. Land management model of the Tenerife Island Management Plan (PIOT). Numbers in red circles are the locations of the sites mentioned in Table 1. Source: modified from [65].

Figure 6. Land management model of the Tenerife Island Management Plan (PIOT). Numbers in red circles are the locations of the sites mentioned in Table 1. Source: modified from [65].

The distribution of communication routes follows this same peripheral pattern, except for a few roads that reach the two main entrances to this central depression—one to the southwest and the other to the northeast, joined by a road that crosses the Caldera de las Cañadas (Figure 3). According to the PIOT, there are two levels of the road and transport network. The basic level network, made up of what are known as island corridors, corresponding to the TF-1 highway, which runs along the entire south from west to northeast; the TF-5, which runs through the northeastern half of the island; the TF-2 that joins both in the east; and a whole series of roads that connect all the towns closest to the coast around the island. In addition, there is the intermediate level network, composed of county roads and complementary local roads that, following the same ring distribution, connect the rest of the municipalities.

In terms of facilities and infrastructure, the island has two airports, Los Rodeos in the northeast and Reina Sofia in the south, as well as three ports, Santa Cruz in the northeast, Granadilla in the south, and Fonsalía in the west (Guía de Isora municipality) (Figure 6). It also has two hospital complexes and health care partners, one in the north and the other in the south, and a further health facility complex in the Orotava Valley. Santa Cruz de Tenerife is also the administrative center of the island, as it is home to several political and administrative bodies (such as the Parliament, Government of the Canary Islands, Cabildo Insular). In addition, in Tenerife, there are four thermal power plants located in Candelaria (fuel oil/diesel, which are in the process of being dismantled), Granadilla de Abona (fuel oil/diesel), Santa Cruz de Tenerife (fuel oil, next to an oil refinery, both in the process of being dismantled), and Arona (diesel).

In contrast, the land for agricultural use is configured in a ring at the base of the central volcanic edifice, divided into the coastal part, with intensive crops, and the inland part, with traditional crops (Figure 6). Separately, the environmental protection areas include most of the forest areas in the central part of the island, the TNP, declared on 22 January 1954, spanning 18,990 ha, and the surrounding forest crown, the two extreme massifs (Anaga and Teno), and the rest of the Protected Natural Spaces. Finally, the territorial protection areas are those considered to be land reserves for the future, which preserve the vacant territory as a fundamental resource, the main ones being Las Américas and the northern midlands.

The high diversity and uniqueness of its landscapes, ecosystems, and natural resources, among other features, have provided Tenerife with an extensive network of protected natural areas (Figure 6). More than 50% of the island is protected as a natural monument, nature reserve, national park, site of geological interest, protected landscape, rural park, or natural park. In addition, the important geodiversity of volcanic products and the many sites of special geological interest [63,66,67] have endowed the island with a unique geological heritage. Given the wide extension of protected areas and the fact that some of the reasons for their protection or conservation interest are due to elements formed from volcanic and/or geological processes of other origin, it is to be expected that in many of these areas, a natural hazard will prevail. This is shown in Table 1.

The TNP was classified as a UNESCO World Heritage Site in 2007 and now receives around 3.5 million visitors annually [63]. Among the many visitors, there have always been many students and academics from universities and research centers. The reason for this is the visibility of most of the park's geological outcrops, where most textbook volcanic processes and products can be directly observed and studied [63]. The park embraces the Las Cañadas caldera complex and the twin stratovolcanoes of Teide and Pico Viejo, as well as numerous intra- and extra-caldera volcanic vents, some of which are related to the Dorsal and Santiago del Teide active rift systems (Figure 1). High interest within the international scientific community has led to a considerable number of studies (see [50]) and the consequent volume of information (geological, volcanological, geophysical, geomorphological, hydrogeological, petrological, etc.) about Las Cañadas and El Teide–Pico Viejo and their formation. However, the information available to visitors on the wide geodiversity of this area is small or nonexistent—or even erroneous when compared to existing scientific information. Likewise, available outreach and dissemination resources for visitors and park guides are few and far between, and are often out-of-date and lack the scientific rigor to be expected for such a geologically important site [63].

4.3.4. Natural Risk Management

The observation, monitoring, and communication of volcanic activity and seismic movements in Spain, alongside the determination of the associated risks, are a function of the Directorate General of the IGN, based in Madrid, with a department in Santa Cruz de Tenerife, in accordance with ROYAL DECREE 1476/2004 of 18 June 2004. However, there are other networks, such as the Spanish National Research Council (CSIC), and other institutions, such as the ITER Group (Technological and Renewable Energy Institute), that have expertise in volcanic monitoring. In addition, the Spanish Geological and Mining Institute (IGME), in accordance with its Statute approved by Royal Decree 1953/2000 of 1 December 2000, has functions in the area of forecasting, prevention, and mitigation of geological risks. On the other hand, in accordance with Law 12/1990 of 26 July 1990, the Island Water Council of Tenerife (CIATF) is responsible for the direction, organization, planning, and management of the waters of the island of Tenerife. The Council of Tenerife, through the Natural Environment Management and Safety Area, has responsibility for the prevention and extinction of forest fires, in accordance with Decree 111/2002 of 9 August 2002. Regarding weather-related hazards, according to Article 1.3 of Royal Decree 186/2008 of 8 February 2008, the State Meteorological Agency (AEMET) oversees predicting and monitoring adverse weather phenomena.

The autonomous community of the Canary Islands has several territorial plans to deal with emergencies. These plans are divided according to the geographical area for which they act, and their activation depends upon the area of incidence and the scope of each emergency. In this way, at a municipal level, the Municipal Emergency Plan (PEMU) is activated. Likewise, each Island Council must develop its own island plan. Emergencies at the regional level are those that affect more than one island in the Archipelago, or those whose magnitude of the incident requires the use of means outside the affected island. The Territorial Civil Protection Plan of the Autonomous Community of the Canary Islands (PLATECA) is activated when an emergency is declared at the Autonomous Community level. PLATECA includes all the previous territorial plans and, in addition, distinct Special Plans. These plans are divided into Basic Plans (nuclear and war emergencies, both of which are the responsibility of the State) and Special Plans for other risks (floods, earthquakes, chemicals, transport of dangerous goods, forest fires, and volcanic activity). If we focus on geohazards, this last category includes the following Special Plans for the Canary Islands:

- Special Plan for Civil Protection and Attention to Emergencies due to Volcanic Risk in the Autonomous Community of the Canary Islands (PEVOLCA).
- Special Plan for Civil Protection and Emergency Attention due to Seismic Risk in the Autonomous Community of the Canary Islands (PESICAN).
- Special Plan for Civil Protection and Emergency Attention due to Forest Fires in the Autonomous Community of the Canary Islands (INFOCA).
- Special Plan for Civil Protection and Emergency Attention due to Flood Risk in the Autonomous Community of the Canary Islands (PEINCA).

In addition to these, there are two Specific Plans:

- Specific Plan for Civil Protection and Emergency Attention of the Autonomous Community of the Canary Islands due to risks of adverse meteorological phenomena (PEFMA).
- Specific Plan for accidental marine pollution emergencies in the Canary Islands (PECMAR).

However, each of these plans refers to only a specific hazard and its possible consequences in case should it occur, and involves different groups of decision makers and first responders for each situation. None of them take into account possible interactions between hazards or multi-hazard management, which means that their effectiveness may be reduced in the event of more than one hazard occurring at the same time, as coordination problems may arise during a multi-hazard crisis.

5. Discussion

As we have seen in the previous section, the level of risk imposed by the occurrence of natural hazards on Tenerife is high. Regarding the type of hazards, their frequency is very variable, as is the affected area and the degree of impact. Some hazards, such as forest fires, floods, torrential avenues, droughts, coastal erosion, and hazes, are directly dependent on climate change and should be expected to increase in frequency and severity in the coming years. Concerning volcanic activity, Tenerife has not shown an increase in its frequency or intensity during the Holocene, but the fact that the last eruptions from Teide and from the basaltic system occurred about 1000 and 100 years ago, respectively, indicates that the probability of new eruptions from either of the 2 systems is not negligible [68]. Furthermore, according to the risk cartographies collected in the Island Territorial Emergency Plan (PEIN) (available directly at https://transparencia.tenerife.es/archivos/110/documento-plan-39-16-03-2020-analisis-de-riesgos-1502.pdf, accessed on 27 December 2022) and the map shown in Figure 3, many of the high-risk areas for any of the phenomena mentioned are densely populated. This is, for example, the case of the valleys of Icod and La Orotava, with high volcanic risk due to eruptions that can originate from Teide and the two rifts zones, as well as forest fires, which also pose a high risk to the cities of San Cristóbal de La Laguna and Santa Cruz de Tenerife. The latter two also have a high risk of flooding.

The possible problems that Tenerife has in relation to land use planning are diverse and include aspects derived from the extraction and use of natural resources (water, rock materials, and soils), landscape, ecosystems, and geological heritage conservation, in addition to those derived from natural risks that may affect the island—some of these will be aggravated due to climate change. For example, the scarcity of drinking water is already a problem on the island, with an evident annual decrease in natural water resources and the increasing demand from the permanent population and tourism [69]. A similar situation is observed with the extraction of natural material for construction, as currently there is only one legally authorized quarry for aggregate extraction [70]. Forest fires, floods, torrential avenues, rock slides, and small landslides are recurrent problems that also require attention. These destructive processes affect soil and landscape stability and their related ecosystems. The main zones affected by soil erosion correspond to the landslide valleys of Icod and La Orotava at the northern side of the island and the Guímar Valley in the southeast, as well as the older corners of Teno and Anaga. The application of nature-based solutions, such as soil–vegetation solutions that enhance soil function and soil resilience (e.g., better infiltration, soil stability, and soil roughness, etc.) and landscape solutions, considering hillslope morphology, runoff pathways, topographic humidity, and water and sediment sinks, would be effective approaches to determine the potential for water and sediment transport, and to evaluate and reduce soil and landscape degradation [4]. These solutions should be applied in land use planning in these areas of Tenerife to preserve the health of soils and landscapes.

For volcanic hazards, the problem changes due to the lack of risk perception by most inhabitants of the island and its visitors. Even though the Canary Islands is an active volcanic region that has suffered two volcanic eruptions in recent years (El Hierro in 2011–2012 and La Palma in 2021), the possibility of having an eruption on Tenerife is regarded as less probable, in part due to the long eruption frequency of its volcanoes. However, the likelihood of having a new eruption cannot be neglected, especially when we consider the time that has passed since previous eruptions. In addition, the presence of the Teide–Pico Viejo complex, a high-risk volcanic system [71] able to produce explosive eruptions of considerable size, should be a matter of serious concern for local authorities and must, therefore, be considered in the land use and emergency planning for the island. However, at the time of writing, there is no comprehensive volcanic risk reduction plan for Tenerife based on a long-term hazard assessment, so existing land use planning does not consider potential volcanic hazards. What does exist is a monitoring plan of volcanic activity, run by IGN and duplicated to a certain extent by other institutions (CSIC, ITER), and the consideration of Teide–Pico Viejo as an effusive volcano in the emergency plan to be applied to manage a volcanic crisis (PEVOLCA). However, land use planning for Tenerife (Figure 6) only considers land classification according to its level of environmental and economic protection and its potential use in development. Obviously, this is not the best way to address land use planning in an area threatened by active volcanoes.

If we consider, for example, the Icod Valley (Figure 1), where there are more than 50,000 inhabitants, and which constitutes an important economic and touristic area of Tenerife, we observe that most products from the latest eruptions of Teide–Pico Viejo have been emplaced there [23,71], in addition to the products from some historical eruptions, such as those of Garachico (1706) and Chinyero (1909), which had a significant impact on the area [46]. The demographic and economic development in this area, also affected by other natural hazards [54,55], make it of higher risk if we take into consideration the potential impact of volcanic hazards. With the degree of development already achieved in this area, it is difficult now to carry out reasonable land use planning to preserve it, but there is still time to apply some nature-based solutions to reduce risk and to provide simultaneous benefits to society, the economy, and nature. The most urgent actions should include: (1) a long-term development plan based on hazard assessment and risk management (these long-term development plans should be based on long-term risk assessment, which will come from the historical record of events, to find out the frequency, type of events and interrelationships, susceptibility, hazard, and others, as well as risk simulations, monitoring, and short-term analysis); (2) rationalization of construction and demographic expansion according to the potential volcanic and associated hazards that may impact the zone—those places not suitable for construction (e.g., recreation parks, tracking areas, etc.) and that can still provide some benefits to society could be utilized non-permanently; and (3) the mobility, energy, and water supply networks should be revised and, if necessary, redesigned to ensure their functionality, even in the case of severe impacts on the area. Additionally, coastal management should be implemented to mitigate the effects of climate change, as well as the restoration of floodplains, to reduce the risk of downstream flooding. In summary, these solutions would contribute to the sustainability and security of the area by maintaining or enhancing its economic development, with clear benefits for the environment and human health.

Another important aspect that we need to consider in the case of Tenerife, one of the most visited places in the world, is the role of tourism. Tourism is the main source of employment and income for local inhabitants and is also an important component of regional development, while also contributing to the preservation of natural and cultural heritage as a source of income [72–75]. However, tourism in Tenerife demands better rationalization and planning if it is expected to become a sustainable solution for the economy of the island. As for the rest of the Canary Islands, tourism in Tenerife started in the 1960s as mass tourism and has continued in this way until the present. It has not been until very recently that rural tourism, which is more interested in natural aspects and is much more respectful to the environment, has started to mature. This is probably the reason why, despite the existence in Tenerife of many protected areas and it having of one of the main national parks in Europe, the amount of scientific information and outreach material to be distributed among visitors remains scarce.

Geotourism is fast becoming a new way of generating income, and so it is important to foster it and ensure that it is as sustainable as possible. Examples of how to make geotourism sustainable and a valuable element in the development of a particular area or region have been documented elsewhere, e.g., [76]. However, these examples also reveal how demanding this type of tourism is. For this reason, it requires information that is based on rigorous scientific knowledge and employs properly trained communicators who can transmit natural values to visitors. At the same time, geotourism needs to be included in land use planning in order to determine the best and most informative places to be visited and the routes to reach them. This same land use planning based on risk analysis should include not only the main attractions and activities that add value to geotourism, but also the accessible infrastructure, accommodation, and facilities, so that these are also located in safe areas, with a lower environmental impact, and facilitate sustainable tourism. Otherwise, massive tourism may become a source of negative environmental impacts, including heavy metal pollution of soils due to an excess of oil-dependent transport, degradation of the landscape and the geoheritage, and the perturbation of ecosystem equilibrium, e.g., [75].

In the case of Tenerife, as in most volcanic areas, tourism must be incorporated into land use planning and risk management. The presence of a growing tourism industry requires having adequate infrastructure and services, as well as territorial planning, in accordance with the increase in mechanical transport and the presence of people in places that are not necessarily suitable for it. Moreover, security is one of the most important aspects for tourism development [77]. In volcanic areas, the main attraction is to observe active volcanoes or their products and forms from past eruptions, in addition to the ecosystems that have developed around them. In Tenerife, where there is no active volcanism, the main touristic interest is geoheritage. Therefore, ensuring the presence of tourism means ensuring the preservation of the volcanic heritage and safety in the area. This requires effective territorial planning and risk management to prevent possible impacts due to the occurrence of various natural phenomena typical of the island and the degradation of its natural heritage—but also due to the presence of tourism itself. Warnings in multiple languages; recommendations designed for a transient population, not just for local people or scientists; guides trained by geologists with experience in disaster management; recognition of the hazards of each area and indications for visitors in case of emergency; and knowledge of the health problems that can occur in areas with some geological risk, as well as how to detect their symptoms in order to call for immediate help, are some of the safety measures that need to be improved in many of the cases [78,79]. Even in the event of an eruption, depending on its size and conditions, it may have positive aspects by attracting tourism and generating income when it is well-managed and the safety of visitors is guaranteed, despite the potential damage it may cause. However, it may also become a disaster when the eruption exceeds the management capabilities in the affected area. This all depends, of course, on the size and style of the eruption—but also on the degree of prevention and preparedness carried out as part of the risk management program that should be implemented in any active volcanic area.

Finally, it is worth mentioning the relevance of protected natural spaces in a volcanic island like Tenerife. Well-managed protected natural spaces may represent an important social and economic improvement, but they also may raise awareness and knowledge of geology, for both the local population and the visitors [45]. Responsible management implies a correct definition of geosites of geological interest, interpretation guides, training of geotourism guides, etc., but also good planning of the routes to and within these spaces—in addition to having adequate services and an adequate risk management plan based on a long-term hazard assessment. The different programs of the protected natural space entail better participation of the communities that live inside them, and therefore, this predisposes them to appreciate the richness of these areas. Consequently, a well-informed populace facilitates policy makers to design thorough risk mitigation policies. Protected natural areas also facilitate the zoning and management of the territory, which entails better planning and adequate infrastructure, research, monitoring, alert levels, response plans, including evacuation routes, etc., alongside effective communication. Tongariro (New Zealand), Hawaii (USA), and Iceland are good examples of where there are participation spaces where both authorities and the local population participate according to their decision level, making it much easier to involve the public in emergency planning and response. The development and implementation of environmental education programs of the protected natural spaces is a great tool to develop capacities and awareness, and in places like Tenerife, it would contribute to volcanic risk reduction. In this sense, one of the tools to disseminate volcanological knowledge and security perception when visiting these protected areas is geotourism. The equipment and guides that partake in geotourism are the key actors to improve the knowledge of both the local population and the visitors about the geological and volcanological characteristics of the area, while at the same time being active participants in the definition of volcanic risk management plans. The high number of protected natural spaces in Tenerife (more than 50% of the island has some type of protection) should be sufficient reason to undertake these types of policies, thus making the island much safer and more sustainable. The information shown in Table 1 should be presented to visitors and should help to raise awareness about geological risks on the island.

6. Conclusions

Active volcanic islands are prone to the impact of many natural hazards, the severity of which will increase due to climate change. Therefore, to ensure a safe society, we must design and implement adequate risk mitigation plans. In this sense, nature-based solutions are a key component for adapting to climate change and the impacts of natural hazards by increasing the resilience of society and ensuring its sustainability.

However, climate change is not only having direct effects on the population (increasing global temperature, extreme heat and cold waves, droughts and/or torrential rains, sea level rise, etc.), but is also increasing the magnitude and frequency of some natural hazards and altering the interrelationships between them. Volcanic islands, such as Tenerife, are particularly vulnerable to these changes or impacts derived from natural hazards, and they are also major tourist destinations that have recently experienced significant demographic expansion, resulting in a population that is increasingly exposed to natural hazards. For this reason, it is essential to focus efforts on developing risk mitigation strategies based on long-term hazard assessment and to transform these areas into sources of nature-based solutions.

Moreover, volcanic islands, due to their geographic condition and geological characteristics, are perfect laboratories to innovate in so-called multi-risk scenarios—a burgeoning concept and one of the objectives of the current Sendai Framework for Disaster Risk Reduction (2015–2030)—and how to apply it to territorial management. The reason volcanic islands are good test beds for multi-risk is because they have clear maritime boundaries and already many protected natural areas, as is the case of Tenerife. However, it is precisely these limits that present an even greater challenge: a limited space for demographic expansion and resource exploitation, characterized by associated risks in many of them.

In the case of Tenerife—as occurs in many other volcanic islands, and in general, many volcanic areas—one of the main existing problems is demographic expansion and the progressive increase of tourism, which requires changes in land use, a feature that is not always in accordance with the required solutions to reduce risk. In Tenerife, tourism is by far its main income, and this forces local policies to prioritize land occupation for construction and other uses for services to tourism. In Tenerife, there are no well-established land use planning policy measures for managing volcanic risk. Scientific information about natural hazards is not being incorporated effectively into land use planning. There is no risk reduction program; most of the emergency plans are reactive rather than proactive; and each of them addresses only a specific hazard, without ever considering a multi-hazard approach. This limits the effectiveness of possible risk reduction plans, which should incorporate hazard and vulnerability information into land use planning to be proactive and successful. Land use planning based on hazard and vulnerability studies limits the exposure of people, critical infrastructure, and valuable assets to natural hazards, thus anticipating and mitigating possible impacts derived from these hazards.

Author Contributions: Conceptualization, M.L.-S., J.M. and L.P.; formal analysis, M.L.-S.; funding acquisition, M.L.-S. and J.M.; methodology, M.L.-S. and J.M.; validation, M.L.-S., J.M. and L.P.; investigation, M.L.-S. and J.M.; resources, M.L.-S., J.M. and L.P.; writing—original draft preparation, M.L.-S. and J.M.; writing—review and editing, M.L.-S. and J.M.; visualization, M.L.-S.; supervision,

J.M.; project administration, M.L.-S. and J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the European Commission (EC) DG ECHO Horizon 2020, grant number 826292. Marta López-Saavedra received an FPU PhD grant, grant number FPU19/02413, from the Ministerio de Ciencia, Innovación y Universidades of Spain.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We warmly thank Land Editorial Office for its invitation to contribute a paper to this Special Issue of Land. The English text has been reviewed and revised by Grant George Buffett.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Geoheritage (2022) 14: 65
https://doi.org/10.1007/s12371-022-00698-5

ORIGINAL ARTICLE

The Volcanic Geoheritage of El Teide National Park (Tenerife, Canary Islands, Spain)

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Received: 26 July 2021 / Accepted: 27 April 2022 / Published online: 12 May 2022

Abstract
El Teide National Park on the island of Tenerife (Canary Islands) is home to one of the most spectacular volcanic landscapes in the world. Although the conservation of its geodiversity is not a major problem given that it is governed by strict Spanish laws on geoconservation and is, in addition, a UNESCO World Heritage site, the diffusion of its geological values among the general public is more of a challenge due to the lack of any specific program for scientific knowledge transfer to visitors. The volcanological history of this national park needs to be transmitted in a clear and comprehensible fashion. However, the lack of adequate outreach material and of any coherent and consistent narrative regarding the significance of the island's geological heritage makes it difficult to incorporate its geological history into the minds of visitors. This engenders a perception of its geoheritage that underestimates its importance. To remedy this misconception, the following tasks need to be carried out: (1) a compilation of all current scientific knowledge of the geology and volcanology of the area; (2) the identification of key geosites that offer the best means of understanding the history and evolution of this volcanic area; (3) the production of outreach and diffusion programs specifically designed to transmit this scientific knowledge to the general public; and (4) the establishment of permanent training programs for park and tourist guides that will guarantee the efficacy of this knowledge transmission. This contribution summarizes the main aspects of the geological history of El Teide National Park, identifies the elements that best exhibit its geological heritage, discusses the main problems observed in transmitting these geological values to visitors, and provides some clues as to how to face up to these challenges.

Keywords El Teide National Park · Tenerife · Volcanic geoheritage · Geodiversity · Conservation

Introduction

Due to their geological richness, volcanic zones are important geoheritage sites. Active volcanic fields are of special interest because they facilitate the observation of the complex and interesting stratigraphic relationships that characterize their products and processes, and, furthermore, often contain landscapes of unusual beauty (Nemeth et al. 2017; Casadevall et al. 2019; Planagumà and Martí 2020). Visitors to these geological sites would be able to appreciate the full complexity of volcanic activity and the need to preserve the geoheritage sites if the scientific information explaining the geologic processes is available, explained in such a way that public in general, particularly tourists, could understand these processes. Like the rest of knowledge-based tourism, it is a very effective interdisciplinary way of ensuring that tourism is compatible with the conservation and interpretation of our geological heritage. Additionally, this type of tourism aids the economic and social development of local communities, especially on volcanic islands whose main income is from tourism (Newsome and Dowling 2010; Sigurdsson, and Lopes-Gautier 2000; Erfurt-Cooper 2011; Dóniz-Páez 2014). Volcanoes and volcanic terrains have a worldwide fascination and many are visited by huge numbers of people every year (e.g., Iceland, Canary Islands, Hawaii, Yellowstone, Etna, and Vesuvius). These visits to both live and extinct volcanic landscapes provide much public recreation, adventure and enjoyment, while also affording opportunities for observing, learning, and appreciating the power and role of volcanism in building our planet's surface, and for raising awareness of associated risks. Geotourism and, in particular, volcanic tourism may have other significant

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benefits including self-esteem, employment, and wealth generation for local and regional communities, above all if it is organized and managed in a sustainable way (Planagumà and Martí 2018).

El Teide National Park (TNP) was declared on 22 January 1954 and was then one of only three national parks in Spain. Subsequently, the park was reclassified in 1981 as an area with a special legal regime. In 1989, the park was awarded the European Diploma of Protected Areas by the Council of Europe, which was renewed in 1994, 1999, and 2004. Finally, it was classified as a UNESCO World Heritage Site in 2007. Its 18,990 ha embraces Las Cañadas caldera complex and the twin stratovolcanoes of Teide and Pico Viejo, as well as numerous intra- and extra-caldera volcanic vents, some of them related to the active rift systems of Dorsal and Santiago del Teide (Fig. 1). With around 3.5 million visitors annually, it is one of the most visited national parks in the world.

The caldera of Las Cañadas and El Teide-Pico Viejo active volcanic complex is a well-exposed and highly interesting volcanic setting (Fig. 2). Proof of this is the interest that it has always stimulated within the international scientific community, having been studied ever since the early nineteenth century (see Martí 2019). These studies have provided a considerable volume of information (geological, volcanological, geophysical, geomorphological, hydrogeological, petrological, etc.) on Las Cañadas and El Teide-Pico Viejo and various theories about their formation have been advanced, which over time have fuelled one of the most surprising and long-lasting of all data-based volcanological controversies (see Martí 2019).

Among the many visitors that come to the TNP every year, there are always a large number of students and academics from universities and research centers. They are principally attracted by the visibility of most of the park's geological outcrops and have great interest in training, learning,

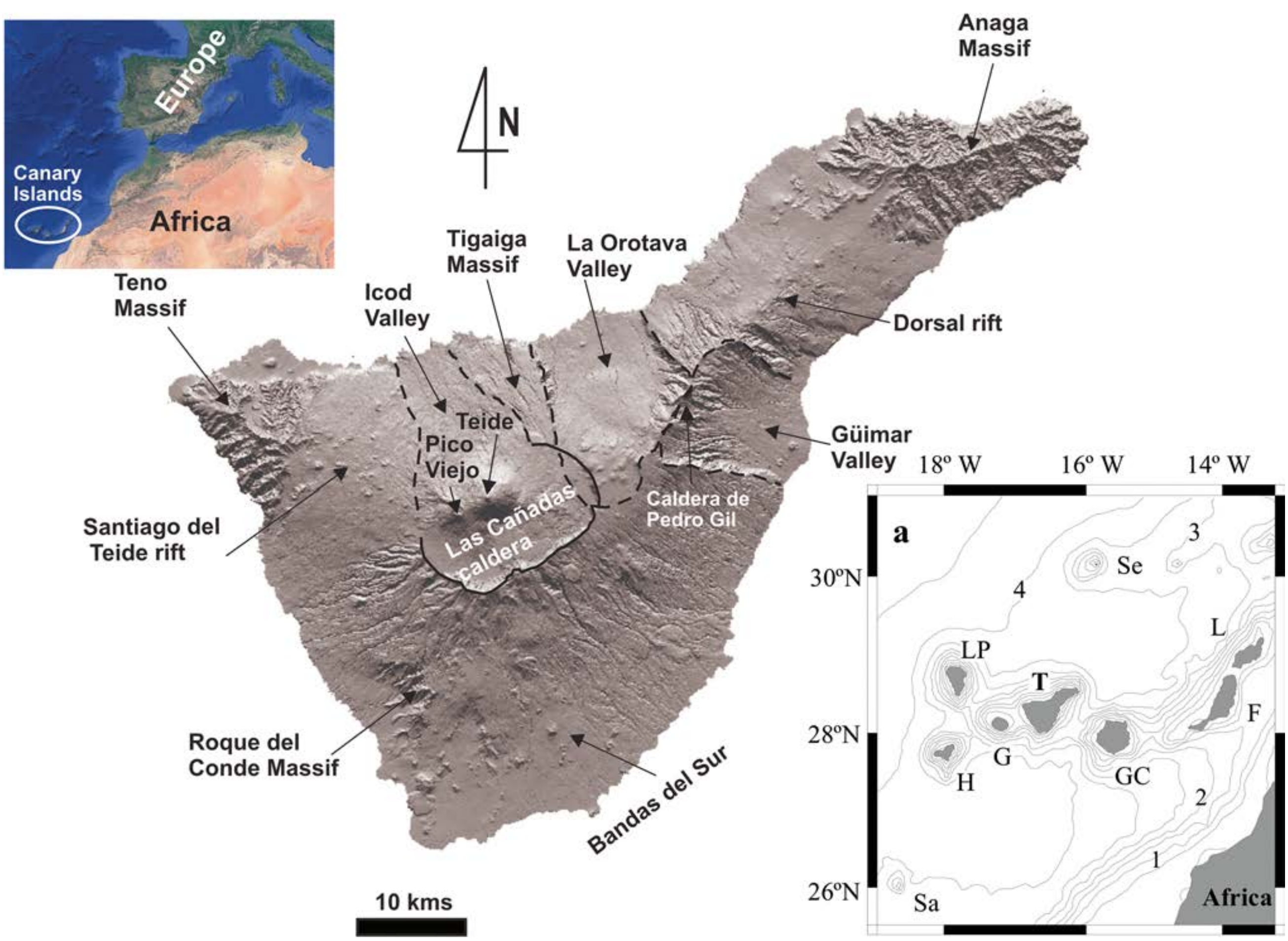


Fig. 1 Shaded relief of a DEM of Tenerife showing its main morphological, volcanological and structural features (the 25 m DEM is geocoded to the UTM grid system, sector 28 N, GCS_WGS_1984, datum: D_WGS_1984). The upper inset shows a Google image including Europe and Africa for regional reference of the location of the Canary Islands. The lower inset shows the location and distribution of the Canary Islands. Main islands: LP: La Palma; H: El Hierro; G: La Gomera; T: Tenerife; GC: Gran Canaria; F: Fuerteventura; L: Lanzarote. Islets and Seamounts: Sa: Saharan seamounts; Se: Selvagem islands

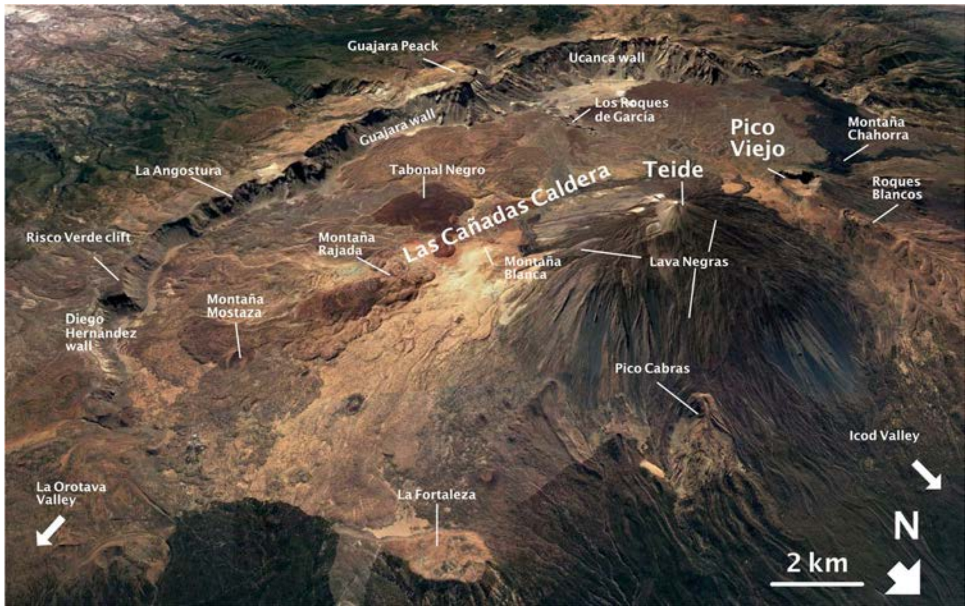


Fig. 2 Aerial view of Las Cañadas caldera and El Teide-Pico Viejo Complex, with an indication of the main geological elements of this sector of the TNP (view from the north-west) (Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image © 2019 GRAFCAN, obtained from Google Earth)

and conducting research into the different volcanological outcrops that are exposed. In this sense, it is not pretentious to say that the TNP constitutes one of the best natural volcanological schools anywhere in the world, and one in which most textbook volcanic processes and products can be directly observed and studied.

However, despite this richness in geological and volcanological values, the paucity of the information available to visitors is surprising. For example, the amount of information on the wide geodiversity of this park found on webpages such as Wikipedia, in both its Spanish and English versions (https://es.wikipedia.org/wiki/Parque_nacional_del_Teide, https://en.wikipedia.org/wiki/Teide_National_Park), or on the park's webpages (http://www.gobiernodecanarias.org/parquesnacionalesdecanarias/es/Teide/; https://parquesnacionales.cnig.es/teide), is slight or non-existent, or even erroneous if compared to existing scientific information. Likewise, available outreach and dissemination material for visitors is few and far between, and often out-of-date and lacking the scientific rigor to be expected for such a geologically important site. In addition, information on the geoheritage of the park transferred to potential park guides (e.g., https://www.miteco.gob.es/es/red-parques-nacionales/boletin/guias-pn-teide.aspx) is insufficient for them to show and explain to visitors all the geological and volcanological values of the park. Therefore, the role of the TNP in promoting geological and volcanological knowledge is still not as relevant as it should be, despite the potential it possesses.

In order to improve the current understanding of this unique geological scenery and to increase awareness among the general public, this contribution aims to provide an overview of the geoheritage preserved in the TNP, offer a synthesis of the volcanological evolution it reveals, identify its main geosites, and discuss the actions that could be undertaken to enhance communication, outreach, and the preservation of these geological values.

Geological Setting

The island of Tenerife in the Canary Islands (Spain) lies in the east-central Atlantic Ocean, about 300 km off the coast of Morocco (NW Africa), and is one of the largest and most complex volcanic systems on Earth. Tenerife rises nearly 8000 m above the Miocene oceanic crust (Watts et al. 1997) and began to grow very quickly due to the accumulation of basaltic lavas during fissure eruptions, which gave rise to a shield volcano that comprises almost 90% of the island (Fig. 1). Remnants of this basaltic shield emerge at the corners of Anaga and Teno and in Roque del Conde (Fig. 1). These subaerial rocks date from between 12 and 3.3 Ma according to existing radiometric data (K–Ar and Ar–Ar) (Ancochea et al. 1990; Thirlwall et al. 2000).

Following this phase of basaltic volcanism and after an erosive period, which duration is still not well constrained, the eruption of phonolitic magmas started to occur from much more localized centers. Their products (lavas and pyroclasts) built Las Cañadas Edifice in the center of the island. This phonolitic volcanism alternated with basaltic volcanism, and both have continued up to the present day on the island. Las Cañadas Edifice, aged over > 3.5 Ma, covers a large part of the subaerial sectors of the initial basaltic edifice. The construction of Las Cañadas Edifice by basaltic and phonolitic magmas—the latter generating highly explosive eruptions—is a feature that sets Tenerife (as well as Gran Canaria; Fuster et al. 1968a) apart from other large oceanic volcanic systems such as Hawaii or La Reunion where the volcanism is practically only basaltic. Las Cañadas Edifice (Fuster et al. 1968b; Araña 1971) overlies an erosional unconformity at the top of the lower basaltic shield (Old Basaltic Series, Fuster et al 1968; Ancochea et al. 1990), although the contact zone is not clearly exposed. Las Cañadas Edifice is a large composite stratovolcano consisting of a predominantly mafic-to-intermediate Lower Group (> 3.5– < 2 Ma) and an Upper Group (1.6–0.18 Ma) comprising the products of three basaltic-to-phonolitic volcanic cycles, each one representing a different stratigraphic formation (Ucanda, Guajara, Diego Hernandez), which terminated with caldera collapse events (Martí et al. 1994) (Fig. 3). The phonolitic rocks from each formation are mostly pyroclastic and have petrological and geochemical features that separate them from those of the other formations (Zafrilla 2001). Phonolitic rocks from the Ucanca Formation overlie the Lower Group and range in age from 1.57 to 1.07 Ma, while those of the Guajara Formation were emplaced between 0.85 and 0.57 Ma. The phonolitic pyroclastic rocks of the Diego Hernández Formation range in age from 0.37 to 0.18 Ma. Volumes of several tens of cubic kilometers have been estimated for the largest pyroclastic deposits (Martí et al. 1994; Bryan et al. 2000; Edgar et al. 2002, 2007, 2017), while a minimum volume of 140 km^3 has been calculated for the whole pyroclastic sequence of the Upper Group (Martí et al. 1994). A large variety of Las Cañadas Edifice pyroclastic and associated deposits, including welded and non-welded air-fall deposits with different grain sizes, dense (ignimbrites) and dilute (pyroclastic surges) pyroclastic density current (PDC) deposits, lahars, debris avalanche deposits, and secondary volcaniclastic deposits, as well as lava flows of different thickness and a large variety of dykes, can be observed along the magnificently exposed caldera wall.

The final part of the construction of the central volcanic complex of Tenerife corresponds to El Teide-Pico Viejo, which began to develop about 17–18 Ka years ago inside Las Cañadas caldera, a depression created by several caldera collapse episodes that truncated the top of Las Cañadas Edifice (Martí et al. 1994; Martí and Gudmundsson 2000; Martí 2019). Several large episodes of flank collapse also occurred during the construction of Tenerife (Bravo 1962; Coello 1973; Carracedo 1994; Watts and Masson 1995, 2001; Ablay and Hurlimann 2000; Hurlimann et al. 2004; Hunt et al 2011, 2013a, 2013b). The Icod landslide is thought to have occurred between ~ 0.165 and ~ 0.179 Ma (Martí et al. 1994, 1997; Boulesteix et al. 2012; Hunt et al. 2011), while the age of the Güímar landslide is well-constrained between 0.86 and 0.83 Ma (Ancochea et al. 1990). However, the age of La Orotava landslide is less precise and is constrained only between 0.69 and 0.56 Ma (Ibarrola et al. 1993). The Güímar valley contains deposits from the Guajara and Diego

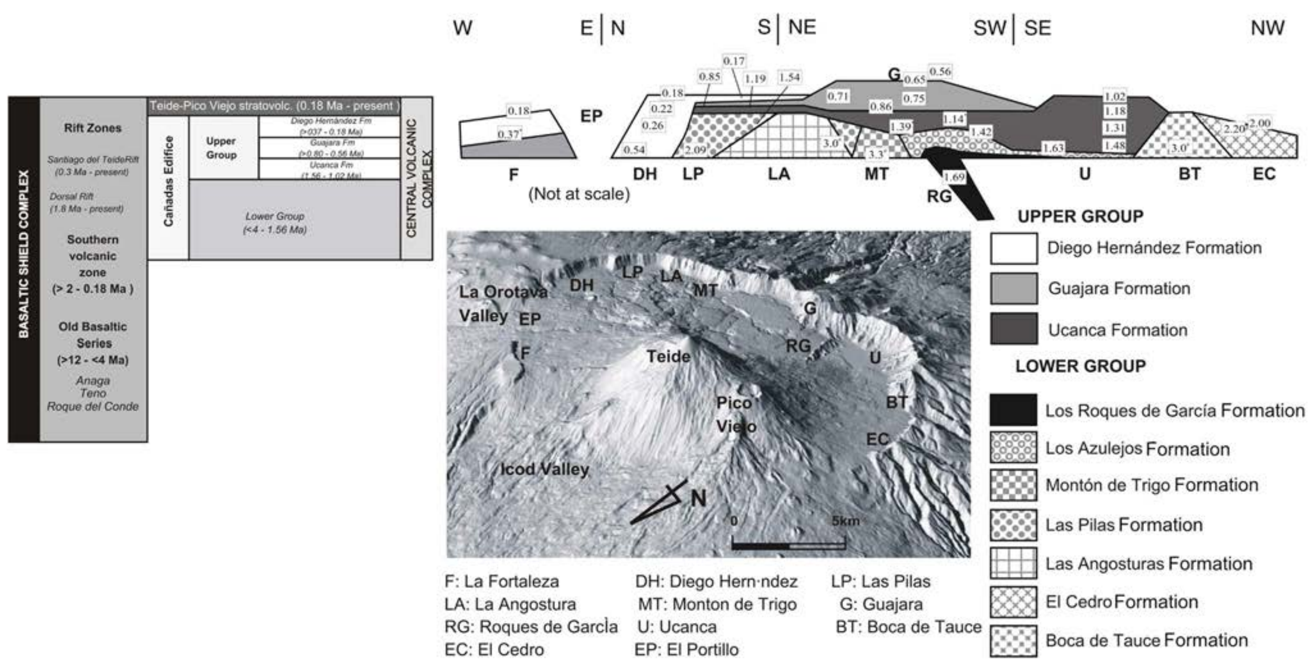


Fig. 3 Left: simplified stratigraphy of Tenerife (after Ablay and Martí 2000). Rest of the figure: schematic illustration of the stratigraphy of Las Cañadas caldera wall, showing the Lower Group and Upper Group formations (modified from Martí et al. 1994). Isotopic ages in boxes are taken from Martí et al. (1994) and Ancochea et al. (1990, 1999, 2000). The shaded relief of the central part of Tenerife, showing the caldera wall sectors and El Teide-Pico Viejo stratovolcanoes, was taken from the same DEM as in Fig. 1

Hernandez formations, while La Orotava valley has deposits from the whole Diego Hernandez Formation, in addition to later basaltic lavas. The Icod valley only contains lavas and pyroclastic deposits from El Teide and Pico Viejo complex and from the Santiago del Teide rift.

Basaltic volcanism continues today at multiple eruption sites, including the north-eastern (Dorsal Rift) and north-western (Santiago Rift) fissure vent systems (Fig. 1), and in several small scoria-lava cones located at the heads of major landslide valleys (La Orotava, Güímar, Icod) and elsewhere. The two active rift systems (Fuster et al. 1968; Carracedo 1994; Carracedo et al. 2011; Geyer and Martí 2010; Delcamp et al. 2010, 2012, 2014) (Fig. 1) have hosted all the Tenerife historical eruptions. The interior of these rift systems has recently been imaged using gravimetric inverse modelling, which has shown that they correspond to shallow structures that facilitate the lateral migration of deep basaltic magmas that rise close to the surface (Sainz-Maza et al. 2019).

The Overall Geological and Volcanological History of El Teide National Park

The most important question that needs to be answered when designing an education plan for the geoheritage of this protected area is what type of history should be taught to visitors to El Teide National Park. We first need to take into account current scientific knowledge, which should provide the basis for any outreach and public-awareness programme. Well-informed tourism is one of the best ways of disseminating scientific knowledge related to geoheritage preservation since what visitors will take back to their respective homes is the essence of the geoheritage message.

In summary, the geological and volcanological history of TNP represents the last phase in the evolution of a large composite volcano, named the Cañadas Edifice. This history embraces a wide diversity of eruption styles, the origin of the Las Cañadas caldera, the formation of the Icod and La Orotava landslide valleys, and the birth and further evolution of El Teide and Pico Viejo stratovolcanoes inside the caldera depression. The origin of Las Cañadas caldera and its relation to the Icod and La Orotava valleys, an interesting example of cascading extreme hazards, could be misunderstood if it is not well presented and transmitted (see Martí 2019). The origin and evolution of El Teide and Pico Viejo is not unanimously agreed upon by the scientific community, which means that differing opinions regarding the significance and current state of volcanic activity in the park is transferred to the visitors, thereby creating confusion if they compare the information they have received. This is why only the direct observation of the exposed geosites throughout the TNP, accompanied by an objective and concise explanation of their meaning and significance can guarantee that visitors receive an unbiased view of the island's unique geoheritage.

Las Cañadas caldera is a multicycle overlapping collapse caldera that formed over a period of more than one million years. It is the result of different caldera-forming events that occurred at the end of each of the phonolitic cycles identified in the Upper Group (Fig. 4). Although much of the evidence that supports the origin and internal structure of this caldera derives from indirect indications provided by geophysical studies (Ortiz et al. 1986; Camacho et al. 1991; Pous et al. 2002; Coppo et al. 2008, 2010; Gottsmann et al. 2008; Blanco-Montenegro et al. 2011; García-Yeguas et al. 2017), other relevant aspects for interpreting the caldera formation can be directly observed. These include (a) the morphology of the caldera wall, which shows the embayments corresponding to each caldera sector and the degree of erosion of each of them as a consequence of their different age of formation; (b) the presence of faults that controlled the collapse events in some sectors of the caldera; (c) the succession of deposits derived from some of the caldera collapse episodes; and (d) the geometry and cross-cutting relationships of different families of sheet intrusions that were related to the plumbing system of Las Cañadas Edifice.

The roots of Las Cañadas Edifice can be observed today in the form of dykes and other types of phonolitic intrusions, as well as in certain older volcanic deposits that crop out in the interior of the caldera along Los Roques de García spur and various sectors of the caldera wall. All these rocks have been exposed on the surface due to caldera collapse events and the subsequent erosion of the resulting caldera walls (see itineraries 2, 3, and 5). Phonolitic sheet intrusions represent the remnant of the different shallow plumbing systems that were installed when Las Cañadas Edifice was being constructed. Different sets and geometries of sheet intrusions, including radial, concentric, and inclined (cone sheets) dykes, as well as plugs formed at the intersection of dykes, can also be viewed (Martí et al. 1994; Galindo et al. 2005; Soriano et al. 2006). They have different thicknesses, from decimeters to meters, appear as single or multiple intrusions, and exhibit a range of different cross-cutting relationships. This suggests that these sheet intrusions formed at different times and from different pressure sources (magma chambers) during the construction of Las Cañadas Edifice. Moreover, it is worth mentioning that many of these dykes have pyroclastic textures, thereby indicating that they were feeder dykes originating from the phonolitic eruptions that produced the deposits observable along the caldera wall.

Los Roques de García Formation belongs to the Lower Group (Fig. 3) and forms the morphological and structural barrier that divides Las Cañadas caldera into two morphological depressions, the eastern side being 150 m higher than the western one (Martí et al. 2010). This spur controlled the distribution of El Teide and Pico Viejo lava flows emplaced

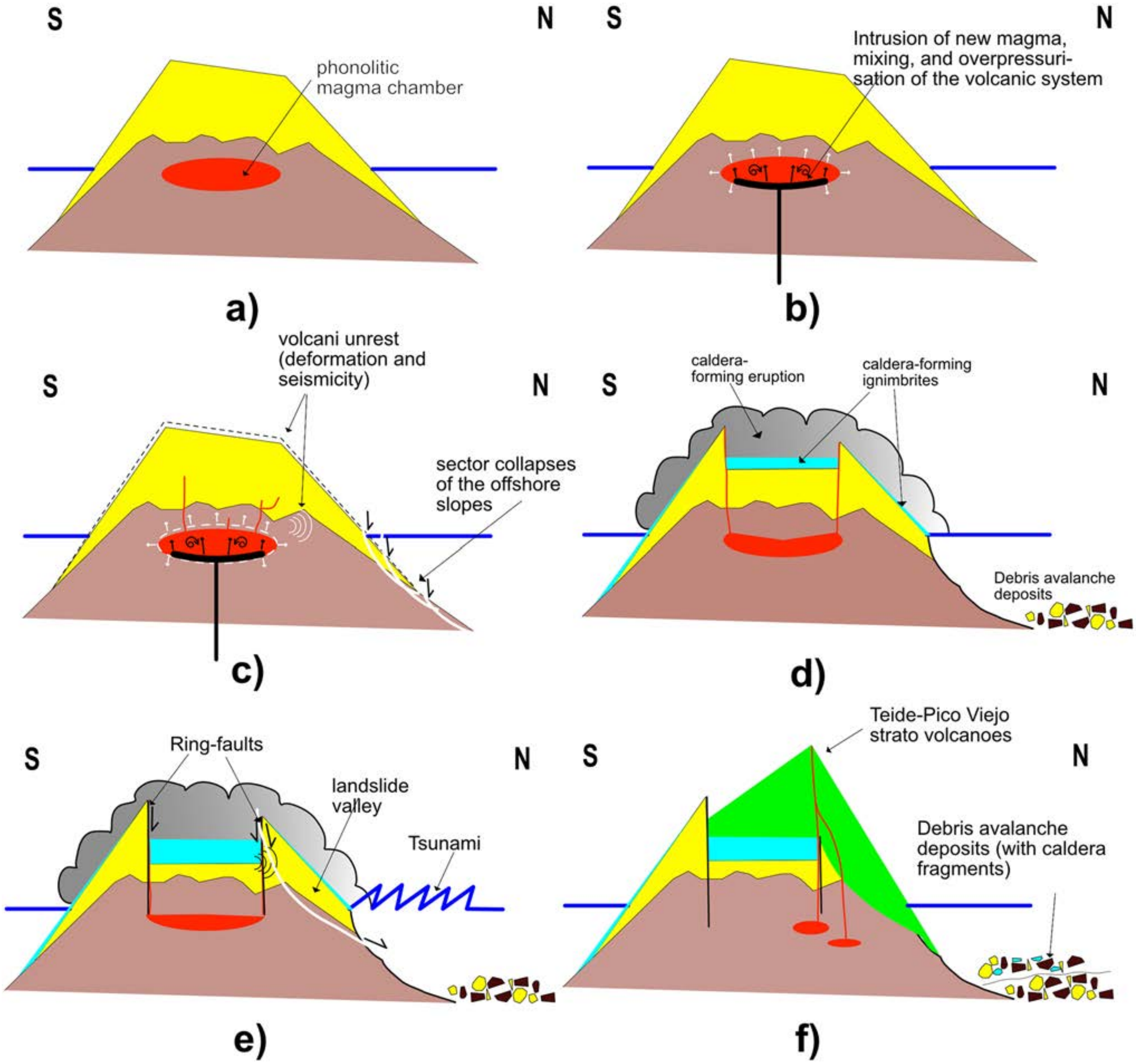


Fig. 4 Depiction of the succession of events that led to the formation of Las Cañadas caldera and their relationship with the landslide valleys (modified from Martí, 2019) (see text for explanation)

in the caldera from the southern flanks of the volcanoes. The rocks forming Los Roques de García consist of several successions of proximal pyroclastic and sedimentary (epiclastic) deposits, predominantly breccias, all of which were intruded by a dense network of phonolitic dikes and necks. The central sector of Los Roques de García spur is highly fractured due to the movement of several normal faults. It has also undergone strong hydrothermal alteration that has conferred on the exposed rocks a large variety of colors (blue, green, yellow, white, etc.), which makes this zone (Los Azulejos) one of the most attractive places in Las Cañadas caldera. In addition to its beauty, Los Roques de García are crucial for understanding and interpreting correctly the formation of Las Cañadas caldera (Martí et al. 2010). This stratigraphic succession is concordant with the rest of Las Cañadas caldera wall and corresponds to the lower part (Lower Group) of Las Cañadas Edifice but has no relation to any of the later explosive episodes that were responsible for the deposition of its upper part (Upper Group). The lithological, sedimentological, and volcanological characteristics of Los Roques de García rocks allow them to be interpreted either as an older Las Cañadas intracaldera sequence or as the apron of a previous stratovolcano, unlike previous interpretations (Ancochea et al. 1999; Cantagrel et al. 1999; Arnaud et al.

2001) that suggested that they correspond to the products of a major debris avalanche event that contributed to the formation of the present caldera.

The slopes of Tenerife are affected by several huge landslide scars and valleys (Bravo 1962; Carracedo 1994, Watts and Masson 1995, 2001; Ablay and Hurlimann 2000; Masson et al. 2002; Paris et al. 2017), the most important of which are those of the Icod, La Orotava and Güímar valleys (Fig. 1) whose headwalls are included within the limits of the TNP.

In the debate on the origin of Las Cañadas caldera, some authors (e.g., Bravo 1962; Coello 1973; Carracedo 1994; Watts and Masson 1995, 2001; Boulesteix et al. 2012; Paris et al. 2017) have suggested that it formed as a result of the same landslide process as the Icod valley, which would mean that the whole caldera wall would be the product of a single event and be the headwall of this valley. This idea is explained to visitors and backed up by the TNP (Fig. 5), mainly due to the fact that it was suggested by local geologists (e.g., Bravo 1962; Coello 1973; Carracedo 1994). However, all available geological and geophysical evidence strongly supports the idea of the caldera collapse origin explained above, with a cause/effect relationship operating between the Guajara and Diego-Hernández caldera-forming events and the landslides of the La Orotava and Icod valleys, respectively (see Martí 2019 for a review on this controversy). A visit to the TNP should provide objective information on these processes and on their possible spatial and temporal relationships, and try and avoid the misinterpretations of the geological evidence that exist in the park literature. As an example, the above-mentioned simple observation of the different degrees of erosion affecting the various sectors of the caldera wall is evidence enough to be able to convincingly reject the idea that Las Cañadas caldera was formed as the result of a single destructive event.

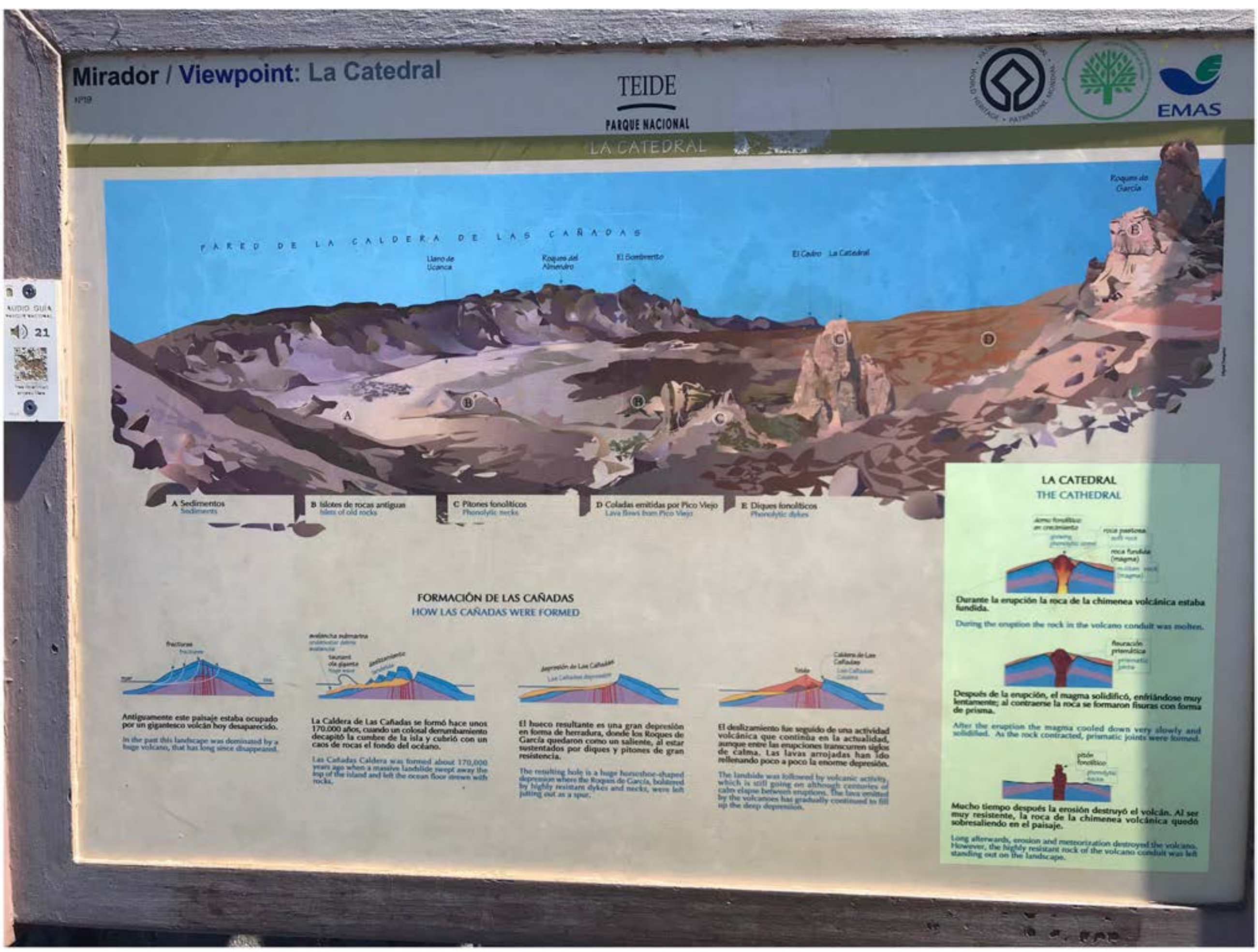


Fig. 5 Explanatory panel located at Las Ruleta viewpoint looking toward the Ucanca depression, which explains the origin of Las Cañadas caldera and Icod Valley as the result of the same massive landslide in contradiction with most current scientific evidence

In fact, vertical collapses occurred several times during the evolution of the Upper Group; the collapses that culminated the phonolitic cycles of the Guajara and Diego Hernández formations were associated with the formation of La Orotava and Icod valleys, respectively. In these two cases, the succession of events that may be deduced from the geological record includes the following (Fig. 4): (a) previous situation (state of equilibrium); (b) an overpressurized phonolitic magma chamber due to the arrival of new magma; (c) increase in seismicity and deformation (unrest episode) caused by magma chamber overpressurization, which could provoke flank instability, thereby triggering a sector collapse to the north originated in the offshore sector of the volcano; (d) large-volume, phonolitic eruption forming a widespread ignimbrite covering part or all of the island, and also emplacing offshore in some directions, and causing caldera collapse; (e) the seismicity associated with the caldera collapse and the gravitational instability generated by these large eruptions triggered a landslide in the onshore sector of the volcano, partially affecting the northern sector of the newly formed caldera and generating the valleys and associated tsunamis; and (f) after the last episode of caldera formation, basaltic magmas rose again to the surface and started to construct El Teide-Pico Viejo complex in the northern sector of the caldera ring fault.

El Teide and Pico Viejo started to grow inside the northern border of the caldera just after the formation of its final eastern sector (Diego Hernández) (Ablay and Martí 2000). The products of these two volcanoes—mainly lava flows and pyroclastic deposits of basaltic-to-phonolitic composition—constructed two large stratovolcanoes rising to altitudes of 3135 and 3715 m a.s.l at Pico Viejo and Teide, respectively. They also infilled the caldera depression and the Icod and La Orotava valleys with over 600-m- and 500-m-thick deposits, respectively. Only the deposits from the final eruptions are currently visible, although a large variety of lava flow morphologies (e.g., blocky, aa, pahoehoe, lava tubes, levees, lava fronts, etc.) are all easily observed (Fig. 2). The presence of different craters in both stratovolcanoes is also of interest and gives a clue as to the complexity of their evolution. The current degree of activity in both volcanoes is low; the only evidence being the permanent fumaroles at and around the summit crater on El Teide and frequent low-magnitude seismic swarms (see https://www.ign.es/web/ign/portal/vlc-area-volcanologia). Despite this, neither should be considered as extinct, as they have erupted several times during the Holocene (past 10,000 years), having its last eruption (Lavas Negras) occurred about 1000 years ago. In addition to the Teide-Pico Viejo stratovolcanoes, the most recent volcanic activity inside the TNP has also occurred in relation to the two rift zones.

Identification and Observation of the Main Geological and Volcanological Values

Two of the main advantages of the TNP are the excellent state of preservation of most of its outcrops and the lack of vegetation cover over much of its surface area that enable good views to be had of all its geosites. In addition, the excellent network of paths and trails, all well preserved and indicated, allow visitors to reach all observation points on foot (Fig. 6). The following is a description of the main observation points (Table 1) that can provide visitors with a complete overview of the volcanological geoheritage of the TNP. Access to these points is along paths and trails, and occasionally along the main roads that cross the park. This description is based on the itineraries that take visitors to the main observation points and a number of isolated sites, and aims to take in the most relevant geological sites in the TNP.

Itinerary 1: Pico Viejo Crater and La Fortaleza Viewpoints

Itinerary 1 (Fig. 7) follows the path along the former crater of Pico Teide (La Rambleta) between the Pico Viejo viewpoint to the west and La Fortaleza viewpoint to the east (paths 12 and 11 in Fig. 6, respectively), and provides an aerial view of the whole Las Cañadas caldera. The objective of this itinerary is to visit the caldera wall, identify its main stratigraphic units, and observe the geometry of Los Roques de García spur. It also allows visitors to admire the Pico Viejo crater and the connection of this volcano with the NW rift, the Montaña Blanca complex, the northern sector of the caldera wall at La Fortaleza, and the La Orotava Valley. The itinerary starts at the Mirador de Pico Viejo, which can be reached by cable car and then on foot along paths 12 and 11 (Fig. 6), on foot from the Montaña Blanca trail to the Refugio de Altavista and then Pico Teide (path 7 in Fig. 11), or from Pico Viejo (paths 9 and 23 in Fig. 11). This itinerary includes the following observation points (OP) (Figs. 7 and 8).

OP 1.1: Pico Viejo Crater Viewpoint

The general view of the Pico Viejo crater and the northwestern rift (Santiago del Teide rift) is defined by an alignment of scoria cones and basaltic lava flows (Fig. 8a). The Pico Viejo crater is 1500-m wide and 150-m deep, and corresponds to a collapse caldera of a 'summit crater'-type that truncates the top of the volcano. The bottom of the caldera is relatively flat except for the presence of a funnel-shaped pit crater in the SW part of the caldera, with

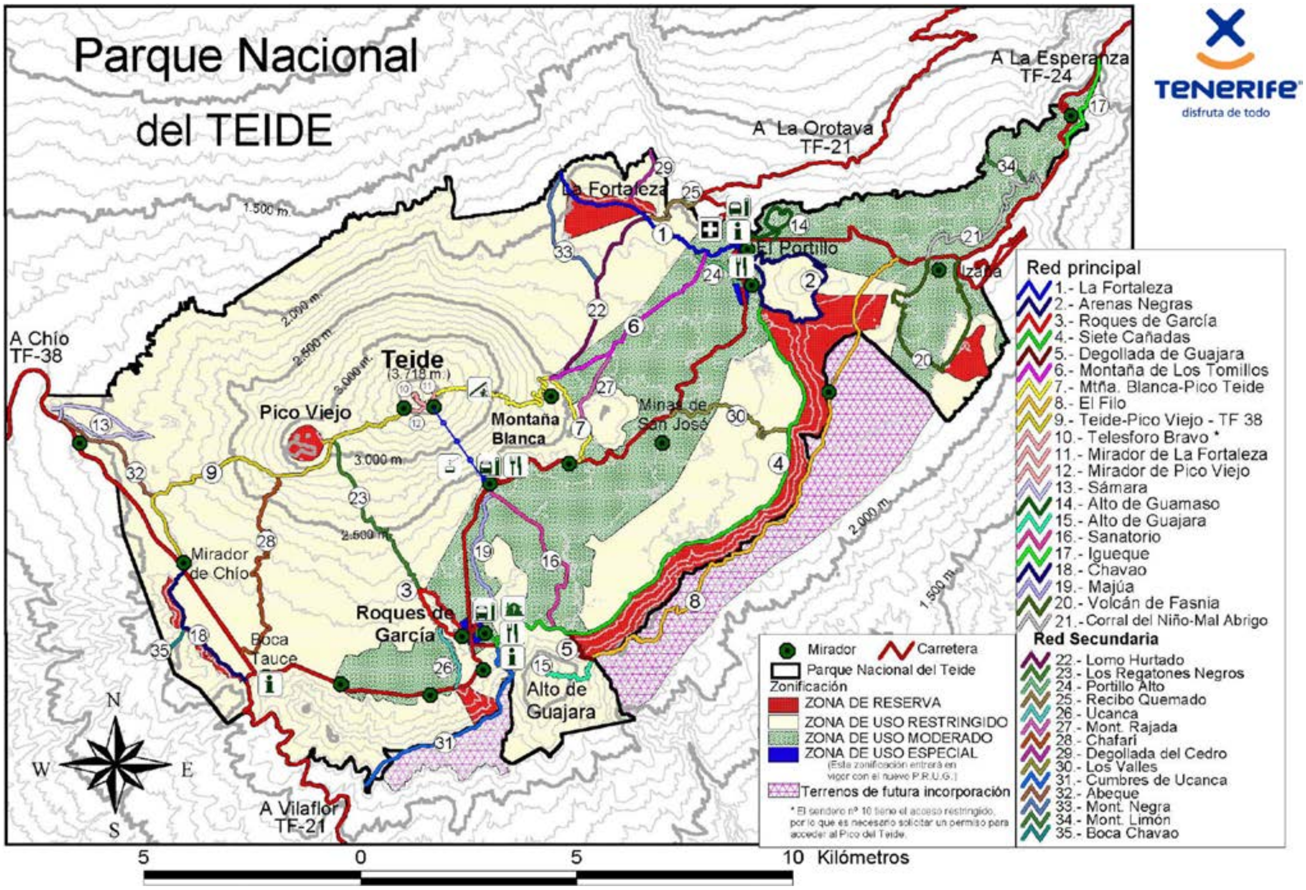


Fig. 6 Official path network in El Teide National Park (https://www.webtenerife.com/es/mapas/documents/mapa-parque-nacional-del-teide-permisos-de-rodaje.pdf)

an additional depth of 100 m. The caldera wall exposes lava flows that dip out of the caldera at angles between 25° and 35°.

Resting against the southern edge of the wall, there is an isolated block that represents a succession of massive, horizontally arranged phonolitic lava flows that exhibit a clear unconformity with the previous lavas. At the top of this block, there is a dilute PDC deposit (pyroclastic surge) of basaltic composition and the products of a phreatic explosion. This explosion generated a widely dispersed grey deposit, and is very rich in lithic fragments of different lithologies, including significant amounts of nepheline syenites and gabbros. This block of lavas represents the remnants of a lava lake that formed a thick succession of phonolitic lavas in the interior of the crater. This same succession can be observed at the pit wall, today displaced 150 m below its original position, which is evidence for the existence of a caldera collapse episode in the upper part of Pico Viejo volcano.

OP 1.2: Ucanca Depression Viewpoint

A general view of the western sector of the caldera (Ucanca depression) from which the morphology and stratigraphy of this sector of the caldera wall, the morphology of the filling lavas from El Teide-Pico Viejo complex, and the geometry of Roques de García can be observed (Fig. 8b). Among the deposits of the Ucanca and Guajara successions, it is worth highlighting the presence of thick (up to 120 m) welded rock units (proximal pumice fall deposits) that make up the most abrupt scarps of the wall. These deposits are examined in detail at observation points OPs 4.2 and 4.3 on itinerary 4.

OP 1.3: Guajara Depression

A general view of the central sector of the caldera (Guajara), from where the succession of deposits of the Guajara Formation and El Teide lavas that infilled the caldera depression can be observed (Fig. 8c). The Guajara Formation is

Table 1 Location with UTM coordinates of all geosites described in this study

Itinerary	Observation point	Description	X coordinate	Y coordinate
1	OP 1.1	Pico Viejo crater viewpoint	338,656.00	3,128,195.00
	OP 1.2	Ucanca depression viewpoint	339,005.00	3,128,120.00
	OP 1.3	Guajara depression	339,263.00	3,128,207.00
	OP 1.4	La Fortaleza viewpoint	339,228.00	3,128,670.00
2	OP 2.1	Overview of the Ucanca depression and caldera wall	339,969.00	3,122,993.00
	OP 2.2	Los Roques de García viewpoint	339,534.00	3,121,691.00
	OP 2.3	Boca de Tauce viewpoint	335,299.00	3,122,075.00
	OP 2.4	Chahorra or Narices del Teide viewpoint	333,379.00	3,124,814.15
3	OP 3.1	North end of the Diego Hernández wall	347,358.00	3,129,448.00
	OP 3.2	Central sector of the Diego Hernández wall	347,849.00	3,128,952.90
	OP 3.3	Risco Verde clif	347,783.00	3,127,950.00
	OP 3.4	The Angostura volcanic edifice from the Lower Group	344,753.00	3,124,799.00
	OP 3.5	Montón de Trigo Formation	343,429.00	3,123,264.00
	OP 3.6	Montaña Guajara viewpoint	342,744.00	3,122,976.00
	OP 3.7	Phonolitic dykes and plugs	341,673.00	3,123,181.00
4	OP 4.1	El Capricho	340,831.00	3,122,653.00
	OP 4.2	Ucanca and Guajara welded rocks	341,155.00	341,155.00
	OP 4.3	Barranco del Rio	340,694.00	3,121,109.00
	OP 4.4	Los Azulejos graben	340,138.00	3,120,825.00
5	OP 5.1	Epiclastic Upper Member and pyroclastic cone-sheet	339,928.00	3,123,139.00
	OP 5.2	Pico Viejo lava flows	339,718.00	3,123,490.00
	OP 5.3	Phonolitic multiple dykes	339,626.00	3,123,557.00
	OP 5.4	Pyroclastic Lower Member	339,086.00	3,123,977.00
	OP 5.5	Overview of multiple phonolitic dykes (La Escalerita)	339,312.00	3,123,456.00
	OP 5.6	La Catedral	339,455.00	3,123,062.00
	OP 5.7	Los Azulejos graben fault	340,264.00	3,122,622.97
	OP 5.8	Los Azulejos Formation	340,326.00	3,122,404.00
Other	OP 6.1	La Orotava overview	352,812.00	3,132,913.72
	OP 6.2	Güimar Valley and Caldera de Pedro Gil	354,763.00	3,136,327.00
	OP 6.3	Mirador del Tabonal Negro: Eastern part of the Teide-Pico Viejo complex	341,986.00	3,126,939.58

characterized by large scarps of welded rocks. From this observation point, the centers of Montaña Blanca, Montaña Rajada, and the scoriaceous lava of Tabonal Negro, all products of the Montaña Blanca eruption (2020 BP), can be observed.

OP 1.4: La Fortaleza Viewpoint

This observation point offers a general view of the eastern and northern sectors of the caldera, from where visitors can appreciate the head of La Orotava Valley, as well as the intersection of this area of the caldera and the northeastern rift (Dorsal de La Esperanza rift), the Icod valley to the west, and the Tigaiga massif in the middle separating the two valleys (Fig. 8d). La Orotava valley is infilled by phonolithic pyroclastic deposits corresponding to the Diego Hernández Formation and lava flows from El Teide. The southern end of the Tigaiga massif was intersected by the formation of the caldera and forms part of its northern wall, which is hidden on both sides below lavas from El Teide emplaced toward La Orotava and Icod valleys. The upper part of the southern end of the Tigaiga massif corresponds to La Fortaleza phonolithic welded rock unit, over 100 m thick, corresponding to the Diego Hernández Formation.

Itinerary 2: Ucanca Caldera Wall

This itinerary runs along roads from La Ruleta observation point at Los Roques de García to the Las Narices del Teide viewpoint (Figs. 7 and 9). Visitors can examine the western sector (Ucanca) in more detail and also gain a general view of Los Roques de García and Azulejos, and the 1798 Chahorra eruption craters and lavas. Specific aspects to be examined include the stratigraphy of the caldera wall and

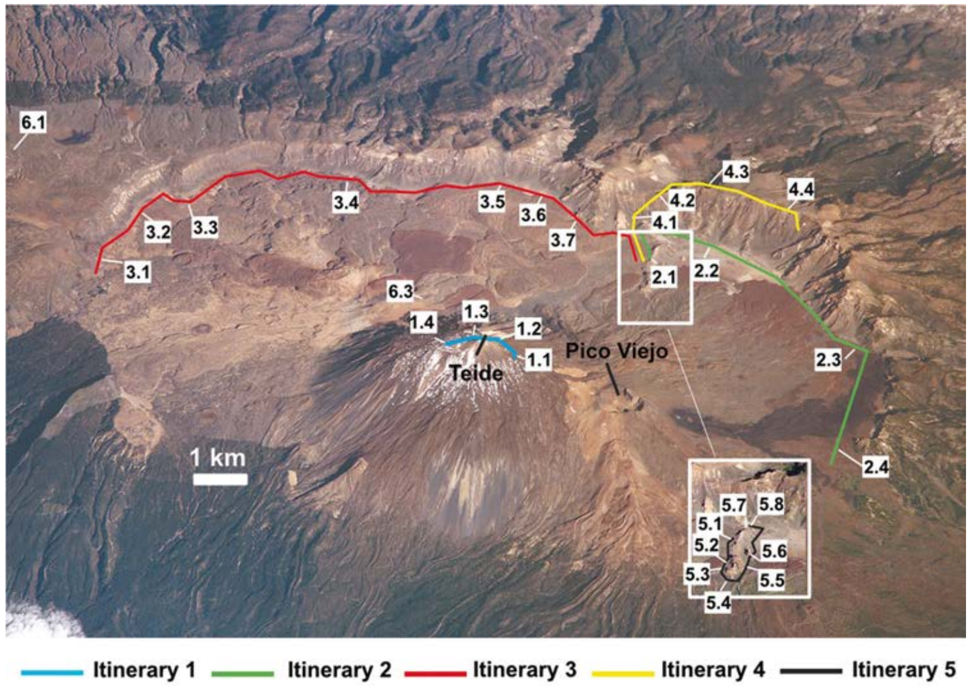


Fig. 7 Itineraries and observation points (OP) described in this study

its morphological evolution, the general stratigraphy of Los Roques de García, the hydrothermal alteration of Los Azulejos, Los Azulejos graben, different sets of phonolitic dikes, the Boca de Tauce edifice, and the Narices del Teide eruption (1798) and its relationship with the Santiago del Teide rift. Likewise, El Teide-Pico Viejo complex and the head of La Orotava valley can also be appreciated.

OP 2.1: General View of the Ucanca Depression and Caldera Wall

This viewpoint offers a general view of the Ucanca depression and the western caldera wall, as well as part of Los Roques de García and recent lavas from Pico Viejo (Fig. 9a).

OP 2.2: Los Roques de García Viewpoint

As indicated above, Los Roques de García (Fig. 9b) is key to understanding the origin of the caldera. Various authors (Ancochea et al. 1999; Cantagrel et al. 1999; Arnaud et al. 2001) who favor the hypothesis of lateral collapse as the origin of Las Cañadas caldera have proposed that Los Roques de García represent part of the avalanche deposits of this collapse and interpret its components as being blocks and megablocks from that avalanche. Conversely, others authors postulate a hypothesis of vertical collapse (Araña 1971; Martí et al. 1994; Martí and Gudmundsson 2000; Galindo et al. 2005; Martí et al. 2010), while current geophysical data (Pous et al. 2002; Coppo et al. 2008) suggest that Los Roques de García represent the eroded remnants of the wall resulting from the intersection between two caldera depressions (Ucanca and Guajara) and a true structural barrier up to several kilometers deep. Nevertheless, the stratigraphy and volcanology of Los Roques de García (Martí et al. 2010) reveals that this succession of deposits, together with the adjacent sequence of Los Azulejos toward the south, correspond to a set of pyroclastic (ignimbrites, lag breccias, pyroclastic surge deposits) and epiclastic materials (breccias and conglomerates) of proximal character belonging to the Lower Group. They have a concordant stratigraphic position within the whole Las Cañadas Edifice and form part of its Lower Group. This succession of old deposits is intruded by a dense network of phonolitic dikes and necks, and corresponds to a caldera fill sequence formed prior to the formation of the current caldera (Upper Group).

OP 2.3: Boca de Tauce Viewpoint

From this point and looking toward the southeast, the geometrical relationship and relative age of various sets of phonolitic dykes (inclined, radial, and concentric) can be observed (Fig. 9c). The presence of these intrusions reveals the existence of shallow magma chambers that controlled their location during different phases of magma rising. A structural analysis based on the statistical study of the distribution and geometry of these sheet intrusions allows us to reconstruct the position of the magma chambers from which they originated, and to infer the existence of several such centres in the western and central zones

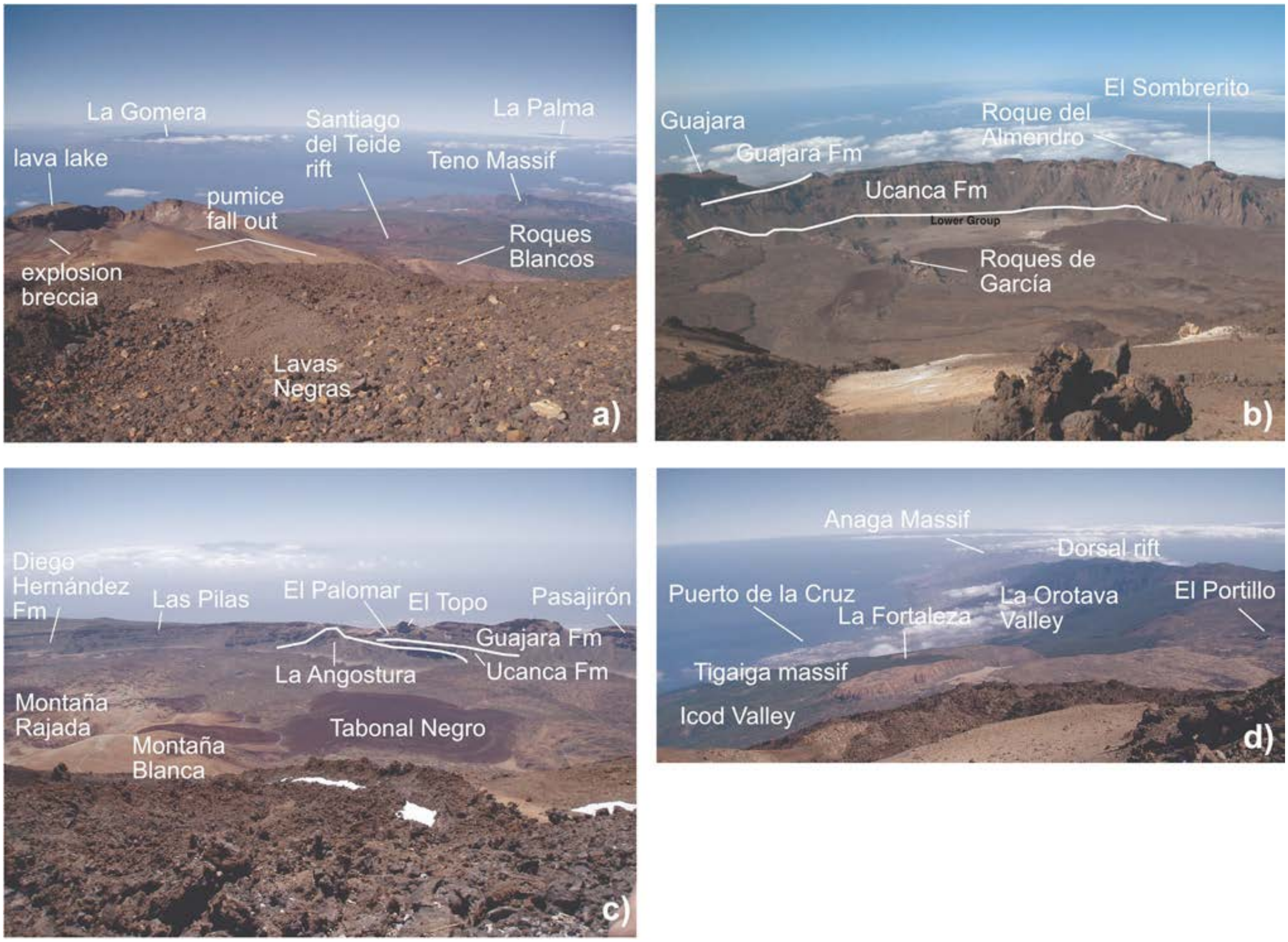


Fig. 8 The main geological and volcanological features observable along itinerary 1: **a** OP 1: general view of Pico Viejo crater and Santiago del Teide rift; **b** OP 2: general view of western sector of the caldera (Ucanca depression); **c** OP 3: general view of the central sector of the caldera (Guajara); **d** general view of the eastern and northern sectors of the caldera from the viewpoint of La Fortaleza

during the construction of the upper part of Las Cañadas Edifice (Martí et al. 1994; Galindo 2005).

From here and looking toward de southwest, we can also appreciate the presence of the Boca de Tauce Edifice, a remnant of the basaltic shield on which Las Cañadas Edifice was constructed. It is formed of dense plagioclase basalts, mostly autobrecciated lava flows, which produce a positive gravimetric anomaly throughout the entire western area of the caldera, extending northwards below Pico Viejo (Ablay and Kearey 2000; Gottsmann et al. 2008). The continuity of the Boca de Tauce Edifice below Las Cañadas suggests the presence of a continuous basaltic shield that links the remnants of this shield that emerges in Teno, Anaga, and Roque del Conde. This idea differs from the model positing the existence of isolated edifices forming the initial subaerial phase of Tenerife (Ancochea et al. 1990), which visitors to the TNP see on some information panels.

OP 2.4: Chahorra or Narices del Teide Viewpoint

The Chahorra or Narices del Teide eruption (1798) is the only one to have occurred inside the caldera in historical times. This eruption is associated with a magma of tephritic composition and occurred along an eruptive fissure forming an angle of about 30° with the main axis of extension of the Santiago del Teide rift on the western flank of Pico Viejo (Fig. 9d). This eruption was Strombolian-to-violent-Strombolian in type and generated spatter and ash deposits, as well as a broad lava flow field. It seems to have also been the cause of the phreatic explosion that originated the Pico Viejo pit crater (Ablay and Martí 2000).

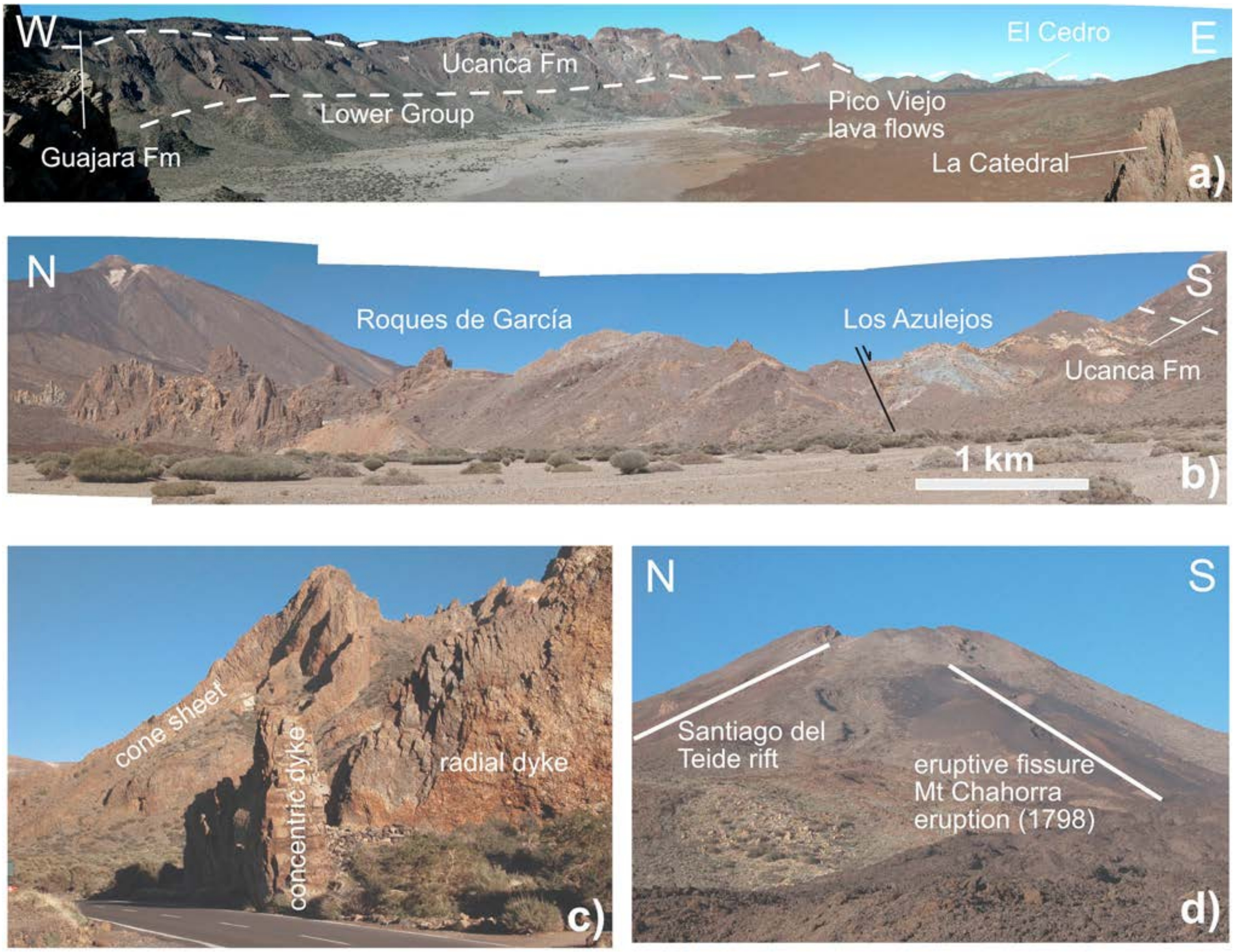


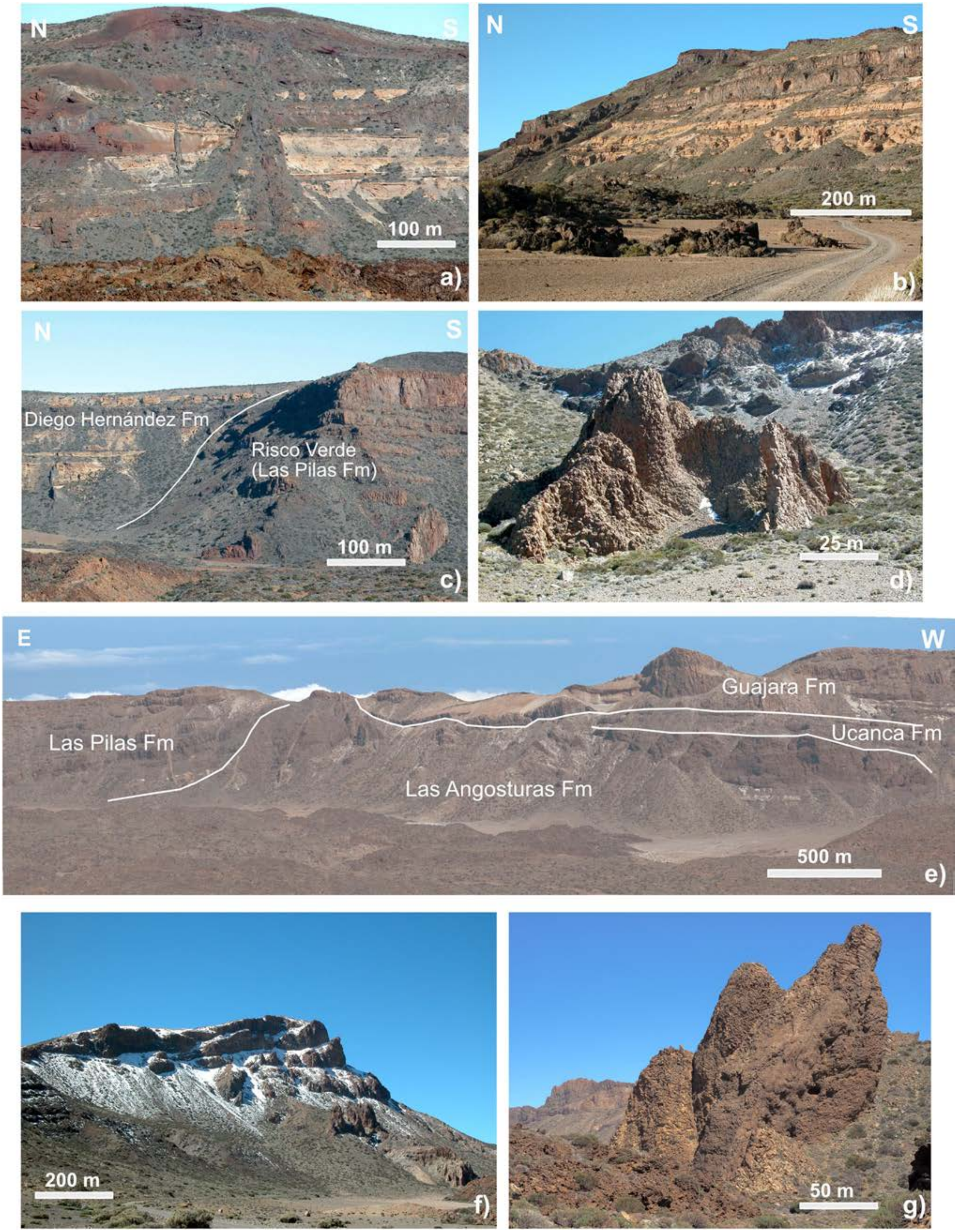
Fig. 9 The main geological and volcanological features observable along itinerary 2. **a** OP 2.1: view of the Ucanca depression and western caldera wall from La Ruleta observation point. La Catedral phonolitic plug (Roques de García) and lava flows from Pico Viejo are also observable from this point. **b** OP 2.2: panorama of Los Roques de García and Los Azulejos (Lower Group) in concordant contact with the Ucanca Formation (Upper Group) from Los Roques de García viewpoint. The line of the northern fault of Los Azulejos graben is indicated (Galindo et al. 2005). **c** OP 2.3: cross-cutting relationship between phonolitic sheet intrusions (concentric, radial and cone sheet dykes) in the western wall of the caldera. **d** OP 2.4: view of the western flank of Pico Viejo showing the orientation of the Santiago del Teide rift and the eruptive fissure of the Chahorra eruption (1798)

Itinerary 3: Eastern and Central Sectors of the Caldera Wall

This itinerary runs along the entire route of the Siete Cañadas track (path 4 in Fig. 6) at the base of the caldera wall in its eastern and central sectors, from El Portillo to the Parador. Along this itinerary, different aspects of the geology and volcanology of Las Cañadas Edifice and caldera, all well-exposed along the caldera wall, can be observed. The most relevant features are the presence of basaltic volcanism at the intersection between the NE rift (Dorsal de la Esperanza) and the central complex, the pyroclastic sequence of the Diego Hernández Formation, the Risco Verde scarp corresponding to the headwall of La Orotava valley, different sequences of the Lower Group (Angostura, Montón de Trigo, Capricho), and the presence of numerous dikes and phonolitic necks. In addition, the morphology of the fronts of the lavas flows from El Teide volcano is also visible.

OP 3.1: North end of the Diego Hernández Wall

At this point, there is a magnificent exposure of basaltic volcanism originating from the Dorsal rift. It is represented by a set of dykes, sills, scoria cones, and lava flows (dark colors), which in this sector are interbedded in or intersect the pyroclastic products (light colors) from Las Cañadas Edifice (Diego Hernández Formation) (Fig. 10a). The whole complex was affected by the formation of the caldera, thereby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100 m
a)
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Diego Hernández Fm
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W
Guajara Fm
Las Pilas Fm
Ucanca Fm
Las Angosturas Fm
500 m
e)
200 m
f)
50 m
g)

◂**Fig. 10** The main geological and volcanological features observable along itinerary 3. **a** OP 3.1: interaction between the basaltic volcanism (dark colour) of the Dorsal rift and the phonolithic (light colour) of Las Cañadas Edifice at the northern end of the Diego Hernández wall. **b** OP 3.2: detail of the pyroclastic succession (non-welded ignimbrites, pyroclastic surges and air fall deposits) of the Diego Hernández Formation with some interbedded basaltic lava flows from the Dorsal rift in this sector of the caldera wall. **c** OP 3.3: view of the Risco Verde cliff in which the unconformity between the Diego Hernández deposits (left) and those of Las Pilas Formation (right) is clearly visible. **d** OP3.4: view of La Angostura Formation in which the complex stratigraphic relationship between the successions from the Lower to Upper groups can be appreciated. **e** OP 3.5: example of an intrusive body (plug) of phonolitic composition that corresponds to one of the feeder conduits of the Guajara Formation. Note the radial distribution of some dikes with respect to the cylindrical central intrusion. **f** OP 3.6: view of the Guajara succession from the east, where at least four thick, strongly-welded units can be recognised overlying non-welded deposits. **g** OP3.7: dense arrangements of sheet intrusions and plugs of phonolitic composition

demonstrating the synchronicity of the basaltic activity along the Dorsal rifts and the explosive volcanism in the central edifice.

OP 3.2: Central Sector of the Diego Hernández Wall

Both in its proximal (caldera wall) and distal sectors (Bandas del Sur), the Diego Hernández Formation (Fig. 10b) is the most-studied sector of Las Cañadas Edifice and the site for which the greatest amount of stratigraphic, petrological, volcanological, and geochronological data exists (e.g., Martí et al. 1994; Edgar et al. 2002, 2007, 2017; Brown et al. 2003; Brown and Branney 2004; Pittari 2004; Pittari et 4al. 2008). This formation is made up almost entirely of non-welded, dense phonolitic PDC deposits (ignimbrites) with some associated pyroclastic surge deposits, along with air fall-deposits rich in lithic fragments from the substrate. Occasionally, the presence of banded pumice becomes evident, the result of the mixing of basaltic and phonolitic magmas. The directions of flow observed in the PDC deposits, as well as their geometry, indicate that these materials originate from a vent area located in the easternmost sector of Las Cañadas Edifice, which later collapsed to form that sector of the caldera (Martí et al. 1994). The products erupted from that vent area were mainly emplaced within a paleovalley excavated out of older materials on the eastern flank of Las Cañadas Edifice, corresponding to the head of La Orotava valley, formed by gravitational sliding (Bravo 1962; Hurlimann et al. 2004). Interbedded with the Diego Hernández phonolitic materials, there are also a number of different basaltic deposits (lavas and pyroclasts) derived from activity at the Dorsal rift. These basaltic vents correspond to monogenetic cones located at the northern end of the wall and form one of the borders of the paleovalley (Fig. 2). It is difficult to determine the time elapsed between eruptions along the Diego Hernández succession, although the absence of well-developed paleosols indicates that these eruptions occurred relatively frequently, with maximum time intervals in the order of just a few thousand years. The highly explosive character of the materials in the Diego Hernández Formation is reflected in the nature of the deposits: the abundance of lithic clasts, some of them hydrothermally altered, together with the type of alteration of the deposits, demonstrates the existence of phreatomagmatic phenomena that increased the explosiveness of some of the eruptions. The presence of banded pumice in some deposits suggests that some eruptions may have occurred as a consequence of the intrusion of hotter and more fluid basaltic magma into the phonolitic chamber.

OP 3.3: Risco Verde Cliff

The Risco Verde cliff represents the eastern end of the Diego Hernández caldera wall and corresponds to the succession of lavas and welded pyroclastic deposits of phonolithic composition of Las Pilas Formation belonging to the Lower Group (Fig. 3). This sector of Las Cañadas Edifice was partially destroyed by the formation of La Orotava valley, and was later infilled with pyroclastic deposits from the Diego Hernández Formation (Fig. 10c).

OP 3.4: Las Angosturas Volcanic Edifice from the Lower Group

Unlike the Upper Group, whose materials are distributed homogeneously and sub-horizontally along most of the wall, the Lower Group sequences are clearly associated with localized centres, and always have unconformities with the materials from adjacent centers (Fig. 10d). In the case of Las Angosturas Formation, the phonolitic PDC deposits (ignimbrites and pyroclastic surges) are limited in extent and are interbedded with very localized basaltic materials and epiclastic deposits.

OP 3.5: Montón de Trigo Formation

In this area, in addition to observing another of the sequences of the Lower Group (Montón de Trigo Formation, Martí et al. 1994), numerous phonolitic intrusive bodies (dikes and necks) can be observed. These were emplaced into the rocks of the Lower Group and Ucanca Formation, and correspond to feeding conduits for the eruptions of the Guajara Formation (Fig. 10e).

OP 3.6: Montaña Guajara Viewpoint

From this point, the full succession of the Guajara Formation is visible, separated from the Ucanca Formation

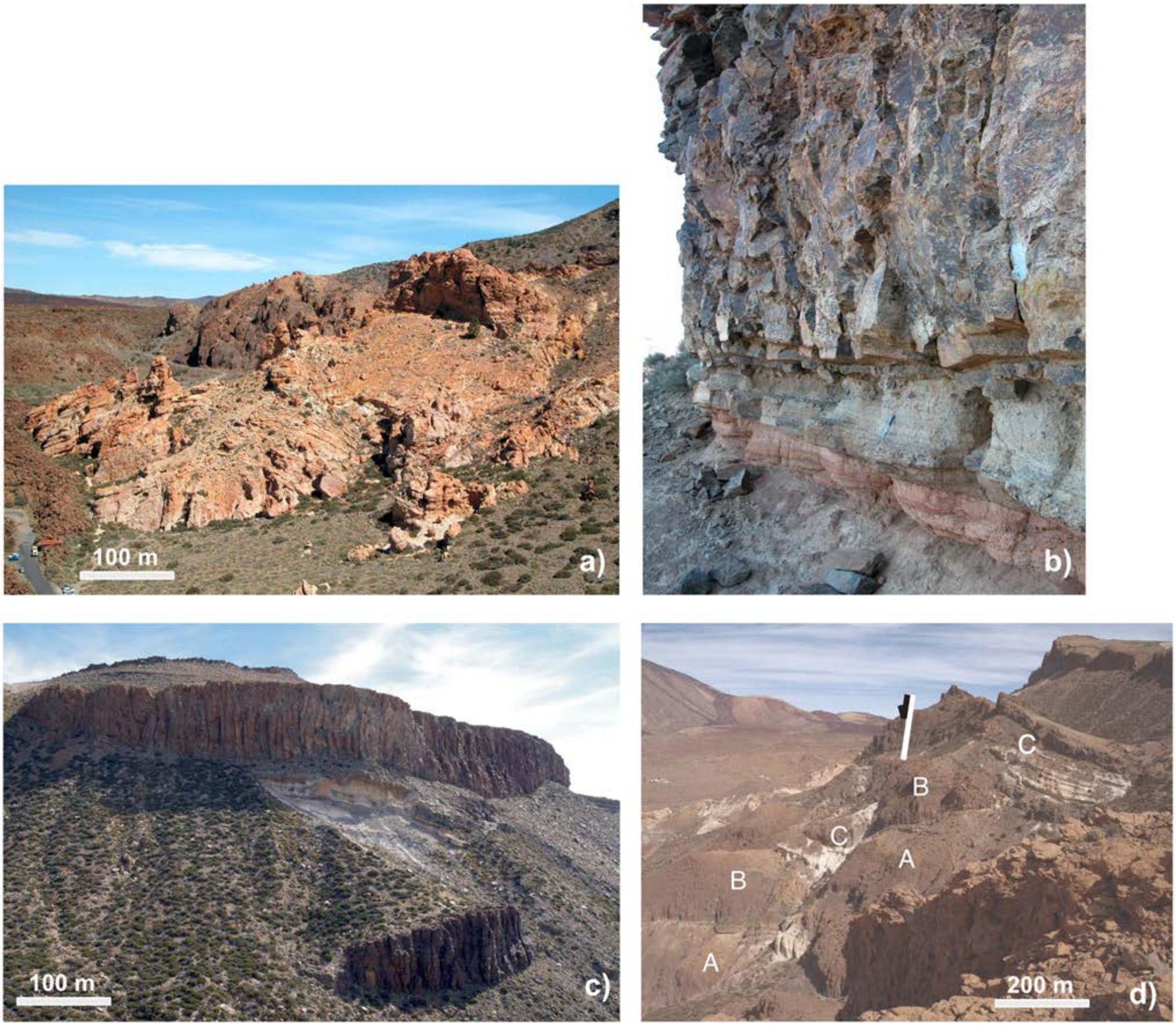

Fig. 11 The main geological and volcanological features observable along itinerary 4. **a** OP 4.1: general view of El Capricho pumice cone from the path to the Degollada de Ucanca. Note the stratification of the pumice layers in opposite directions. **b** OP 4.2: example of welded rock, with a non-welded base (for explanation, see text). **c** OP 4.3: view of alternating welded and non-welded pyroclastic deposits from the Guajara Formation at the Barranco del Rio. **d** OP 4.4: view of the Ucanca fault forming the southern boundary of Los Azulejos graben from the edge of the caldera wall in the Ucanca sector. Equivalent units on both sides of the fault plane are indicated by the same letter. The fault plane line and its relative movement are also indicated

by discontinuous basaltic scorias and lavas and intruded at its base by several dykes and plugs (Fig. 10f). The Guajara Formation has a maximum thickness of 250 m at Montaña Guajara and becomes progressively thinner toward the east (La Angostura and Las Pilas Cañadas). The phonolitic pyroclastic deposits of the Guajara Formation display a wide range of lithofacies with both welded and non-welded components. Most of the deposits dip gently (4–7°) southwards. The non-welded deposits include several horizons of well-stratified pumice lapilli beds, pumice breccia beds of fallout origin, pumice-rich ignimbrites with associated pyroclastic surge deposits, and some breccias. Welded rocks have a well-developed eutaxitic texture, defined by large, 1–20 cm in length, dark glassy or pale green devitrified fiamme. Most of the welded rocks resemble proximal welded fallout deposits (Martí et al. 1994), the exception being the uppermost unit, which is a classic welded ignimbrite consisting of a welded matrix with fiammes and lithic fragments. At this point, path 5 starts (Fig. 6) and climbs up to Montaña Guajara.

OP 3.7: Phonolitic Dykes and Plugs

This sector of the itinerary displays a large variety of sheet intrusions and plugs, which form dense arrangements and sometimes even conceal the host rocks (Fig. 10g). They are radial, concentric, and mostly single and multiple cone-sheets. They range in thickness from one to tens of meters, and their textures change from aphyric to porphyric with large plagioclase phenocrysts. Contacts with the host rocks or between different intrusions are marked by chilled margins. Most of these intrusions are massive, although some pyroclastic intrusions are also present. Some plugs appear at the intersection of several families of dykes, forming a much thicker intrusion with roughly circular morphology.

Itinerary 4: Deposits from the Ucanca and Guajara Formations

This itinerary (Fig. 7) (path 31 in Fig. 6) includes the ascent to the Ucanca caldera rim (Degollada de Ucanca) and then turns west along the caldera border for several kilometers toward Boca de Tauce. Midway along the route, Los Azulejos graben is perfectly visible. Observations to be made during this itinerary include, in addition to this first-order tectonic accident, the pumice cone of Capricho (Lower Group), the welded rock sequences of the Ucanca Formation, and the alternation of welded and non-welded pyroclastic materials from the Guajara Formation.

OP 4.1: El Capricho

El Capricho consists of the remnants of a pumice cone that has been eroded into uniquely capricious forms (hence its name), in which the internal stratification with opposite-facing dips to the north and south can still be observed (Fig. 11a). This structure was once a pumice cone formed by the accumulation of fallout pumice fragments around an emission centre during an eruption on the southeast flank of El Teide that was similar to that of Montaña Blanca (2020 bp). This unit belongs to the Lower Group and is located stratigraphically above Los Azulejos and below the Ucanca Formation.

OP 4.2: Ucanca and Guajara Welded Rocks

These thick units of welded rocks corresponding to proximal fall deposits constitute the most significant lithological feature of the Ucanca and Guajara formations (Martí et al. 1994; Soriano et al. 2002), and are one of the most characteristic features along the central and western sectors of the caldera wall. In general, the base of these units is well-stratified and non-welded, but there are also some spatter agglutinate beds, non-welded pumice fragments, beds rich in lithic fragments, and alternations of non-welded and welded deposits blending upwards into an up-to-120-m thick, densely welded, lava-like unit (Fig. 11b). In the transitional zone from non-welded to welded, there are highly vesiculated pumice fragments, highly flattened obsidian fiammes, obsidian spatter, and lithic fragments. The fiammes and spatters are thought to have been deposited from a low fountain-like eruption column, while the non-collapsed, vesiculated fragments are believed to have been transported high into the column where they cooled before deposition. The welded units are characterized by a well-developed eutaxitic texture defined by large (2–24 cm in length), flattened obsidian or pale green devitrified glass fragments. They lack a fine-grained matrix and often grade up from coarse, pumice-rich, non-welded fall deposits. These welded fall deposits formed by the accumulation of large fragments of magma that were still very hot during emplacement, and were able to sinter and weld when reaching the ground, thereby giving rise to a compact deposit that even had the ability to flow (rheomorphism) down the slope to generate a lava-like rock. Although confusion between phonolitic lavas and rheomorphic welded fall deposits is common, there are certain characteristics of welded fall deposits that separate them from phonolitic lavas: welded fall deposits grade laterally and vertically into non-welded deposits, have mantle topography, contain lithic clasts and do not have autobreccias at their margins unless they have become rheomorphic, in which case autobrecciation can occur and form deposits that are meters-to-tens of meters thick.

The gradual transition from non-welded to strongly welded shown by most of these units reflects a change in the physical conditions of the eruptive magma (fall in gas content, increase in temperature, fall in viscosity, etc.) within a zoned magma chamber. This creates a progressive change in the eruption style, from a typically Plinian phase (gas-rich magma) to a less explosive phase characterized by a much lower pyroclastic fountain (gas-poor magma) (Fig. 11b) (Soriano et al. 2002; Martí et al. 2020). Occasionally, these deposits may pass laterally into unwelded Plinian fall deposits, when more distant from the vent. In proximal areas, where these deposits behave rheomorphically, they may flow down the slope for several kilometers. In extreme cases, the front of the rheomorphic flow can detach itself from the rest of the deposits and slide down the slope for a few kilometers (Fig. 11b).

OP 4.3: Barranco del Rio

Looking east from this observation point at the top of Degollada de Ucanca, a north–south cross-section of the entire sequence of the Guajara Formation and part of that of Ucanca can be seen (Fig. 11c). It is worth noting here the above-mentioned alternation of non-welded pyroclastic


5 m
a)
10 m
b)
5 m
c)
10 m
d)
10 m
e)
10 m
f)
20 m
g)
20 m
h)
5 m
i)
5 m
j)

◂**Fig. 12** The main geological and volcanological features observable along itinerary 5. **a** OP 5.1: Roque Cinchado succession, forming part of Los Roques de García Upper Member and containing different units of proximal epiclastic deposits (breccia, cross-bedded sandstones, and conglomerates, intruded on top by an inclined sheet of phonolitic composition). **b** OP 5.1: cone-sheet, with pyroclastic texture and chilled margins. **c** OP 5.2: close-up view of Pico Viejo phonolitic lava flows. **d** OP 5.3: detail of a set of phonolitic intrusions showing columnar jointing. **e** OP 5.4: detail of the Lower Member pyroclastic rocks from Los Roques de García Formation, consisting of altered primary lithic and pumice rich ignimbrites. **f** OP 5.4: co-ignimbrite lag breccia deposits consisting of coarse lithic breccias with a high content of large lithic fragments embedded in an ignimbritic matrix. **g** OP 5.5: overview of a multiple phonolitic intrusion with well-developed columnar jointing. **h** OP 5.6: La Catedral plug, characterized by well-developed columnar jointing arranged in different directions. **i** OP 5.7: detail of Los Azulejos fault, which corresponds to the northern border of Los Azulejos graben (Galindo et al. 2005) as seen from the observation point OP 4.4. **j** OP 5.8: succession of strongly hydrothermally altered phonolitic pyroclastic deposits in Los Azulejos Formation

deposits (pumice fall, ignimbrites, and pyroclastic surges) with welded rock units.

OP 4.4: Los Azulejos Graben

Los Azulejos graben in the western sector of Las Cañadas caldera wall is 1 km wide and is limited by two important NE-SW oriented normal faults: Los Azulejos and Ucanca (Fig. 11d) (Galindo et al. 2005). This graben was active for at least 0.5 Ma, from the end of the Ucanca Formation to the end of the Guajara Formation, clearly before the collapse of Las Cañadas Edifice that formed the eastern sector of the caldera. A transtensional tectonic regime acted on the graben as demonstrated by kinematic indicators. The extension of the Dorsal rift zone toward Las Cañadas Edifice is the most probable volcano-tectonic origin of this graben, which facilitated the formation of the western and central sectors of the caldera. In this context, the inflation of the associated shallow phonolitic magma chambers could have caused the inverse reactivation of the normal faults. The main hydrothermal alteration of Los Azulejos occurred before the formation of this graben, while a secondary hydrothermal alteration associated with these normal faults occurred during and after its formation (Galindo et al. 2005).

Itinerary 5:se Los Roques de García and Azulejos Formations

This itinerary (Fig. 7) corresponds to path 3 in Fig. 6 and takes visitors around the main part of Los Roques de García spur. Several observation points allow visitors to appreciate the main geological features of this part of Las Cañadas caldera. The succession mainly consists of polygenetic breccias of volcanic (lithic-rich ignimbrites and co-ignimbrite lag breccias) and sedimentary (debris flows and alluvial fan deposits) origin, rich in fragments of basaltic and phonolitic lavas, all intruded by a dense network of phonolitic dykes and plugs. Martí et al. (2010) distinguish two main members in Los Roques de García Formation. The Lower Member is continuous along most of the exposure of Los Roques de García spur and mainly comprises proximal lithic-rich pyroclastic deposits. Although the lower contact of the Lower Member is not visible, the upper contact corresponds to an erosive contact with the Upper Member, which is mostly composed of different types of well-stratified, proximal, epiclastic breccias derived from the reworking of volcanic material, with some interbedded pyroclastic deposits and epiclastic sandstone and conglomerate units.

In the southeastern part of the spur, Los Roques de García sequence is in contact through a normal fault (Los Azulejos fault, Galindo et al. 2005) with the younger volcanic sequence of Los Azulejos (OP 4.4), which is conformably overlain by El Capricho eroded pumice cone (OP 4.1).

OP 5.1: Epiclastic Upper Member and Pyroclastic Cone-Sheet

The Upper Member of Los Roques de García Formation consists of an up-to-200-m-thick sequence of proximal epiclastic deposits and minor primary volcanic deposits. It constitutes the thickest accumulation of reworked volcanic material in the whole Las Cañadas caldera. Although the base of the Upper Member is characterized by a sharp contact that cuts into the deposits of the Lower Member, the upper stratigraphic contact is nowhere exposed. The Upper Member is mainly composed of thick sequences of highly indurated epiclastic breccias (up to 25 m thick), alternating with minor cross-bedded sandstones, conglomerates, lavas, and pyroclastic units. All of them have crude internal bedding that is consistent with the northeast-dipping bedding displayed by the remaining units in Los Roques de García spur. Epiclastic breccias are heterolithologic and contain fragments from up to 2 m in diameter to centimeter-to-millimeter-sized fragments in the matrix, with erosive-to-planar bases. Minor lenses of pebbles and coarse sands also occur, which occasionally display cross-bedding (Fig. 12a). The lithological and sedimentological characteristics of the Upper Member deposits indicate that they correspond to a proximal sedimentary sequence derived from the erosion and alluvial reworking of primary volcanic material, including the Lower Member rocks.

Looking westwards from the same observation point, there is an interesting visible example of a cone-sheet, inclined northwards and turning vertically upwards in its upper part. Its main characteristic is its pyroclastic texture, very similar to some of the welded ignimbrites that outcrop along the caldera wall (Fig. 12b). This intrusion has chilled margins at its borders, which were formed by the rapid cooling of magma during emplacement, and contains abundant lithic fragments and fiammes of glassy pumices elongated parallel to the flow direction. This pyroclastic texture and the fact that the dyke turns vertically upwards in its uppermost part suggest that it was a feeder that reached the surface during the eruption.

OP 5.2: Pico Viejo Lava Flows

At this point, it is possible also to observe several recent phonolitic lava flows from Pico Viejo that were superimposed in the interior of the caldera, all with different morphologies and textures. The lobes formed by some of these lavas are clearly visible, as are the levées that originated on both sides of some of them, forming a channel along the lava flow that controlled its emplacement. Lava morphologies observable from this point include the classical pahoehoe roped surface in some areas, as well as aa-to-blocky morphology in others. Another curiosity of some of these lavas is the presence of plagioclase feldspar megacrysts that measure one or more centimeters across (Fig. 12c).

OP 5.3: Phonolitic Multiple Dykes

One of the main characteristics of Los Roques de García is the large number of phonolitic intrusions that in some places make it difficult to distinguish the host rock, which can be massive or pyroclastic, single or multiple, vertical or inclined, with plagioclase phenocrysts or nearly aphyric, from a few decimeters to several meters thick. In most cases these intrusions exhibit well-developed columnar jointing perpendicular to the intrusion surfaces. Here, it is also possible to study one of these multiple intrusions, where several dykes have intruded along the same discontinuity to form what appears at distance to be a very thick single intrusion (Fig. 12d). The presence of these sheet intrusions, as in many other parts of the caldera wall, is evidence for the presence of a number of shallow magma chambers that underwent several inflation episodes, thereby causing the rupture of the chamber walls and the intrusion of magma into this sector of the original Las Cañadas Edifice.

OP 5.4: Pyroclastic Lower Member

The Lower Member of Los Roques de García Formation is better exposed in the northern sector of the spur. However, it continues toward the central and southern sectors, despite the fact that intra-formational and later faulting, hydrothermal alteration, and erosion all mask its presence in these other zones. It contains a well stratified, up to 150-m-thick succession of proximal primary pyroclastic deposits (Fig. 12e), which include massive, lithic, and pumice-rich deposits (i.e., ignimbrites), as well as pyroclastic breccias and fine-grained, thinly bedded deposits. The ignimbrites range from one to several metres in thickness and tend to have planar lower and upper contacts, which are sometimes associated with thin, fine grained (ash) layers with unidirectional sedimentary depositional structures. No paleosoils, erosion surfaces, or intraformational unconformities have been observed in this sequence, which suggests that the whole sequence corresponds to a single eruptive event consisting of several phases (see Martí et al. 2010 for more details).

All the deposits have been diagenetically and probably also hydrothermally altered, and all primary glass has been transformed into clay minerals and zeolites, giving rise to a strong induration of the rocks. However, some original, non-reworked pumice (vesiculated) textures have been preserved and it is possible to recognise the primary character of the pyroclastic deposits. All the deposits have a high content of angular-to-subrounded lithic fragments, mainly massive porphyritic phonolites, with subordinate fragments of basaltic and intermediate massive volcanic rock.

Some units correspond to coarse lithic breccias (Fig. 12f) that resemble ignimbrites; however, they can be distinguished by their greater content of larger lithic fragments, some several metres in diameter. Most of the lithic clasts are subrounded and consist of massive porphyritic phonolites. Some of these clasts have chilled margins and occasionally internal fractures, which in some cases also reflect a jigsaw-like texture. The matrix also contains ash fragments, but much less abundantly. Each individual coarse lithic breccia unit is several metres thick and has planar contacts. These breccias can be interpreted as co-ignimbrite lag breccias, which sometimes appear associated with ignimbritic deposits in proximal areas (see Walker 1985). The presence of co-ignimbrite lag breccias has also been noted in Las Cañadas Edifice Upper Group (Martí et al. 1994; Bryan et al. 1998; Pittari 2004; Pittari et al. 2008) and suggests evidence of caldera collapse events.

OP 5.5: Overview of Multiple Phonolitic Dykes (La Escalerita)

Here, visitors can enjoy an aerial view of an impressive multiple phonolitic intrusion with well-developed columnar jointing, whose discontinuity throughout the whole unit reveals the presence of several parallel sheet intrusions in the same structural plane (Fig. 12g).

OP 5.6: La Catedral

La Catedral is the most representative plug structure in Las Cañadas. This 120-m-diameter structure formed at the intersection of several families of dykes. It is characterized by well-defined columnar jointing, with pristine subhorizontal prisms in a radial arrangement, which form a rim around the inner part of the intrusion where the columns are vertical (Fig. 12h).

OP 5.7: Los Azulejos Graben Fault

Los Azulejos Formation is separated from Los Roques de García by the fault that marks the northern limit of Los Azulejos graben (Galindo et al. 2005), and can be viewed from observation point OP 4.4. The repeated movement of this fault during the evolution of Las Cañadas caldera is responsible for the chaotic distribution of the rocks on both sides of the fault plane (Fig. 12i). Additionally, minor normal faults with vertical displacements up to 40 m are present to the north and south of Los Azulejos Fault; they cause further disruption to the stratigraphy of Los Roques de García and Los Azulejos sequences and intensify the chaotic aspect of the central sector of Los Roques de García spur.

OP 5.8: Los Azulejos Formation

Los Azulejos Formation is unconformably underlain by the Ucanca Formation and consists of a succession of 220-m-thick phonolitic pyroclastic breccias, interbedded with pumice-rich ignimbrites, and surge and air-fall deposits (Fig. 12j). They exhibit well-preserved bedding that dips gently to the southwest. These breccias correspond to proximal facies and include intra-formational breccia deposits and epiclastic breccias. The lithic fragments are of the same composition as those found in Los Roques de García Formation. These rocks have been strongly altered by hydrothermal processes that occurred before the intrusion of the dyke systems related to the deposition of the Upper Group. This suggests that Los Roques de García and Los Azulejos formations represent an important volcanic edifice, constructed during the early stages of the upper part of Las Cañadas Edifice, which had no relation to the later caldera-forming eruptions (Martí et al. 2010). This is confirmed by the fact that both formations are intruded by the same dyke systems as those that affected other sectors of Las Cañadas caldera wall. The hydrothermal alteration gave rise to the characteristic bluish, greenish and yellowish colors of this formation, caused by the transformation of the original glass components into zeolites and clay minerals.

Additional Viewpoints

OP 6.1: La Orotava Vantage Point

This observation point (Fig. 7) affords the best view over La Orotava valley. It allows visitors to distinguish the alignment of Strombolian cones along the uppermost part of the valley, the infill by a succession of lavas from El Teide and the Dorsal rift, and the phonolitic pyroclastic deposits of Las Cañadas that underlie them. It is also interesting to view from here the stratification of the rocks that form the Tigaiga massif on the western wall of the valley, as well as the presence of various younger monogenetic cones inside the valley (Fig. 13a).

OP 6.2: Güímar Valley and Caldera de Pedro Gil

This observation point (Fig. 1) offers excellent views of two structural features that developed in relation to the Dorsal rift: the Güímar valley and Caldera de Pedro Gil (Fig. 13b). The Güímar Valley was the result of a catastrophic flank failure that affected the southern slopes of Tenerife several hundred thousand years before the formation of La Orotava valley on the northern side of the island (Ancochea et al. 1990). The Guïmar valley has no obvious relationships with any caldera-forming episode. The walls of the valley clearly show the succession of lavas and pyroclastic deposits from the basaltic edifices due to the activity of the NE rift, as well as numerous sheet intrusions of basaltic composition associated with the rift activity. In the valley itself, the Arafo volcano, a cinder cone and its associated lava flow, formed in the historical eruption of 1705, is visible. This cone is related to the Fasnia-Siete Fuentes eruptions that took place along the same SW-NE trending fissure.

Part of the Güímar valley headwall visible from this observation point was affected by another collapse event that formed Caldera de Pedro Gil. This depression is approximately 3 km wide and 540 m deep. However, assuming vertical collapse, its true diameter is probably only 1.5 km and its depth 700 m (Galindo 2005). A paleomorphologic analysis suggests that it formed about 0.81 Ma (Ancochea et al. 1990) after the vertical collapse of the Pedro Gil Edifice (Galindo 2005). The observed cross-cutting relationships suggest that the Güímar valley occurred before Caldera de Pedro Gil, and that this latter structure affected the location of the headwall of the former (Galindo 2005).

OP 6.3: Mirador del Tabonal Negro: Eastern part of El Teide-Pico Viejo Complex

From the Mirador del Tabonal Negro (Fig. 7), there is a panorama of the central and eastern sectors of the caldera (Fig. 13c). The relatively flat caldera floor comprises lavas from Montaña Blanca and isolated vents not obviously associated with the stratovolcanoes. Beneath these felsic rocks, there are 560 m of intermediate Teide products infilling the uppermost part of the caldera depression (see Martí 2019). Thick lobate lava flows from the caldera-floor vents of Montaña de la Cruz and Montaña Majua lie to the west

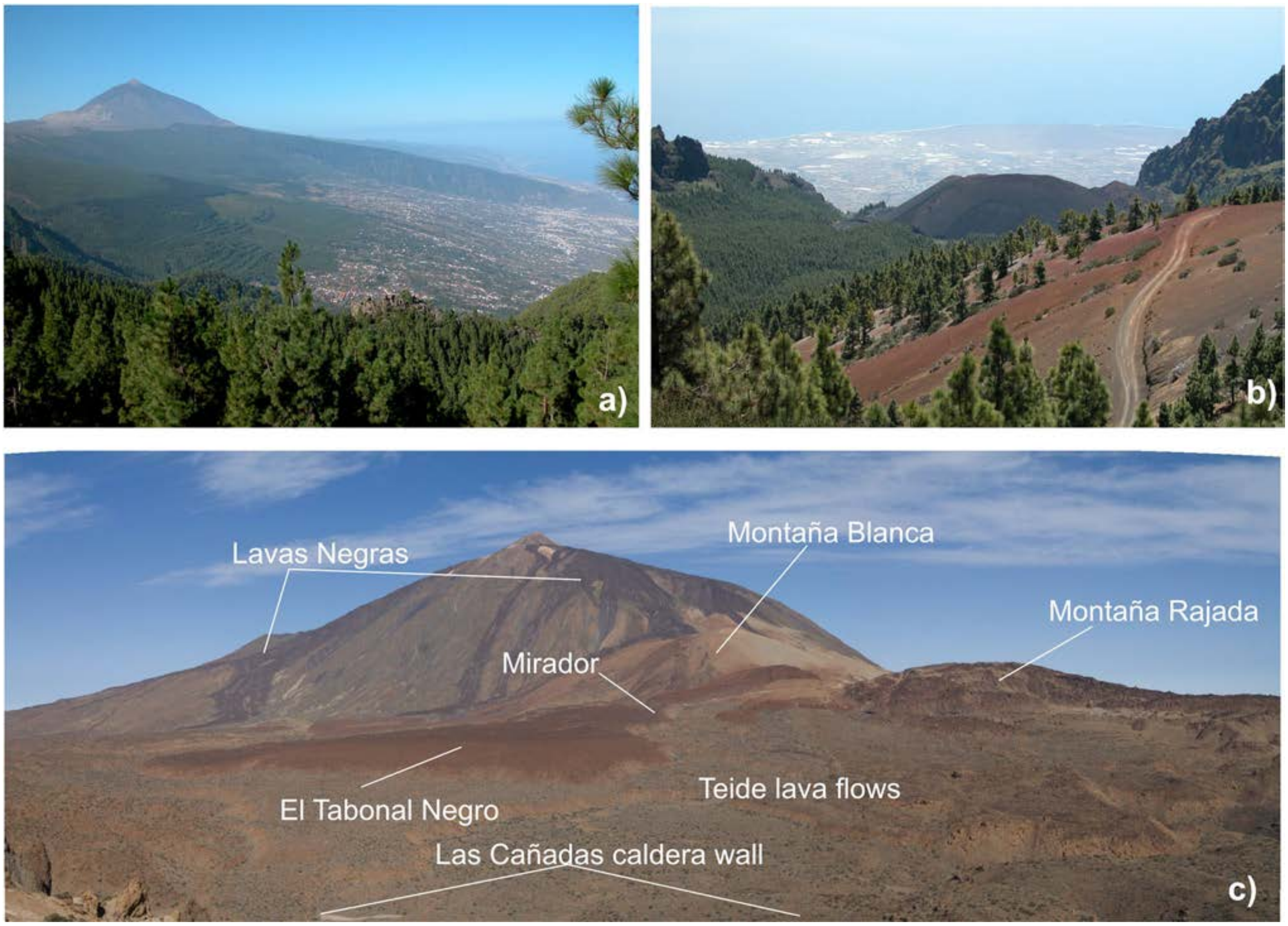

Fig. 13 The main geological and volcanological features observable in the additional stops. **a** OP 6.1: overview of La Orotava valley; **b** OP 6.2: overview of the Güímar valley and the Caldera de Pedro Gil at the head of the Güímar valley; **c** OP 6.3: overview from the central sector of the caldera wall of intracaldera Teide lavas, the Montaña Blanca pumice cone and lavas, the Montaña Rajada lava dome, and the most recent lavas from Teide (Lavas Negras) from the central sector of the caldera wall

and south. These trachyphonolite flows are less silica-undersaturated than the phonolites of Montaña Blanca or Pico Viejo, and both have petrological affinities with El Teide products (Ablay et al. 1998). Montaña Majua is a strombolian pumice cone breached by lobate lava flows. To the east, the foreground is occupied by phonolitic lavas from the Arenas Blancas member. Further south and east run mafic lava flows and scoriae erupted from vents close to the eastern caldera wall. These alkali basalts are the most primitive magmas to have erupted within the Las Cañadas caldera, and are believed to represent the parental magmas that feed El Teide-Pico Viejo system (Ablay et al. 1997). In the foreground, El Tabonal Negro is a thick vitric phonolitic lava flow that appears dark due to its relative youth. Beneath El Tabonal, there are more thick, lobate phonolitic lava flows that were emplaced during the early development of Montaña Blanca from a linear array of vents (Ablay et al. 1995).

Montaña Blanca represents the products of a significant explosive eruption that occurred about 2020 years ago (Ablay et al. 1995). Its visible products, from base to top, include (i) the El Tabonal flow, which represents an initial phase of effusive activity; (ii) a thick pumice fall deposit that forms most of the cone, composed of angular, well-sorted unwelded phonolitic pumice lapilli, corresponding to the explosive subplinian phase of the eruption; (iii) a distinctive unit of densely welded obsidian with a strong rheomorphic fabric, which grades laterally into a spatter-fed obsidian lava flow; and (iv) several small domes and stubby lava flows that erupted during a late effusive phase, some from the Montaña Blanca eruptive fissure.

Discussion and Conclusions

The previous sections offer a summary of the geological and volcanological history of TNP, as well as a description of the main geosites from which this history can be discerned. Knowledge of these elements is crucial for understanding the evolution of one of the most impressive and beautiful volcanic landscapes in the world. Unfortunately, a considerable amount of work still remains to be done on how this knowledge can be transmitted to visitors, starting with the precise transfer of current scientific knowledge to the professionals (e.g., park and tourist guides) whose task is to explain to visitors the park's geological and volcanological riches, and to those in charge of the preservation of this important and unique geoheritage (e.g., park managers).

One of the greatest problems facing the Canary Islands—and Tenerife in particular—is the result of the decision taken in the 1960s and 1970s to promote mass tourism. Despite the wealth it creates and the fact that it is still the region's main source of income, it is not clear whether the millions of tourists who visit the Canary Islands every year are particularly interested in the natural world. In the case of the TNP, the number of tourists that arrive every year is so great that not all can benefit from a measured explanation of the park's geological treasures. This situation is an obstacle to the establishment of awareness of the importance of preserving this geoheritage.

A further issue shared by local geologists is that there has been little or no political interest in analyzing this question and drawing appropriate conclusions. Local scientists are trusted but this is not sufficient to make up for the lack of political or collective structures, with rational and open mentalities, that could define which concepts should be presented to visitors.

The communication and preservation of the park's geological heritage needs to be based on high quality, objective scientific research, untainted by popular knowledge lacking any scientific basis. Today, in many regions, geotourism is becoming a new way of generating income and so it is important to foster it and ensure that it is as sustainable as possible. Examples of how to make geotourism sustainable and a valuable element in the development of a particular area or region have been documented elsewhere (e.g., Planagumà and Martí 2020). However, these examples also reveal how demanding this type of tourism is. For this reason, it requires information based on rigorous scientific knowledge and properly trained communicators who can transmit natural values to visitors. In the case of the TNP, it is vital to seriously consider implementing this type of tourism to ensure the correct diffusion and preservation of the park's geoheritage.

A number of initiatives needs to be undertaken if all the necessary information on the geoheritage of the TNP is to be gathered together and transmitted to visitors in an appropriate fashion. The amount of scientific knowledge, that today exists regarding this particular geological and volcanological site, is sufficient to provide visitors with a clear and well-defined picture of what they are seeing. The managers of the national park should make more efforts to extract information from objective researches and avoid relying on the opinion of local advisors. Currently, political rather than knowledge-based reasons seem to hold sway, which works against the interests of visitors. The information centers that exist in the park should be better prepared and offer objective scientific knowledge rather than the highly limited and often very biased information that is currently provided. Additionally, a complete network of information panels, with representations and descriptions based on the scientific knowledge described here, and illustrations and texts capable of explaining the observable volcanic features at each viewpoint, as well as field guides and mobile and tablets apps, is essential for reaching freelance tourists. The professionals in charge of transmitting the geological values of the park to visitors should have more opportunities for training and for learning and documenting new ideas. Excellent scientific knowledge is not enough if it cannot be adequately communicated to the general public; this is the responsibility of scientists, as well as park managers and other professionals, whose task it is to transfer this knowledge. All should work together to improve the knowledge, communication and outreach of the park's geoheritage.

This contribution aims to synthesize the current scientific knowledge of one of the most impressive and instructive volcanological sites anywhere in the world, which is, nonetheless, still poorly understood by visitors and by those whose role it is to portray and preserve it. The set of geological elements that can be observed in the park are pieces of a puzzle that explain the evolution of Las Cañadas caldera and El Teide-Pico Viejo stratovolcanoes, a unique and complex central volcanic system. Its importance makes it imperative that visitors interested in knowing and understanding how such a volcanic system works are provided with precise information based on objective scientific knowledge. Otherwise, the knowledge acquired by visitors will not be transmitted adequately, which could lead to a progressive loss of interest in visiting this area. This could have important cultural and socio-economic consequences in the long term and lead to an underestimation of the magnitude and characteristics of the geohazards that have occurred on the island in the past and may occur in the future.

Acknowledgements This contribution is the result of scientific research undertaken over more than 30 years on the geology and volcanology of El Teide National Park, which has included the supervision of several PhD theses and work with a number of geological and geophysical studies and numerous research groups. This research would have not been possible without permission from El Teide National Park or funding from different EC and national grants (TEIDE: European Laboratory Volcano, ERUPT, EXPLORIS (EVR1-CT-2002-40026), and VUELCO (FP7-ENV-2011 282729), MCyT TECTOTENE, MCyT FONOTEN, MEC TEGETEIDE (CGL2004-21643-E), MEC TENERISK (CGL-2006-13830), MEC PR-2006-0499, MICINN (CGL2010-11983-E), EXPLOTEI MICINN (CGL2008-04264), MEC (CGL-2004-21247), and EVE (EC DG ECHO H2020_826292). Finally, we express our heartfelt gratitude to all the staff at Parador de Las Cañadas. OD and MLS are supported by the MICINN grants FPU18/02572 and FPU19/02413, respectively. We thank the Geoheritage Editor, Kevin Page, and two anonymous referees for their constructive reviews. English text has been reviewed and revised by Michael Lockwood (Walking Catalonia).

Author Contribution JM designed the study and wrote the manuscript. MLS and ODG participated in the field work, revised and contributed to the final version of the manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. Partial support was provided by funding from different EC and national grants (TEIDE: European Laboratory Volcano, ERUPT, EXPLORIS (EVR1-CT-2002–40026), and VUELCO (FP7-ENV-2011 282729), MCyT TECTOTENE, MCyT FONOTEN, MEC TEGETEIDE (CGL2004-21643-E), MEC TENERISK (CGL-2006–13830), MEC PR-2006–0499, MICINN (CGL2010-11983-E), EXPLOTEI MICINN (CGL2008-04264), MEC (CGL-2004–21247), and EVE (EC DG ECHO H2020_826292).

Data Availability Not applicable.

Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate All authors declare to consent to participate of this study.

Consent for Publication All authors declare to consent the publication of this study.

Conflict of Interest The authors declare no conflict of interest.

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Confirmation of participation

To whom it may concern,

We hereby confirm the participation of Marta López Saavedra, Universidad Autónoma de Barcelona, Spain in the EGU General Assembly 2022, 23–27 May 2022, in Vienna, Austria.

Presentations
Marta López Saavedra co-authored the following presentations:

- "Cascading Effects of Extreme Geohazards on Tenerife (Canary Islands)" by *Marta López-Saavedra*, Joan Martí, Jose Luis Rubio, and Karim Kelfoun, session NH10.1/CL3.2.18/HS13.9, abstract EGU22-956, oral presentation.

Kind regards,

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Abstract Number	IUGG23-1490
Topic Area	Joint Symposium - Oral Session
Topic	JS09d - Early Warning Systems for Geohazards (IASPEI, IAVCEI, IAHS, IAG)
Presentation preference	Oral
Abstract Title	Reviewing the multi-hazard concept. Application to volcanic islands.
Authors	Marta López-Saavedra[1,2], Joan Martí[1]. [1]Geosciences Barcelona GEO3BCN - CSIC, Geosciences Barcelona GEO3BCN - CSIC, Barcelona, Spain. [2]Faculty of Earth Sciences University of Barcelona, Department of Earth and Ocean Dynamics, Barcelona, Spain.
Study Group	
Abstract Text	Because of their social, economic and political contexts, and their intrinsic multi-hazard nature, volcanic islands are one of the most vulnerable environments, where natural hazards (volcanic and non-volcanic) tend to occur in a simultaneous way causing cascading effects. To date, most of the scientific knowledge, as well as hazard assessment and risk management protocols focus on individual hazards and risks, while it remains a challenge to correctly predict the outcomes and impacts of a multi-hazard scenario where several hazardous phenomena may interact in simultaneous or consecutive ways. The multi-hazard concept originated in the 1990s in the international political context precisely to respond to this need. After its first appearance, different–and often, contradictory–usage perspectives of the multi-hazard concept have been increasingly put forward, thus making it difficult for this new approach to be fully implemented into disaster reduction policies. The present study assesses the current status of the application of the multi-hazard approach in existing risk management systems, and proposes future improvements to disaster risk reduction. It also presents the multi-hazards to which volcanic islands are exposed and analyses their potential impacts, taking the Canary Islands as a case study. In doing so, it emphasizes the need to establish a cross-sectoral, climate change-oriented, socially-inclusive, multi-risk management system, based on scientific knowledge and linked to critical societal demands and solutions.
COI	Disclosure Statement: This abstract was partially supported by the EG grant EVE (DG ECHO H2020 Ref. 826292) and the CSIC grant MAPCAN (CSIC Ref. 202130E083). Marta López-Saavedra received an FPU PhD grant (FPU19/02413) from the Ministry of Science, Innovation and Universities of the Government of Spain.

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Abstract accepted at the IUGG Berlin 2023 at the time of submission of this doctoral thesis, pending oral communication during the congress.

Annex 3. Other publications

Advances in Science, Technology & Innovation
IEREK Interdisciplinary Series for Sustainable Development

Ana Malheiro · Francisco Fernandes ·
Helder I. Chaminé *Editors*

Advances in Natural Hazards and Volcanic Risks: Shaping a Sustainable Future

Proceedings of the 3rd International Workshop on Natural Hazards (NATHAZ'22), Terceira Island—Azores 2022

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The series is intended for professionals in research and teaching, consultancies and industry, and government and international organizations. Published in collaboration with IEREK, the Springer ASTI series will acquaint readers with essential new studies in STI for sustainable development.

ASTI series has now been accepted for Scopus (September 2020). All content published in this series will start appearing on the Scopus site in early 2021.

Ana Malheiro • Francisco Fernandes •
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Editors

Advances in Natural Hazards and Volcanic Risks: Shaping a Sustainable Future

Proceedings of the 3rd International Workshop on Natural Hazards (NATHAZ’22), Terceira Island—Azores 2022

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ISSN 2522-8714 ISSN 2522-8722 (electronic)
Advances in Science, Technology & Innovation
IEREK Interdisciplinary Series for Sustainable Development
ISBN 978-3-031-25041-5 ISBN 978-3-031-25042-2 (eBook)
https://doi.org/10.1007/978-3-031-25042-2

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Multi-Hazard Risk Assessment at the Canary Islands

Marta López-Saavedra and Joan Martí

Abstract

The term “multi-hazard” is a concept that is increasingly gaining ground in national and international disaster reduction policies. However, its implementation is still timid, and the initiatives that have been carried out are important but insufficient. Multi-hazard scenarios are still difficult to implement due to the complexity of the interactions between the different hazards, the lack of addressed research on this topic, and the uncertainty of their consequences at different spatial and temporal scales. Due to their intrinsic multi-hazard nature and their social, economic, and political context, volcanic islands are particularly vulnerable to these scenarios. These environments require adopting a multi-hazard perspective to design new multi-risk management programmes to reduce risk effectively. The case of the Canary Islands, an active volcanic archipelago that also suffers from multiple non-volcanic geohazards, is a clear example of such complex multi-hazard scenarios. With a worrying overpopulation and tourism that make this management difficult, and with emergency plans that do not consider this multi-hazard perspective, natural disasters may accentuate in the near future. This is also applicable to other volcanic islands in similar situations.

Keywords

Multi-hazard • Multi-risk • Cascading • Volcanic islands • Canary Islands

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1 Introduction

In the last decade, the concept of “multi-hazard” has progressively emerged among national and international disaster reduction policies. However, conflicts in terminology and the complexity of the concept make it difficult to fully enter into risk management plans. Increasingly, some countries are implementing multi-hazard early warning systems and are undertaking the design of risk reduction strategies considering multi-hazard scenarios. However, not all regions with multi-hazard potential are implementing this concept, and those that are implementing or have implemented it have only applied this concept to some aspects of the entire risk management framework or only to some regions from their entire territory. Occasionally, this implementation is done on an individual level, ignoring the scope of the consequences of some events, so that international cooperation is necessary, and those that consider an international level, sometimes, for political reasons, only take into account those regions with which they have signed agreements or have some relationship.

The assessment of multi-hazard scenarios is complex due to the uncertain interrelationships between the different hazards. For this reason, it is often difficult to analyse such scenarios, causing problems in implementing this multi-hazard approach in hazard assessment and risk analysis. For example, volcanic islands are environments that are more susceptible to receive the impact of multiple natural hazards that sometimes may show cascading effects. In addition, they are, in many cases, highly vulnerable areas due to their demographic expansion in a small space and the reception of a large number of tourists, which cause problems of supply, pollution, and, above all, increasing exposure to risk, and also making emergency management difficult in terms of evacuation and assistance. On the other hand, most of their inhabitants live from local commercial activities, such as fishing, agriculture, and tourism, making them even more vulnerable to the long-term effects of certain

A. Malheiro et al. (eds.), *Advances in Natural Hazards and Volcanic Risks: Shaping a Sustainable Future*,
Advances in Science, Technology & Innovation, https://doi.org/10.1007/978-3-031-25042-2_2

natural hazards. Furthermore, their location, sometimes former colonies of countries located far away from them, makes it difficult to receive external aid.

For this reason, multi-risk management plans should be mandatory in these special regions. In this contribution, we review the evolution of the multi-hazard concept and its most important aspects. We then focus on the situation of volcanic islands and the multiple hazards to which they are subject. Finally, we end by analysing the Canary Islands' situation in terms of multi-hazard assessment and management in that region.

2 The "Multi-Hazard" Concept

The first reference to the term multi-hazard appeared in the international policy with the United Nations' Agenda 21 for sustainable development (United Nations Homepage, 2022). They called for multi-hazard research for pre-disaster plans for any human settlement. This claim is made again with the Johannesburg Plan (UN, 2002). However, the action was not taken until the Second World Conference on Disaster Risk Reduction (held in Japan in 2005); when the Hyogo Framework for Action 2005–2015 (United Nations for Disaster Risk Reduction Homepage, 2022) was adopted, implementation of the multi-hazard concept began. Nevertheless, the real actions in those ten years were driven by two major events with extensive damage: Hurricane Katrina in 2005 and the tsunami in Japan in 2011.

Despite this slow awakening, the engineering field has the greatest awareness (Ellingwood, 2010). Fortunately, with the Third World Conference on Disaster Reduction, the Sendai Framework for Disaster Risk Reduction 2015–2030 (UN-ISDR, 2015) was adopted with seven objectives and four priorities for action that advocate for a multi-hazard approach to the management of disaster risk through developmental planning and practices across all the sectors involved (United Nations for Disaster Risk Reduction Homepage, 2022). Some countries and regions have developed multi-hazard forecasting and early warning system initiatives to meet these objectives.

The UN Sustainable Development Summit was held in the same year, culminating in adoption of the 2030 Agenda for Sustainable Development, with 17 Sustainable Development Goals (SDGs). One of these goals highlights the importance of multi-hazard early warning systems. This goal emphasises climate-related hazards and disasters in the context of climate change. In this sense, other multi-hazard scenarios, such as those caused by some geohazards (volcanic eruptions, earthquakes, tsunamis, etc.), are sidelined and comparatively do not receive the same attention when some of them may be aggravated by global change.

Despite all these efforts, basic conflicts such as contradictory terminology, lack of uniformity, and lack of consensus among researchers and users of the concept hinder the efficient implementation of such a multi-hazard approach (Kappes, 2011). From all definitions, it is clear that the concept of multi-hazard refers to multiple hazards occurring simultaneously or separated in time in a given region. Whether or not they occur simultaneously determines whether or not they are related to each other. These relationships may be of different types, such as cascading effects. Due to the complexity of these interactions and the wide range of consequences depending on their combination, some authors have tried to classify them into broad groups (e.g., Kappes et al., 2010; Gill & Malamud, 2016): (1) those events that are triggered by others, (2) those events that maintain some relationship and alter in frequency or magnitude mutually, (3) those that are unrelated or independent even though they coincide in space and time, and (4) those that exclude each other.

From a management point of view, we can distinguish between multiple extreme and non-extreme event scenarios. The former cannot normally be managed due to the magnitude of the impact, but they can be foreseen and prevented. The latter are scenarios for which good risk and emergency management plans can be designed, considering the possible interactions and interrelationships that may arise.

3 Multi-Hazard on Volcanic Islands

Volcanic islands are fragile economic systems and highly vulnerable communities due to their social, political, and economic context. Their main monetary income is from tourism and local economic activities, such as fishing and agriculture. Therefore, many are former colonies dependent on a sovereign country, usually far away from them. However, most volcanic islands are self-governing territories with their own management of natural hazards, which exerts greater local pressure. On the other hand, volcanic islands are prone to experience complex successions of disastrous events, as is evident from any examination, for instance, of the geological record of regions such as Hawaii, the Canary Islands, Reunion, and Indonesia. Created by the growth of volcanoes in the sea and modified by natural and anthropogenic processes, volcanic islands are subject to the impact of multiple natural hazards, including extreme geohazards and wildfires, cyclones, and floods. In this context, climate change may increase the number and intensity of these events, and population expansion and increased tourism elevate exposure and vulnerability. The result is a tendency to increase risk in the future, so the need to devise new strategies to manage multi-hazard and multi-risk is becoming increasingly evident. In this review, we will focus only on geohazards, although it should not be forgotten that many are caused and/or altered by climatic hazards and/or human action and, in turn, also affect the environment and human health.

3.1 Geohazards: Volcanic and Non-volcanic Events

The rapid growth and configuration of volcanic islands, by the successive accumulation of magma, solid rock, altered rock, volcanic sediments, and hydrothermal systems, together with their steep slopes, favour the instability of these terrains compared to many continental areas. In addition, they are weak structures affected by intense faulting, alteration, and avalanche structures resulting from constructive and destructive processes that account for their entire evolution. In addition, many of them are seismically and volcanically active areas. Therefore, we must distinguish between volcanic events, associated hazards, and non-volcanic geohazards.

Volcanic activity and eruptions themselves are sources of multiple hazards and are susceptible to cascading effects. Sequences involving an eruption, seismicity, mega-landslide, and tsunami are, fortunately, a non-frequent but common multi-hazard scenario in volcanic islands. Some examples are the last caldera-forming eruption that occurred 180 ka ago in Tenerife, the Santorini caldera-forming eruption in 1610 BCE ±14 years, the tsunami and the pyroclastic flow associated with the eruption of Krakatoa in 1883, and the dome collapse in Montserrat island in 2003. Other associated hazards are, for example, lava flows and related wildfires (e.g. Kilauea eruption in 1983), and rockfall and landslides (e.g. flank collapse at Stromboli in 2002), among many others. In the long term, extreme events can cause climatic effects that, in turn, cause famine and disease (e.g. the year after the Tambora eruption in 1815).

On the other hand, the geodynamic context of these types of islands makes them seismically active areas, so they may also suffer the effects of large tectonic earthquakes and those of volcanic origin. An example is a seismic crisis in the Azores in 2005 or the Indonesia earthquake in 2004. Some of these earthquakes, as happened in the last example, are tsunamigenic, so these regions, either because they are in the tsunami source areas or because they are in the tsunami path, and surrounded by the ocean, are severely affected by this derived hazard (e.g. effects of the Japan tsunami in 2011 in the Galápagos Islands). Landslides can also result from this seismicity, and heavy rainfall events (e.g. the Vila Franca 1522 earthquake or the Azores landslide in 2013) and can also trigger tsunamis (e.g. the landslide in the Azores in 1847). Landslides, in turn, can block river channels and cause flooding, another common event following extreme rainfall and torrential downpours (e.g. the landslide in Mt. Pelee in 2010). Torrential floods are accentuated in these environments due to the steep slopes. It should be added that, on the one hand, their geographical location means that these areas are frequently in the path of cyclones (e.g. cyclone Pam as it passed through Vanuatu in 2015), and, on the other hand, their topography may cause large local climatic differences with some extreme episodes of rainfall (e.g. Madeira in 2010) and, finally, they are also sometimes the target of pests (e.g. Lanzarote in 2004) and epidemics (e.g. Cape Verde dengue epidemic in 2009) due to this geographical-climatic combination.

4 The Case of the Canary Islands

The Canary Islands is an active volcanic archipelago in the Atlantic Ocean off the coast of southern Morocco. It is a group of eight islands whose origin is still a subject of debate. Some of these islands have experienced extreme events that can occur again in the future (López-Saavedra et al., 2021) and are, in turn, susceptible to practically all the hazards mentioned in the previous section.

Since its colonisation by the Spanish in the fifteenth century, the Canarian Archipelago has undergone an intense demographic expansion, especially in the coastal areas, and receives millions of tourists yearly. This increase in exposure and pressure on local resources, combined with climate change, has increased risk in all senses, both for the Canarian population and tourists. As an autonomous community of the Spanish State, it is responsible for its natural risk management, so they are obliged to develop the corresponding emergency plans against natural impacts.

Local and regional emergency plans have been developed during the last decades, each facing one particular hazard. In this sense, the Municipal Emergency Plan (PEMU) is activated at a municipal level. Likewise, each Island Council must develop its island plan. Emergencies at the regional level affect more than one island of the Archipelago or those whose magnitude of the incident requires using means from outside the affected island. The Territorial Civil Protection Plan of the Autonomous Community of the Canary Islands (PLATECA) is activated when an emergency is declared at the Autonomous Community level. The PLATECA includes all the previous territorial plans and, in addition, the different Special Plans. These plans are divided into Basic Plans (nuclear and war emergencies, both of which are the responsibility of the Spanish State), and Special Plans for other risks (floods, earthquakes, chemicals, transport of dangerous goods, forest fires, and volcanic). If we focus on geohazards, this last category includes the following Special Plans for the Canary Islands:

- Special Plan for Civil Protection and Attention to Emergencies due to volcanic risk in the Autonomous Community of the Canary Islands (PEVOLCA).
- Special Plan for Civil Protection and Emergency Attention due to seismic risk in the Autonomous Community of the Canary Islands (PESICAN).
- Special Plan for Civil Protection and Emergency Attention due to Forest Fires in the Autonomous Community of the Canary Islands (INFOCA).
- Special Plan for Civil Protection and Emergency Attention due to Flood Risk in the Autonomous Community of the Canary Islands (PEINCA).

In addition to these, there are two Specific Plans:

- Specific Plan for Civil Protection and Emergency Attention of the Autonomous Community of the Canary Islands due to risks of adverse meteorological phenomena (PEFMA).
- Specific Plan for accidental marine pollution emergencies in the Canary Islands (PECMAR).

Focusing on volcanic risk, PEVOLCA considers volcanic earthquakes, pyroclast projection, ash fall, pyroclastic flows, lava flows, structural collapse, lahars, and volcanic gases. It also includes self-protection measures for ash fall. On the other hand, the PEVOLCA includes a "volcanic traffic light" consisting of four colours (green—pre-alert, yellow—alert, orange—maximum alert, and red—emergency) corresponding to four risk situations that serve to inform the population, as well as 3 levels within the emergency situation (0–1—island level, 2—autonomous, and 3—national). However, PEVOLCA does not contemplate any possible interaction between any of these processes or with other processes unrelated to volcanism itself (e.g. forest fires and floods) to which a volcanic eruption could interact or trigger. In the same way, the other Spatial Plans are restricted to the corresponding individual hazard, not assuming any possible interaction with other hazards.

5 Discussion

Multi-risk management is a problem facing society. The complexity of the relationships between the different possible hazards that can impact a territory makes it difficult to implement a multi-hazard concept into risk reduction programmes. The obstacles are accentuated if the lack of research for developing multi-hazard assessments is added. For this reason, although the concept of "multi-hazard" is increasingly being discussed and considered, from its inception to the present day, it has only been used in non-binding agreements and frameworks. Although sometimes big steps are taken, such as some multi-hazard early warning systems or some multi-hazard risk reduction strategies, these are still a few and are often triggered by a disaster that has affected society's economy. In addition, many of these initiatives are geared towards climate-related hazards, as the main focus is now on climate change. However, many other hazards have always been there and will continue to cause millions of losses and many deaths, which the global change may also accentuate. Therefore, it is unnecessary to wait for an event to occur before taking action, and we already have sufficient examples of multi-hazard natural disasters with human losses, which should be reason enough to start taking action at all political levels.

Change must begin by building consensus around the multi-hazard concept and developing competent studies to understand better the possible succession of events, their relationships, and the consequences of multi-hazard scenarios. These studies must not only consider the intrinsic nature of the hazards and their impacts individually but how they may interact and how this interaction may condition the final impact. Also, it is necessary to consider how human pressures through population growth and tourism may influence the occurrence and impact of multi-hazard events. Finally, we must also investigate how global change may influence multi-hazard scenarios. In this respect, volcanic islands are particularly vulnerable to these situations. For this reason, natural risk management must go hand in hand with proper territorial and tourism planning, as resources are scarce in these environments and hazards are manifold. This overpopulation also makes risk management more difficult, as it requires a greater effort and mobilisation of resources during an emergency in a limited space compared to the mainland.

In the case of the Canary Islands, volcanic risk management was again tested during the eruption of 19 September 2021 at La Palma Island. The strengths of this management were highlighted in how an efficient evacuation and confinement of the population at risk was carried out. As a result, there were no direct casualties from the eruption, and the necessary resources were mobilised to attend to the affected population. Nevertheless, the lack of a multi-hazard perspective in the PEVOLCA made the Scientific Committee fearful of the risk of triggering other events, such as lahars or blockages of sewage and other municipal facilities due to the threat of heavy rainfall following the deposition of large thicknesses of ash. The Canarian emergency plan does not cover this scenario. However, some problems were difficult to manage, such as the excessive pressure from media and social networks, and the lack of clear protocol in certain scientific actions (e.g. sample collection and analysis) and communication strategies. Also, the lack of a long-term hazard assessment for the whole Canary Islands does not help define precise emergency plans and implement risk reduction programmes.

As for non-volcanic risks, the Canary Islands are subject to floods and landslides every year, as well as sometimes to forest fires (e.g. the fires of 2019) or earthquakes (e.g. the seismic crisis in Tenerife in 2004). Despite this, disaster reduction initiatives and strategies do not keep pace with the occurrence of these events, and every year the same towns continue to be flooded, the same bridges continue to be washed away, the same seafronts continue to be affected, and the same roads continue to be cut.

With unstoppable climate change and repeating the same mistakes despite our globalisation and technological development, it is time to become aware of the risk posed by these multi-hazard scenarios and invest effort and money in foresight, prevention, and mitigation in front of such complex situations.

6 Concluding Remarks

This paper has reviewed the evolution and status of the multi-hazard concept and its application to volcanic islands. With a high vulnerability and exposure to multi-hazard scenarios, the need for multi-hazard management becomes more evident in these environments. A consensus must be reached on this emerging but increasingly topical perspective and the necessary investment in research to better understand the interactions between events and the regional and global consequences of such scenarios. In addition, awareness must be raised of the increasing difficulties volcanic islands encounter when facing multi-hazards due to overpopulation. If we add to this the responsibility that many of these regions have to manage their own emergencies with their own local resources, and the added difficulty of managing them with an excess of tourism from different origins, other needs such as territorial planning and a redesign of risk management policies are highlighted.

A clear example is the case of the Canary Islands, a region susceptible to multiple geohazards and with a worrying overpopulation. The eruption of September 2021 in La Palma allowed us to see the strengths and weaknesses of the management plans in this territory. However, like many others, this region suffers from hazards of lesser media interest but with equal or greater impact. The solution is not to wait until they occur and the population becomes temporarily aware but to invest in prevention and preparedness. Moreover, for this to happen, the multi-hazard perspective needs to be fully integrated into disaster risk reduction policies in a binding way.

Acknowledgements Marta López-Saavedra received an FPU Ph.D. grant (FPU19/02413). This research was partially funded by the EC Grant EVE (DG ECHO H2020 Ref: 826292).

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Paper accepted for publication as a Chapter in the book "Geoethics for Future: Facing Global Challenges" by Elsevier, edited by S. Peppoloni, G. Di Capua. Under revision at the time of the deposit of this doctoral thesis.

Multi-Hazard Analyses and Their Implications for the Defense of Society Against Natural Phenomena

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Abstract

The Sendai Framework for Disaster Risk Reduction (2015 – 2030) calls for incorporating science into the policy process. However, this carries the risk of politicizing science, and therefore, may blur the boundaries of the roles of the different risk management actors. These difficulties are aggravated in the context of an emergency or natural disaster, where scientists advise the authorities. In these situations, decision-makers need to respond with the utmost precision to three basic questions: i) what phenomena will occur, ii) when will they occur, and iii) where will they impact? Despite the efforts of the scientific community to conduct increasingly accurate studies of these natural events, uncertainty is often high and/or unavoidable. This uncertainty, in an environment of pressure, urgency, and ineffective communication, can lead to the proliferation of non-consensual, incomprehensible, misunderstood, and erroneous information. In an extreme case, it can even aggravate the impact of such a natural disaster (e.g., l'Aquila earthquake in 2009). On the other hand, in a context of climate change—where the magnitude and frequency of many events are increasing—and unstoppable demographic expansion, the trend is towards greater risk. Moreover, the appearance of increasingly complex and strong relationships between different types of events, with the occurrence of concatenations and cascading effects, increases uncertainty, and therefore makes it difficult to design strategies for prevention, action, and recovery. Multi-hazard analyses can help to reduce this uncertainty in the multi-hazard scenarios that are plaguing society today and will continue to do in the future.

Multi-hazard analyses are a first step towards a transdisciplinary, cross-sectoral, and cross-border multi-risk management plan that is based on scientific knowledge. The greater precision of risk estimation will contribute to better supporting decision-makers, thus implying the ethical communication of information that reduces misunderstanding, thereby contributing to the resilience of societies.

Keywords: geoethics, multi-hazard assessment, risk management, decision-making, resilience

Annex 4. Supplementary Material 1: Tables

Table 16. Summary of Historical Multi-Hazard Events That Have Had a Major Impact on Society.

PAST NATURAL DISASTERS											
Event	**Date/Duration**	**Location**	**Cascading effects/Hazards**	**Main affected areas**	**Fatalities**	**Injuries**	**Displacements**	**Economic, social and natural losses**	**Resilience/mitigation actions**	**Dependency**	**Observations**	**References**
Tonga eruption 2022	20th December, 2021 – 15th January, 2022	Tonga, Hunga-Tonga-Hunga-Ha'apai volcano	Eruption Steam-and-gas plumes Tephra ejection Explosion Pressure waves Pyroclastic flows Ash fall Tsunami Flooding	Fiji, Japan, Peru, Samoa, Tonga	3	Not counted but reported	More than 1,500	US$ 90.4 million. Direct damages to around 300 residential buildings, non-residential buildings, infrastructure, agriculture (85% of agricultural households nationwide affected to some extent), forestry, fishing. Ash clean-up costs are estimated to be just under US $5 million for buildings and paved road infrastructure.	On 19 January, the Government of Tonga issued a State of Emergency. Elsewhere in the Pacific tsunami warnings were lifted. The government deployed two vessels with health teams and water, food and tents to the Ha'apai group. The risk of infectious diseases was monitored. The World Bank provided an immediate US $8 million in emergency funding to reestablish basic services and help Tongan families most affected. The following weeks after the eruption 90% of power was restored. Efforts continued with the clearing of ash debris and coordinating relief distribution to affected communities. NEMO and humanitarian partners established 16 water stations areas around Tongatapu.	The Kingdom of Tonga	The eruption was one of the biggest in Tonga in the past 30 years. The local transmission of COVID has also further complicated procedures and the lockdown is likely to lead to further delays. The spread of COVID had a negative impact on the aid delivery and further relief and recovery planning. The low level of fatalities partly reflects Tonga's effective early warning systems, combined with previous experience of natural disasters in Tonga.	ACAPS (2022) OCHA Services (2022). The Prime Minister's Office (2022). The World Bank (2022).
Canary Islands wildfires 2019	10th - end of August, 2019	Gran Canaria, Tenerife and Lanzarote (Canary Islands, Spain, Atlantic Ocean)	Heat wave Strong winds Man-made fire Wildfires	NW of Gran Canaria (Artenara, Cazadores, Valleseco), S of Tenerife (Vilaflor), N of Lanzarote (Haría).	0 (some livestock and 50 millions of bees from 1,000 hives).	2 (firefighters).	9,000	84% of the over 10,000 hectares (25,000 acres) of land affected by the wildfire, i.e. 8,709.5 hectares (21,522 acres), was part of protected natural spaces. Livestock and agricultural losses. 1,000 hives (50 million bees died). Biodiversity damages.	More than 700 firefighters and 16 aircraft battled to contain the flames. Fires were under control or extinguished by the end of August 2019, but ecological losses will take hundreds of years to recover, some biodiversity maybe would not recover any more.	Autonomous community of Spain.	The worst fires were those which affected Gran Canaria. The heat wave during the 2019 summer, combined with strong winds and the island's mountainous terrain made extinguishing activities exceptionally difficult.	Minder (2019) Portillo (2019) Rogers (2019)
Anak Krakatau eruption 2018	18th June, 2018 - 17th April, 2020	Krakatoa Archipelago, in the Sunda Strait (Indonesia)	Eruption Ash fall Landslide (Flank collapse) Tsunami	Indonesia and coastal zones of the Indian Ocean.	430	14,000	33,000	US $658 million	Within hours after the tsunami, Indonesia Red Cross Society (PMI) deployed teams to support the emergency response and mobilized HKD 2.6 million from its Disaster Relief Emergency Fund (DREF) on 25 December 2018 to assist a total of 7,000 people in 1 month for immediate relief. The response was locally coordinated in a command post, along with the establishment of field kitchens and displacement sites. Heavy equipment was dispatched to clear debris to ease evacuation and response efforts. Affected families began moving into transitional shelters by March 2019. Construction of permanent shelters in Banten started in August 2020. By September 2020,	Dependent on the Republic of Indonesia.	Tsunami early warning systems are exclusively equipped to detect tsunamis that are generated by earthquakes, so this volcanic collapse-caused tsunami took place without a warning.	The Business Time (2018) Hong Kong Red Cross (2018) International Federation of Red Cross And Crescent Societies (2021) UN Office for Outer Space Affairs (2019) Walter et al. (2019)

PAST NATURAL DISASTERS

Event	Date/Duration	Location	Cascading effects/Hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Resilience/mitigation actions	Dependency	Observations	References
									141 permanent shelters have been constructed. In 2019, 1073 household in Banten province received shelter support using the Cash and Voucher assistance modality from PMI. The communities are now adhering the strict “no permanent building/shelter” at the red zones area especially at the area where the tsunami hit.			
Kilauea eruption 2018	3rd January, 1983 - 5th September, 2018	Hawaii Island, USA, Pacific Ocean.	Earthquakes Collapse of the crater floor Explosions Lava flows Small fires	Southeast of Hawaii Island.	0	24	1,700 - 2,000	US $211.2 million direct cost of Hawaii National Park’s closure so far, rising to US $282.46 million (£222 million) when factoring indirect jobs. Over 700 homes and structures destroyed. Nearly US $37 million in vacation rentals and US $14 million from agriculture, including half of the state’s entire cut-flower industry and 80 percent of its papaya crop.	Recovery can take anywhere from 5-10 years. U.S. President Donald Trump approved federal emergency housing aid and other relief for victims. The Hawai’i Emergency Management Agency (HI-EMA) and the Federal Emergency Management Agency (FEMA) announced $3.7 million in disaster recovery grants for the Hawai’i County’s Department of Parks and Recreation to fund ongoing recovery.	State of the United States of America.	Economic losses were mainly due to a decrease in visitor spending to Hawaii Volcanoes National Park. 23 people were injured after molten rock running into the ocean exploded and threw chunks of lava onto a tour boat near the Kilauea volcano.	Hawaii Emergency Management Agency (2020). Hopps (2018). Klemetti (2018). Rice (2018). Rosa (2018).
Gas emissions Vulcano 2015	April 2015	Vulcano Island (Italy, Mediterranean Sea).	Gas emissions (CO_2, H_2S)	Levante Beach (north of Vulcano Island).	0	1	Not reported	Not reported	The child was rescued by an air ambulance to the hospital of Lipari. Soon after this event the Major of Lipari installed at Levante Beach some panels informing tourists on gas hazard.	Dependent on Italy.	According to La Republica (22 June 2015), doctors attributed the malaise to a high CO_2 air concentration. In summer 2015 they performed a geochemical survey of the Levante Beach sector (onshore and offshore) and of the mud pool. The total gas flux in the Levante Beach area, from 0.3 km^2, was estimated in 1 t/day of CO_2 and 16,1 kg/day of H_2S.	Carapezza et al. (2016).
Vanuatu cyclone Pam 2015	9th - 20th March, 2015	Vanuatu, South Pacific Ocean.	Cyclone Pam Floods	Vanuatu, Kiribati, Tuvalu, Solomon Islands, Fiji, New Caledonia, northeastern N ew Zealand.	11 - 16 (in Vanuatu)	132,000 affected in Vanuatu	3,300	Total damage in Vanuatu reached VT63.2 billion (US $600 million).	The Tukoro, Vanuata's most significant patrol vessel, was washed ashore on Moso Island. Repairs took 16 months. According to UNESCO, a total of $268.4 million is needed for total recovery and rehabilitation of the nation.	Republic of Vanuatu.	All deaths were reported in Vanuatu. Local people highlighted two for the low death toll: (1) the cyclone moved relatively slowly as it headed towards Vanuatu giving time for warnings and preparation, and (2) the cyclone hit the populated areas during daylight hours allowing people on the islands to monitor the direction of the cyclone and shelter accordingly. Researchers think that it was due to effective warnings, self-reliance and traditional knowledge and preparation, training and evacuation,	BBC News (2015) Handmer and Iveson (2017)

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Event	**Date/Duration**	**Location**	**Cascading effects/Hazards**	**Main affected areas**	**Fatalities**	**Injuries**	**Displacements**	**Economic, social and natural losses**	**Resilience/mitigation actions**	**Dependency**	**Observations**	**References**
											shelter and housing, and an early identification of the cyclone.	
Azores landslide 2013	14th March, 2013	Azores Islands, Atlantic Ocean	Heavy rainfall Landslide Floods (some for obstruction)	San Miguel Island, Port Judeu in Terceira Island (Azores)	3	"Some" but no number reported	30 in Terceira Island due to floods.	Three houses buried, many infrastructures damaged, many roads blocked and interrupted traffic.	Not reported.	Autonomous region of Portugal.	The mayor of Povoação that the houses were "very old buildings," over 100 years old, located at the bottom of a slope.	La Voz de Galicia (2013).
Eruption Mt Gamalama and mudflow / lahar Ternate Island 2011	Eruption: 4th - 23rd December 2011 Mudflow/Lahar: 27th December 2011	Ternate Island off the western coast of Halmahera (Indonesia).	Seismicity Eruption Ash fall Heavy rainfall Mudflow / Debris flow / Lahars	Most of Ternate Island covered by ash, Tubo and Tofure districts, and locations along the Togorara and Marikurubu rivers destroyed by lahars.	4	Dozens	2,561	Ash fall caused loss of electricity in some areas around the slopes of the volcano. 3,490 people lost their homes. The National Disaster Mitigation allocated US$121,000 in emergency funds for the affected residents affected. Thousands of farmers had their crops destroyed by ash erupted. Agricultural losses were especially devastating. 16 residential houses in Tubo village, bridge and embankments that would need billions of rupiah to rehabilitate the damaged facilities.	The National Disaster Mitigation Agency (Badan Nasional Penanggulangan Bencana, BNPB) allocated 1.1 billion Indonesian Rupiah (US $121,000) in emergency funds for the residents affected by the eruption. On 1 January 2012, up to 3,490 people were still being housed in ten different emergency shelters. Residents living along rivers descending the flanks of the volcano could return to their homes but were advised to be aware of the dangers of lahars.	Dependent on the Republic of Indonesia.	Heavy rains caused cold lava and debris to flow into villages near Mount Gamalama in Ternate. Other lahars were originated previously with no casualties since the eruption started. Main injuries ranged from broken bones to head wounds.	Smithsonian Institution (2013).
Japan tsunami 2011 in the Galápagos Islands	11th March, 2011 (in the Galápagos Islands) (Total duration of the tsunami: 11th March - 14th March, 2011)	Japan (Pacific Ocean)	Earthquake Tsunami Floods	Japan and coastal zones of the Pacific Ocean, including the Galápagos Islands.	0 (In the Galápagos Islands)	0 (In the Galápagos Islands)	Not reported in the Galápagos Islands (evacuation of all coastal zones of Galápagos).	Facilities destroyed, workshops, laboratories and storage buildings flooded, while scattering equipment in a wide radius around the station. Animals affected by the waves included the flightless cormorant (which suffered some nest destruction), sea turtles and marine iguanas. In Fernandina island, destruction of existing nests. Occasional mortalities were evident (sea turtles and marine iguanas) at the upper limits of the wave. Marine turtle and iguana nesting was affected depending upon wave height, beach profile and nesting behavior. The Charles Darwin Research Station's (CDRS) marine biology lab and its equipment were largely destroyed.	Many affected businesses repairing and restarting operations quickly after the tsunami.	Dependent on the Republic of Ecuador.	Tsunami caused waves 1.77 meters in height in the Galápagos Islands that coincided with a high tide to lash the shore.	Hong (2014) UNESCO (2011).
Massive landslide in Mt. Pelée, 2010	11th May, 2010	Samperre cliff in Martinique Island (Lesser Antilles, Caribbean Sea)	Massive landslide Accumulation in the river bed Non-eruptive lahar Floods	Damage of the Prêcheur bridge and inundation of the Abymes quarter.	Not reported	Isolation of ~ 8000 people.	Not reported	Destruction of the bridge and submerged roads.	Local population was forced to use fishing boats to go from one side of the village to the other whilst the bridge was being repaired. It was destroyed twice beforehand (1976, 1980).	Dependent on the Republic of France.	51 non-eruptive *lahars* have been reported between 1932 and 2010, including 27 that occurred in 2010.	Aubaud et al. (2013). Leone et al. (2019).

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Eyjafjallajökull eruption 2010	20th March - 23rd June, 2010	Iceland	Eruption Ash fall Lahars Floods	Iceland, Europe and west of Asia.	0	0 (long-term injuries)	800	4.7 billion US dollars (global GDP losses) 1.4 billion US dollars (airline industry losses)	The European Aviation Crisis Coordination Cell (EACCC) was set up in the wake of the 2010 events to ensure better co-ordination of activities at Union level. Since then, various improvements have been made. Before 2010, the guidance was that if there was any risk of ash being present, then the airspace should be closed. Today, the vast majority of EUROCONTROL Member States follow the so-called Safety Risk Assessment method that envisages keeping national airspaces open, leaving the decision to fly to the airlines.	Iceland	Due to the amount of ash emitted, this eruption was one of the biggest economic losses in the aviation sector in Europe. However, with the lessons learned and the improved communication and volcanic risk management system especially for eruptions, it is estimated that the losses would be much lower if a similar eruption were to occur again.	Carlsen et al. (2012) Ellertsdottir (2014) Eurocontrol (2021) Gunnarsson (2010)
Madeira floods and mudslides 2010	20th February, 2010	Madeira Islands, Atlantic Ocean.	Extreme weather (heavy rainfall) Strong winds Landslides and mudslides Floods	City of Funchal, Madeira Island (Madeira archipelago).	42 (people still missing)	100	Not reported.	Communications disrupted, airport closed, buildings and cars damaged, bridges washed away. Full restoration of all affected infrastructure may cost around US $1,498,105,229,784.71 (€1.4 billion).	Local government authorities made temporary shelters available for the homeless, estimated in the hundreds. The Portuguese military sent a naval frigate, containing medical equipment and a helicopter, to Madeira. Reconstruction and cleaning work started a few hours after the rainfall. On the same day, several dozen units of heavy machinery and trucks were seen in the streets of Funchal and other major affected sites, cleaning streets as well as rocks and mud accumulated in the "ribeiras". In the next few days this number peaked to several hundred heavy units and trucks operating in all affected sites. In spite of some access restrictions in the center of Funchal and some other parts of the island, all services were soon fully functional and normal life was restored. No tourist resorts were affected by the event, except for a few small hotels inland where some blocked roads caused access restrictions. While full restoration of all affected infrastructure may take up to a few years, most of the island is fully functional.	Autonomous region of Portugal.	In support of the flood victims, Real Madrid footballer and noted Madeiran Cristiano Ronaldo pledged to play in a charity match in Madeira, between the Portuguese Liga club Porto and players from Madeiran-based Portuguese Liga clubs C.S. Marítimo and Nacional. On 7 March 2010, the Mota-Engil group announced that it would make an investment of €1.2 million to build 10 houses for those who were made homeless as a result of the floods. The rainfall was associated with an active cold front and an Atlantic low-pressure area that was over the Azores and moved northeastwards on 19 February 2010. The storm was exacerbated by the eruption cloud of the Soufrière Hills volcano.	BBC News (2010) Lusa (2010) Pita (2010) Reuters (2010) Tolentino de Nóbrega (2010)

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Cape Verde dengue epidemic 2009	September - November 2009	Cape Verde, Central Atlantic Ocean	Dengue fever epidemic	Santiago, Brava, Fogo, Maio, Santo Antão, São Vicente, São Nicolau,Sal, Bavista Islands (Cape Verde).	6	25,245	Not reported	US $109,429.81 (101,867 euros) has been allocated from the Federation’s Disaster Relief Emergency Fund (DREF) to support the National Society in delivering immediate assistance to some 75,000 beneficiaries.	The Red Cross' response included social mobilization, vector control and enhanced management of clinical cases in hospitals and health centers. The Ministry of Health and the WHO office in Praia also responded by implementing a rapid monitoring system. The Cape Verde Red Cross assisted the Department of Public Health by mobilizing its volunteers in community-level awareness, as well as sanitation activities and distribution. By coordinating with health authorities and partners in the country, all actors involved were able to respond effectively to the epidemic. these two cities continue having high mosquito indices performed in the studies carried out. Hence, given the ubiquity of the virus in the tropics, with Asia and America considered to be areas of greatest risk, and with constant contact with Cabo Verde, through an increase in the incidence of international travelers the risk of dengue and other arboviruses is eminent in the country.	Republic of Cabo Verde	The geographical location of Cape Verde makes the Sotavento Islands meet climatic characteristics similar to those of other dengue-endemic areas. The urban expansion in the last decades, the increase in international travel and the global warming process are factors justifying the spread of the disease. The lack of truly effective measures of control of the mosquito, before the dengue outbreak, makes it possible to understand the real dimension of the problem at the moment. 4,92% of the general population from Cape Verde was affected. Despite the presence of the vector identified as *A. a. formosus* and the tropical climate, dengue cases were never registered in the country until the year 2009. This outbreak, the first one on the archipelago, came after three years of increased dengue activity in West Africa, with epidemics affecting Ivory Coast, Mali, and Senegal.	OCHA (2009) Sangare et al. (2018)
Azores seismic crisis 2005	10th May - December, 2005	Fogo-Congro seismogenic region (San Miguel Island-Azores, Atlantic Ocean).	Unrest volcanic period More than 46000 earthquakes Ground deformation Erosion Landslides Environmental damage due to the addition of heavy sediment loads to the stream lines	Within the epicenter zone, especially San Miguel Island (Azores) but also the rest of the archipelago.	0	Not reported	Not reported	Earthquakes did not cause severe damage.	Not reported.	Autonomous region of Portugal.	A volcanic unrest episode occurred in San Miguel Island, in the Fogo-Congro volcanic system, originated an intense seismic activity and ground deformation that caused surface ruptures and triggered many landslides.	Marques et al. (2006)
Indonesia tsunami 2004	00:58:53 UTC - 15:36 UTC, 26th December 2004	Epicenter in the coast of Banda Aceh, in the north of the Sumatra Island (Indonesia).	Major earthquake Tsunami Diseases	Indonesia and coastal zones of the Indian Ocean, specially Sri Lanka and Thailand.	230,000 - 260,000 (some deaths due to diseases, such as meningitis and Acute	125,000 (+85% of the survivors contracted diarrhea, + 35 cases of measles,	1,700,000	US $13.6 billion	To protect future classes and give children a safe learning environment, UNICEF supported the design and construction of new earthquake-proof buildings, with deeper foundations and stronger support systems. UNICEF then used these plans to build 300 more	In the case of Sumatra, dependent on the Republic of Indonesia.	In the town of Calang two weeks after the December 2004 tsunami found that 100% of the survivors drank from unprotected wells, and that 85% of residents reported diarrhea in the previous two weeks. Clusters	Inderfurth et al. (2005) Schwartz et al. (2006) Sewert (2005) Sunil (2005) Unicef (2020) WHO (2006)

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					respiratory infections, 20 deaths due to tetanus).	+106 cases of tetanus)			schools in Aceh province. Construction of earthquake-resilient schools, introduction of safer water supplies, ensuring that schools prepare children for emergencies and improvement of legal and social measures to protect children. Investment in building resilience to shocks and disasters by supporting decentralized and community-based health, water and sanitation, education, and social protection systems, working with government and civil society to provide tangible services for children and their families. Some 57,000 people are still living in camps and shelters. In Aceh, within five years, individuals were back in homes they owned, often on their original land, in communities with new schools and in many cases improved infrastructure. Ten years later, these communities have new residents as well as old, as a result of births and of in-migration.		of both hepatitis A and hepatitis E were noted in Aceh.	
Extreme weather episode Canary Islands 2004	19th February, 2004	Canary Islands (Atlantic Ocean)	Haze Plague of locusts Storm Strong winds Heavy rainfall Flooding	La Palma Island, Tenerife Island, Gran Canaria Island	0	0	0	At least US $16,832.88 (15,669.60 euros) in Tenerife. Destruction of the dune area of Maspalomas, damages to crops.	Experts estimate that it will take several years for the Maspalomas dune area to recover its best profile.	Autonomous community of Spain.	None	Arroyo (2009)
Dome collapse Montserrat island 2003	12th to 13th July, 2003	Soufrière Hills Volcano, Montserrat island (Caribbean)	8 years of eruption and lava dome growth Intense rainfall Mudflows Earthquake swarm Rock fall Dome collapse Vulcanian explosions Shockwaves Sulphur dioxide cloud Ash fallout Pyroclastic Density Currents/Block-and-ash flows Phreatic explosions (shore) Inland-directed	Montserrat and Guadeloupe islands	0 people. Animals were killed 4 km northwards of the Tar River Valley.	Not reported but it is said that there were no serious injuries.	Not reported, but probably not due to the current exclusion zone already created after the eruption of 2000, which obligated people to leave that area.	Destruction of fishing boats on Guadeloupe, damage to the coasts of Guadeloupe and Montserrat islands. Roofs collapses due to tephra fall in Montserrat. A shock wave associated with a vulcanian explosion caused structural damage to buildings 3 km north of the volcano. Sever damage to structures in Harris, 3km from the volcano. Ash fall and broken trees heavily impacted spring water sources. Power outages and surges have damaged parts of the electrical switch gear of the pump station. Replacement cost US $7,023.94 (6,538.40 euros).	The government of Montserrat declared the island an emergency zone after the Soufriere Hills volcano started erupting on July 12, 2003. The government requested the donation of dust masks for the population. Power from national grid intermittent but some hospitals have their own generator plus alternative source of power from the national emergency office nearby. Some water storage tanks were down, but Environmental Health Department assisted with water needs. Catchment areas were being cleaned. Needs to repair water system were being met by the Emergency Department. Debris removal was in progress and drains were cleaned to ensure rainfall runoff.	Dependent on United Kingdom	210 million m^3 of lava dome and talus collapsed to the east, generating large pyroclastic flows in the Tar River Valley. Dome collapses are very common at Soufrière Hills Volcano, like the ones occurred on 20 March 2000, 29 July 2001, 12 July 2003, 20 May 2006, 30 June 2006, 8 January 2007, 11 February 2010. Some of these collapses have been triggered by intense rainfall or earthquakes. Tephra fall reached over 15 cm uncompacted thickness. Pressure-wave arrivals were recorded in Martinique (240 km to the south). After the Soufriere Hills Volcano erupted in 2000,	Herd et al. (2005) PAHO (n.d.)

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			pyroclastic surge Tsunami								three-quarters of the population left Montserrat, so currently there is an exclusion zone around the volcano.	
Flank collapse Stromboli 2002	28th - 30th December, 2002	Sciara del Fuoco, on the western flank of Stromboli volcano, Aeolian Islands.	Effusive flank eruption Lava flows 2 flank collapses (submarine landslides) Tsunamis	Stromboli, Ginostra, Panarea and adjacent coasts, such as the Sicily coast.	0	6	140	Not reported. The waves spread onto the villages of Stromboli and Ginostra damaging buildings and boats.	Two helicopters from the Air Force have taken part in rescue operations after the event. Since the tsunami occurred in late December, the island was not filled with tourists and the reports on the casualties state that there were no deaths. The main initiatives, implemented during the 2003 crisis, consisted of the creation of new geophysical and geochemical volcanic detection networks and a local civil protection structure (AOC, Advanced Operations Centre), where signals from volcanic monitoring are displayed in real-time and possibly used by the staff of the Civil Protection Department (DPC) for the immediate activation of response procedures. In 2005, at the DPC in Rome, the Central Functional Volcanic Risk Centre (CFCRV) was established, where the most relevant monitoring signals of the active volcanoes are displayed in real-time and where simple processing activities are carried out daily, for risk assessment and data sharing within the scientific community, coordinated by civil protection personnel with training in volcanic problems. Hotel owners and other touristic facilities were given leaflets and further information which has been spread among tourists to increase awareness. Most of the inhabitants thought that giving this information to the visitors would have had a negative impact on tourism; actually, this never happened because Stromboli is still considered a 12-month destination from tourists all over the world. Increasing involvement of the local population in civil protection activities led to establishing two groups of civil protection volunteers on the island. These two groups took active part in the	Dependent on Italy.	The volume of the first landslide was estimated at ~6 x 106 m3 of rock while the second was smaller at ~5 x 106 m3 of rock. These landslides detached the lava from the 28 December eruption along the slope together with a large portion of the ground below. Not many casualties occurred because of the lack of residents during the winter season. The events of 30 December led to a “voluntary evacuation” by Stromboli’s inhabitants. On 5 January 2003, the health minister accused journalists of damaging Island tourism and the economy since the regional newspapers described the events of 2002–2003 with more alarmist and negative tones.	Bonaccorso et al. (2003) Chiocci et al. (2008) Smithsonian Institution (2013)

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									tsunami information campaign “Io non Rischio” in 2015 and 2016, which were right in the middle of the summer period.			
Vulcan and Tavurvur eruption 1994	19th September 1994 - 16th April, 1995	New Britain Island, Papua New Guinea	Seismicity 2 simultaneous eruptions Ash fall Lightning Lava flows Pyroclastic flows	West of Papua New Guinea, especially Rabaul.	5 (4 due to roof collapses and 1 struck by a lightning)	Not reported	50,000	The total direct losses are estimated to be 5% of GNP, the equivalent of two years of national public spending for health. The cost to rebuild infrastructure is estimated at $70 million. Insured losses were $50 million; private, uninsured losses are estimated to be double that amount. Airline companies sustained additional fuel costs because of aircraft diversions on longer routes.	The government has made land available to disaster victims at a safe distance from the volcanoes. Most housing areas and the administrative center are being rebuilt in Kokopo, a village 20 km from Rabaul and 15 km from the nearest active volcano. The Kokopo airport has been upgraded to replace that of Rabaul. Under the smoke of the still-active Tavurvur volcano, however, the harbor of Rabaul was reopened.	Dependent on the Independent State of Papua New Guinea.	1 person died struck by a lightning. This event led to the destruction of most of Rabaul, a bustling port town and the political and commercial powerhouse of the New Guinea Islands region. Papua New Guinea’s last major eruption had occurred in 1951 at Mount Lamington in Papua. Despite a sparser population than on the Gazelle Peninsula, approximately 3000 lives were lost. Remarkably, only five deaths directly resulted from the 1994 eruptions, four of them in Rabaul, due to the early evacuation and people knowledge about past eruptions. The fact that almost 20,000 Rabaul residents and tens of thousands of villagers evacuated without major incident, in the dark and on roads that could be hazardous at the best of times, was miraculous. Rabaul residents and Tolai villagers, rather than RVO scientists and the disaster committee, knew when it was time to leave, and accurately predicted that a major disaster was only hours away. Local villagers said that they observed natural warnings indicating that an eruption was imminent. People certainly identified such signs (the barking of dogs or the strange behavior of birds, for example) retrospectively. Tolai people who had witnessed the 1937 eruption recognized that these tremors were very similar to those that preceded the earlier eruption, and urged their	IDNDR (1996). Neuman (2014). OSU (2020)

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											fellow villagers to heed the warning.	
Merapi explosion 1992	5th July 1992 (eruptive period: 15th January 1987 - 12th August 1994)	West Sumatra, Sumatra Island (Indonesia)	Explosions Ballistic (bombs fall) Ash and lapilli fall Seismicity	Crater area and slopes of Mt. Merapi.	1 (due to bombs)	5	Not reported	Not reported	Hazard warning had been in effect since 1987.	Dependent on the Republic of Indonesia.	Bombs killed one person, seriously injured three, and caused minor injuries to two others. The victims had climbed to the summit without consultation with the Mt. Merapi Volcano Observatory or local authorities, although a hazard warning had been in effect since 1987. During June, 45 deep and 312 shallow volcanic earthquakes, 108 volcanic tremor episodes, and 2,104 explosion earthquakes were recorded.	Global Volcanism Program (1992)
Karangetang eruption 1992	2nd July, 1991 - 31st December, 1993	Siau Island, off the coast of Sulawesi (Indonesia)	Seismicity Ash explosions and bombs Ash fall Lava flows Pyroclastic flows Hot mudflows	North of Siau island, Indonesia.	6	Not reported	452	Destruction of more than 30 houses and ~2 km^2 of coconut, cassava, and nutmeg farms.	Not reported	Dependent on the Republic of Indonesia.	The pyroclastic flow was generated by the collapse of the lava flow front.	Hidayat et al. (2020a). Smithsonian Institution (2013).
Gas emission Azores 1992	1992	Graciosa Island, Azores (Atlantic Ocean)	Gas emissions (CO_2)	Furna do Enxofre lava cave, San Miguel and Faial islands.	2	Not reported	In San Miguel and Faial islands some people were evacuated from their homes due to the presence of high indoor CO2 level.	Not reported	Evacuation of some people.	Autonomous region of Portugal.	Visitors were from the Portuguese Navy and were asphyxiated by higher than normal levels of CO_2 in the fumarole situated in the intracaldera Furna do Enxofre lava cave in the Caldera Volcano which has not been active in the last few thousand years.	Ferreira et al. (2005) Gaspar (1996) Wallenstein et al. (2007)
Pinatubo eruption 1991	15th March - 15th June, 1991	Luzon Island (Philippines)	Earthquakes Landslide Eruption Ash fall Lahars Caldera formation Pyroclastic flows Climate effects Diseases	Philippines, Singapore, Malaysia, southeast of Asia.	740 (+349 deaths in evacuation centers due to diseases)	2,000,000 (+18,000 cases of measles)	220,000	US \$100 million losses for affected air companies. US \$450 million in damage to property. Natural resources have been severely damaged. 18,000 hectares of forest land and 96,200 hectares of agricultural land have been buried in ash falls. At least eight major river systems have been clogged up by lahar, namely Balin-Baquero Bacao, Santo Tomas, Gumain, Porac, Pasig Potrero, Abacan, Bamban and Tarlac Rivers.	About 20,000 in population, the Aetas had been safely evacuated before the eruption. People from the lowlands heeded also the warnings and fled to safer distance from the volcano. Also, more than 15,000 American servicemen and their dependents had evacuated from Clark Air Base before the eruption. The Philippine Congress and the Office of the President had passed and promulgated a series of laws and regulations that governed the country's comprehensive response. On 26 June 1991, President Corazon C. Aquino, through Memorandum Order No. 369, created the Presidential Task Force	Dependent on Republic of the Philippines.	The death toll in evacuation centers reached 349 in the first 12 weeks. Deaths were caused by measles (31%), diarrhea (29%), and respiratory infections (22%). Living conditions were extremely difficult in camps: tents provided only minimal shelter from the elements, and evacuees experienced extremely hot days and cold, damp nights. Malnutrition and lack of basic sanitation also contributed to high death rates among children. For years, lahars continued to flow down the major river systems.	De Guzman, E.M. (2004) Floret et al. (2006) Newhall et al. (2005) Volcano Discovery (2020)

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									on the Rehabilitation of Areas Affected by the Eruption of Mount Pinatubo or Task Force Mt. Pinatubo. It was succeeded the next year by the Mount Pinatubo Assistance, Resettlement and Development Commission, which, with a term of six years, mandated, among others, to formulate policies and plans, to coordinate the implementation of programs and projects, and to administer the initial 10-billion peso fund appropriated for the “aid, relief, resettlement, rehabilitation and livelihood services as well as infrastructure support for the victims.” Executive Order No. 4, issued on 5 March 2001, created an ad hoc body to complete the wind up activities of the Commission. Executive Order No. 5, issued on 5 March 2001, transferred the administration of upland Pinatubo resettlement communities from the Commission to the concerned local government units. In the same year, it created under the Council the Pinatubo Project Management Office (PPMO) to manage the resettlement areas.			
Gas emissions Vulcano 1988 - 1990	1988 - 1990	Vulcano Island (Italy).	Gas emissions (CO_2, H_2S)	Vulcano Porto and Levante Beach (north of Vulcano Island).	2 (and some animals).	Not reported	Not reported	Not reported	Civil Protection authorities installed at Levante Beach some panels informing tourists on gas hazard.	Dependent on Italy.	The accumulation of CO_2 in morphological depressions or excavation provoked the death for asphyxiation of two children in the area of Vulcano Porto and of some small animals at the base of the crater area. Risk is higher during stable atmospheric conditions, with weak or null wind.	Carapezza et al. (2016). Granieri et al. (2014).
Colo eruption 1983	18th July, 1983 - 16th ± 15 days December, 1983	Una-Una Island (Indonesia, Gulf of Tomini)	Seismicity Volcanic eruption and explosion Ash cloud and ash fallout Pyroclastic Density Currents	Una-Una, Sulawesi and Borneo Islands (Indonesia).	0	Not reported	7,000	700,000 coconut trees and all livestock on the island must have been burned. Almost all houses and buildings in the eight villages near the volcano had been destroyed. Some airline industry losses.	The island was home to around 7,000 people before the eruption. Today, only 1,000 people live on the island and the rest were relocated.	Dependent on the Republic of Indonesia.	Una-Una depends basically on fishing and it has been known as a location for scubadiving since the 1990s. The main cause of destruction was pyroclastic density currents. All people were evacuated with enough time, so no fatalities occurred.	Hidayat et al. (2020a). Smithsonian Institution (2013).
Truk State cholera epidemic 1982	August 1982 - 1985	Truk/Chuuk Lagoon, Micronesia (Pacific	Cholera epidemic Famine	Truk state (Micronesia).	> 20	831 cases in 1982 337 cases in 1985	Not reported	US $20.0 million, destined to develop water wells, drillings, for drill equipment, health education, medicines, toilets,	Three major programs were established for the physical improvement of the islands during the cholera epidemic: the Rural	Federated States of Micronesia, associated	It is believed that one of the cargo vessels carrying an Asiatic flag about seven months before August of	Alfred et al. (1984). Harris et al. (1986).

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Event	Date/Duration	Location	Cascading effects/Hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Resilience/mitigation actions	Dependency	Observations	References
		Ocean).						desalination, medical supplies, doctors, etc. 50% drop in the number of tourists coming in from the foreign countries, so 50% decrease in the revenues from tourism. Exportation of sea products (excluding fish) dropped from $569.71 to $313.72 average sale, causing a loss of $256 every month. Within the entire 18 month period that cholera was present in Truk a total of $5,646.96 receipt and $4,608 shortage resulted from exportation.	Sanitation Program, the Health Education Program, and the Beautification Program. After the epidemic, there existed a cleaner, a neater, and a more sanitary Truk. People realized that personal cleanliness and neatness are necessary for healthy life.	with the United States.	1982, dumped its waste materials into the sea. Present among the garbage was this bacterium we know of as vibrio cholera. An unfortunate fellow picked it up, probably through marine food like clams and fish, and went off to attend some risky arid unsanitary activities in which the disease was eventually passed on. Personal cleanliness is poor on the islands of Truk. The process of making food is seen to be unsanitary. Drinking water is left exposed. In the fishing markets, customers come in to buy fish that have been contaminated. From oceanic food, other types of food exposed to flies, and from persons who have the sickness, cholera was eventually "transmitted uncontrollably.	
Gamalama eruption 1980	4th - 23rd September, 1980	Ternate Island off the western coast of Halmahera (Indonesia).	Explosions Seismicity Ash, tephra and incandescent material (bombs) falls Forest fires	All Ternate Island.	0	Not reported	40,000	Not reported	Most evacuees had returned home, but some small villages in the NE sector red zone remained evacuated. However, in 2017, the population on Ternate Island was 211,937 people.	Dependent on the Republic of Indonesia.	Incandescent material fell 500-750 m from the crater, starting brush and forest fires. Ash fell on the entire island, accumulating to a depth of 10 cm by the second day of the eruption at Ternate City, 7-8 km E of the crater.	Hidayat et al. (2020a,b). Smithsonian Institution (2013).
Mount Pelée eruption 1902	23rd April 1902 - 5th October 1905	Martinique Island (Lesser Antilles, Caribbean Sea)	Phreatic explosions Caldera collapse Lahars Explosion of the lava dome Pyroclastic density currents Small tsunamis Ash fall Gas emissions Earthquakes Climate effects Famine	St. Pierre city, north of the Martinique island and possibly the nearest islands.	29,000 (+ 2,000 rescuers, engineers, and mariners bringing supplies to the island during a second eruption; a second pyroclastic density current struck Morne Rouge, killing at	Not reported, but probably.	25,000	US $1 billion.	Boats arrived to remove survivors, evacuation of nearby towns after the initial disaster, housing and rations, monetary support for the 25,000 displaced persons. US Congress voted for $200,000 of immediate assistance. By August 15, refugees were no longer given support, and encouraged to return to their towns. Government provided funding for new construction of settlements, worldwide donations (temporarily). Relief program for refugees inconsistent, with no plan for long-term resettlement, compensation, reintegration.	Dependent on the Republic of France.	The 29,000 deaths were due to a single pyroclastic current. Results from the impacts were blown down buildings and only a few partially remaining walls, mostly those parallel to the coastline, in the southern part of the city.	Associação Médica de Minas Gerais (2020). Hidayat et al. (2020a).

PAST NATURAL DISASTERS												
Event	**Date/Duration**	**Location**	**Cascading effects/Hazards**	**Main affected areas**	**Fatalities**	**Injuries**	**Displacements**	**Economic, social and natural losses**	**Resilience/mitigation actions**	**Dependency**	**Observations**	**References**
					least 800, Ajoupa-Bouillon causing 250 fatalities, parts of Basse-Pointe causing 25 fatalities, and Morne-Capot, killing 10).							
Martinique floods 1891	18th August, 1981	Martinique Island (Lesser Antilles, Caribbean Sea)	Cyclone San Magín Floods Diseases	All over Martinique.	700	1,000	Not reported	Between US $11.6 and US $14.5 million approximately (between 72 million and 88 million francs), loss of coffee, sugar and cotton crops had a large effect on Martinique's economy.	Over the next few months, worker's organizations, Martinique's local government, the central French government, concerned individuals, and particularly other Caribbean islands all donated to help victims. By December 1891, over 791,000 francs in financial and in-kind assistance had been provided.	Dependent on the Republic of France.	Although the hurricane affected the Lesser Antilles, the Dominican Republic, the Bahamas, Gulf of Mexico, U.S. and Florida, the storm made landfall on the island of Martinique.	Aubaud et al. (2013) Church (2019) Church (2014).
Martinique fires 1890	22nd June, 1890	Martinique Island (Lesser Antilles, Caribbean Sea)	Fires Explosions	Fort-de-France (Martinique).	13	Not reported	Not reported but probably due to the destruction of 1600 homes	Between US $8.1 and US $11 million approximately (50 - 67 million francs)	Collections began in Martinique's parishes and townships, raising over 100,000 francs (24,415 francs from Episcopal and 79,650 francs from municipal donations). The governor himself provided a credit of 100,000 francs to be distributed among Fort-de-France's victims, equating to 10 francs per victim. A second such credit was opened in August. Within days of the fire, the mayor of Fort-de-France, Osman Duquesnay, created squads of workers to clear the rubble from the city, offering a pay rate of 2 francs per day supplemented with food rations. Support arrived from Saint-Thomas, Trinidad, and Demerara, and since Fort-de-France's most immediate need was food, Jamaica sent 300 barrels of flour and 300 bags of rice. 1,7 million francs raised for relief and some of the money received for hurricane relief the next year was used to rebuild some buildings destroyed by the fire, as well as some "relief measures" from the 1891 hurricane to assist the fire victims who were still struggling. part of the funds and foodstuffs were used for the hurricane relief	Dependent on the Republic of France.	Poor members of the black working class could not afford proper glass lanterns or globes and the use of ad-hoc lighting brought an increase in the number of urban fires throughout the region. Many filled their improvised lanterns with unstable, highly flammable low-grade oil since proper kerosene was so high. The storage of this volatile fuel, combined with the ferocity of the region's trade winds, the aftermath of a prolonged drought and homes mainly rebuilt with wood to prevent collapses during an earthquake, set the stage for a disastrous fire outbreak.	Church (2014, 2019).

PAST NATURAL DISASTERS												
Event	**Date/Duration**	**Location**	**Cascading effects/Hazards**	**Main affected areas**	**Fatalities**	**Injuries**	**Displacements**	**Economic, social and natural losses**	**Resilience/mitigation actions**	**Dependency**	**Observations**	**References**
									of 1891.			
Flank collapse Ritter Island 1888	13th March, 1888	Ritter Island, Papua New Guinea (southwestern Pacific Ocean)	Lateral flank collapse Tsunami	Ritter Island and adjacent shores, such as those of New Guinea Island.	Several hundreds - 1,000	Not reported, but probably.	Not reported	Little damage was done to European infrastructure at Finschhafen, but Melanesian people there lost canoes and shoreline houses.	There is no clear indication from the account of the relief party of major losses of life having resulted from the Ritter tsunami along the shorelines of Kaiser-Wilhelmsland. Indeed, the relief effort apparently represented more a commercial company interested in the immediate fate of its employees than representatives of a government being concerned about the condition of its subjects.	Dependent on Papua New Guinea.	The collapse reduced the 780 m high, 1.5 km wide island to a thin remnant of only 100 m maximum height. It had removed much of the western submarine flank of the volcano as well. As much as 5 km3 of material collapsed, making this the largest historical island volcano collapse in the world. (Its volume is about twice the volume of the 1980 collapse of Mount St Helens). The associated tsunami had run-up heights of more than 20 m on the neighboring islands and reached settlements 600 km away from its source. According to local people and volcanologist from that époque, this is unlike Krakatau in 1883 when huge volumes of pumice were produced. There was at Ritter, in contrast, no noise, no earthquakes, no visible eruption column, no incandescence, no ash fall — apart from the '-ne, barely perceptible rain of ash' at Finschhafen — and no oating pumice. This apparent discrepancy was not addressed until after volcanological lessons began to be learnt from the Mount St Helens eruption in the western United States in 1980.	Johnson (2013) Ward and Day (2003)
Krakatau eruption 1883	20th May - 21st October, 1883	Krakatoa Archipelago, in the Sunda Strait (Indonesia)	Earthquakes Caldera eruption Tsunami Ash fall Climate effects Acid rain	Indonesia and coastal zones of the Indian Ocean.	36,417 – 120,000	Not reported, but probably.	Not reported, but probably.	Crops and livestock losses in several parts of the world. Destruction and severe damages to many parts of Indonesia and coasts of the Indian Ocean.	The climatic response started the following year producing the "year without summer" and the effects and consequences lasted a few more years.	Dependent on the Republic of Indonesia.	Deaths were mainly due to the tsunami triggered by the pyroclastic density current. The consequences of the eruption of Krakatoa had a significant effect among	BBC News (2018) Olson et al., (2007)

PAST NATURAL DISASTERS

Event	Date/Duration	Location	Cascading effects/Hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Resilience/mitigation actions	Dependency	Observations	References
											European cultural elites of the late nineteenth century. The cultural impact of the eruption was noted in the paintings of the time. One of the best examples is the agonized painting of Edvard Munch (The Scream) and the effect of the eruption of Krakatoa in European skies in the years following 1883.	
Landslide Azores 1847	9th July, 1847	NW coast of Flores Island, Azores (Atlantic Ocean)	Landslide Tsunami	Flores and Corvo Islands, Azores	10	More than 100	Not reported	Not reported	Not reported	Autonomous region of Portugal.	The tsunami was triggered by a rotational slide during a sea cliff failure with more than 350 meters high at Quebrada Nova on the western seaboard of Flores island which produced a 5-7 m-high tsunami. It is said that the rock fall compressed the air which, in turn, compressed the seawater, causing a great cloud of dust and water currents that reached 66–88 m in height, submerging some islets, including the 'Ilhéu do Monchique'.	Gaspar et al. (2011)
Earthquake 1839 east of Martinique	11th January, 1839	West of the subducting St. Lucia Ridge (Lesser Antilles, Caribbean Sea).	Earthquake	Fort-de-France (Martinique).	700	Not reported, but probably.	Not counted but reported due to the destruction of many houses.	US $14.5 million	Majority of the city's homes had been rebuilt as single-story units made entirely of wood, preventing them from collapsing during an earthquake.	Dependent on the Republic of France.	The earthquake had a magnitude of 7.8 and a focal depth of 33 kilometers. The rebuilt of home with wood facilitated the propagation of the fire occurred in 1980.	Feuillet et al. (2011). Nicoletti (2015).
Tambora eruption 1815	1812 - 15th July, 1815	Sumbawa Island (Indonesia)	Caldera eruption Pyroclastic Density Currents Earthquakes Ash fall Acid rain Tsunami Climate effects Famine Diseases and epidemics	Indonesia, coastal zones of the Indian Ocean, climate effects worldwide.	92,000	Not reported, but probably.	Not reported	Crops and livestock global losses.	The effects of the eruption persisted the following year, causing the "year without summer", and causing famine to the population in many parts of Europe and even North America due to the impossibility for crops to grow.	Dependent on the Republic of Indonesia.	Deaths were mainly due to starvation. Ash covered nearly the whole north hemisphere, dropping the average global temperature three degrees Celsius, which caused the known "year without summer", and it is believed that this bad weather inspired Mary Shelley to write her Frankenstein novel.	NOAA (2020)
Vila Franca 1522 earthquake (Azores)	21st - 22nd October, 1522	Municipality o f Vila Franca do Campo, San Miguel Island (Azores, Atlantic Ocean).	Earthquake (and 4 aftershocks) Landslides Lahars Tsunami	Municipality of Vila Franca, the neighboring settlements of Ponta Garça, Maia and Porto Formoso.	3,000 - 5,000	Not reported, but probably.	Over 5,000	Much of the central part of the town was covered in mud and landslide material, with the port disappearing under a layer of pumice.	It resulted in the economic, social and political migration of settlers from the municipality of Vila Franca and the growth of the city of Ponta Delgada, then an economic rival in the region.	Autonomous region of Portugal.	The earthquake had a maximum intensity of X (i.e., "Very destructive") on the European macroseismic scale. Landslides were affected by the saturation of the sub-soil from by torrential rainfall several days earlier. The island's	Marques (2006) Silveira (2002)

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Event	Date/Duration	Location	Cascading effects/Hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Resilience/mitigation actions	Dependency	Observations	References
											volcanic terrain, consisting of low-density pyroclastic materials (such as the pumice stones that comprised the flanks of the Água do Pau Massif), was susceptible to landslides, and eventually resulted in the creation of lahars. Up to 6,750,000 cubic meters (238,000,000 cu ft.) of debris ran down the ravine, at a speed that was estimated at between 1–3 meters per second (3.3–9.8 ft./s), reaching the center of the village in a few minutes and covering it completely. In Maia, a gigantic avalanche of mud descended along the flanks of Monte Rabaçal, followed the course of the Ribeira da Mãe de Água and later spread over the whole town.	
Santorini eruption 1610 BCE ± 14 years	1610 BCE ± 14 years	Southern Aeg ean Sea, about 200 km southeast from Greece	Earthquakes Caldera eruption Ash fall Tsunami Climate effects	Greece, Near East and possibly worldwide effects.	>20,000	Not reported, but probably.	Not reported, but probably.	Crops and livestock losses in Thera, difficulties in maritime trade, depression and decline, withering of cereals in China.	The effects of the eruption persisted for years, causing the decline, according to some historians, of the Minoan civilization.	Dependent on Greece.	Many scientists link the rapid decline of the Minoan Civilization centered on Crete with the eruption, although there is controversy about whether the decline was due to the eruption or to other factors.	Sparks (1979) Whipps (2008)
Toba eruption 73 ka ago	73 ka ago	Northern of Sumatra, Indonesia.	Caldera eruption Ash fall Climate effects (cooling, drought) Environmental and ecological effects (deforestation)	Indonesia, coastal zones of the Indian Ocean and worldwide effects.	Mass extinction? (controvers y)	Not reported	Not reported	Genetic bottleneck in humans.	The Toba eruption led to prolonged drought and deforestation in India, probably lasting for 1000– 2000 years. Six-year volcanic winter (controversial hypothesis). Global primary productivity declined catastrophically for nearly two millennia. It may have been responsible for the late Pleistocene population bottlenecks reflected in the genetic structure of living human. A major isochronous change in vegetation from forest before the eruption to open woodland or grassland thereafter in central India.	Dependent on the Republic of Indonesia.	Genetic changes among humans and other animals and ecological changes after the Toba eruption. Severe environmental degradation could have been responsible for large mammal extinctions in southeast Asia and genetic bottlenecks in humans and other species that occurred in Africa and southeast Asia at this time. However, different studies and evidences reflected that no significant cooling occurred after Younger Toba eruption.	Newitz (2018) Williams et al. (2009)
Mount Pelée flank collapses 126 ka, 25 ka, 9 ka	1st collapse: 126 ± 2 ka 2nd collapse: 25 ka 3rd collapse: 9 ka	Martinique Island (Lesser Antilles, Caribbean Sea)	Lava flows Megalandslides (flank collapses) Tsunamis Pyroclastic Density Currents	Coastal zones on the Caribbean Sea, probably Central America and	Not reported	Not reported	Not reported	Destruction and/or severe damage to the affected sectors of the island.	Not reported	Dependent on the Republic of France.	Each flank collapse occurred after an active volcanic period of Mt. Pelée and supposed the end of each constructional period of this part of the island.	Germa et al. (2015).

PAST NATURAL DISASTERS

Event	Date/Duration	Location	Cascading effects/Hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Resilience/mitigation actions	Dependency	Observations	References
				north of South America.								
Flank collapse Tenerife 170 ka	180 - 170 ka	Tenerife Island, Canary Islands (Atlantic Ocean)	Caldera-forming eruption Pyroclastic Density Currents Co-ignimbrite plume Climate effects Seismicity Landslide Tsunami	Canary Islands and probably coastal zones of the Atlantic Ocean.	Not reported	Not reported	Not reported	Destruction of the central and northern part of Tenerife island, and severe damage to the whole island and coastal zones of the rest of Canary Islands and Atlantic Ocean. Probably global climate effects and environmental consequences.	Not reported	Autonomous community of Spain.	The caldera-forming eruption is known as El Abrigo eruption. It involved more than 20 km^3 of erupted material, covering the island with ash deposits between 2 and 20 m thick, seismicity with a Mw between 5 and 7, a landslide in the north that removed around 60 km^3 of subaerial material, forming the Icod valley and triggering a tsunami that left deposits in some coastal locations at altitudes up to 132 a.s.l.	Hunt et al. (2011) Hürlimann et al. (2000) López-Saavedra et al. (2021) Martí, Mitjavila, et al. (1994) Martí et al. (1997) Paris et al. (2017)

Table 17. Historical Record of Non-Extreme Events Occurring on the Island of Tenerife (Canary Islands) in the Period 1496 - 2020.

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
VOLCANIC ERUPTIONS											
Chinyero eruption 1909	18 to 27 November, 1909	Santiago Rift Zone, flank of Abeque (Chinyero)	Seismicity before, during and after the eruption Fumaroles before and after the eruptive period Opening of a volcanic fissure Explosions Lava flows Ash fallout Lapilli, scoria and bombs fallout Rupture of the retention dike formed by erratic blocks in the lava flow drainage channels and the consequent lava avalanche with overflows Plague of ants	Seismicity especially felt in La Orotava, Icod, Puerto de la Cruz, Los Realejos, Alta Vista Mountain, La Rambla, Garachico, Santiago del Teide, Chinyero, Vilaflor, Guía de Isora, but some earthquakes were reported to be felt in the northern coast, in the whole island, and even in Gran Canaria island. Only the most intense earthquakes were felt in Guamasa, La Esperanza, San Cristóbal de La Laguna and Santa Cruz. Ash reached Icod, La Orotava and, the smallest fragments, arrived to Punta del Hidalgo. 1,290,000 m^2 covered by lava flows.	0	Not reported.	It is known that many people abandoned their houses in Garachico and Icod and went to other places, such as La Orotava, La Rambla.	Around 16,000 pesetas due to the loss of a piece of land affected by the lava. Loss of an unproductive piece of land belonging to the State, which was sown with rye by the inhabitants of the Valley and Las Manchas, paying a small fee for it.	The Mayor of Garachico, Mr. Manuel Valcárcel and Salazar communicated the event to the higher authority. The councilor of that town council, Gaspar de Ponte y Cólogan, volunteered to go and recognize the phenomenon. When he arrived at the village of La Culata, the inhabitants had abandoned their houses, had taken out the image of the Virgin to whom they prayed, and had climbed onto the reliefs formed by the lava from the previous volcano, thinking that the new lava flows would not pass over the previous ones but over depressed reliefs. The higher authorities sent aid to some villages, and the Captain General of the Province, His Excellency Mr. Martítegui, the Chief of Staff Colonel Domingo, Assistants, and the interim Governor Mr. Luengo, visited some villages, transmitting tranquility and faith. The neighbor and landowner José Miguel González y Gorrín offered to accompany them, who reported on their return that there was no danger from the lava flows, so people returned to their homes. However, hours later Mr. Cura del Tanque announced that the lava flows were heading that way, so some people stayed on the quay until dawn in order to escape by sea. Many people abandoned their houses in Garachico, Icod, and went to La Orotava, La Rambla or other nearby places. Some processions were organized, and some images of devotion were taken out for praying to them. Gaspar de Ponte y Cólogan made an exhaustive survey of the terrain, writing down all the observations with analytical data such as temperature, dimensions of the deposits and other elements, and the speed of advance of the lavas, and once the eruption was over he continued with the survey of the terrain to check for other anomalies that could give indications of other subsequent eruptions, checking the temperature of other mountains, including Teide, and analyzing emitted gases and fumaroles.	VEI = 2[b] Lava volume = 0.010 km^3 and pyroclasts volume = 0.005 km^3.[h] Fissure volcanic edifice, 5 craters aligned east to west. Thermal anomalies, limited to the area where the emission centers were opened, were described. The first stage was explosive; the second was mixed (explosive/effusive); the third was also mixed but predominantly effusive; the last stage was explosive. Average speed for one of the lava flows of around 16 m/hour, and temperatures between 1.200 and 2.400 ºC (deduced from coloring and fluidity). Lava flows accumulated around the south of the effusive fissure and were retained there to form an immense lava pool. This delay in the flow of the lava flows benefited the populations that were at risk of being hit by them. However, the blockage dike subsequently broke, resulting in the formation of a lava avalanche with overflows. The lava flows advanced about 400 m. A day after, the erratic blocks coming from the lapilli mountain would again obstruct the lava flow channels, thus interrupting the flow of effusions. Many populations escaped from the lava flows because these emerged each time from a different source, and were therefore often retained by lava deposits already consolidated from the previous flows.	Romero (1990) Romero & Beltrán (2007) Carracedo et al. (2008) Smithsonian Institution (2013)
Chahorra / Narices del Teide eruption 1798	9 June to 14 or 15 September, 1798	SW flank of Pico Viejo (Chahorra)	Seismicity Opening of a volcanic fissure Explosions Rock falls Lava flows Ash fallout Lapilli and bombs fallout Probably fires	Seismicity was probably felt in some areas around the island but it is only known to have been felt in La Orotava Valley. Ash fallout was produced also in La Gomera, El	0	Not reported.	Not reported.	The ashes covered roofs and vegetation in many places with a layer a few millimeters thick in Los Realejos, La Orotava, Icod and Garachico. Destruction of some arable fields.	Not reported.	VEI = 3 It was the longest lasting historical eruption. Fissure eruption, with a N40º E direction and 800 m long, and with both explosive and effusive stages. Lava volume = 0.016 km^3 and pyroclasts volume = 0.009 km^3. Water/magma contact stages.	Romero (1990) Romero & Beltrán (2007) Carracedo et al. (2008) Sobradelo et al. (2011) Smithsonian Institution (2013)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				Hierro and Gran Canaria islands. Lava flows were developed within the Teide area. 4,566,693 m^2 covered by lava flows.							
Garachico / Arenas Negras eruption 1706	5 May to 13 June, 1706	Santiago Rift Zone, flank of Abeque, (Garachico)	Seismicity Opening of cracks Opening of a volcanic fissure with several emission centers Gas emissions Lava flows Ash fallout Fires	Northern side of the island of Tenerife due to seismicity. Harbor and part of the city of Garachico due to lava flows. Also damages in El Tanque and San Pedro de Daute villages. 7.6 km^2 covered by volcanic products.	0	Not reported.	It is known that many people abandoned the city of Garachico and go to Icod, La Orotava village and the city of San Cristóbal de La Laguna.	During the first year, 41,000 reales were spent on dock work and cleaning. Impact on trade and economic decline. Destruction of some crops, orchards, neighborhoods and the pine forest. Obstruction of springs.	Many people abandoned Garachico. The City Council gave a subsidy to take the nuns to San Cristóbal de La Laguna, and General Don Agustín de Robles spent more than 3,000 pesos to bring sustenance to the wandering neighbors and provide them with horses for transport. Franciscan friars, Dominicans and nuns left their convents in Garachico and were distributed among various convents in Icod, La Orotava and San Cristóbal de La Laguna, taking some devotional images with them. Forty days after the lava flows reached Garachico, the natives, the clergy and the religious men and women returned to the town to rebuild their houses. On April 4, 1741 the Cabildo met in an assembly where the representative of Garachico requested that money be invested to fix the town. It was not until 1737 - 1741 that the church of Santa Ana and the Franciscan convent of Our Lady of the Angels were rebuilt. At that time, work was again carried out in the port, and traffic could be enabled. In 1798, improvement works were carried out again. In 1934 the project for the port works was approved. In the 1940s, maritime traffic in the port was reestablished with limitations. The parish of Santa Ana, destroyed by fire, was rebuilt between 1714 and 1721, seven years after the eruption, with contributions from neighbors and alms. The nuns were able to return to the Convent of San Diego only 4 years after the fire destroyed it, thanks to the contributions of the neighbors.	VEI = 2 Opening of a new fissure of 1 km of length with a direction NW-SE. Two effusive stages. The wind blew from the north to the south. Lava volume = 0.022 km^3 and pyroclasts volume = 0.014 km^3. Average emission rate of 47,500 m^3/hour. It is the eruption that more economic impact and damages caused.	Cioranescu (1977) Romero (1990) Romero-Ruiz et al. (2006) Carracedo et al. (2008) Sobradelo et al. (2011) Smithsonian Institution (2013)
Arafo (or Arenas)-Fasnia-Siete Fuentes eruption 1704-1705	31 December, 1704 to 27 March, 1705 Siete Fuentes eruption: 31 December, 1704 to 4 or 5 January, 1705. Fasnia eruption: 5 January to 16 January 1705.	Dorsal Rift Zone (Siete Fuentes, Fasnia, Güímar) Siete Fuentes eruption: Reverse of Las Cañadas. Fasnia eruption: Southern slope of Izaña. Arafo eruption: flank of Pedro Gil.	Seismic crisis prior to and during each eruption Rock fall Ground deformation and cracking Fumaroles and gas emission Increase in the water flow of the Barranco de Badajoz (ravine) Fracture opening and propagation Triple eruption	Almost 4.5 km^2 covered by lavas. Most intense earthquakes were felt around the whole island of Tenerife, but especially in La Orotava, Realejos and Güímar, and even in La Gomera.	16 (it is believed to have been due to the collapse of some houses in Güímar and due to the horror and fright caused by the tremors prior to the Arafo eruption). The death of	Many injuries were reported, but they were not accounted for.	Not reported. Minimum of 70 people due to the destruction of 70 houses during seismicity prior to the Arafo eruption. It is known that many people abandoned their houses and went to live in the	Seismicity effects were really destructive in both valleys of Güímar and La Orotava, causing the total ruin of the city of Güímar and important damages in the village of La Orotava and the cities of Los Realejos and Candelaria. Other damages were caused in Puerto de la Cruz and seismicity was felt in Icod and Garachico. Destruction of vegetation along the area covered by the lava deposits. Most of the lava flows flowed along the bottom of valleys and ravines without affecting the cities, except for the destruction of some agricultural fields.	Many people from the most affected sites, such as Arafo and other villages in the Güímar Valley, abandoned their houses and convents due to seismic shocks and decided to go to some cities such as Candelaria or San Cristóbal de La Laguna. People who could not easily leave their homes wandered the streets and squares, since they did not know what to do. As seismicity continued, some of them decided to build straw huts in the courtyards and orchards, and others went out to live in the fields, where they placed various altars with images of devotion and prayed for help. The Religious Communities also installed their rooms outside in the orchards of their convents. During the time that seismicity and eruptions lasted, processions were held, public penances were	VEI = ≤2 Volcans were produced by fissure eruptions along a fracture with N 40º E direction and 10 km long. During the eruption of Siete Fuentes and Fasnia, lava was emitted along the entire fracture, as a fissure eruption, while Arafo/Arenas was a unique center. Minimum speed for lavas was 20 m/hour for Siete Fuentes and Fasnia volcanoes, and the average minimum speed for Arafo/Arenas was 6 m/hour, reaching during the first week and a half 16 m/hour. The erupted lava volume was about 0.004 km^3, and 0.002 km^3 for pyroclasts, for Siete Fuentes/Fasnia,	Romero (1990) Solana (1996) Coello et al. (2006) Carracedo et al. (2008) Smithsonian Institution (2013)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
	Arafo eruption: 2 February to 27 March 1705.		Ash fallout Lapilli, bombs and scoria fallout Lava flows Probably forest fires Several subsequent landslides and collapses in the cones until today		one Bishop was also reported, due to a not specified accident, together with attacks and fright and bad living conditions during the seismic period.		fields or walk along streets during seismic shocks.		performed and priests gave talks. Many churches of parishes and convents took out the S. S. Sacrament and devotional images and held penitential processions, or placed the images outside to protect them from building collapse, so people could pray to them. Some priests climbed to the summits to exorcise. The Distinguished Bishop D. Bernardo de Vicuña y Suazo authorized all priests to hear confessions and ordered them to make spells. Several men were sent to survey the land, and they stated that they had seen at least two volcanoes form. One Dominican Religious and two Benedictine Priests brought the Blessed Virgin to the city of San Cristóbal de La Laguna. Currently, vegetation is still scarce in the area covered by the main lava deposits, but many trees, mainly *Pinus canariensis*, and some shrubs have grown in this sector, especially in the adjacent areas, and big cities are built in the area that was then affected.	and 0.035 km^3 and 0.008 km^3 respectively for Arafo. Approximate maximum intensity of precursor earthquakes between VII and VIII, according to the M. S. K. scale. All three volcanoes had an initial explosive stage followed by a mixed stage. Throughout the active period, the duration and intensity of the eruption increased, giving rise to three very unequal in size.	
EARTHQUAKES											
Earthquake 2020	16 July, 2020	N of Buenavista del Norte	Seismic shock Minor rock falls	Arona, Granadilla, Santiago de Teide, Icod de los Vinos, Garachico, Los Silos, La Orotava, Los Realejos, Puerto de la Cruz and others	0	0	0	No damage	Not reported.	mbLg (L) = 4.0	Torres (16 July, 2020) IGN (2021)
Earthquake 2019	18 January, 2019	SE of Tenerife, Atlantic Zone Tenerife - Gran Canaria	Seismic mainshock Aftershocks	Candelaria, Granadilla de Abona, Tegueste, Güimar, La Orotava, Santa Cruz de Tenerife, Arafo, Fasnia, Arico, La Matanza, San Cristóbal de La Laguna, Arona and Santa Lucía de Tirajana	0	0	0	No damage	Not reported.	mbLg (L) = 4.2	Diario de Avisos (18 January, 2019) IGN (2021)
Earthquake 2017	10 October, 2017	S of Tenerife, Atlantic Ocean	Seismic shock	Many parts of the island of Tenerife, but especially Arona	0	0	0	No damage	Not reported.	mbLg (L) = 4.0	Gobierno de Canarias e Instituto Geográfico Nacional (2017) IGN (2021)
Earthquake 2016	30 October, 2016	E of Tenerife, Atlantic Ocean	Seismic shock	Northeast of Tenerife	0	0	0	No damage	Not reported.	mbLg (L) = 3.8	Elchaplon (30 October, 2016) IGN (2021)
Earthquake 2015	6 November, 2015	SE of Tenerife, Atlantic Ocean	Seismic shock	La Orotava	0	0	0	No damage	Not reported.	mbLg (L) = 3.7	El Eco de Canarias (6 November, 2015) IGN (2021)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Earthquake 2014	13 March, 2014	NE of Tenerife, Atlantic Ocean	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	mb (V-C) = 4.0	IGN (2021)
Earthquake 2013	17 March, 2013	N of Tenerife, Atlantic Ocean	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	mb (V-C) = 3.7	IGN (2021)
Earthquake 2012	17 December, 2012	NE of Tenerife, Atlantic Ocean	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	mb (V-C) = 4.8	IGN (2021)
Earthquake 2012	18 August, 2012	NW of El Sauzal	Seismic mainshock Aftershocks	El Sauzal, La Matanza de Acentejo, La Orotava, Punta del Hidalgo, San Cristobal de La Laguna, Santa Cruz de Tenerife	0	0	0	Not reported.	Not reported.	mbLg (L) = 3.8	RTVE (18 August, 2012) IGN (2021)
Earthquake 2010	5 February, 2010	SE of Santa Cruz de Tenerife	Seismic shock	Many parts of the island of Tenerife	0	Not reported.	Not reported.	No damage	Not reported.	Mw = 4.5	El País (5 February, 2010) IGN (2021)
Earthquake 2009	13 June, 2009	N of Tenerife, Atlantic Ocean	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	mb (V-C) = 3.5	IGN (2021)
Earthquake 2009	10 March, 2009	N of Tenerife, Atlantic Ocean	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	mb (V-C) = 3.6	IGN (2021)
Earthquake 2008	13 May, 2008	E of Tenerife, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Northeast of Tenerife	0	0	0	No damage	Not reported.	mbLg (L) = 3.5	Diario de Navarra (13 May, 2008) IGN (2021)
Earthquake 2005	22 November, 2005	N of Tenerife, Atlantic Ocean	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	mb (V-C) = 4.0	IGN (2021)
Earthquake 2004	17 July, 2004	NE of Tenerife, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	mb (V-C) = 3.6	IGN (2021)
Earthquake 1998	13 February, 1998	N of Gran Canaria, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.1	IGN (2020, 2021)
Earthquake 1995	13 April, 1995	E of San Miguel de Tajao, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	No damage	Not reported.	M = 3.5	IGN (2020)
Earthquake 1992	3 October, 1992	E of Porís de Abona, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Many parts of the island of Tenerife	0	0	0	No damage	Not reported.	M = 3.8 Maximum intensity observed = 4	El País (5 October, 1992) IGN (2020)
Earthquake 1990	20 May, 1990	N of Tenerife, Atlantic Ocean	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.5 Maximum intensity observed = 3	IGN (2020)
Earthquake 1990	8 January, 1990	N of Buenavista del Norte, Atlantic Ocean	Seismic shock	Some parts in the north of Tenerife	0	0	0	Not reported.	Not reported.	M = 3.7 Maximum intensity calculated (epicentral) = 4.1	Diario de Burgos: de avisos y noticias (10 January, 1990) IGN (2020)
Earthquake	29 May,	E of Porís de	Aftershock related	All the island of	0	Not	Not reported.	Not reported.	Not reported.	M = 4.0	IGN (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
1989	1989	Abona, Atlantic Zone Tenerife - Gran Canaria	to the 9 May earthquake	Tenerife		reported.					
Earthquake 1989	9 May, 1989	E of Santa Cruz de Tenerife, Atlantic Zone Tenerife - Gran Canaria	Aftershock related to the previous earthquake	All the island of Tenerife	0	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.0	IGN (2020)
Earthquake 1989	9 May, 1989	W of Mogán, Atlantic Zone Tenerife - Gran Canaria	Seismic mainshock Aftershocks	All the island of Tenerife	0	Not reported.	Not reported.	Some broken windows and displaced furniture. Compensation payments were made by the Insurance Compensation Consortium.	Not reported.	M = 5.0 Maximum intensity calculated (epicentral) = 6.7 The earthquake was accompanied by underground noise	IGME (2006) IGN (2020) COPE (27 January, 2021)
Earthquake 1981	22 April, 1981	E of San Miguel de Tajao, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	0	0	0	No damage	Not reported.	M = 3.8 Maximum intensity calculated (epicentral) = 6.4	IGN (2020)
Earthquake 1979	31 October, 1979	NE of Puertito de Güimar, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	0	0	0	No damage	Not reported.	M = 3.6	IGN (2020)
Earthquake 1977	3 November, 1977	E of San Miguel de Tajao, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	San Miguel de Tajao	0	0	0	No damage	Not reported.	M = 4.3	Diario de Avisos (3 November, 1977) IGN (2020)
Earthquake 1977	18 July, 1977	SE of Candelaria, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Santa Cruz, Güímar, La Orotava, Santa Úrsula, Izaña	0	0	0	No damage	Not reported.	M = 4.2 Maximum intensity calculated (epicentral) = 4.4	IGN (2020)
Earthquake 1971	5 January, 1971	N of Izaña Observatory(Güímar Valley)	Seismic shock	Los Realejos, Fasnia, Güimar	0	0	0	No damage	Not reported.	M = 3.5 Maximum intensity calculated (epicentral) = 4.0	El Eco de Canarias (6 January, 1971) IGN (2020)
Earthquake 1966	28 May, 1966	S of El Médano, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	El Médano	0	0	0	No damage	Not reported.	M = 4.8	IGN (2020)
Earthquake 1964	22 May, 1964	W of Tasarte Beach, Atlantic Zone Tenerife - Gran Canaria	Seismic shock Aftershock	Santa Cruz de Tenerife, Tacoronte, Adeje	0	0	0	No damage	Not reported.	M = 4.7	El Eco de Canarias (22 May, 1964) IGN (2020)
Earthquake 1964	22 May, 1964	W of Taurito, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Santa Cruz de Tenerife, Tacoronte, Adeje	0	0	0	No damage	Not reported.	M = 4.5 Maximum intensity calculated (epicentral) = 5.2	El Eco de Canarias (22 May, 1964) IGN (2020)
Earthquake 1962	6 December, 1962	Tacoronte	Seismic shock	Tacoronte	0	Not reported.	Not reported.	No damage	Not reported.	M = 3.8 Maximum intensity calculated (epicentral) = 4.5	IGN (2020)
Earthquake 1950	23 February, 1950	W of Fasnia, Atlantic Zone Tenerife - Gran	2 seismic shocks	Santa Cruz de Tenerife (also in Gran Canaria	0	Not reported.	Not reported.	No damage	Not reported.	M = 3.9 Maximum intensity calculated (epicentral) = 4.7	Falange: Diario de la tarde (25 February, 1950)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
		Canaria		Island)							IGN (2020)
Earthquake 1947	7 May, 1947	E of Santa Cruz de Tenerife, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Many parts around the island of Tenerife	0	Not reported.	Not reported.	No damage	Not reported.	M = 4.7 Maximum intensity calculated (epicentral) = 5.9	Falange: Diario de la tarde (8 May, 1947) IGN (2020)
Earthquake 1947	23 January, 1947	W of Puertito de Güimar, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Santa Cruz de Tenerife and La Laguna (also in Gran Canaria Island)	0	Not reported.	Not reported.	No damage	Not reported.	M = 4.4 Maximum intensity calculated (epicentral) = 5.5	IGN (2020)
Earthquake 1947	23 January, 1947	W of Puertito de Güimar, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Santa Cruz de Tenerife and La Laguna (also in Gran Canaria Island)	0	Not reported.	Not reported.	No damage	Not reported.	M = 4.3 Maximum intensity calculated (epicentral) = 5.3	IGN (2020)
Earthquake 1937	7 July, 1937	Teno Lighthouse	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.1 Maximum intensity calculated (epicentral) = 5.0	IGN (2020)
Earthquake 1937	21 June, 1937	NE of Garachico, Icod Valley	Seismic mainshock Aftershocks Rock fall	Garachico	0	0 (some people suffered syncope due to the shock)	Not reported.	No damage	Not reported.	M = 4.6 Maximum intensity calculated (epicentral) = 5.8	Gaceta de Tenerife (22 June, 1937) IGN (2020)
Earthquake 1935	7 December, 1935	SE of San Miguel de Tajao, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.7 Maximum intensity calculated (epicentral) = 6.2	IGN (2020)
Earthquake 1935	13 November, 1935	N of Gran Canaria, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 3.8 Maximum intensity calculated (epicentral) = 4.5	IGN (2020)
Earthquake 1930	13 December, 1930	SW of Puerto de la Cruz, La Orotava Valley	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 3.5 Maximum intensity calculated (epicentral) = 4.0	Galbis (1940) IGN (2020)
Earthquake 1930	11 December, 1930	SW of Puerto de la Cruz, La Orotava Valley	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 3.5 Maximum intensity calculated (epicentral) = 4.0	Galbis (1940) IGN (2020)
Earthquake 1927	15 May, 1927	E of Santa Cruz de Tenerife, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Santa Cruz de Tenerife	0	0	0	No damage	Not reported.	M = 4.7 Maximum intensity calculated (epicentral) = 6.0	El Progreso (16 May, 1927) Galbis (1940) IGN (2020)
Earthquake 1926	16 August, 1926	NW of Izaña Observatory, Güímar Valley	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.9 Maximum intensity calculated (epicentral) = 6.3	Galbis (1940) IGN (2020)
Earthquake 1926	3 June, 1926	NW of Izaña Observatory, Güímar Valley	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.5 Maximum intensity calculated (epicentral) = 5.7	Galbis (1940) IGN (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Earthquake 1911	22 December, 1911	W of Güímar, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Earthquake was felt in many parts of the island of Tenerife, but especially in Güímar, Santa Cruz de Tenerife, San Cristóbal de La Laguna and La Orotava	0	0	0	No damage	Not reported.	M = 5.1 Maximum intensity calculated (epicentral) = 6.6 The earthquake was accompanied by underground noise	El Progreso (23 December, 1911) Galbis (1940) IGN (2020)
Earthquake 1910	15 March, 1910	Chinyero Volcano, Icod Valley	Seismic shocks after the eruption	Earthquake was felt in Icod de los Vinos and La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.8 Maximum intensity calculated (epicentral) = 6.1	Galbis (1940) IGN (2020)
Earthquake 1909	4 December, 1909	Chinyero Volcano, Icod Valley	Seismic shocks after the eruption	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.5 Maximum intensity calculated (epicentral) = 5.6	Galbis (1940) IGN (2020)
Earthquake 1909	21 November, 1909	Chinyero Volcano, Icod Valley	Seismic shocks after the eruption	Earthquake was felt in Vilaflor	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.5 Maximum intensity calculated (epicentral) = 7.2	Galbis (1940) IGN (2020)
Earthquake 1909	19 November, 1909	Chinyero Volcano, Icod Valley	Seismic shocks after the eruption	Earthquake was felt in the surrounding villages, especially in the Icod Valley and around the Chinyero volcano	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.4 Maximum intensity calculated (epicentral) = 7.0	Galbis (1940) IGN (2020)
Earthquake 1909	15 November, 1909	S of Garachico, Icod Valley	Seismic shock	Earthquake was felt in many parts of the island of Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.3 Maximum intensity calculated (epicentral) = 5.4	Galbis (1940) IGN (2020)
Earthquake 1909	14 November, 1909	S of Garachico, Icod Valley	Seismic shock	Earthquake was felt in many parts of the island of Tenerife, but especially in La Orotava, Santa Cruz de Tenerife, Santiago del Teide and Icod de los Vinos	0	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.5 Maximum intensity calculated (epicentral) = 7.3	Galbis (1940) IGN (2020)
Earthquake 1909	14 November, 1909	S of Garachico, Icod Valley	Seismic shock	Earthquake was felt in many parts of the island of Tenerife, but especially in La Orotava, Santa Cruz de Tenerife, Santiago del Teide and Icod de los Vinos	0	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.0 Maximum intensity calculated (epicentral) = 6.3	Galbis (1940) IGN (2020)
Earthquake 1909	14 November, 1909	S of Garachico, Icod Valley	Seismic shock	Earthquake was felt in many parts of the island of Tenerife, but especially in La Orotava, Santa	0	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.6 Maximum intensity calculated (epicentral) = 5.8	Galbis (1940) IGN (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				Cruz de Tenerife, Santiago del Teide and Icod de los Vinos							
Earthquake 1909	23 September, 1909	S of Garachico, Icod Valley	Seismic shock	Earthquake was felt in La Paz (La Orotava)	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.9 Maximum intensity calculated (epicentral) = 5.3	Galbis (1940) IGN (2020)
Earthquake 1909	19 June, 1909	S of Garachico, Icod Valley	Seismic shock	Earthquake was felt in La Orotava and Icod de los Vinos	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.2[1ci] Maximum intensity calculated (epicentral) = 6.7	Galbis (1940) IGN (2020)
Earthquake 1909	25 May, 1909	S of Garachico, Icod Valley	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.1 Maximum intensity calculated (epicentral) = 6.6	Galbis (1940) IGN (2020)
Earthquake 1909	12 January, 1909	W of Agaete (Gran Canaria), Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.3 Maximum intensity calculated (epicentral) = 5.4	Galbis (1940) IGN (2020)
Earthquake 1909	5 January, 1909	W of Agaete (Gran Canaria), Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Earthquake was felt in the port of La Orotava	Not reported.	Not reported.	Not reported.	Minor damages, only falling objects.	Not reported.	M = 5.4 Maximum intensity calculated (epicentral) = 7.0	Galbis (1940) IGN (2020)
Earthquake 1909	5 January, 1909	W of Agaete (Gran Canaria), Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Earthquake was felt in the port of La Orotava	Not reported.	Not reported.	Not reported.	Minor damages, only falling objects.	Not reported.	M = 5.5 Maximum intensity calculated (epicentral) = 7.3	Galbis (1940) IGN (2020)
Earthquake 1909	5 January, 1909	Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Earthquake was felt in the port of La Orotava	Not reported.	Not reported.	Not reported.	Minor damages, only falling objects.	Not reported.	M = 3.7 Maximum intensity calculated (epicentral) = 4.4	Galbis (1940) IGN (2020)
Earthquake 1909	5 January, 1909	SE of Santa Cruz de Tenerife, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Earthquake was felt in the port of La Orotava	Not reported.	Not reported.	Not reported.	Minor damages, only falling objects.	Not reported.	M = 4.7 Maximum intensity calculated (epicentral) = 6.0	Galbis (1940) IGN (2020)
Earthquake 1909	4 January, 1909	SE of Santa Cruz de Tenerife, Atlantic Zone Tenerife - Gran Canaria	Seismic shock	Earthquake was felt in the port of La Orotava, Santa Cruz de Tenerife, San Cristóbal de La Laguna, Los Realejos, La Matanza de Acentejo	0	0	0	Minor damages, only falling objects.	Not reported.	M = 4.5 Maximum intensity calculated (epicentral) = 5.7	El Progreso (5 January, 1909) Galbis (1940) IGN (2020)
Earthquake 1908	19 December, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in Puerto de la Cruz	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.8 Maximum intensity calculated (epicentral) = 6.1	Galbis (1940) IGN (2020)
Earthquake 1908	19 December, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.8 Maximum intensity calculated (epicentral) = 6.1	Galbis (1940) IGN (2020)
Earthquake	19	S of Cueva del	Seismic shock	Earthquake was	Not	Not	Not reported.	Not reported.	Not reported.	M = 4.8	Galbis (1940)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
1908	December, 1908	Viento, Icod Valley		felt in Puerto de la Cruz	reported.	reported.				Maximum intensity calculated (epicentral) = 6.1	IGN (2020)
Earthquake 1908	8 December, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in the east flank of Mt Teide	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.8 Maximum intensity calculated (epicentral) = 6.1	Galbis (1940) IGN (2020)
Earthquake 1908	24 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 3.8 Maximum intensity calculated (epicentral) = 4.5	Galbis (1940) IGN (2020)
Earthquake 1908	18 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 5.2 Maximum intensity calculated (epicentral) = 6.8	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	18 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 4.2 Maximum intensity calculated (epicentral) = 5.1	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	18 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 3.5 Maximum intensity calculated (epicentral) = 4.1	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	18 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 4.8 Maximum intensity calculated (epicentral) = 6.1	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	18 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 4.8 Maximum intensity calculated (epicentral) = 6.1	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	18 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 4.7 Maximum intensity calculated (epicentral) = 6.0 It is said that there was an underground noise	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	18 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 4.2 Maximum intensity calculated (epicentral) = 5.1	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	17 November, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava Valley	0	0	0	No damage	Not reported.	M = 4.7 Maximum intensity calculated (epicentral) = 6.0	El Progreso (19 November, 1908) Galbis (1940) IGN (2020)
Earthquake 1908	9 September, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Undetermined	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 3.5 Maximum intensity calculated (epicentral) = 4.0	Galbis (1940) IGN (2020)
Earthquake 1908	28 July, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	Undetermined magnitude, but it is said that it was felt with less intensity than previous ones	Galbis (1940) IGN (2020)
Earthquake 1908	28 July, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	Undetermined magnitude, but it is said that it was felt with less intensity than previous ones	Galbis (1940) IGN (2020)
Earthquake 1908	28 July, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in many parts of the island of Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	Undetermined magnitude, but it is said that a violent jolt was felt with less intensity than previous one	Galbis (1940) IGN (2020)
Earthquake 1908	28 July, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in many parts of the island of Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	Undetermined magnitude, but it is said that a violent jolt was felt	Galbis (1940) IGN (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Earthquake 1908	27 July, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.4 Maximum intensity calculated (epicentral) = 7.1	Galbis (1940) IGN (2020)
Earthquake 1908	27 July, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.2 Maximum intensity calculated (epicentral) = 5.1	Galbis (1940) IGN (2020)
Earthquake 1908	26 March, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.8 Maximum intensity calculated (epicentral) = 6.1	Galbis (1940) IGN (2020)
Earthquake 1908	26 March, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.2 Maximum intensity calculated (epicentral) = 5.1	Galbis (1940) IGN (2020)
Earthquake 1908	23 March, 1908	S of Cueva del Viento, Icod Valley	Seismic shock	Earthquake was felt in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 3.5 Maximum intensity calculated (epicentral) = 4.1	Galbis (1940) IGN (2020)
Earthquake 1900	2 September, 1900	S of La Orotava, La Orotava Valley	Seismic shock	Earthquake was felt in many parts of the island of Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 3.6 Maximum intensity calculated (epicentral) = 4.3	Galbis (1940) IGN (2020)
Earthquake 1798	11 June, 1798	Chaorra Volcano	Seismic shocks during eruption	Earthquake was felt in all the surrounding villages, especially in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.0 Maximum intensity calculated (epicentral) = 4.9	Rodríguez (2016) IGN (2020)
Earthquake swarm 1798	9 June, 1798	Chaorra Volcano	Seismic shocks prior to eruption Aperture of fractures Volcanic eruption	Earthquakes were felt in all the surrounding villages, especially in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.0 Maximum intensity calculated (epicentral) = 6.4	Rodríguez (2016) IGN (2020)
Earthquake 1797	1 May, 1797	NW of Vilaflor	Seismic shocks prior to eruption	Earthquake was felt in all the surrounding villages, especially in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.3 Maximum intensity calculated (epicentral) = 5.4	Rodríguez (2016) IGN (2020)
Earthquake 1797	1 May, 1797	NW of Vilaflor	Seismic shocks prior to eruption	Earthquake was felt in all the surrounding villages, especially in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 4.3 Maximum intensity calculated (epicentral) = 5.4	Rodríguez (2016) IGN (2020)
Earthquake 1797	30 April, 1797	NW of Vilaflor	Seismic shocks prior to eruption	Earthquake was felt in all the surrounding villages, especially in La Orotava	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	M = 5.0 Maximum intensity calculated (epicentral) = 6.4	Rodríguez (2016) IGN (2020)
Earthquake 1730	1 September, 1730	Undetermined	Seismic shock	Earthquakes were felt in some parts of the island of Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	The chronicles of the time say that these tremors were due to the eruption that began in Lanzarote, however, it is not believed that they are related, but that the eruption coincided with a seismic crisis on the island of Tenerife.	Cólogan (Manuscript) IGN (2020)
Earthquake swarm	4 to 5 May, 1706	Garachico Volcano, Icod	Seismic shocks prior to eruption	Earthquakes were felt in all the	Not reported.	Not reported.	Not counted but reported.	Not reported.	Not reported.	The most intense earthquakes had a M = 5.4 - 6.1	Romero (1990) Romero &

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
1706		Valley	Aperture of fractures Volcanic eruption	surrounding villages, especially in Garachico						Maximum intensity calculated (epicentral) = 7.0 - 7.5	Beltrán (2007) IGN (2020)
Earthquake swarm 1705	30 January to 4 February, 1705	Arafo Volcano, Güímar Valley	Seismic shocks prior to eruption Rock fall Aperture of fractures Increase in the flow of some affected rivers Volcanic eruption	Earthquakes were felt in all the surrounding villages, especially in La Orotava valley and Güímar Valley	Not reported.	Not counted but reported.	Not counted but reported.	General damages to houses and buildings. On February 2, the tremors dislodged the timbers of the Church. Collapses in the churches.	Prayers, penances and processions continue, images are taken out of the churches, people are housed in straw huts.	The most intense earthquakes had a M = 5.4 - 6.3 Maximum intensity calculated (epicentral) = 7.0 - 7.5	Romero (1990) IGN (2020)
Earthquake swarm 1705	5 January to 29 January, 1705	Fasnia Volcano, Güímar Valley	Seismic shocks prior to eruption Rock fall Aperture of fractures Increase in the flow of some affected rivers Volcanic eruption Seismic shocks after the eruption	Earthquakes were felt in all the surrounding villages, especially in La Orotava valley and Güímar Valley	Not reported.	Not counted but reported.	Not counted but reported.	Destruction and severe damage to some houses in La Orotava Valley. A canvas fell from the wall of the Church of San Juan. On January 27, 70 houses were destroyed and the rest seriously damaged in Güímar. On the 29th the houses that remained standing were also demolished.	Prayers and confessions continue, crying out for forgiveness. License was given to all Priests who were not Confessors so that they could give confession, public penitences, Processions and Rogations increased. The Blessed Virgin was transferred to San Cristobal de La Laguna. Eviction of houses. The Mayor obliged a group of neighbors to go around the streets to watch over the houses that had been evicted so as not to suffer more robberies.	The most intense earthquakes had a M = 5.6 - 6.3 Maximum intensity calculated (epicentral) = 7.4 - 8.2	Romero (1990) IGN (2020)
Earthquake swarm 1704 - 1705	24 December, 1704 to 4 January, 1705	Siete Fuentes Volcano, Güímar Valley	Seismic shocks prior to eruption Rock fall Volcanic eruption	Earthquakes were felt in all the surrounding villages, especially in La Orotava, the Güímar Valley, Puerto de la Cruz, Los Realejos, Candelaria, Arafo	Not reported.	Not reported.	Not counted but reported.	Movement of buildings, creaking timbers of houses. With the strongest tremors, the timbers of some churches were dislocated and some pieces of walls collapsed.	The inhabitants evacuated their houses, placed several Altars in the fields with the main Devotional Images to pray and ask for help. On the 28th, when the tremors were greater, they increased the prayers and took out the Blessed Sacrament. The Religious Communities presided by the Illustrious Bishop, formed penitents and Processions. Priests went to hear confessions, others went up to the mountains to exorcise. Many people who left their homes wandered the streets because they had nowhere to go, and many others did not know what to do or decide what the wisest course of action was. Later, thatched huts were built in the courtyards and orchards to house the evictees.	The most intense earthquakes had a M = 5.4 - 6.3 Maximum intensity calculated (epicentral) = 7.3 - 7.8	Romero (1990) IGN (2020)
FLOODING											
Flooding 2020	3 December, 2020	Many parts of the island of Tenerife	Storm Strong winds Heavy swell Torrential rains Landslides Flash floods Overflow Flooding	Santa Cruz de Tenerife, San Cristóbal de La Laguna	0	Not reported.	Not reported.	Sewer overflow. Floods and general damages in streets, houses, buildings and infrastructures in the affected municipalities. Delays on the roads. Dragging of material from sewage works on the roadway.	The Security and Emergencies area of the Government of the Canary Islands uses Twitter to warn the population to take precautions. Many of the minor incidents were resolved throughout the day and over the next few days.	None.	Tenerife Ahora (3 December, 2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Flooding 2020	26 November, 2020	Many parts of the island of Tenerife	Storm Strong winds Heavy swell Torrential rains Landslides Flash floods Overflow Flooding	Santa Cruz de Tenerife, San Cristóbal de La Laguna	0	Not reported.	Not reported.	Floods in streets, houses and buildings in the affected areas, mainly due to problems with the sewage system in Santa Cruz de Tenerife and San Cristóbal de La Laguna. Damage on the Igueste San Andrés road and on the San Andrés road between Santa Cruz de Tenerife and Las Teresitas, due to two landslides. Road closures. Electrical failures, many due to the fall of public lighting poles. Damage to vehicles washed away by water and falling trees. Falling trees.	The Government of the Canary Islands, following warnings from the State Meteorological Agency (Aemet), activated the alert for rain, wind and waves. The municipalities of Santa Cruz de Tenerife and San Cristóbal de La Laguna activated the Municipal Emergency Plan (PEMU) as of 7 a.m. From this plan, the Local Operational Coordination Center (CECOPAL), part of Civil Protection, began to act in both municipalities. Action together with the Local Police to clear the roads of landslides and resolve several incidents. Suspension of the events planned for that day. Many of the minor incidents were resolved throughout the day and over the next few days.	9.7 l/m2 accumulated in one hour in La Laguna.	Tenerife Ahora (26 November, 2020)
Flooding 2020	20 October, 2020	Many parts of the island of Tenerife	Storm Strong winds Torrential rains Flash floods Flooding	Icod, Tacoronte, Puerto de la Cruz, La Orotava, Arona, Adeje, San Cristóbal de La Laguna	0	Not reported.	Not reported.	Minor flooding in several affected municipalities. Traffic cuts, traffic jams, accidents. Air traffic problems. Damage to cars. Falling stone walls. The sewerage system was not able to cope with the volume of water, causing manhole covers to burst. Dumping of sewage. Falling trees.	Not reported.	None.	CTQ (21 October, 2020)
Flooding 2018	18 November, 2018	Many parts of the island of Tenerife	Storm Heavy swell Torrential rains Flash floods Overflow Flooding	Garachico, Tacoronte, Adeje, Puerto de la Cruz	0	Not reported.	At least 39 in Garachico. Other evacuations reported in other municipalities.	Flooding and general damage to streets, homes, buildings and infrastructure. Damage to buildings on the seafront due to waves. Traffic interruptions.	The special flood plan was activated.	The waves in Garachico broke the balcony of a third floor of a building on the seafront. The waves reached in some points in the north, more than 6 meters high.	Agencias (19 November, 2018) Acosta (2019)
Flooding 2016	4 and 5 November, 2016	N and NE of Tenerife	Storm/Thundersto rm Hail Maritime storm Small tornado at sea Heavy swell Torrential rains Rock falls Flash floods (sediment-laden) Overflow Flooding	San Cristóbal de La Laguna, Santa Cruz de Tenerife, Las Mercedes, Jardina, Tegueste, San Andrés, Las Gaviotas, Taganana, Tacoronte, El Sauzal, El Rosario	0	Not reported.	Not reported.	Flooding and general damage to streets, houses, buildings and infrastructure in the affected areas. Power outages. Road outages. Difficulty of circulation on roads, as in the TF-5 at the height of La Laguna - Los Rodeos, and in the TF-13 in the Vía de Ronda de La Laguna.	The State Meteorological Agency (Aemet) activated the orange alert during the afternoon of November 4, which was later downgraded to yellow the following day. Then, the General Directorate of Security and Emergencies of the Canary Islands Government activated the pre-alert for rains in Tenerife. Finally, the rainfall alert situation was declared during the afternoon of the 5th but returned to the pre-alert situation at 19:30 pm. The City Council of Santa Cruz de Tenerife requested caution via Twitter.	Rainfall data registered until 8 p.m. of 5th November: La Victoria de Acentejo = 64.2 l/m^2 La Orotava = 93 l/m^2 Aeropuerto de Tenerife Norte (until 8:30 p.m.) = 49.2 l/m^2 La Laguna = 21.3 l/m^2	El Mundo (5 November, 2016) Ginovés & Castellano (6 November, 2016)
Flooding 2016	19 February, 2016	N and NE of Tenerife	Storm Snow Hail Strong winds Heavy swell Torrential rains Rock falls Flash floods (sediment-laden) Overflow Flooding	Santa Cruz de Tenerife, La Orotava Valley, La Victoria, Puerto de la Cruz, Icod de los Vinos, Los Realejos, San Cristóbal de La Laguna, San Andrés, Anaga, Candelaria	0	Not counted but reported due to multiple traffic accidents.	Not reported.	Flooding and general damage to streets, houses, buildings and infrastructure in the affected areas. Traffic accidents. Falling branches and walls. Road closures. Damage to vehicles. Severe damage and destruction of some trees.	Firefighters' action to drain water and remove fallen trees. Unipol agents rescued an 11-month-old baby who was isolated in a house in the ravine of María Jiménez. In addition, Unipol also helped other isolated vehicles. Municipal agents required the intervention of firefighters from the Tenerife Consortium to repair the facade of a building and remove a damaged sign, among other actions. Many of the minor incidents were resolved throughout the day and over the next few days.	Rainfall data for 24 hours: Llano de Los Loros = 78.8 l/m^2 La Victoria de Acentejo = 61.2 l/m^2 Aeropuerto de Tenerife Norte = 39.5 l/m^2 Anaga = 37.6 l/m^2	Fumero et al. (19 February, 2016)
Flooding 2015	19 to 24 October, 2015	NE of Tenerife	Storm Strong winds Heavy swell	Santa Cruz de Tenerife	0	Not reported.	Not reported.	6,053,055 euros. Flooding and general damage to streets, houses, buildings and infrastructure in the affected areas. Damage	Firefighters, local police, mobility agents, civil protection and basic services personnel. In addition, the intervention of the State Security	None.	Jefatura del Estado (31 October, 2015)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
			Torrential rains Rock falls Flash floods Overflow Flooding					to the sewage system. Road closures due to falling rocks, trees and flooding. Damage to the port of Santa Cruz de Tenerife. Severe damage and destruction of some trees and crops.	Forces and Corps and the mobilization of the Military Emergency Unit were requested. On October 30, 2015, DECREE 352/2015, of October 28, 2015, on exceptional aid to families to mitigate the damage caused by the rains that fell in the Canary Islands archipelago from October 20 to 25, 2015, enters into force. On October 31 of the same year, Royal Decree-Law 12/2015, of October 30, comes into force, adopting urgent measures to repair the damages caused by rainstorms in the Autonomous Community of the Canary Islands and in the south and east of the peninsula in the months of September and October 2015. Many of the minor incidents were resolved throughout the day and over the next few days		Presidencia del Gobierno (30 October, 2015) López et al. (2018)
Flooding 2014	19 October, 2014	NE and E of Tenerife	Storm/Thunderstorm Heavy swell Torrential rains Landslides Fire Flash floods (sediment-laden) Overflow Flooding	Güímar Valley, Anaga, San Andrés, ravine of San Andrés, Barranco de Santos (ravine: Santa Cruz de Tenerife)	1	At least 2, due to a lightning strike on his vessel.	At least 3 people were rescued from a cave in Barranco de Santos.	7,423,819 euros in economic losses. However, 18 million euros were invested to alleviate damages and resolve many black spots. Flooding and general damage in the affected areas. In San Andres 15 vehicles and 20 homes were flooded. Three access tunnels to Santa Cruz de Tenerife were flooded. Cancellation of transport. Road closures. The University Hospital of the Canary Islands lost power supply at one point, affecting 4,000 people. Broken streets, trapped vehicles, falling walls, displacement of containers. Traffic accidents. Fire due to the fall of a ship moored in the Fishing Dock.	Some people were rescued. On October 28, 2014, DECREE 102/2014, of October 23, 2014, on exceptional aid for deaths and to families to mitigate the damages caused by the rains that fell on the island of Tenerife, on October 19, 2014. Minor incidents were resolved and most of the roads were reestablished during the following days.[1bn] Within 1 month in 2014, the emergency work to recharge the Las Teresitas (San Andres) beach with sand from El Aaiun in Morocco was completed. It should be noted that this beach is artificial, with white sand instead of black as in the rest of the island.	The storm, considered as a cold drop, discharged more than 6,500 lightning strikes. Rainfall data for 24 hours: María Jiménez = 151 l/m^2 La Cuesta = 147 l/m^2 Los Andenes - Taco = 142 l/m^2 La Gallega = 136 l/m^2 Santa Cruz de Tenerife = 140.6 l/m^2 Las Cañadas del Teide = 100 l/m^2 Candelaria = 83 l/m^2 Güímar = 79 l/m^2 Chío = 118 l/m^2 Valle de Güímar = 118 l/m^2 Taganana = 114 l/m^2 Majuelos = 111 l/m^2 Alcalá = 104 l/m^2	Ministerio para la Transición Ecológica y el Reto Demográfico (2014) Presidencia del Gobierno (28 October, 2014) Barquín (2015) Pérez (2016) Del Pino (19 October, 2020)
Flooding 2014	9 January, 2014	N of Tenerife	Storm Torrential rains Flash floods Overflow Flooding	La Orotava, Santa Cruz de Tenerife	0	Not reported.	Not reported.	Flooding and general damage in the affected areas. Traffic light outages. Overflowing of sewers. Damage to asphalt. Damage to many trees and probably destruction of some of them.	A rain and thunderstorm warning is declared. The risk level was raised to orange (high risk). The cleaning staff went to several points, such as the TF-12 at the height of El Bailadero, to clean and clear the road of mud and mud. The Local Police and the Guardia Civil acted in the García Escaméz-Chamberí tunnel due to the amount of water registered inside it. Local Police officers went to the neighborhood of María Jiménez due to the danger of collapse of a wall of an abandoned house. The CECOPAL (Municipal Operational Coordination Center) recommended to the population to avoid walking in wooded areas, next to walls of old houses, scaffolding, illuminated signs and billboards, and to stay away from beaches, promenades and piers to avoid being hit by the waves. Minor incidents were resolved and most of the roads were reestablished during the following days.	None.	García (9 January, 2014) Ministerio para la Transición Ecológica y el Reto Demográfico (2014) Rodríguez de la Cruz (2016)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Flooding 2013	9 to 11 December, 2013	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Storm Torrential rains Landslides Strong winds Heavy swell Flash floods (sediment-laden) Overflow Flooding	Municipalities from the NE and E of the island	0	At least 2 injured when a plane trying to land at Tenerife North Airport skidded off the runway.	Not counted but reported, specially people from the caves located along the Barranco de Santos (ravine; Santa Cruz de Tenerife)	1,378,395 euros. Flooding and general damages to the streets, buildings and infrastructures in the affected areas. Road closures. Power outage at traffic lights in Güímar. Multiple manhole covers burst. Cancellation of flights, suspension of maritime traffic. Telephone outages.	Tenerife was under red warning and maximum alert for two days. A wind alert and a maximum rainfall alert were declared. On the 12th at 13:30h, the PEFMA pre-alert situation for rains, storms, winds and coastal phenomena was activated. On the 10th at 3:00 p.m., school activities were suspended until the 12th. A person needed to be rescued from her car. On December 23, 2013, DECREE 118/2013, of December 19, 2013, on exceptional aid to mitigate the damages caused by the rain and wind storm that hit the islands of the Canary Islands from 9 to 12 December 2013, came into force. Minor incidents were resolved and most of the roads were reestablished during the same day or the following day.	Rainfall data for 24 hours: Tenerife South Airport = 108.6 l/m^2 Los Silos = 166 l/m^2 San Miguel de Abona = 168 l/m^2 Taucho = 149 l/m^2 Arona = 158 l/m^2 Tacoronte = 79 l/m^2 Santa Úrsula = 93.1 l/m^2 Garachico = 126 l/m^2 Puerto de la Cruz = 66 l/m^2 Los Realejos = 63 l/m^2 La Guancha = 98 l/m^2 Icod de los Vinos = 58.4 l/m^2 Anaga (station 1) = 105 l/m^2 Anaga (station 2) = 108.5 l/m^2 Izaña = 87.6 l/m^2 Adeje = 122.8 l/m^2 Arico = 122.8 l/m^2 Candelaria = 122.4 l/m^2 Las Mercedes = 74.8 l/m^2 San Andrés = 63.2 l/m^2 La Victoria = 62.2 l/m2 San Juan de la Rambla = 63.8 l/m2	Yáñez (2014) Barquín (2015) Pérez (2016) Rodríguez de la Cruz (2016)
Flooding 2013	2 December, 2013	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Storm/Thunderstorm Torrential rains Landslides Flash floods Overflow Flooding	Fasnia, Güímar, Arafo, Candelaria	0	Not reported.	Not reported.	726,439 euros. Flooding and general damages to the streets, buildings and infrastructures in the affected areas. Flight cancellations. Road closures. Power outages.	On the 2nd at 10:51 am (official time) the first orange warning was issued in the province of Santa Cruz de Tenerife and lasted until 10:00 pm. Some people needed to be evacuated and rescued. Classes and outdoor activities were suspended in several municipalities. On December 20, 2013, DECREE 115/2013, of December 5, 2013, on exceptional aid to mitigate the damages caused by the fire mitigate the damages caused by the fire that occurred in the municipality of La Vega de San Mateo on October 24 and by the rains in the Archipelago on December 2, 2013. Minor incidents were resolved and most of the roads were reestablished during the same day or the following day.	Between 0:00 and 17:00 55.1 l/m^2 was recorded at Tenerife North airport. Rainfall data for 24 hours: Lomo de Mena = 304 l/m^2 El Pinar de El Hierro = 213 l/m^2 Valverde = 196 l/m^2 Candelaria = 116 l/m^2 Güímar = 190 l/m^2 Frontera = 102 l/m^2 Arico = 170 l/m^2	Presidencia del Gobierno (20 December, 2013) Yáñez (2014) Pérez (2016) Rodríguez de la Cruz (2016)
Flooding 2013	3 November, 2013	S of Tenerife	Storm/Thunderstorm Torrential rains Snow Strong winds Heavy swell Waterspout Flash floods Flooding	Many municipalities from the south.	0	Not reported.	Not reported.	Flooding and general damages to the streets, buildings and infrastructures in the affected areas.	Not reported.	None.	Asociación Canaria de Meteorología (ACANMET) (2013b)
Flooding 2013	3 to 5 March, 2013	Some parts of the island of Tenerife, especially the south	Storm Thunderstorm Torrential rains Hail Strong winds Heavy swell Flooding	Puerto de La Cruz, Las Cañadas del Teide, Guía de Isora, Barranco Guía (ravine; Guía de Isora), El Médano, Los Cristianos, Güímar	0	Not reported.	Not reported.	In the coastal town of Playa San Juan alone, the damages exceed 100,000 euros. In Güímar, damages amounted to 15,000 euros. Flooding and general damages to the streets, buildings and some infrastructures in the affected cities. Flooding in coastal areas. Power outages. The port of Los Cristianos is inoperative. Closure of the TF-47 road due to the overflowing of a ravine. Fall of a fence on three parked cars in El Médano.	Classes are suspended at all educational levels. From the first day of the storm, the Cabildo sent road maintenance crews to several municipalities to clean and repair the roads. Minor incidents were resolved and most of the roads were reestablished during the same day or the following days.	138.4 l/m^2 were registered in Monte Breña and in Mazo and 102.2 l/m^2 in the Las Cañadas Parador. It is said that the overflowing of the Guía ravine was caused or favored by a fire last summer that affected the Chirche area, wiping out a vegetation cover that normally serves as a first brake on the water. In some garages in Guía de Isora, the	Asociación Canaria de Meteorología (ACANMET) (2013a) Europa Press (5 March, 2013) Feo (7 March, 2013) La Información (4

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
								Destruction or serious damage to the irrigation system of many farmers. Serious damage to the municipal piping system in Guía de Isora, interrupting the supply of drinking water to the town of Alcalá. Damage and destruction of some trees.		water reached a height of more than half a meter.	March, 2013) Pérez (2016)
Flooding 2012	24 and 25 December, 2012	N of Tenerife	Storm Torrential rains Flash floods Landslides Overflow Flooding	Los Realejos, Icod de los Vinos, La Orotava	0	Not reported.	Not reported.	Flooding and general damages to the streets and buildings in the affected cities. Road closures. Isolation of the Tigaiga neighborhood and water supply cut in a large part of the municipality of Los Realejos.	Not reported.	From 7 p.m to 10 p.m., 124 l/m^2 were registered in Los Realejos on 24 December. In La Orotava, 100 l/m^2 were registered and more than 70 l/m^2 in Icod.	Cabildo Insular de Tenerife (2004) Pérez (2016)
Flooding 2012	2 to 7 November, 2012	N of Tenerife, but it also affected other islands of the Archipelago	Storm Thunderstorm Torrential rains Snow Strong winds Landslides Flash floods (sediment-laden) Overflow Flooding	Puerto de La Cruz, Tacoronte, Taganana, El Sauzal, Los Realejos, Icod de los Vinos, San Cristóbal de La Laguna, Santa Cruz de Tenerife, San Andrés, San Juan de la Rambla, Anaga, Valle Brosque, Valle Crispín, Los Dos Barrancos, Barranco del Cercado (ravine; San Andrés)	0	Not reported.	Not reported.	Road closures, such as the TF-31 in Puerto de La Cruz at Km. 3.2, the TF-232 in La Laguna, the TF-31 at Km. 3,200, or the TF-235 in Tacoronte, or the closure of one lane on the TF-5 at El Sauzal or the TF-5 at Barranco de Ruiz at Km. 45, due to landslides and a fallen tree. Traffic delays. Damage to roads, especially in Anaga, due to landslides and overflowing of ravines. Other landslides in several cities and villages. Flooding of streets, houses, buildings. Traffic accidents. Water supply cuts. Damage to a vehicle in Santa Cruz de Tenerife due to the fall of a tree branch. Damage and destruction of some trees.	The CEO of Security and Emergencies of the Government of the Canary Islands, based on the forecast of the State Meteorological Agency (AEMET), declared a yellow alert for rainfall in Tenerife. The regional Executive applied the Specific Emergency Plan of the Canary Islands for Risks of Adverse Meteorological Phenomena (PEFMA). Suspension of extracurricular activities, sports and cultural events planned in Santa Cruz de Tenerife, San Cristóbal de La Laguna and Los Silos from 15h on the 6th. Road crews of the Cabildo de Tenerife worked during the 7th to reestablish the affected roads. The Firefighters Consortium also acted in houses flooded by water. All the municipal services together with the Road Maintenance teams worked from the early morning of the 6th to reestablish the traffic in Anaga. The presence of the Local Police, the Forestry Unit, the Civil Protection Volunteers Group, the technical services and the cleaning and water supply concessionary companies was reinforced in the affected areas. Firefighters intervened to drain water from garages, houses, stores, ravines, roads, public roads and for the removal of stones, debris and fallen trees. Minor incidents were resolved and most of the roads were reestablished during the same day or the following day.	Water reached a height of 35 cm in the Plaza del Charco (Puerto de la Cruz) due to the accumulation of debris that clogged some drains.[1ay] Puerto de la Cruz reached 112.4 l/m^2.	EFE (7 November, 2012a) EFE (7 November, 2012b) El Día (7 November, 2012a) El Día (7 November, 2012b) Europa Press (7 November, 2012a) Europa Press (7 November, 2012b) Europa Press (7 November, 2012c)
Flooding 2010	9 and 10 October, 2010	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Maritime storm Strong winds Heavy swell Torrential rains Flooding	Buenavista del Norte, Garachico, San Cristóbal de La Laguna, Los Silos	0	Not reported.	Not reported.	190,293.85 euros as indemnification by the Insurance Compensation Consortium. General damage to houses, buildings, infrastructure and streets in the affected areas. Damage to the road TF-42 from Km. 0 to 7.5 and damage to the breakwater at the port of Garachico.	Not reported.	None.	Dirección General de Protección Civil (2014)
Flooding 2010	17 and 18 February, 2010	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Storm Maritime storm Strong winds Heavy swell Torrential rains Flash floods Flooding	Arona, Granadilla de Abona, Puerto de la Cruz, San Cristóbal de La Laguna, Santa Cruz de Tenerife, Santa Úrsula	0	Not reported.	Not reported.	18,539.72 euros as indemnification by the Insurance Compensation Consortium. General damage to houses, buildings, infrastructure and streets in the affected areas. Damage to road TF-66 in Arona in Km. 5.5. Flight delays. 900,000 people in Tenerife were left without electricity supply. Probably agricultural losses. Damage to crops and trees.	A yellow alert was decreed, which later changed to orange throughout the archipelago. In view of the storm forecast, school and university classes were suspended throughout the island of Tenerife. On March 3, 2010, Decree 21/2010, of February 25, 2010, came into force, approving urgent and exceptional aid and measures to repair the damage caused by the storm in the Archipelago from February 15 to 18, 2010. On March 11, 2010, Law	Rainfall data (for 24 hours on 17 February): Los Baldíos = 161.2 l/m^2 El Rosario-Los Baldíos = 161.2 l/m^2 El Frontón = 117.1 l/m^2 Vilaflor-El Frontón = 117.1 l/m^2 Aripe = 91.9 l/m^2 Guía Isora-Aripe-Llanitos = 91.9 l/m^2 El Bueno = 86.1 l/m^2 Arico-El Bueno (Los Helechos) = 86.1	Consejería de Empleo, Industria y Comercio (13 May, 2010) Jefatura del Estado (11 March, 2010) Ministerio de la Presidencia (23 March, 2010)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
									3/2010, of March 10, came into force, approving urgent measures to alleviate the damage caused by forest fires and other natural disasters in several Autonomous Communities. On March 23, 2010, Royal Decree 344/2010, of March 19, 2010, was published, extending the scope of application of Law 3/2010, of March 10, 2010. On April 24, 2010, ORDER TER/1005/2010, of April 22, 2010, on the procedure for granting subsidies to alleviate the damage caused by forest fires and other natural disasters in several Autonomous Communities came into force. On May 7, 2010, the ORDER TIN/1162/2010, of May 4, 2010, came into force, by which rules are issued for the application of the provisions of Article 9 of Law 3/2010, of March 10. On May 13, 2010, the ORDER of May 4, 2010 was approved, by which the bases were approved and the granting of aids was summoned to repair the damages caused to vehicles and to businessmen or professionals (excluding agriculture and tourism), in the Archipelago, due to the events of November and December 2009, and the events of February 2010. On July 31, 2010, the ORDER VIV/2078/2010, of July 21, 2010 which establishes the conditions, requirements and procedure applicable to the granting of the exceptional subsidies in the field of housing, for the housing subsidies to repair the damage caused by forest fires and other disasters occurred in several Autonomous Communities, under Autonomous Communities, under Law 3/2010, of March 10. On November 19, 2010, Decree 231/2010, of November 11, 2010, which amends some articles of Decree 21/2010, of February 25, 2010, was published. On July 20, 2011, the ORDER of July 8, 2011 came into force, establishing the financing of the aids approved in the ORDER VIV/2078/2010, of July 21.	l/m^2 Añavingo = 75.6 l/m^2 Arafo-Añavingo = 75.6 l/m^2 Chío = 70.0 l/m^2 Guía de Isora-Chío = 70.0 l/m^2 La Orotava-La Perdoma Ratiño = 65.4 l/m^2 La Orotava - La Perdoma Ratiño = 65.4 l/m^2 El Tanque - Ruigómez - Gª Cubo = 54.0 l/m^2 Icod Vinos - Redondo = 52.5 l/m^2	Ministerio de Medio Ambiente, y Medio Rural y Marino (2010) Ministerio de Política Territorial (24 April, 2010) Ministerio de Trabajo e Inmigración (7 May, 2010) Ministerio de Vivienda (31 July, 2010) Presidencia del Gobierno (19 November, 2010) Presidencia del Gobierno (3 March, 2010) Consejería de Empleo, Industria y Comercio (20 July, 2011) Dirección General de Protección Civil (2014) Pérez (2016) Agencia Estatal de Meteorología (2021)
Flooding 2010	1 and 2 February, 2010	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Storm/Thunderstorm Maritime storm Heavy swell Torrential rains Landslides Flash floods (sediment-laden) Overflow Flooding	Adeje, Anaga, Arafo, Arico, Arona, Buenavista del Norte, Candelaria, Fasnia, Granadilla de Abona, Guía de Isora, Güímar, Icod de los Vinos, La Orotava, Los Realejos, El Rosario, San Cristóbal de La Laguna, San Juan de la Rambla, San Miguel de Abona, Santa Cruz de Tenerife, Santiago	0	Not counted but reported.	Not counted but reported.	15,440,190.75 euros as indemnification by the Insurance Compensation Consortium and 348,822.24 euros subsidized. General damages and flooding of buildings, houses, cars and other infrastructures. Road closures. Power outages. Suspension of bus and streetcar public transportation. Difficulties in the docking of ships in the port of the south of Tenerife. Agricultural losses. Many gardens and crops were destroyed or severely damaged.	The intervention of the UME (Military Emergency Unit) was requested and the CECOPI (operational coordination center) was formed. The Sports Pavilion of Santa Cruz de Tenerife was set up as a temporary shelter for people evicted in some neighborhoods due to damage to their homes. On February 9, Decree 12/2010, of February 4, 2010, on urgent and exceptional aid and measures to repair the damage caused by the rains in the Archipelago on January 31 and February 1 and 2, 2010, came into force. On March 11, 2010, Law 3/2010, of March 10, came into force, approving urgent measures to alleviate the damage caused by forest fires and other natural disasters in several Autonomous Communities. On March 23, 2010, Royal Decree 344/2010, of March 19, 2010, was published, extending the	Rainfall data (for 24 hours): Rodeos - Tenerife Norte Airport (18/02/2010)= 126.0 l/m^2 Topo Negro (01/02/2010) = 217.8 l/m^2 Barranco Badajoz (01/02/2010) = 227.1 l/m^2 Añavingo (01/02/2010) = 156.3 l/m^2 Izaña (01/02/2010) = 143.0 l/m^2 Barranco Puente (01/02/2010) = 131.6 l/m^2 El Bueno (01/02/2010) = 167.3 l/m^2 Aripe (01/02/2010) = 105.3 l/m^2 Ruigómez (01/02/2010) = 105.9 l/m^2 El Bueno (02/02/2010) = 80.4 l/m^2 Aripe (02/02/2010) = 61.4 l/m^2	Cabildo Insular de Tenerife (2004) Jefatura del Estado (11 March, 2010) Ministerio de Política Territorial (24 April, 2010) Ministerio de la Presidencia (23 March, 2010) Ministerio de Trabajo e Inmigración (7 May, 2010) Ministerio de Vivienda (31 July, 2010)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				del Teide, Los Silos, Tacoronte, Tegueste, La Victoria de Acentejo, Barranco de Valleseco (ravine; Valleseco), Barranco del Hierro (ravine; Santa Cruz de Tenerife), Barranco de La Leña (ravine; Santa Cruz de Tenerife), Barranco de Casalón (ravine; specific location unknown), Barranco del Aceite (ravine; Santa Cruz de Tenerife), Barranco de Santos (ravine; Santa Cruz de Tenerife), Barranco del Bufadero (ravine; NE of Valleseco), Barranco de Los Pocitos (ravine; between Añaza and Acorán), Barranco Valle Grande (ravine; SW of Valle Crispín), Barranco de Valle Brosque (ravine; NE of Valle Crispín)					scope of application of Law 3/2010, of March 10, 2010. On April 24, 2010, ORDER TER/1005/2010, of April 22, 2010, on the procedure for granting subsidies to alleviate the damage caused by forest fires and other natural disasters in several Autonomous Communities came into force. On April 26, 2010, the ORDER of April 12, 2010 came into force, by which aids are called for the repair of direct material damages caused to tourist, hotel and catering establishments, as well as to tourist infrastructures in municipal ownership, as a consequence of the rains that occurred in the Archipelago on January 31 and February 1 and 2, 2010. On May 7, 2010, the ORDER TIN/1162/2010, of May 4, 2010, came into force, by which rules are issued for the application of the provisions of Article 9 of Law 3/2010, of March 10. On May 13, 2010, the ORDER of May 4, 2010 was approved, by which the bases were approved and the granting of aids was summoned to repair the damages caused to vehicles and to businessmen or professionals (excluding agriculture and tourism), in the Archipelago, due to the events of November and December 2009, and the events of February 2010. On July 31, 2010, the ORDER VIV/2078/2010, of July 21, 2010 which establishes the conditions, requirements and procedure applicable to the granting of the exceptional subsidies in the field of housing, for the housing subsidies to repair the damage caused by forest fires and other disasters occurred in several Autonomous Communities, under Autonomous Communities, under Law 3/2010, of March 10. On July 20, 2011, the ORDER of July 8, 2011 came into force, establishing the financing of these last aids.		Presidencia del Gobierno (9 February, 2010 Ayuntamiento de La Villa de La Orotava (2011) Dirección General de Protección Civil (2014) Ayuntamiento de Santa Cruz de Tenerife (2015) Barquín (2015) Rodríguez de la Cruz (2016) Consejo Insular de Aguas de Tenerife (2019) Agencia Estatal de Meteorología (2021)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Flooding 2009	22 and 23 December, 2009	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Storm Maritime storm Heavy swell Torrential rains Flash floods Flooding	Buenavista del Norte, Icod de los Vinos, Santa Cruz de Tenerife, El Tanque, El Sauzal	0	Not reported.	Not reported.	57,006.86 euros as indemnification by the Insurance Compensation Consortium. General damage to houses, buildings, infrastructure and streets in the affected areas. Agricultural losses. Some crops were severely damaged.	On January 5, 2010, Decree 167/2009, of December 29, 2009, came into force, approving urgent and exceptional aid and measures to repair the damage caused by the rain and wind storm of December 22 and 23 in the Archipelago. On April 26 of the same year, the ORDER of April 12, 2010 was published, by which aids are called for the repair of direct material damages caused in tourist, hotel and catering establishments, as well as in tourist infrastructures of municipal ownership, as a consequence of the storm. On May 13, 2010, the ORDER of May 4, 2010 was also approved, by which the bases were approved and the granting of aids was summoned to repair the damages caused to vehicles and to businessmen or professionals (excluding agriculture and tourism), in the Archipelago, due to the events of November and December 2009, and the events which occurred later in February 2010. Finally, on July 20, 2011, the ORDER of July 8, 2011 came into force, establishing the financing of these last aids.	Rainfall data (for 24 hours on 23 December): El Pinalete = 110.2 l/m^2 Chavao = 104.6 l/m^2 El Frontón = 73.8 l/m^2 Valle Arriba = 59.5 l/m^2 El Palmar = 46.0 l/m^2 Ortiz = 40.6 l/m^2 Aripe = 39.0 l/m^2	Consejería de Empleo, Industria y Comercio (13 May, 2010) Consejería de Empleo, Industria y Comercio (20 July, 2011) Presidencia del Gobierno (5 January, 2010) Consejería de Turismo (26 April, 2010) Dirección General de Protección Civil (2014) Agencia Estatal de Meteorología (2021)
Flooding 2009	16 and 17 November, 2009	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Storm / Thunderstorm Strong winds Torrential rains Landslides Flash floods (sediment-laden) Overflow Flooding	La Guancha, Guía de Isora, Icod de los Vinos, La Matanza de Acentejo, La Orotava, Puerto de la Cruz, Los Realejos, San Cristóbal de La Laguna, San Juan de la Rambla, Santa Cruz de Tenerife, Santa Úrsula, El Sauzal, Los Silos, Tacoronte, El Tanque, Vilaflor, Barranco de San Felipe (ravine; La Orotava)	0	Not counted but reported.	Not counted but reported.	1,284,878.06 euros as indemnification by the Insurance Compensation Consortium and 507,882.88 euros subsidized. Flooding of streets, roads, buildings and other infrastructures. General damage in the affected areas. Cuts in several roads due to landslides, such as the TF-5, at the height of San Juan de la Rambla and the fire station of La Orotava. 6 cars dragged and destroyed by mud and stones in the Barranco de San Felipe (ravine; Puerto de la Cruz). Disappearance of the Jardín Beach. Agricultural losses. Many gardens and crops were severely damaged or destroyed.	As of 19:00 h Emergency Level One of Insular Scope was declared. At the same time an operative was working on the rescue of a goatherd trapped in the Barranco de Godínez (Rambla de Castro). Two school centers were enabled to accommodate several families. On November 30, 2009, Decree 147/2009, of November 24, came into force, approving urgent exceptional aid and measures to repair the damage caused by the storm. On May 13, 2010, the ORDER of May 4, 2010, came into force, approving the bases and announcing the granting of aid to repair the damages caused to vehicles and to businessmen or professionals, due to the events of November 2009, December 2009, and January and February 2010. On March 11, 2010, Law 3/2010, of March 10, came into force, approving urgent measures to alleviate the damage caused by forest fires and other natural disasters in several Autonomous Communities, including the event of November 2009 in the Canary Islands. On April 24, 2010, ORDER TER/1005/2010, of April 22, 2010, on the procedure for granting subsidies to alleviate the damage caused by forest fires and other natural disasters in several Autonomous Communities, including the 2009 event in the Canary Islands, came into force. On April 24, 2010, ORDER TER/1005/2010, of April 22, 2010, on the procedure for granting subsidies to alleviate the damage caused by forest fires and other natural disasters in several Autonomous Communities came into force. On May 7, 2010, the ORDER TIN/1162/2010, of May 4, 2010, came into force, by which rules are issued for the application of the provisions of Article 9 of	Rainfall data (for 24 hours on 16 November): Los Realejos-Palo Blanco = 145.1 l/m^2 La Orotava-La Perdoma Suerte = 120.5 l/m^2 La Orotava-La Perdoma Ratiño = 114.6 l/m^2 Icod de los Vinos-Redondo = 107.1 l/m^2 Santa Úrsula-La Corujera = 104.7 l/m^2 Santa Úrsula-Las Tierras = 99.8 l/m^2 La Orotava-Aguamansa = 94.6 l/m^2 It is said that this event was similar to the one occurred on November 24, 1968.	Cabildo Insular de Tenerife (2004) Asociación Canaria de Meteorología (ACANMET) (2009c). Presidencia del Gobierno (30 November, 2009). Consejería de Empleo, Industria y Comercio (13 May, 2010). Jefatura del Estado (11 March, 2010). Ministerio de Política Territorial (24 April, 2010). Ministerio de Trabajo e Inmigración (7 May, 2010). Ministerio de Vivienda (31 July, 2010). Consejería de Empleo, Industria y Comercio (20 July, 2011). Consejería de Turismo (26 April, 2010). Ayuntamiento de La Villa de La

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
									Law 3/2010, of March 10. On July 31, 2010, the ORDER VIV/2078/2010, of July 21, 2010 which establishes the conditions, requirements and procedure applicable to the granting of the exceptional subsidies in the field of housing, for the housing subsidies to repair the damage caused by forest fires and other disasters occurred in several Autonomous Communities, under Autonomous Communities, under Law 3/2010, of March 10. On July 20, 2011 the ORDER of July 8, 2011 comes into force, which establishes the financing of the aids to repair damages caused to vehicles and to businessmen or professionals due to the aforementioned events.		Orotava (2011) Dirección General de Protección Civil (2014) Pérez (2016) Rodríguez de la Cruz (2016)
Flooding 2007	18 and 19 March, 2007	Many parts of the island of Tenerife but it also affected other islands from the Archipelago.	Storm / Thunderstorm Small tornado Snow Hail Torrential rains Landslides Flash floods (sediment-laden) Overflow Flooding Haze	La Matanza de Acentejo, San Cristóbal de La Laguna, Santa Cruz de Tenerife, Santa Úrsula, San Andrés, Tegueste, El Sauzal, Tacoronte, La Victoria de Acentejo.	0	At least 3 injured in some traffic accidents.	Not reported.	144,797.70 euros as indemnification by the Insurance Compensation Consortium. General damages and flooding to streets and buildings and other infrastructures of the affected areas. Road closures, landslide on a hillside near the Ruiz ravine (Los Realejos) which invaded the TF-5 road at km 44, up to 12 walls with rock falls in La Matanza and other rock falls in El Sauzal. Damage to vehicles. Suspension of electricity supply. General damage in the affected areas. Delays in 32 flights at Los Rodeos airport. Flooding of houses and buildings. Some traffic accidents. Rescue of a dozen people in Las Cañadas park who were trapped by snow and ice. Suspension of school activities, especially at the Buen Consejo school in San Cristóbal de La Laguna. Flooding of some greenhouses in Tejina. Overflowing of culverts. Some crops and gardens were flooded.	Roads were closed to prevent access to risk areas and due to collapses at several points. A yellow alert was activated. School activities were suspended due to the possibility of increased adversities. Emergency personnel acted during the 19th to clear roads, lighten traffic and replace overflowing culverts. A GIE helicopter flew over the Tahodio pond and the Socorro ravine (Tejina) to assess the risk of overflowing. Emergency teams, led by Civil Guard specialists, rescued a dozen people trapped in Las Cañadas National Park and accompanied them to the Red Cross post. Firefighters and local police officers acted to solve many problems. Operators of the Road Service of the Cabildo carried out the cleaning of the roads affected by the landslides. The Civil Guard rearranged the traffic. Municipal workers solved several problems of landslides and road closures. The traffic situation returned to normal during the day on the 19th, and the flight situation was restored after midday. The operation organized by municipal workers, Civil Protection and Police allowed that by the afternoon of the 19th 95% of the problems of flooding of streets and buildings, detachment of walls and damaged cars were solved at least in Tacoronte.	Storm produced by a cold drop. The entry of calima favored the improvement of the weather. Rainfall data: Rodeos - Tenerife Norte Airport (18/03/2007, 6 h)= 120.8 l/m^2 Cruz del Camino (19/03/2007, 9 h) = 115.7 l/m^2 Ravelo (19/03/2007, 9 h) = 108 l/m^2 Lomo (19/03/2007, 9 h) = 106.6 l/m^2 La Corujera (19/03/2007, 9 h) = 100.3 l/m^2 Santa Cruz de Tenerife (18/03/2007, 6 h) = 74.1 l/m^2 Rodeos - Tenerife Norte Airport (19/03/2007, 9 h) = 2.9 l/m^2 El Bueno = 42.8 l/m^2 Santa Cruz de Tenerife = 6.6 l/m^2	Asociación Canaria de Meteorología (ACANMET) (2009b) Dirección General de Protección Civil (2014) Pérez (2016) Agencia Estatal de Meteorología (2021)
Flooding 2006	1 November, 2006	Many parts of the island of Tenerife but it also affected other islands from the Archipelago.	Storm / Thunderstorm Torrential rains Rock falls Flash floods Flooding	Arona, Candelaria, Granadilla de Abona, Guía de Isora, Los Realejos, El Rosario, Puerto de la Cruz, San Cristóbal de La Laguna, San Miguel de Abona, Santa Cruz de Tenerife, Santiago	0	Not reported.	Not reported.	1,041,932.68 euros as indemnification by the Insurance Compensation Consortium. General damages and flooding to streets, buildings and other infrastructures, such as the airport of Los Rodeos, of the affected areas. Power outages. Flooding of the health centers of Guía de Isora, Güímar, Santiago del Teide and Hospiten in Puerto de la Cruz, due to the obstruction of the sewage system. Diversion of five flights due to flooding of the runway and terminal of the Reina Sofía airport and a two-hour delay in a flight departing from Los Rodeos airport.	Not reported.	One of the power outages was caused by a lightning strike.	Asociación Canaria de Meteorología (ACANMET) (2009a) Dirección General de Protección Civil (2014)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				del Teide, Tegueste							
Flooding 2006	24 January, 2006	NE of Tenerife	Torrential rains Rock falls Flash floods Flooding	El Rosario, Santa Cruz de Tenerife, Güímar, Arico	0	Not reported.	Not reported.	83,674.19 euros as indemnification by the Insurance Compensation Consortium. General damages and flooding to streets and buildings of the affected areas. Rock falls affected the TF-1.	Not reported.	None.	Dirección General de Protección Civil (2014) Ayuntamiento de Santa Cruz de Tenerife (2015) Rodríguez de la Cruz (2016) Agencia Estatal de Meteorología (2021)
Flooding 2005	19 and 20 December, 2005	S - SW of Tenerife	Torrential rains Flash floods Overflow Flooding	Adeje, Guía de Isora, Barranco de Fañabé (ravine; Adeje).	1	1	Not reported.	104,381.79 euros as indemnification by the Insurance Compensation Consortium. General damages and flooding to streets and buildings of the affected areas. Cutting of the TF-1 highway due to road flooding; cancellation of flights at Reina Sofia airport.	Not reported.	Rainfall data (for 24 hours on 20 December): El Pinalete = 120.1 l/m^2 El Pozo = 118.5 l/m^2 Los Llanitos = 107 l/m^2 Guía de Isora = 97.1 l/m^2 Playa San Juan = 96.9 l/m^2 Charco del Pino = 78.1 l/m^2 Llanos de San Juan = 44.6 l/m^2 El Bueno = 42.8 l/m^2 Santa Cruz de Tenerife = 6.6 l/m^2	Cabildo Insular de Tenerife (2004) Arranz (2006) Dirección General de Protección Civil (2014)
Tropical storm Delta 2005	28 November, 2005	Many parts of the island of Tenerife, but it also affected other islands of the Archipelago	Storm Strong winds Heavy swell Torrential rains Flash floods (not overflow) Minor flooding	Many parts of the island, but especially Santa Cruz de Tenerife and Güímar.	0 (in Tenerife, but 6 people died in an immigrant boat at the south of the Archipelago)	Not reported.	Not reported.	Damages in excess of 24 million euros. The State contributed 20,855,143 euros; the Autonomous Community, 15,656,929, the local councils, 3,890,887 euros and the municipalities, 1,307,339 euros. In Santa Cruz de Tenerife, damages were estimated at 14.5 million euros and a loss of 1/3 of the tree mass. 200,000 people were left without electricity in the metropolitan area of Tenerife. General damage in urban areas. Agricultural losses. Closure of ports and airports. Many gardens and crops were destroyed or severely damaged. A loss of 1/3 of the tree mass was estimated in Santa Cruz de Tenerife.	The Royal Decree-Law 14/2005, of December 2, 2005, adopting urgent measures to repair the damage caused by tropical storm Delta in the Canary Islands on November 28 and 29, was approved. Later, the Royal Decree 610/2006, of May 19, 2006, developing certain measures approved by Royal Decree-Law 14/2005, of December 2, 2005, was approved. On May 2, 2006, the ORDER of April 20, 2006 came into force, regulating the granting of aid to repair the damages caused to businessmen or professionals by the passage of tropical storm Delta through the Canary Islands Archipelago on November 28 and 29, 2005. November 29, 2005. Other orders were approved for the anticipated call for aid and other operations related to the passage of the Delta storm. By December 2005, the population in the most affected areas had not yet recovered.	None.	Jefatura del Estado (6 December, 2005) Arranz (2006) Consejería de Industria, Comercio y Nuevas Tecnologías (2 May, 2006) Jefatura del Estado (20 May, 2006) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011) Pérez (2016) Rodríguez de la Cruz (2016) Agencia Estatal de Meteorología (2021)
Flooding 2005	17 and 18 August, 2005	S of Tenerife	Torrential rains Flash floods Overflow Flooding	Adeje, Arona, San Miguel de Abona	0	Not reported.	Not reported.	63,907.35 euros as indemnification by the Insurance Compensation Consortium. General damages and flooding to streets, buildings and roads in the affected areas, such as at two points in the south on the TF-	The emergency coordination center of Santa Cruz de Tenerife declared the alert after receiving the meteorological reports from the National Meteorological Institute. However, this declaration came 16 hours late since the	Rainfall data (for 24 hours on 18 August): Vilaflor = 115.0 l/m^2 Ravine Badajoz = 72.8 l/m^2 El Bueno = 71.4 l/m^2	Tavío (5 October, 2005) Dirección General de Protección Civil (2014)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
								1 highway.	information contained in the meteorological reports was incorrect and it did not foresee the real situation.	Arona = 57.2 l/m^2 San Miguel de Abona = 45.5 l/m^2 Santa Cruz de Tenerife = 25.7 l/m^2	
Flooding 2004	14 December, 2004	Some parts of the S - SW of the island of Tenerife but the storm also affected other islands of the Archipelago	Storm / Maritime storm Strong winds Heavy swell Flooding	Las Galletas, El Sauzal	0	Not reported.	Not reported.	Flooding of houses, bars and stores in the three main streets of center of Las Galletas. Damage to houses in El Sauzal.	Not reported.	The center of Las Galletas was flooded because the sewage system was not able to absorb all the rainwater, but this had already happened more than once in the last five years before 2004, without remedy.	Cabildo Insular de Tenerife (2004) Pérez (2016)
Flooding 2004	19 and 20 February, 2004	Some parts of the S - SW of the island of Tenerife but the storm also affected other islands of the Archipelago	Storm / Maritime storm Strong winds Heavy swell Flooding	Arona, Adeje	0	Not reported.	Not reported.	15,669.60 euros as indemnification by the Insurance Compensation Consortium. General damages and flooding to streets and buildings in the affected areas.	Not reported.	None.	Pérez (2016) Dirección General de Protección Civil (2014)
Flooding 2003	12 to 15 April, 2003	Some coasts and areas of the island of Tenerife in the W and the N	Storm / Maritime storm Strong winds Heavy swell Flooding	Adeje, Garachico, Puerto de la Cruz, San Cristóbal de La Laguna	0	3	Not counted but reported from residential properties due to wave impacts on their foundations in Adeje.	449,062.30 euros as indemnification by the Insurance Compensation Consortium. 1.2 million euros of losses estimated only in Garachico. General damages and flooding to streets, buildings and some roads, such as the road TF-42 between the Km. 5.000 and 5.700. Damage to breakwaters, maritime avenues, sports centers, tourist complexes and urban furniture, as well as flooding of stores and restaurants.	Not reported.	Waves up to 8 meters high.	Dirección General de Protección Civil (2014) Pérez (2016) Yanes (2017)
Flooding 2003	10 and 11 April, 2002	Some coasts of the island of Tenerife	Maritime storm Heavy swell Flooding	Puerto de La Cruz, especially the Martiánez Lake	0	12	Not reported.	General damages and flooding to the area of the Martiánez Lake.	Not reported.	Waves of up to 6 meters crashed against the wall of Lake Martiánez and entered causing damage and injuries.	Pérez (2016)
Flooding 2002	16 to 18 December, 2002	Many parts of the island of Tenerife but it also affected other islands from the Archipelago.	Storm Strong winds Torrential rains Rock falls Flash floods Overflow Flooding	Adeje, Arico, Arona, Candelaria, Granadilla de Abona, Guía de Isora, Güímar, Icod de los Vinos, El Rosario, Santiago del Teide	0	Not reported.	Not reported.	891,899.11 euros as indemnification by the Insurance Compensation Consortium. Flooding and general damage to streets and buildings of the affected areas. Road closures.	Not reported.	277 l/m^2 were collected in Las Cañadas, 193 l/m^2 in Arafo and 102 l/m^2 in Los Rodeos.	Dirección General de Protección Civil (2014) Ayuntamiento de Santa Cruz de Tenerife (2015) Rodríguez de la Cruz (2016) Agencia Estatal de Meteorología (2021)
Flooding 2002	12 to 13 December, 2002	Many parts of the island of Tenerife but it also affected other islands from the Archipelago.	Storm Strong winds Torrential rains Rock falls Flash floods Overflow Flooding	Adeje, Arico, Arona, Candelaria, Granadilla de Abona, Guía de Isora, Güímar, Icod de los Vinos, El Rosario, San Cristóbal de La Laguna, San Miguel de Abona, Santa Cruz de Tenerife, Santiago del Teide,	0	1	Not reported.	359,692.70 euros as indemnification by the Insurance Compensation Consortium. Many people decided not to go to their jobs. The most affected areas were those severely affected by the flooding of March 31, where reconstruction works were not yet finished. The rain aggravated the deterioration of the Fine Arts faculty. Flooding and general damage to streets and buildings of the affected areas. Road closures.	The Emergency and Security Coordination Center of the Canary Islands declared a Maximum Alert situation in Santa Cruz de Tenerife.	Rainfall data (for 24 hours on 12 December): El Bueno = 169.9 l/m^2 Rodeos - Tenerife Norte Airport = 101.6 l/m^2 Guía de Isora = 97.1 l/m^2 Las Galletas = 76.2 l/m^2 Las Caletillas = 66.0 l/m^2 Santa Cruz de Tenerife = 23.2 l/m^2	Dirección General de Protección Civil (2014) Barquín (2015) Rodríguez de la Cruz (2016) Agencia Estatal de Meteorología (2021)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				Tegueste							
Flooding 2002	31 March, 2002	NE, E and S of Tenerife, but the storm also affected other islands of the Archipelago.	Storm Torrential rains Landslides Flash floods Overflow Flooding	Arafo, Arona, Candelaria, Fasnia, El Rosario, San Cristóbal de La Laguna, Santa Cruz de Tenerife, Tacoronte, Barranco de Santos (ravine; Santa Cruz de Tenerife), Barranco de San Andrés (ravine; San Andrés), Barranco del Hierro (ravine; Santa Cruz de Tenerife).	08-sep	30	500	32.165.968,95 euros as indemnification by the Insurance Compensation Consortium, however, losses were estimated to be more than 120 million euros. Flooding of streets and general damages to the affected areas. Road closures and blocking access at some points to the city of Santa Cruz de Tenerife. Isolation of several coastal neighborhoods due to landslides, cuts in the electricity supply that left 80% of the population of the city of Santa Cruz de Tenerife without water and electricity, and the cutting of 17,000 telephone lines. Destruction of homes and serious damage to buildings. Around 355 houses were destroyed or severely damaged. Explosion in a building when the pillars of the structure yielded. Damage to the Fumero dam. Interruption of air and port traffic. Probably severe damages to crops, gardens and many trees.	Previous days, the CEO of Civil Protection received warnings of adverse meteorological phenomena affecting the Autonomous Community of the Canary Islands. In this case, the Autonomous Community must assume the competences in matters of Civil Protection. On March 29, the CEO of Civil Protection sent the weather report for the province of Santa Cruz de Tenerife to the Government Subdelegation, which transmitted a series of warnings to all the state-owned bodies so that they would be aware of the phenomenon that could take place. All the agencies involved were in a situation of prevention and the weather reports and warnings were renewed. At 17:05 h the mayor of Santa Cruz asked the subdelegate of the Government for the immediate support and intervention of the army. The head of the civil protection unit of the subdelegation of the Government was notified and immediately contacted the team organized by the city council and went to the CECOP (operational coordination center) that had been organized in the City Hall, called Cecopal. The Civil Guard mobilized its resources. The army was in a state of prevention and, upon alert from the sub-delegate of the Government, an emergency protocol was immediately put in place, deploying 120 troops (people) in Santa Cruz, to collaborate with the rescue and debris removal tasks, carrying shelter material, machinery, and up to 1,250 full rations of food. The REMER (National Emergency Radio Network) was activated. Intervention of the army in the evacuation of the population, together with the intervention of different security forces, such as the Fire Department, the Canary Islands health service, the Emergency Service of the Government of the Canary Islands, Civil Protection volunteers and members of the Civil Protection of the Subdelegation (REMER), and Red Cross units. Enabling an area for evacuees at the fairgrounds to supply them with means. Mobilization for four days of the entire island's environmental staff of the island in the cleaning of the city. In Santa Cruz de Tenerife, the CECOPI was constituted at the headquarters of the Local Police, which was attended by the Minister of the Presidency, the Undersecretary of the Interior, the CEO of Civil Protection, the CEO of the Police, the Government Delegate of the Canary Islands, the Subdelegate of the Government in Santa Cruz de Tenerife, the Mayor of the city of Santa Cruz de Tenerife, the President of the Government in the Canary Islands, the Vice President of the Regional Executive and other Authorities.	Rainfall data (for 24 hours on 31 March): S. C. de Tenerife - Residential area of Anaga = 252.0 l/m^2 S. C. de Tenerife - CMT = 232.6 l/m^2 Anaga - Tahodio Pozo Lara = 225.3 l/m^2 Anaga - Ravine Huertas = 222.6 l/m^2 Anaga - San Andrés = 191.0 l/m^2 Laguna - Mountain Ofra = 129.0 l/m^2 S. C. de Tenerie - Hoya Fría = 98.3 l/m^2 Anaga - Bodegas = 96.5 l/m^2 Anaga - Valle Jiménez = 96.0 l/m^2 Maximum intensities around 160 $l/m^2/h$, and more than 224 l/m^2 in two hours.	Consejería de Empleo y Asuntos Sociales (13 May, 2002) Grupo Socialista Canario (2 May, 2002) Jefatura del Estado (6 April, 2002) Ministerio de Trabajo y Asuntos Exteriores (14 June, 2002) Ministerio del Interior (27 June, 2002) Presidencia del Gobierno (6 August, 2002) Cabildo Insular de Tenerife (2004) Consejo Insular de Aguas de Tenerife (2004) Arranz (2006) Dorta (2007) Arroyo (2009) Marzol and Máyer (2012) Dirección General de Protección Civil (2014) Rodríguez de la Cruz (2016) Consejo Insular de Aguas de Tenerife (2019) Agencia Estatal de Meteorología (2021)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
									On April 6, 2002, Royal Decree-Law 2/2002, of April 5, 2002, came into force, adopting urgent measures to repair the damage caused by the torrential rains that occurred on March 31, 2002 in Santa Cruz de Tenerife and San Cristóbal de la Laguna (island of Tenerife), and on April 18 of the same year it was approved by the Congress of Deputies. On April 10, 2002, Decree 39/2002, of April 8, on aid, subsidies and exceptional measures to repair damages caused by torrential rains, came into force. On April 18, 2002, the Canary Islands Socialist Parliamentary Group presented a Proposition not of law before the Parliament of the Canary Islands to urge the Government of the Canary Islands that the Department of Health and Consumption of the Government of the Canary Islands should fully cover the medical and pharmaceutical expenses of the affected population for a minimum period of one year and that medical-psychological assistance should be provided to the victims. On May 11, 2002, Royal Decree-Law 4/2002, of May 10, came into force, approving complementary measures to those established by Royal Decree-Law 2/2002, of April 5, and was approved by the Congress of Deputies on May 30, 2002. On May 13, 2002, the ORDER of May 8, 2002, jointly issued by the Ministers of Economy, Finance and Commerce and of Employment and Social Affairs, came into force, regulating the granting of aid for death caused by the torrential rains and storm that occurred on May 31, 2002, in the municipalities of Santa Cruz de Tenerife and San Cristóbal de La Laguna. On May 28, 2002, a collaboration agreement was established between the Ministry of the Interior and the Autonomous Community of the Canary Islands (Department of Economy, Finance and Commerce) for the management of the aid provided for in Royal Decree-Law 2/2002, of April 5. On June 14, 2002, Order TAS/1430/2002, dated June 4, 2002, was published, whereby rules were issued for the application of the provisions of article 4.2 of Royal Decree the provisions of article 4.2 of Royal Decree-Law 2/2002, of April 5, 2002, in order to ensure the effective application of interest-free moratoriums on the payment of Social Security contributions, as well as to unify criteria in their implementation. It was also necessary to approve Law 7/2002, of July 18, 2002, to grant an extraordinary credit in the amount of 65,682,568 euros to finance aid, subsidies and exceptional measures to repair damages, which came into effect on August 6, 2002.Other decrees, orders and resolutions were created to regulate and manage aid to		

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
									repair damages.		
Flooding 2001	20 to 21 November, 2001	Many part of the island of Tenerife, and other islands of the Archipelago	Torrential rains Flash floods Overflow Flooding	Adeje, Arico, Arona, Buenavista del Norte, Fasnia, Granadilla de Abona, La Guancha, Guía de Isora, Güímar, Icod de los Vinos, La Orotava, Puerto de la Cruz, Los Realejos, San Cristóbal de La Laguna, San Juan de la Rambla, San Miguel de Abona, Santa Cruz de Tenerife, Santiago del Teide, Los Silos, Tacoronte, El Tanque, La Victoria de Acentejo, Vilaflor	0	0	0	29,448.62 euros as indemnification by the Insurance Compensation Consortium, and 18,030,000.00 euros as a credit given by the Govern Flooding in La Pinta in Costa Adeje of rainwater and sewage due to overflowing of the sewage system. Flooding and general damages to streets and buildings. Many agricultural losses.	Royal Decree-Law 1/2002, of March 22, 2002, was approved 5 months later, adopting urgent measures to repair the damages caused by the rains, storms and other natural phenomena related to the aforementioned adverse weather conditions, which occurred from the last days of September to the end of February 2002 in the Autonomous Communities of Andalusia, Balearic Islands, Canary Islands, Catalonia, Region of Murcia, Community of Valencia and City of Melilla. This Royal Decree-Law approves and establishes the following: compensation for damage to agricultural production; tax benefits; special tax reductions for agricultural activities; labor measures; hiring regime; emergency aid; preferential credit lines, including a line of loans amounting to 18,030,000.00 euros; cooperation with Local Administrations; Agreements with other Public Administrations. It is not known when the aid arrived and when all the damage was repaired, but it was more than 5 months after the event.	None.	Jefatura del Estado (23 March, 2002) Ministerio del Interior (31 May, 2002) Rajoy (18 April, 2002) Dirección General de Protección Civil (2014) Rodríguez de la Cruz (2016) Consejo Insular de Aguas de Tenerife (2019)
Flooding 2000	11 November, 2000	Several parts of the island of Tenerife	Torrential rains Flash floods Overflow Flooding	Adeje, especially its coasts (access to Torviscas and entrance to the beach Fañabé), Arona, Granadilla de Abona, La Orotava, San Miguel de Abona, Santa Cruz de Tenerife.	0	0	0	990,923.00 euros as indemnification by the Insurance Compensation Consortium. A total of 21 houses affected, together with a section of the TF-1 motorway at Adeje. Flooding and general damage to streets, buildings and infrastructures, such as the power grid.	Not reported.	None.	Dirección General de Protección Civil (2014) Consejo Insular de Aguas de Tenerife (2019)
Flooding 2000	6 to 7 April, 2000	Buenavista del Norte	Torrential rains Flash floods Overflow Flooding	Buenavista del Norte, especially the ravine of Masca.	0	1	106	Not reported.	Not reported.	None.	Dirección General de Protección Civil (2014)
Flooding 1999	1 to 10 January, 1999	Tenerife and the rest of the Archipelago	Storm Thunderstorm Maritime storm Heavy swell Hail Haze Snow Strong winds Torrential rains Landslides Flash floods Overflow Flooding	Adeje, Arafo, Arico, Arona, Buenavista del Norte, Candelaria, Fasnia, Garachico, Granadilla de Abona, La Guancha, Guía de Isora, Güímar, Icod de los Vinos, La Matanza de Acentejo, La Orotava, Puerto de la Cruz, Los Realejos, El	0	There are reports of people injured in the Archipelago but they are not described with detail for Tenerife. At least, 4 people were injured in the port area.	Not reported.	The Cabildo quantified the cost of the losses at approximately 35 million euros. However, the Royal Decree-Law 4/1999, of April 9, 1999, approved two extraordinary credits, one of 300 million pesetas (1,803,036 euros approx.) for the financing of investments by local entities and another of 1,400 million pesetas (8,414,169 euros approx.) for the repair of damages in ports. The rest of the actions would be financed from the budget allocations of the respective ministries. Indemnification by the Insurance Compensation Consortium of 3,613,649.68 euros. Flooding of streets, roads, motorways and buildings, such as some parts of the	On November 12, 1997, the PLATECA, Territorial Emergency Plan for Civil Emergencies of Civil Protection of the Autonomous Community of the Canary Islands, was approved, which details how to act in situations such as this storm, but the measures were not applied during the event. No information was given to population, so the alarm was raised. However, Mr. González Santiago, from the Popular Group, and the Councilor of Territorial Policy and Environment, Mrs. Márquez Rodríguez, explained that the appropriate measures were taken and the PLATECA was applied. That on January 5, Civil Protection informed all the Canary Islands local	In Tenerife, 130 l/m^2 were recorded in El Sauzal and 110 l/m^2 in Izaña in the form of snow. The idea arose of processing a bill on actions for damages caused in an emergency situation that would prevent the Parliament from having to deal with the issue every time a circumstance of this nature occurs with the usual measures that are contained in that bill. Mr. Fresco Rodríguez, deputy of the Socialist Canary Islands Parliamentary Group states that before the storm, none of the phases described in PLATECA of monitoring, pre-	Alcaraz (11 March, 1999) Jefatura del Estado (10 April, 1999) Ministro del Interior (29 April, 1999) Parlamento de Canarias (20 January, 1999) Presidencia del Gobierno (15 January, 1999) Rodríguez (9 January, 1999)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				Rosario, San Cristóbal de La Laguna, San Juan de la Rambla, San Miguel de Abona, Santa Cruz de Tenerife, Santa Úrsula, Santiago del Teide, El Sauzal, Los Silos, Tacoronte, El Tanque, Tegueste, La Victoria de Acentejo; ravines: Barranco de la Barca - Barranco Martiánez, Barranco del Pino, Barranco de la Candía, Barranco de Santos.				motorway TF-5 in the area of Las Arenas or the road TF-112 from San Andrés to Taganana, and some industrial plants. Road closures. Breakage of the Aguamansa Channel due to a rock fall and interruption of drinking water supply to some municipalities. Significant damage to the coastline and its infrastructure. Damage to the electric company's infrastructure, which caused power outages Destruction of many trees, crops and gardens. and serious damage to the company's facilities, with losses amounting to almost five million euros. Company’s facilities, whose losses amounted to almost five million euros. Damages to the fishing port of Candelaria. Serious damage to the fishing docks of Los Llanos and Anaga, in the port of Santa Cruz de Tenerife. In the first of them, the strong waves carried away a container and 70 cars that were parked in the dock for later sale. Destruction of the sailing school of the Island Cabildo and the dock of the University School of Nautical Studies. Sinking of numerous fishing boats in the south of the island and serious damage to some fishermen's shelters. Delays and cancellations on several flights. Cancellation of inter-island transport, serious damage to ports and coastal infrastructures due to the sea storm and wind. Damage to crop production infrastructures and severe agricultural and livestock losses.	corporations of the measures to be adopted, the probability that adverse meteorological phenomena could occur and alerted the personnel, reinforcing the service. On January 6th the intervention and rescue personnel remained on alert and on January 7th a new fax was sent with communications from the meteorological services, although these were not very accurate. On the other hand, Mr. Cabrera Montelongo, from the Coalición Canaria Group, also supports the idea that the Government took the appropriate measures and applied the Emergency Plan, but that the data provided by the meteorological service were confusing. The Government met on January 12 to agree on the creation of the Interdepart On Wednesday, July 21, 1999, slightly more than 5 months after the storm, the ORDER of July 15, 1999 was published in the Official State Gazette, which complements the Order of April 29, 1999, determining the municipalities and population centers to which the measures provided for in Royal Decree-Law 4/1999, of April 9, 1999, are applicable. It is not known when the aid arrived and when all the damage was repaired, but it was more than 5 months after the event. Mental Commission for the adoption of palliative and reparation measures for the damage caused by the storm. For this reason, Decree 1/1999, of January 12, 1999, was approved, creating this temporary Commission. During the storm and during the following days, the President of the Government, the Minister of Public Administrations and the President of the Interdepartmental Commission visited several affected areas and met with the presidents of the local councils, with many mayors and with a large number of presidents of cooperatives. Immediately the surveys and damage estimates were started, information that was managed by the cabildos. A few weeks after the storm, the Comisión Mixta was formed between the Central State Administration and the representation of the Autonomous Government of the Canary Islands, which worked intensively on the assessment and evaluation of the damage caused by the storm. On February 23, a non-legislative proposal was approved. Afterwards, the Royal Decree-Law 4/1999, of April 9, 1999, adopting urgent measures to repair the damage caused by the torrential rains and the storm that occurred in January 1999 in the autonomous community of the Canary Islands, was approved. These measures are, very briefly: a 50% state subsidy for projects of local entities for the repair of municipal infrastructures and equipment; subsidies for	emergency, emergency (pre-alert, alert, maximum alert, progressive action, alarm), nor of prediction of the phenomenon or conditions conducive to its unleashing were declared. Not even when the phenomenon was occurring was the emergency phase declared in the situation of progressive action and the PLATECA was activated. The person in charge of Civil Protection of Santa Cruz says: "our Civil Protection received the weather forecasts of that day on January 8, when everything had already passed". Mr. Luis Suárez Trenor, president of the Port Authority of Santa Cruz de Tenerife says: "we were not informed". However, Mr. González Santiago, from the Popular Group, and the Councilor of Territorial Policy and Environment, Mrs. Márquez Rodríguez, explained that the appropriate measures were taken and the PLATECA was applied. Mr. Francisco Díaz, Minister of Economy and Finance, expressed the need to promote the insurance culture, that is to say, to increase the level of insurance, something that is lacking in the Canary Islands. On the other hand, he also expressed the need to learn from this 1999 storm and from past storms, and to increase the coordination of the emergency and urgency services.	Cabildo Insular de Tenerife (2004) Arranz (2006) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011) Marzol and Máyer (2012) Ayuntamiento de Santa Cruz de Tenerife (2015) Rodríguez de la Cruz (2016) Consejo Insular de Aguas de Tenerife (2019) Agencia Estatal de Meteorología (2021)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
									damages to agricultural installations and production insured by the combined agricultural insurance; declaration of emergency for repair works in port, agricultural, coastal and other environmental infrastructures, bonuses and exemptions in different fees; special tax reductions for agricultural activities; labor measures consisting of a moratorium or exemption from Social Security contributions for companies and self-employed workers. For the financing of this aid, the Royal Decree-Law approves two extraordinary credits, one of 300 million pesetas (1,803,036 euros approx.) for the financing of investments by local entities and another of 1,400 million pesetas (8,414,169 euros approx.) for the repair of damages in ports. The rest of the actions will be financed from the budget allocations of the respective ministries. Other decrees and orders were approved to regulate the granting of aid.		
Flooding 1996	10 to 12 March, 1996	Several parts of the island of Tenerife, but the storm also affected other islands of the Archipelago	Storm Strong winds Torrential rains Landslides Flash floods Flooding	Several parts across the island of Tenerife, but especially around Santa Cruz de Tenerife and San Andrés.	1	Not reported.	Not reported.	Rock falls in many roads, especially the road between Santa Cruz de Tenerife and San Andrés, causing road closures.	Several roads, such as those accessing the Teide National Park, were closed due to the danger of rock falls.	The victim from Tenerife died as a result of a landslide that swept away the shack where she lived.	Fernández (12 March, 1996) Rodríguez de la Cruz (2016)
Flooding 1995	10 to 15 December, 1995	Several parts of the island of Tenerife, but the storm also affected other islands of the Archipelago.	Storm Strong winds Probably heavy swell Torrential rains Flash floods Overflow Flooding	Several parts across the island of Tenerife, such as the Barranco del Bufadero (ravine; Santa Cruz de Tenerife), or in the north, such as Buenavista del Norte.	0	Not reported.	Not reported.	Flooding of streets and buildings and probably general damages to the affected areas and agricultural losses.	Not reported.	Maximum intensity in 24 hours of 219 l/m^2 in Buenavista del Norte.	Cabildo Insular de Tenerife (2004) Rodríguez de la Cruz (2016) Consejo Insular de Aguas de Tenerife (2019) Agencia Estatal de Meteorología (2021)
Flooding 1993	28 October, 1993	Several parts of the S - SE of the island of Tenerife.	Storm Torrential rains Probably maritime storm Flash floods Flooding	S-SE of Tenerife, especially Los Cristianos.	0	Not reported.	Not reported.	Flooding of streets and buildings and probably general damages to the affected areas and agricultural losses.	Not reported.	None.	Martín (5 December, 1991) Diario de Avisos (29 October, 1993) Rodríguez de la Cruz (2016)
Flooding 1993	17 March, 1993	Several parts of the island of Tenerife, but the storm also affected other islands of the Archipelago.	Storm Strong winds Torrential rains Flash floods Flooding	Several parts across the island of Tenerife, but especially in Los Cristianos, Tacoronte, San Cristóbal de La Laguna, El Sauzal.	Not reported.	Not reported.	Not reported.	Floodings of streets and buildings and general damages to the affected areas. Agricultural losses.	Not reported.	Maximum intensity in 24 hours of 330 - 337 l/m^2 in Izaña.	Cabildo Insular de Tenerife (2004) Arroyo (2009) Agencia Estatal de Meteorología (2021)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Flooding 1991	4 December, 1991	Several parts of the island of Tenerife, but the storm also affected other islands of the Archipelago.	Storm Strong winds Maritime storm Heavy swell Torrential rains Probably flash floods Probably flooding	Several parts across the island of Tenerife, but probably the NE.	Not reported.	Not reported.	Not counted but reported in the province of Santa Cruz de Tenerife.	Power outages, delays and saturation at Los Rodeos and Reina Sofía airports, breakage of an antenna tower at Santiago del Teide station that left 30% of La Palma subscribers without power. Agricultural losses. Damages to crops and gardens.	The Civil Government declared a state of pre-alert in the city councils and the governments of the islands and recommended to evacuate some houses.	Maximum intensity in 24 hours of 275 - 330 l/m^2.	Martín (5 December, 1991) Cabildo Insular de Tenerife (2004)
Flooding 1990	6 November, 1990	S of Tenerife	Moderate rains Flooding	Los Cristianos and Las Américas.	0	Not reported.	Not reported.	Flooding of streets and buildings.	Not reported.	None.	Cabildo Insular de Tenerife (2004)
Floodings 1989	24 November to 28 December, 1989	Several parts of the island of Tenerife	Storms Torrential rains Heavy swell Flash floods Overflow Flooding	Guía de Isora, Santa Cruz de Tenerife.	0	Not reported.	Not reported.	Flooding of some buildings in the beach of San Juan.	On June 22, 1990, the Order of June 5, 1990, came into force, establishing urgent aid measures for farmers affected by torrential rains on tomatoes on the island of Tenerife.	Maximum intensity in 24 hours of 210 l/m^2. Currently, there is a parking at the mouth of the ravine.	Consejería de Agricultura y Pesca (22 June, 1990) Cabildo Insular de Tenerife (2004) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1988	1 November, 1988	NE of Tenerife	Storm Torrential rains Flooding	La Orotava, especially the neighborhood of La Luz.	0	Not reported.	Not reported.	Flooding of streets and buildings.	Firefighters intervene to drain water from some flooded houses in the neighborhood of La Luz.	None.	Ayuntamiento de La Villa de La Orotava (2011)
Flooding 1988	24 to 27 February, 1988	N of Tenerife	Storm Torrential rains Probably flash floods Probably flooding	N of Tenerife	Not reported.	Not reported.	Not reported.	Probably flooding of streets and buildings in many parts in the north of Tenerife. Probably agricultural losses.	Not reported.	On the 27th, 110 l/m^2 were collected in 24 hours on the southeast coast of Tenerife.	Agencia Estatal de Meteorología (2021)
Flooding 1987	23 October, 1987	N and NE of Tenerife	Storm Strong winds Heavy swell Torrential rains Flooding	Icod el Alto, Güímar.	0	Not reported.	Not reported.	Flooding of streets and buildings, destruction of 20 meters of the pier of the port of Güímar.	Not reported.	Maximum intensity in 24 hours of 250 l/m^2.	Marzol (2002) Cabildo Insular de Tenerife (2004)
Flooding 1987	11 to 13 April, 1987	E and SE of Tenerife	Storm Strong winds Maritime storm Heavy swell Torrential rains Flooding	Candelaria, Los Cristianos (Arona), Arico.	0	Not reported.	Not reported.	Around 60,100 euros in damages in Candelaria yacht club and surroundings. Overturning and shoring of more than seventy fishing boats in Los Cristianos (Arona). Breakage in two of the Las Maretas pier (Arico).	Not reported.	None.	Marzol (2002)
Flooding 1987	13 January, 1987	Garachico	Storm Heavy swell	Coasts of Garachico	2	Not reported.	Not reported but probably due to the damage of several houses.	Flooding and damage of the streets and buildings near the coast. Severe damages to the tourist facilities and several houses. The waves swept away furniture and vehicles.	Not reported.	None.	Acosta (2019)
Floodings 1979	6 to 23 January, 1979	NE of Tenerife	Storms Strong winds Torrential rains Heavy swell Flash floods Overflow Flooding	La Orotava, Puerto de la Cruz, San Cristóbal de La Laguna, Santa Cruz de Tenerife	0	Not reported.	Not reported.	Flooding and damage of the streets and buildings. Los Cristianos port (SW of Tenerife) was destroyed. Many trees were probably damaged and/or destroyed.	Not reported.	957 l/m^2 accumulated in Izaña, almost all in the form of snow. Maximum intensity in 24 hours of 229 l/m^2.	Quirantes et al. (1993) Cabildo Insular de Tenerife (2004) Dorta (2007) Arroyo (2009) Dirección General de Protección Civil (2014) Consejo Insular de Aguas de Tenerife (2019)
Flooding	10 to 11	The island of	Torrential rains	Bajamar, San	0	Not	Not reported.	Flooding and damage of streets and	Some people were rescued in boats.	Maximum rainfall intensity of 358	El Eco de

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
1977	April, 1977 (Some sources also mention the 7th and the 13th)	Tenerife and other islands of the Archipelago.	Landslides and rock falls Flash floods Overflow Flooding (sediment-laden)	Cristóbal de La Laguna, especially the neighborhood of La Vega Lagunera, Santa Cruz de Tenerife, Garachico, Güímar, Arona, Vilaflor, Barranco de Santos (ravine; Santa Cruz de Tenerife), Barranco de San Juan (ravine; Bajamar).		reported.		buildings. Destruction of part of the road from Bajamar to Punta del Hidalgo, and damage to and traffic disruption in the motorway of the south (TF-1). Damage to a road in Garachico. Few agricultural losses. Air traffic disruption. Some road closures. Some damage to crops and gardens.		l/m^2. Other rainfall data (24 hours): Izaña = 105 l/m^2 (10/04/1977) Güímar-La Planta = 195 l/m^2 (10/04/1977) Arafo = 230 l/m^2 (11/04/1977) El Escobonal = 220 l/m^2 (11/04/1977) The water reached between a meter and a meter and a half in some streets of San Cristóbal de La Laguna, a meter and a half in some streets of Santa Cruz de Tenerife, and two meters in some streets of Los Cristianos. Landslides on the road from Bajamar to Punta de Hidalgo advanced the coastline by 10 meters at Punta del Puerto. The flood of mud and stones in the Barranco de San Juan (ravine; Bajamar) blocked the mouth of the ravine and 40,000 m^3 of this material were accumulated in this last stretch.	Canarias (1977) Quirantes et al. (1993) Cabildo Insular de Tenerife (2004) Consejo Insular de Aguas de Tenerife (2004) Presidencia del Gobierno (2005) Marzol et al. (2006) Dorta (2007) Dirección General de Protección Civil (2014) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1971	12 to 13 February, 1971	Several parts of the island of Tenerife, but the storm also affected other islands of the Archipelago.	Storm Hail Snow Torrential rains Heavy swell Overflow Flooding Landslides	San Cristóbal de La Laguna, Santa Cruz de Tenerife, Güímar, La Orotava, Izaña.	0	Not reported.	Not reported.	Flooding of the streets of Santa Cruz de Tenerife due to heavy rains and heavy waves. General damages on the streets of Santa Cruz de Tenerife and San Cristóbal de La Laguna. Landslides affecting the road from Santa Cruz de Tenerife to San Andrés. Agricultural losses. Damages to crops and gardens.	Firefighters were on hand at all times to help rescue people who were trapped in flooded houses, streets and cars.	Maximum rainfall intensity of 246 l/m^2 in 24 hours. There is a record of the Consejo Insular de Aguas de Tenerife (2019) that states that the floods in La Laguna were due to the dumping of debris in ravines and ditches, on the understanding that this could have caused them to overflow.	El Eco de Canarias (14 February, 1971) Cabildo Insular de Tenerife (2004) Dorta (2007) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1968	December 1968 (exact date/s and durations unknown, but there are two dates/chronicles, one on 13 December and the other on 31 December)	NE of Tenerife	Torrential rains Flooding due to heavy rain Flash floods Flooding due to overflow	Santa Cruz de Tenerife (13 December), neighborhood of La Vega Lagunera (San Cristóbal de La Laguna, 31 December).	Not reported.	Not reported.	Not reported.	Flooding of streets and buildings.	Not reported.	None.	Marzol (2002) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1968	22 to 25 November, 1968	N and NE of Tenerife	Torrential rains Strong winds Maritime storm Heavy swell Flash floods Overflow Flooding	San Cristóbal de La Laguna, Los Realejos, Puerto de la Cruz, Santa Cruz de Tenerife, La Orotava, Barranco de San Felipe (ravine:	2	Not reported but probably.	At least 140 houses were evicted.	Flooding and damage of several streets and buildings. Damage and flooding of 100 houses and destruction of 40 houses by a flood, which also destroyed the canalization walls and covered everything with stones and mud from the ravine of San Felipe to the castle of San Felipe. Building collapses and power cuts. Damages to some roads and	100 houses were evicted.	Rainfall data (for 24 hours): La Orotava = 180 l/m^2 Aguamansa = 216 l/m^2	Gaceta de Tenerife (4 to 5 March, 1920) Antena: Semanario deportivo-cultural (26 November, 1968)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				Puerto de la Cruz), Barranco de Santos (ravine; Santa Cruz de Tenerife)				streets, especially the road from La Orotava to Granadilla (TF-21). Access to Punta Brava was cut off, part of the Calzada de Martiánez (street) was submerged and the beaches of the port were flooded with mud.			Quirantes et al. (1993) Consejo Insular de Aguas de Tenerife (2004) Dorta (2007) Dirección General de Protección Civil (2014) Ayuntamiento de La Villa de La Orotava (2011) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1957	5 December, 1957	N of Tenerife and other islands of the Archipelago	Storm Strong winds Rain Flooding	La Orotava, Puerto de la Cruz, Los Realejos, Santa Úrsula, San Miguel, San Cristóbal de La Laguna.	At least one confirmed, although there is talk of casualties., but perhaps they refer to Gran Canaria Island.	Not reported but probably.	Not reported.	In La Orotava, one third of the banana production was lost. Damage to dwellings and destruction of some houses. General damage in the municipalities, such as power outages, fall of high voltage poles in the hydroelectric plant of La Orotava, telephone breakdowns, communications outages, probably flooding of some houses and streets, damage to infrastructure. Road closures. Agricultural losses. Many trees and crops, especially banana plantations, were destroyed due to strong winds.	Not reported.	The main cause of the damage was the wind.	Ayuntamiento de La Villa de La Orotava (2011)
Cyclone 1953	15 January, 1953	Many parts of the island of Tenerife and other islands from the Archipelago	Cyclone/Storm Thunderstorm Strong winds Rain Maritime storm Heavy swell Flooding	The north of the island, especially La Orotava, Los Realejos, San Juan de la Rambla, Icod de los Vinos, Los Silos, and other parts, such as Güímar, Las Galletas.	2	Not reported but probably.	Not reported.	One thousand million pesetas. Damage to many buildings and destruction of some houses. Agricultural losses. General damage to streets and infrastructures across the affected locations. Flooding of some houses and probably flooding of streets. Damage to ports and sinking of a ship. Road closures. Damage to electrical cables and demolition of telephone poles. Many trees and crops, especially banana plantations, were destroyed due to strong winds.	Work crews worked to clear the roads of fallen trees and municipal authorities and representatives visited the affected areas to assess and take action.	The main cause of the damage was the wind.	Destino (31 January, 1953) Cabildo Insular de Tenerife (2004) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011)
Flooding 1950	8 to 11 November, 1950	NE and center of Tenerife. The storm affected the whole archipelago.	Torrential rains Flash floods Overflow Flooding Thunderstorm Maritime storm Heavy swell	Santa Cruz de Tenerife, San Cristóbal de La Laguna, Adeje, Barranco del Agua (ravine; Güímar), Barranco de Santos (ravine; Santa Cruz de Tenerife), Barranco de San Sebastián (ravine; Santa Cruz de Tenerife), Barranco de los Olivos (ravine; Santa Cruz de	2	There are reports of many injuries but they were not counted.	1000. At least 300 in Santa Cruz de Tenerife.	Flooding of the streets and many buildings of Santa Cruz de Tenerife, San Cristóbal de La Laguna and Adeje. Damage across the cities, especially in the harbor of Santa Cruz de Tenerife, where the strong waves tore the stones out of the harbor dyke, injuring a woman. Damage to many cars and trucks, and across the roads. Agricultural losses. Damage to installations and drinking water network. Many gardens, crops and trees were damaged.	The people evacuated from the area around Barranco de Santos were distributed among the offices of the Navy, Auxilio Social and other institutions. The Captain General of the Canary Islands and the Civil Governor visited the affected areas. The injured were treated in the aid stations.	The water reached between 20 cm to half a meter in the streets of Santa Cruz de Tenerife, especially in Calle de la Marina. Rainfall data (for 24 hours): Santa Cruz de Tenerife = 50.5 l/m^2 (09/11/1950) Rodeos - Airport of North Tenerife = 149.6 l/m^2 (08/11/1950) Izaña = 224.4 l/m^2 (09/11/1950); 360 l/m^2 (11/11/1950) La Matanza = 130 l/m^2 (08/11/1950) Aguamansa = 127.2 l/m^2 (08/11/1950) Punta Hidalgo = 115 l/m^2 (08/11/1950)	La Falange (10 and 16 November, 1950) Pinto (1954) Marzol (2002) Cabildo Insular de Tenerife (2004) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011) Marzol and Máyer (2012) Dirección General de Protección Civil (2014) Consejo Insular de Aguas de

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				Tenerife). The center of the island was also affected by the storm.							Tenerife (2019)
Flooding 1946	29 November to 2 December, 1946	NE of Tenerife	Storm Torrential rains Flash floods Overflow Flooding	La Orotava, La Laguna.	0	Not reported.	Not reported.	Several million pesetas. Probably flooding of streets due to the overflow of some ravines.	Not reported.	Maximum rainfall intensity of 269 l/m^2 in 24 hours on 29 November.	Falange: Diario de la tarde (24 January, 1947) Cabildo Insular de Tenerife (2004) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011)
Flooding 1944	22 October, 1944	NE of Tenerife	Torrential rains Flooding	San Andrés.	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	None.	Marzol (2002) Dorta (2007)
Flooding 1944	4 May, 1944	NE of Tenerife	Torrential rains Hail Thunderstorm Breakage of a high-voltage cable (it killed a person) Dam retaining wall break Flooding Landslide	Santa Cruz de Tenerife and San Andrés, valley of the Buzadero (Mendoza dam), valley between Tahodio and Catalanes. Some damages in San Cristóbal de La Laguna, especially the neighborhood of La Vega Lagunera.	2 people confirmed and 2 disappeared. Many livestock died.	Several people suffered burns from broken high-voltage cable and electric cables.	Not counted but reported.	Flooding of the streets and many buildings of Santa Cruz de Tenerife, San Andrés and San Cristóbal de La Laguna. Flooding of and damage to the road from Santa Cruz de Tenerife to San Andrés and severe damage to a bridge located in the km 4. Flooding of many houses. Interruption of telephone communications due to a lightning strike. Interruption of traffic due to a landslide in km 7 in the road from Santa Cruz de Tenerife to San Andrés. Agricultural and livestock losses. Many crops were lost due to the break of the dam retaining wall.	Action by the fire brigade. Aviation troops and the Civil Guard intervened to save the neighborhood. The Captaincy General's Office sent ambulances to help the neighbors. The following day (5 May), the interrupted telephone communications were re-established.	At the premises of the Frente de Juventudes (in San Andrés, current exact location unknown), the water reached a height of 2 meters.	La Falange (6 and 7 May, 1944) Dorta (2007) Cabildo Insular de Tenerife (2004) Consejo Insular de Aguas de Tenerife (2004) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1926	15 to 17 January, 1926	Many parts of the island of Tenerife, especially in Santa Cruz de Tenerife and San Cristóbal de La Laguna, but it was an event that affected the whole archipelago.	Torrential rains Flooding Heavy swell	The center of the island of Tenerife, but especially Santa Cruz de Tenerife and San Cristóbal de La Laguna.	0 (in Tenerife, but 6 people died in Gran Canaria)	Not reported.	Not reported.	Flooding of the streets of Santa Cruz de Tenerife and San Cristóbal de La Laguna, with accumulation of sediment and stones. Sewer blockage. General damages across the streets. Interruption of activities at the Santa Cruz de Tenerife dock. Agricultural losses. Many crops were lost due to flooding.	Not reported.	On the first day of heavy rains, farmers and other villagers were happy that the drought was finally over and that this meant, according to them, that diseases and epidemics would not spread. But the next day, when the torrential rains began to ruin the crops, the joy was over, with the possibility that these epidemics could also arise as a consequence. In the Paseo de la Universidad (San Cristóbal de La Laguna) the water reached a height of one meter.	El Progreso (16 and 18 January, 1926) Gaceta de Tenerife (16 and 17 January, 1926) Arroyo (2009) Dirección General de Protección Civil (2014)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Flooding 1922	29 November to 1 December, 1922	NE of Tenerife	Storm Constant rains Strong winds Torrential rains Flash floods (sediment-laden) Overflow Flooding Thunderstorm Heavy swell	Especially Santa Cruz de Tenerife and San Cristóbal de La Laguna, Barranco de Santos (ravine; Santa Cruz de Tenerife), Barranco de Almeida (ravine; Santa Cruz de Tenerife), Barranco de Tahodio (ravine; Santa Cruz de Tenerife), Barranco del Aceite (ravine; Santa Cruz de Tenerife), Barranco de la Ruda (ravine; San Cristóbal de La Laguna), Barranco de San Juan (ravine; San Cristóbal de La Laguna).	1 person disappeared. Many livestock died.	There are reports of injuries but they were not counted.	Not counted but reported.	Flooding and damage of the streets and buildings. Work in the industries and in other jobs had to be suspended, with the possibility of losing the payment of these days. The harbor was closed and many ships couldn't dock there, without downloading the goods. Damage to some roads, such as the San Andrés road, the road from Santa Cruz de Tenerife to San Cristóbal de La Laguna, the road to the Nuevo Cementerio, the road of the Rosario, or the road from La Laguna to Las Canteras. Damage to some dams. Damage to the Catalanes aqueduct and other water storage infrastructure for irrigation. Damage to two limestone quarries in Santa Cruz de Tenerife. Damages across the affected cities and to many cars. Interruption of the tramway in Santa Cruz de Tenerife due to the accumulation of sediment and stones. Breakage of telegraph wires, gas pipes, electric lighting and sewers. Flooding of streets, damage and destruction of bridges, such as the Cabo bridge (Santa Cruz de Tenerife), and the retaining walls of the ravines that overflowed. Agricultural and livestock losses. A transfer of 61,656.43 pesetas is proposed. Damages in the mountains of Las Mercedes are estimated in 6,000 pesetas. It is estimated that 150,000 pesetas will be needed to clean and repair the streets of Santa Cruz de Tenerife, and 30,000 pesetas to repair the damage to the bridge at El Cabo. Many gardens and crops were flooded and damaged. The mountains of Aguirre, La Laguna, Las Mercedes and Tegueste have been damaged, with numerous trees uprooted and carried down the ravines.	The municipal architect ordered the closure of the entire citadel due to the danger of building collapse. On 30 November, the civil governor visited all the places affected, making the necessary arrangements to avoid danger. On the night of 30 November, he managed to get a section of the Artillery to start bailing out the water. But as no authority appeared, they abandoned the work, forcing the villagers to leave their houses and take lodgings in neighboring ones. Neighbors offered their homes to house the evicted people. Relief was mainly provided by neighbors. The Red Cross and the Civil Guard also provided assistance. On 1 December, the broken gas pipes were started to be repaired. Clean-up work began on 2 December. After two attempts to get a pump to pump out the water, because the first one did not work and the second one was not lent, the neighbors asked the civil governor for help. Mayor Orozco Batista asked the President of the Council of Ministers and the government for help for the city of Santa Cruz de Tenerife (the worst affected). The chief engineer of public works, Pedro Matos, asked the Director General of Public Works for financial resources to repair the destroyed roads. The Minister of Public Works can only offer twenty thousand pesetas for repairs. The Mayor appointed the architect Otilio Arroyo to direct the reconstruction work, and the municipal architect Antonio Pintor to design a project to repair the damage to the El Cabo bridge, the Santos ravine and Imeldo Serís street. The Civil Guard of La Laguna carried out a reconnaissance of the damage caused on the Las Mercedes hill.	The storm is said to have been similar to the 1920 storm, but although the storm of 1920 lasted longer and more water fell, it is said that this 1922 storm surpassed it in violence and persistence. 269 l/m2 (measurement period of 24 hours). Maximum temperature = 16.1, minimum temperature = 13.3. Atmospheric pressure = 752 - 759.3 hPa (29 November to 1 December). Wind direction = SSE. The height of the water reached a meter in the flooded houses from Calle de la Marina (Santa Cruz de Tenerife), half a meter in Calle el Pilar (Santa Cruz de Tenerife), a meter in the road of San Diego (San Cristóbal de La Laguna), nearly a meter in San Francisco square (San Cristóbal de La Laguna), and a meter and a half in Calle Nava Grimón (San Cristóbal de La Laguna). It is said that the ravine of Tahodio washed away the stones at its mouth allowing the sea to enter up to the first bridge. Waves reached 15 meters in the harbor of Santa Cruz de Tenerife. In San Cristóbal de La Laguna the rain gauge registered 91.00 millimeters on the 30th of November, and 178.00 on the 1st of December. There have been some accidents involving people who have wanted to look around the affected areas by climbing on the towers of temples and rooftops.	El Progreso (30 November, 1, 2, 4 and 6 December, 1922) Gaceta de Tenerife (30 November, 1, 2, and 3 December, 1922) Dorta (2007) Cola (2013)
Flooding 1920	2 to 4 March, 1920	N of Tenerife	Storm Constant rains Torrential rains Flash floods (sediment-laden) Overflow Flooding Landslide Thunderstorm Maritime storm Heavy swell	Santa Cruz de Tenerife, Barranco de Santos (ravine; Santa Cruz de Tenerife), Barranco Salto del Negro (ravine; Santa Cruz de Tenerife), Barranco del Rey (ravine; la Victoria de Acentejo), San Cristóbal de La Laguna, Tacoronte, Icod de los Vinos, los Realejos, la Victoria de	0 people. Some mules and horses died.	There are reports of injuries but they were not counted.	Not reported but probably due to the flooding of and damage to several houses and other buildings.	General damages across the affected cities, especially to the buildings and the retaining walls of the ravines that overflowed. Flooding of several buildings, houses, streets and paths. Damage to the road Tacoronte - Tejina and to the road Fasnia - Arico. Destruction of 5 houses in Tacoronte and damage to other 2, and destruction of 8 houses in la Victoria. Breakdowns in telephone lines and electric lighting. 80 centimeter break in the new Catalanes aqueduct (Cortadura Grande) as a result of rain and a landslide. Agriculture and livestock losses. Many gardens and crops were flooded and damaged. Severe damages to many images from churches.	The barges in the port of Santa Cruz de Tenerife were placed in the shelter of the quay during the first day of rainfall for fear of a repetition of the damage caused by the last storm (1918), and the goods were quickly removed. The Mayor's Office has ordered the immediate repair of the rupture of the Catalanes aqueduct (Cortadura Grande) that supplies the capital as this caused the water to stop flowing. Assistance from the Red Cross and Guardia Civil, and help from neighbors.	The height of the water reached half a meter in Calle Numancia (Santa Cruz de Tenerife), and more than a meter in some points across San Cristóbal de La Laguna. Neighbors commented that they did not remember seeing rain like that. A resident of Fasnia said that by 4 March it had been raining for 25 days. The heavy swell also caused the flooding of some houses located near the coast in Santa Cruz de Tenerife. In San Cristóbal de La Laguna the rain gauge registered 127,00 millimeters on the 3rd of March.	El Progreso (3, 4 and 6 March, 1920) Gaceta de Tenerife (4 to 5 March, 1920) Gaceta de Tenerife (30 November, 1, 2, and 3 December, 1922)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
				Acentejo, Fasnia.							
Flooding 1918	3 to 5 January, 1918	NE of Tenerife	Storm Strong winds Maritime storm Heavy swell Torrential rains Flash floods Overflow Flooding Rock fall	NE, E and SE of Tenerife, especially Santa Cruz de Tenerife, San Andrés, San Cristóbal de La Laguna, La Orotava village, Tegueste, Güímar, Granadilla, la Guancha, Puerto de la Cruz, Tejina, Bajamar, La Punta, and la Victoria de Acentejo, ravine of San Felipe, ravine of Las Cuevas (Tejina), Barranco Martiánez (ravine).	4 people. Some cows were buried under the rubble of houses damaged by the storm.	There are reports of injuries but they were not counted.	Not counted but the lower part of the city of Puerto de la Cruz, for example, is said to have been evacuated due to the flooding of and damage to several houses and other buildings, as well as many families across the affected cities and villages had to leave their houses.	General damages across the affected cities, especially to the buildings and the retaining walls of the ravines that overflowed. Many buildings along the coast, together with a boat, were swept out to sea, and six boats ran aground on the beach. Another schooner was destroyed. Many streets were damaged too and there were some breakdowns in telephone lines and electric lighting. Agriculture and livestock losses. Damage to the San Felipe road and the Port of Santa Cruz. In La Guancha, losses were estimated at around 200,000 pesetas. Many trees, gardens and crops across the affected cities were destroyed or severely damaged. Severe damages to many images from churches.	The following day, the mayor of Santa Cruz de Tenerife toured the entire town to arrange for the immediate repair of the damage. On the advice of the Engineer Director of the Agricultural Farm, he gave orders to the gardener in charge of the avenues and public walks to repair the damage in those areas as soon as possible and to make use of the fallen trees that were of some value. The mayor, also advised by the municipal architect, visited the Archpriest of the capital to take the necessary steps to repair the Hermitage of San Telmo. Traffic was suspended in the nearby streets and the surrounding houses were evacuated so that the tower could be demolished and restored. The deputy mayor of San Andrés opened a subscription so that wealthy people and the town council itself could help those most affected. The mayor of La Orotava called the Government for assistance to affected persons by using the public funds for disasters, as well as for reconstruction works.	One of the victims died due to a rock fall from the cliff known as "Muralla Grande", between the km 7 and 8 of the road of San Andrés, and another drowned due to the strong waves, after jumping into the sea to pick up objects from one of the beached boats. The other two victims are believed to have been swept away by the waves while walking through the harbor. In San Cristóbal de La Laguna the rain gauge registered 109.00 millimeters on the 4th of January.	Gaceta de Tenerife (4 to 8 January, 1918) Gaceta de Tenerife (30 November, 1, 2, and 3 December, 1922)
Flooding 1914	22 November, 1914	Several parts across the island of Tenerife.	Storm Strong winds Thunderstorm Maritime storm Heavy swell Torrential rains Flash floods Overflow Flooding	Santa Cruz de Tenerife, especially the Barranco de Santos (ravine), and San Andrés, especially the ravine of Cercado de San Andrés.	1	There are reports of injuries but they were not counted.	Not reported but probably due to the flooding of and damage to several houses and other buildings.	Nearly 2/3 of the buildings of Santa Cruz de Tenerife, were flooded, including the military hospital and the church of La Concepción again, and lots of them were damaged. Lots of streets, including the street of Iriarte (Santa Cruz de Tenerife), were flooded due to the obstruction of the drains by the amount of stones and mud that were dragged from the ravines and the unpaved areas. The road of San Andrés was also blocked due to the amount of stones and mud coming from the mountains. The lower part of Calle de la Consolación (Santa Cruz de Tenerife) collapsed. Agriculture losses. Some crops and gardens were flooded.	The next day, workers began to clear the drains of stones and mud. Many landlords were criticized for the poor state of many properties prior to the storm, and the authorities were called in order to force them to refurbish their dwellings.	The height of the water reached half a meter in Calle de Iriarte and in the Church of La Concepción, and nearly a meter in a garden.	El Progreso (23 November 1914)
Flooding 1912	5 to 8 February, 1912	Several parts across the island of Tenerife, but the storm mainly affected Gran Canaria.	Storm Strong winds Heavy swell Torrential rains Flooding	Several parts across the island of Tenerife, but especially in La Orotova.	1	There are reports of injuries but they were not counted.	Not reported.	Severe damages across different municipalities of Tenerife. Damage to roads, houses, infrastructures. Even the English steamer "Zoner" lost one of its anchors due to the storm and a boat sank. Serious breakdowns in telephone lines and electric lighting. Many trees fell and were severely damaged. Serious affection to agriculture, crop losses. Crop losses and sever damage to trees.	Not reported.	The person who died was electrocuted by a falling electric cable.	El Progreso (8 February 1912). Gaceta de Tenerife (7 February 1912). Gaceta de Tenerife (9 February 1912). Arroyo (2009)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Flooding 1904	1 to 2 November, 1904	Several parts across the island of Tenerife.	Torrential rains Flash floods Overflow Flooding	San Andrés (Santa Cruz de Tenerife), ravine of Cercado de San Andrés.	0	0	Not reported, but there were probably no displaced people because no houses were destroyed.	Destruction of one of the defense walls of the Cercado de Andrés ravine, damage to the road from Santa Cruz de Tenerife to San Andrés, some damages across San Andrés, damage to agriculture and livestock (pigs). Damage to some vegetable and fruit crops.	Not reported.	The bed of the Cercado de Andrés ravine rose about two meters above its original bed and advanced out to sea, forming a breakwater of about 150 meters.	Diario de Tenerife (8 November 1904) El Tiempo (4 November 1904)
Flooding 1901	10 to 14 April, 1901	North of the Tenerife island	Storm and torrential rains Thunderstorm Strong winds Maritime storm Heavy swell Flash floods Overflow Flooding Rock fall	North of Tenerife, but especially Santa Cruz de Tenerife, San Cristóbal de La Laguna, Tacoronte, Santa Úrsula, Garachico, Icod, La Orotava Valley, San Juan de La Rambla, Puerto de La Cruz, San Nicolás, Buenavista del Norte, Las Cabezas ravine, Martiánez ravine, San Felipe ravine.	8 (also a minimum of two oxen died)	There are reports of injuries but they were not counted.	Not reported but probably due to the destruction of several buildings.	100,000 pesetas approximately. Destruction of and damage to several bridges (old bridge of Las Cañas, Las Aguas and Roque bridges, the bridge of the Siete Ojos), houses (>13), other buildings and infrastructures, such as the road from Garachico to Icod, a road in Santa Úrsula and in San Juan de La Rambla, and a road from San Nicolás to Puerto de La Cruz, or the hermitage of San Pedro in San Juan de La Rambla. Destruction of a boat in Garachico, severe damages to several properties/farms in La Orotava Valley, Puerto de La Cruz, Santa Úrsula and San Juan de La Rambla, such as the properties of La Galvana (¿La Gorvorana?), San Gerónimo and Piedra Redonda, the property of Doña Guadalupe del Hoyo, La Coronela, Las Lagunetas. Damage to agriculture and livestock. Flooding of several fields, crops and gardens.	The injured who could be helped were taken to hospital. Neighbors and even the municipal magistrate provided assistance. In Buenavista del Norte, the legal representatives (judge, mayor and councilors) convened a plenary session in the town hall. They decided to hold a funeral for the deceased, and given the scarcity of resources for such an event, the mayor D. Juan Hernández Segovia covered the expenses. The Tenerife newspaper "Diario de Tenerife" publishes the news and alerts the public and official attention by mentioning some past events and their consequences, such as the flood of 1826. It also calls for contingency plans for future dangers. Today, in Las Lagunetas (Buenavista del Norte) the ravine is paved and has become a street with houses on the sides.	There were also damages in Gran Canaria.	Diario de Tenerife (22 April 1901) Cabildo Insular de Tenerife (2004) Velázquez (2013)
Flooding 1901	1901 (exact date and duration unknown)	El Palmar, Güímar	Torrential rains Flash floods Overflow Flooding	El Palmar, Güímar, Barranco Fregenal (ravine), Barranco del Agua (ravine).	0	Not reported.	Not reported.	Damages to the Guaza bridge, in the road TF-28, and to the infrastructures across Güímar. Damages to agriculture in Güímar.	Not reported.	None.	Duran et al. (1989) Quirantes et al. (1993)
Flooding 1899	22 to 26 December, 1899	Tenerife	Torrential rains Maritime storm Heavy swell Flash floods Overflow Flooding	Guía de Isora, Güímar, San Cristóbal de La Laguna, Santa Cruz de Tenerife, Barranco de Santos (ravine), Santa Úrsula, El Sauzal, La Victoria de Acentejo, Barranco del Cercado de Andrés (ravine), Barranco de Las Huertas (ravine).	0	Not reported.	Not reported.	Damages to houses, to bridges, especially in Güímar, El Sauzal and La Victoria de Acentejo, damages to infrastructures. Flooding of the Church of La Concepcion (supposedly) and several houses in Santa Cruz de Tenerife, probably also across the rest of the affected municipalities. Damages to agriculture.	Not reported. It is known that in Santa Cruz de Tenerife it was decided that year to build another iron bridge across the Barranco de Santos (ravine) upstream. It took 60,000 pesetas from the municipal budget, although it took 6 years to build and was made of concrete, at the height of the street Galceran.	The height of the water reached 1 m in street of La Caleta (Santa Cruz de Tenerife).	Consejo Insular de Aguas de Tenerife (2004) Dorta (2007) Cola (2013) Dirección General de Protección Civil (2014) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1898	28 October, 1989	San Andrés	Torrential rains Flash flood Overflow Flooding	San Andrés	0	Not reported	Not reported	Collapse of the San Andres Tower.	Not reported.	None.	Santa Cruz de Tenerife - Ayuntamiento (10 July, 2022)
Floodings 1895	1895 (exact date and duration unknown)	Tenerife	Big storms It is not known whether flooding occurred, although it is	Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	Coincidentally, on 9 March 1895, the cruise ship Reina Regente sank on its crossing from Tangiers to Cadiz due to a heavy storm. This storm may or may not have affected the island of	Arroyo (2009) Díaz-Ordóñez (2009)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
			likely							Tenerife, and other islands of the archipelago, and could correspond to one of these storms mentioned during 1895.	
Flooding 1894	6 March, 1894	San Andrés	Probably torrential rains Flash flood Overflow Flooding	San Andrés, especially at the mouth of the Barranco del Cercado de San Andrés ravine.	Not reported.	Not reported.	Not reported.	Destruction of the San Andres Valley Tower, previously damaged. The cost of rebuilding it was estimated at 4,535.25 pesetas, but the estimate was not accepted and it was subsequently appraised at 1,083.13 pesetas for public sale at auction.	Not reported. The tower was declared a ruin and is currently still in ruins. In 1977, the Cercado de San Andrés ravine was channeled and the tower area was remodeled by building a bridge over the riverbed. In addition, the Tower of San Andrés was protected from possible floods by means of a stone wall with a palisade	None.	Tous (2012)
Flooding 1893	30 October, 1893	San Andrés	Probably torrential rains Flash flood Overflow Flooding	San Andrés, especially at the mouth of the Barranco del Cercado de San Andrés ravine.	Not reported.	Not reported.	Not reported.	Severe damage of the San Andres Valley Tower.	Not reported.	None.	Tous (2012)
Flooding 1880	18 to 21 December, 1880	Güímar	Probably torrential rains Flash flood Overflow	Güímar	Not reported.	Not reported.	Not reported.	Damages to houses. Damages to agriculture.	Funds were raised in 1880 and 1885 for the relief of the affected people (Junta Real de Socorro de la Ciudad de La Laguna).	None.	Duran et al. (1989)
Flooding 1879	October to December, 1879 (exact date and duration unknown)	San Cristóbal de La Laguna, Santa Cruz de Tenerife, and other parts of the Tenerife.	Storm with torrential rains Flash floods Overflow Flooding	At least, Santa Cruz de Tenerife and San Cristóbal de La Laguna, but probably other parts of Tenerife.	0	Not reported.	Not reported.	Destruction of the El Cabo bridge, flooding of the church (probably the Church of La Concepción or another along the edges of the ravine) and its surroundings. Probably damages across Santa Cruz de Tenerife and San Cristóbal de La Laguna.	Funds were raised in 1880 for the relief of the affected people (Junta Real de Socorro de la Ciudad de La Laguna). Reconstruction works, especially of the El Cabo bridge. The City Council asked the residents to contribute financially. After a year, part of the work on the bridge and the side walls was finished, but due to political conflicts, difficulties in bringing in the necessary material, and lack of money, the work came to a standstill. Its complete reconstruction was completed after 5 years.	The neighborhood of El Cabo and the cemetery of San Rafael and San Roque were cut off, making burials impossible for several days. In San Cristóbal de La Laguna approximately 180 to 200 millimeters were collected during the 24 hours of 19 December.	Gaceta de Tenerife (30 November, 1, 2, and 3 December, 1922) Quirantes et al. (1993) Dorta (2007) Cola (2013)
Flooding 1867	7 March, 1867 (exact duration unknown)	Santa Cruz de Tenerife and La Orotava.	Storm with torrential rains Strong winds Flash floods Overflow Flooding Probably heavy swell	At least, Santa Cruz de Tenerife and La Orotava.	0	Not reported.	Not reported.	Damages to the El Cabo bridge and across the city of Santa Cruz de Tenerife. Probably damages across other parts of this sector of the island. A hurricane destroys the mythical "Drago of La Orotava", an icon of Tenerife.	Funds were raised in 1867 and 1868 for the relief of the affected people (Junta Real de Socorro de la Ciudad de La Laguna). Reconstruction works, especially of the El Cabo bridge. The works would take two years and were financed with money from the residents.	The damage in Santa Cruz de Tenerife was partly caused by the overflowing of the Barranco de Santos (ravine) again.	Dorta (2007) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011) Cola (2013)
Flooding 1865	November 1865	Several parts of the island of Tenerife, probably the NE	Storm Torrential rains Strong winds Probably flash floods Flooding	San Andrés	0	Not reported.	Not reported.	General damages in some parts (undescribed), mainly agricultural losses due to destruction of flowers and fruits still green. Damage to orange, banana, palm and prickly pear trees.	Not reported.	None.	El Eco del Comercio (11 November, 1865) Cabildo Insular de Tenerife (2004)
Flooding 1859	12 December, 1859	Santa Cruz de Tenerife	Torrential rains Flash flood Overflow Flooding	Santa Cruz de Tenerife	Not reported.	Not reported.	Not reported.	Damage to the El Cabo bridge. Probably flooding of other buildings.	Not reported.	None.	Dorta (2007) Cola (2013)
Maritime storm 1856	6 to 7 January, 1856	Garachico, probably other coasts in the north of Tenerife	Maritime storm Heavy swell Flooding	Garachico	2	1	Not reported, but probably due to the flooding of and the damage caused to several	Severe damages to the Monastery of La Concepción. Probably other damages across the city of Garachico.	Not reported.	It is described that such an event usually takes place at the beginning of the tide, i.e. at the beginning of the ebb or flow. At that moment, whenever the storm comes from the north, three waves appear almost a mile from land, hitting the coast, and the third of them	Romero (1990) Acosta (2019)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
							buildings.			ends up entering the streets of the city. The sea foam is also said to extend up to a mile inland and almost three miles along the coast.	
Flooding 1853	1853 (exact date and duration unknown)	Barranco de Santos (ravine), Santa Cruz de Tenerife	Torrential rains Flash flood Overflow Flooding	Santa Cruz de Tenerife	0	Not reported.	Not reported.	Damage to the El Cabo bridge. Probably flooding of other buildings.	Not reported. Reconstruction of the bridge piers.	None.	Dorta (2007) Cola (2013)
Flooding 1849	1849 (exact date and duration unknown)	San Cristóbal de La Laguna (Santa Cruz de Tenerife)	Torrential rains Flooding	San Cristóbal de La Laguna	0	Not reported.	Not reported.	Not reported.	Not reported.	None.	Quirantes et al. (1993) Dorta (2007)
Flooding 1837	8 March, 1837	Barranco de Santos (ravine), Santa Cruz de Tenerife	Torrential rains Flash flood Overflow Flooding	Santa Cruz de Tenerife	0	Not reported.	Not reported, but probably due to the destruction of two houses and the flooding of other buildings.	Destruction of two houses and part of the hospital garden, flooding of the church of La Concepción, the houses from the street of La Noria, the Church Square, and the neighborhood of El Cabo. All parts of the town through which the secondary ravines ran were severely damaged. Loss of part of the hospital garden.	Funds were raised in 1847 for the relief of the affected people (Junta Real de Socorro de la Ciudad de La Laguna). Reconstruction works, which took years due to lack of budget. General Juan Manuel Pereyra y Soto-Sánchez took charge of the reconstruction of the retaining walls of the ravine, extending them up the left bank of the ravine. The work was completed in November 1838.	It rained heavily for 8 hours straight.	Dorta (2007) Cola (2013) Dirección General de Protección Civil (2014)
Flooding 1829	November, 1829 (exact date and duration unknown)	Santa Cruz de Tenerife	Torrential rains Flooding	Santa Cruz de Tenerife	0	Not reported.	Not reported.	Not reported.	Not reported.	None.	Dorta (2007)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
San Florencio Storm or the Storm of 1826	6 to 8 November, 1826	The Canary Islands, especially the Tenerife island.	Storm with strong winds and torrential rains (possibly due to a tropical cyclone) Maritime storm and heavy swell Flash flood (sediment-laden) Filling of old riverbeds with debris. Overflow and flooding (sediment-laden) Formation of new ravines Famine	Almost the entire island of Tenerife (apart from the other islands of the archipelago), but especially the Valley of La Orotava, La Guancha, Güímar, San Cristóbal de La Laguna, Santa Cruz de Tenerife, Candelaria, Icod de los Vinos, Puerto de la Cruz, Los Realejos, San Juan de la Rambla, Santa Úrsula.	There are discrepancies with the total number of fatalities, ranging between 200 and 600. Some counts are: 490 200 (only in La Orotava Valley) 253 >300 (only in La Orotava Valley, Güímar and Santa Cruz de Tenerife) 243 >500 284 261 In addition, hundreds or even 1,009 or 1,080 animals died.	Not reported but probably there were many injuries.	Not reported but probably there were many displacements due to the destruction of hundreds of houses.	£350,000; >7,000,000 pesetas Apart from a great impact on trade, agriculture and livestock farming, as well as severe damage and/or destruction of many houses (499; 423; 344; or even 603), the containment infrastructure in ravines, bridges (16; as El Cabo bridge again, in Santa Cruz de Tenerife), aqueducts (8), mills (10), military constructions, convents and churches, public buildings, ships and their loads, maritime infrastructures, and other municipal infrastructures. There was also a significant backlog of contributions to the Royal Treasury. Severe damage in many forests and crops around the island.	It is said that neither the Canarian nor the national authorities provided sufficient relief to the Canarian population. The main aid came from a subscription opened in London, which was viewed with suspicion by the Spanish government, to the point of issuing a Royal Order was issued so that the authorities were warned to be on the alert as to the intentions of foreigners in such an act of charity. On the other hand, The Bishop of Tenerife, who was asked to contribute to the most pressing needs, replied that he had arranged for masses to be celebrated to alleviate hunger and cover the nakedness. A few weeks later he changed his mind and two hundred bushels of wheat were distributed to the inhabitants of the worst affected areas. This belated generosity could not erase the impression made by the first refusal. The Town Council of Santa Cruz de Tenerife began the works of reconstruction and restoration of the damaged elements, reducing the costs. Works such as the reconstruction of the north wall of the Barranco de los Santos (ravine) were financed with contributions from the neighborhood and sometimes from private individuals, such as Francisco Roca, who advanced the money. It took a year to rebuild the El Cabo bridge in the Santos ravine (Santa Cruz de Tenerife), but the repair of the walls took several more years due to lack of money.	It is considered the biggest meteorological catastrophe of the islands, responsible for the greatest geomorphological and socio-economic impact of the archipelago. Maximum wind gusts probably exceeded 120-150 km/h, coming especially from the SE, SW and NW. Rainfall probably reached more than 100 mm/24 hours, or even more than 500 mm in some places (category of a torrential rain). The height of the water in the torrent of Luchon (Güímar), for example, was about 5 meters. The primitive image of the Patron Saint of the Canary Islands, the Virgin of Candelaria, disappeared in the sea due to a flash flood. The bridge of Zurita, built in Barranco de los Santos (ravine; Santa Cruz de Tenerife), was the only bridge left standing.	Martínez (>1807) Pinto (1954) De León (1966) Hernández (1968). Quirantes et al. (1993) Berthelot (1997) Consejo Insular de Aguas de Tenerife (2004) Dorta (2007) Bethencourt et al. (2008) Arroyo (2009) Ayuntamiento de La Villa de La Orotava (2011) Marzol and Máyer (2012) Cola (2013). Dirección General de Protección Civil (2014) Consejo Insular de Aguas de Tenerife (2019)
Flooding 1821	November, 1821 (exact date and duration unknown)	North of the Tenerife island.	Storm with torrential rains Flash flood/flooding (no more specifications)	La Guancha, La Orotava village, and probably other areas in the north of the island.	Not reported, probably 0.	Not reported.	Not reported.	Damage to houses and crops. Damage to the old Drago tree located in La Orotava village (the tree no longer exists in this place, as it was destroyed during the storm of 1867).	Not reported.	None.	Quirantes et al. (1993) Dorta (2007) Arroyo (2009)
Flooding 1820	5 November, 1820	NE of Tenerife	Torrential rains Flash flood Overflow Flooding	Tacoronte, ravine of Las Lajas.	0	Not reported.	Not reported.	General flooding.	Not reported.	None.	Peraza (2015)
Flooding 1815	1815 (exact date and duration unknown)	La Orotava	Probably torrential rains Flash flood/flooding (no more specifications)	La Orotava, specific site is unknown.	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	None.	Quirantes et al. (1993) Dorta (2007)
Flooding 1781	21 February, 1781	Ajar (current location unknown)	Probably torrential rains Flash floods Overflow Flooding	Ajar (current location unknown)	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	None.	Quirantes et al. (1993) Dorta (2007)
Flooding 1773	27 December, 1773	Garachico	Storm Heavy swell Flooding	Coast of Garachico	0	Not counted but reported	Not reported but probably due to the	Several houses and buildings near the coast were destroyed or severely damaged.	Not reported.	None.	Acosta (2019)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
							destruction of several buildings.				
Flooding 1773	1773 (exact date and duration unknown)	Barranco de los Santos (ravine; Santa Cruz de Tenerife)	Torrential rains Flash flood Overflow	Barranco de los Santos (ravine; Santa Cruz de Tenerife), probably other parts of the city were also affected but they are not reported.	Not reported.	Not reported.	Not reported.	The El Cabo bridge across the ravine was severely damaged again. Probably some damages around Santa Cruz de Tenerife.	The General Commander López Fernández de Heredia ordered a commission headed by Mayor Bernardo Rodríguez Carta, who raised the necessary resources with contributions from the neighborhood, to repair the El Cabo bridge.	None.	Dorta (2007) Cola (2013)
Flooding 1769	spring 1769 (exact date and duration unknown)	San Andrés	Probably torrential rains Flash floods Overflow Flooding	San Andrés, especially at the mouth of the Barranco del Cercado de San Andrés ravine.	Not reported.	Not reported.	Not reported.	Destruction of the San Andres Valley Tower.	Nine months after the flood, the tower was rebuilt.	None.	Tous (2012)
Flooding 1759	1759 (exact date and duration unknown)	Barranco de los Santos (ravine; Santa Cruz de Tenerife)	Torrential rains Flash flood Overflow	Barranco de los Santos (ravine; Santa Cruz de Tenerife), probably other parts of the city were also affected but they are not reported.	Not reported.	Not reported.	Not reported.	The El Cabo bridge across the ravine was destroyed again. Probably some damages around Santa Cruz de Tenerife.	The El Cabo bridge was rebuilt in the same site. The Island Council was again responsible of this work.	None.	Dorta (2007) Cola (2013)
Flooding 1752	1752 (exact date and duration unknown)	Barranco de los Santos (ravine; Santa Cruz de Tenerife)	Torrential rains Flash flood Probably overflow	Barranco de los Santos (ravine; Santa Cruz de Tenerife), probably other parts of the city were also affected but they are not reported.	Not reported.	Not reported.	Not reported.	Destruction of the quay.	Not reported.	The bridge of El Cabo, destroyed two years before (in 1750), was not yet rebuilt.	Hernández (1968) Quirantes et al. (1993) Dorta (2007) Cola (2013)
Flooding 1750	1750 (exact date and duration unknown)	Barranco de los Santos (ravine; Santa Cruz de Tenerife)	Rainstorm and strong winds Flash flood Overflow	Barranco de los Santos (ravine; Santa Cruz de Tenerife), probably other parts of the city were also affected but they are not reported.	0	Not reported.	Not reported.	The El Cabo bridge across the ravine was destroyed, and a parish was flooded, probably the parish of Los Remedios. Probably severe damages around Santa Cruz de Tenerife.	A direct access to the El Cabo neighborhood was also done by building a new bridge in another site, today near the Rambla Pulido, to avoid dependence on the El Cabo bridge. The Island Council was responsible of this work. But a new bridge was rebuilt in the same site as El Cabo bridge, thanks to the important financial contribution of the ombudsman Roberto La Hanty.	Today the ravine is channeled and several flood containment works have been carried out.	Dorta (2007) Cola (2013)
Flooding 1749	1 November, 1749	San Cristóbal de La Laguna (Santa Cruz de Tenerife)	Torrential rains Flooding	San Cristóbal de La Laguna, especially the neighborhood of San Juan.	Not reported, but 200 houses were swept away by the flood, so there were probably several deaths.	Not reported, but probably.	Not reported, but probably they would have been due to the destruction of 200 houses.	200 houses were swept away by the flood, and other damages around the city.	Not reported.	None.	Pinto (1954) Quirantes et al. (1993) Dorta (2007)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Flooding 1733	27 December, 1733	Garachico	Probably heavy swell Flooding	Garachico	Not reported.	Many people are said to have been injured.	Not reported, but probably they would have been due to the destruction of many houses in one of the streets, such as the Town Halls.	Many houses were destroyed in one of the streets of Garachico, such as the Town Halls, and there were other damages around the town.	Not reported.	The flooding of the city was caused by the rising sea, probably due to strong waves during a storm.	Romero (1990)
Flooding 1722	25 October, 1722	Barranco de los Santos (ravine; Santa Cruz de Tenerife)	Rainstorm and strong winds Flash flood Probably overflow	Barranco de los Santos (ravine; Santa Cruz de Tenerife), probably other parts of the city were also affected but they are not reported, and San Andrés.	0	Not reported.	Not reported.	The El Cabo bridge across the ravine was destroyed. Probably severe damages around Santa Cruz de Tenerife. Probably, damage to the San Andrés Valley Tower.	The El Cabo bridge was rebuilt in the same site. The Island Council was responsible of the rebuilding.	Today the ravine is channeled and several flood containment works have been carried out. However, in 1605, Bishop Francisco Martínez de Ceniceros ordered the construction of a palisade to protect the church from floods, and in 1645 another bishop, Francisco Sánchez de Villanueva, ordered the defenses to be repaired and completed. From this information we know that there were floods and overflows before 1722, and at least one between 1605 and 1645.	Hernández (1968) Quirantes et al. (1993) Dorta (2007) Tous (2012) Cola (2013)
Flooding 1719	19 April, 1719	Garachico	Probably heavy swell Flooding	Almost the entire town of Garachico.	0	0	0	Minor damage in the town of Garachico.	Not reported.	The sea invaded almost the entire town of Garachico and reached the steps of the rebuilt convent of San Francisco (current Casa de la Cultura), which is 14 meters high and 540 meters above sea level.	Romero (1990) Acosta (2019)
Flooding 1713	24 to 27 January, 1713	San Cristóbal de La Laguna (Santa Cruz de Tenerife)	Torrential rains Flooding Flooding of the lagoon of San Cristóbal de La Laguna Probably maritime storm	San Cristóbal de La Laguna (Santa Cruz de Tenerife), especially the Convent of San Francisco, now the Royal Sanctuary of Santísimo Cristo de La Laguna, Barranco de La Vega (ravine) in Arucas.	0	Not reported.	The friars of the convent had to be evacuated and relocated.	The Convent of San Francisco was flooded and many pieces of furniture and ornaments were lost. It needed around 1,000 pesos/escudos to be rebuilt.	The Island Council offered the hospital of San Sebastián to relocate the friars; the friars took out the Holy Christ, as well as the Eucharist, and took refuge in the house of the Count of Valle Salazar. Later, following a royal decree of authorization, in the same year of 1713 the Island Council offered a thousand pesos of its own funds for the rebuilding of the convent, which quickly repaired the damage caused by the flood.	The storm started in Tenerife on 24 January and moved to Gran Canaria, where it did cause several deaths. Around 1770 the lagoon disappeared.	Rumeu de Armas (1947) Pinto (1954) Cioranescu (1965) Hernández (1968) Quirantes et al. (1993) Quintana (2002) Dorta (2007)
Flooding 1649	1649 (exact date and duration unknown)	The whole island of Tenerife, but it affected all the archipelago	Storm and maritime storm Heavy swell Strong winds Probably flooding but not reported	Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	None.	Arroyo (2009)
San Damaso Flood 1645	11 December, 1645	Garachico	Torrential rains Flooding (sediment-laden, alluvium)	Garachico, especially the neighborhood of Los Reyes and the harbor, and the nearby mountains, in particular the area of San Juan del Reparo.	>100 (one citation mentions around 600 disappeared).	Not reported.	Not reported.	300,000 ducats - >300,000 pesos. 80 houses and 40-46 ships were destroyed, the harbor was damaged and, together with the bay, they were filled with sediment and debris carried by the flood, apart from other damages around the village of Garachico. It marked the beginning of the decline of the port of Garachico	Not reported.	The torrent was generated in the mountains near Garachico, when torrential rains formed a pool in the area of San Juan del Reparo and it overflowed. New ravines were created, and the flash flood flowed into the harbor, pushing the coastline a few meters out to sea and covering the harbor and the bay with sediment and	Pinto (1954) Hernández (1968) Romero (1990) Quirantes et al. (1993) Dorta (2007) Arroyo (2009)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
										debris. In 1706 the port would be again destroyed by the eruption of Arenas Negras.	
Flooding 1594	1594 (exact date and duration unknown)	Santa Cruz de Tenerife	Torrential rains Flooding (sediment-laden, alluvium) Probably strong swell	Santa Cruz de Tenerife, especially the harbor.	0	Not reported.	Not reported.	Damage to ships and the harbor.	Not reported.	None.	Hernández (1968) Quirantes et al. (1993) Dorta (2007)
Flooding 1590 (San Andrés storm)	1590 (exact date and duration unknown)	Tegueste, especially El Socorro (Santa Cruz de Tenerife)	Torrential rains Flooding (sediment-laden, alluvium)	Tegueste (probably other parts were also affected but they are not reported).	0	Not reported.	Not reported.	The Socorro chapel was destroyed.	Not reported.	None.	Pinto (1954) Quirantes et al. (1993) Dorta (2007) Dirección General de Protección Civil (2014)
Flooding 1550	1550 (exact date and duration unknown)	San Cristóbal de La Laguna (Santa Cruz de Tenerife)	Flooding of the lagoon of San Cristóbal de La Laguna (causes are unknown)	Current Plaza de la Constitución of San Cristóbal de La Laguna	0	0	0	The old Pila Baja fountain and its steps were flooded.	The fountain was moved to another place in the square and was renamed the Pila Seca. Prohibition of building in the Villa Arriba, which lasted from 1500 to 1511, to avoid the risk of flooding.	Around 1770 the lagoon disappeared.	Rumeu de Armas (1947) Cioranescu (1965)
LANDSLIDES											
Rock fall 2020	5 December, 2020	28.557507, -16.332872	No effects	Road TF-13 Kp. 16.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	5 December, 2020	28.5536, -16.2056	No effects	Road TF-34 Kp. 1.43	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	5 December, 2020	28.51048, -16.17961	No effects	Street Playa de las Teresitas	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	25 November, 2020	28.5322, -16.2592	No effects	Road TF-12 El Bailadero 56-68	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	17 November, 2020	28.37704, -16.36516	No effects	Highway TF-1, between Las Caletillas and Candelaria	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	16 May, 2020	28.535564, -16.131902	No effects	Playa de Antequera (beach)	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	Rock fall from the cliff.	IGME (2020)
Rock fall 2020	7 May, 2020	28.392355, -16.607718	No effects	Road TF-5 Kp. 42.85	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	6 May, 2020	28.392401, -16.607817	No effects	Road TF-5 Kp. 42.85	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	6 April, 2020	28.4227, -16.2951	No effects	Street Marítima de Añaza, Añaza	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	4 April, 2020	28.3947, -16.497	No effects	Slope over the road to Pino Alto in La Orotava	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2020	19 February, 2020	28.3957, -16.6516	No effects	Charco de la Laja	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	5 December, 2019	28.5099, -16.18618	No effects	Street Playa de las Teresitas, nº 111	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Rock fall 2019	5 December, 2019	28.5412, -16.2126	No effects	Road El Cercado 41-101	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	5 December, 2019	28.526, -16.2862	No effects	Road TF-12, Las Mercedes	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	5 December, 2019	28.5139, -16.1766	No effects	Road TF-121, road Igueste of San Andrés, from Santa Cruz to San Andres	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	Rock fall at the base of the road.	IGME (2020)
Rock fall 2019	28 October, 2019	28.392274, -16.603666	No effects	Road TF-5 Kp. 42.25	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	28 October, 2019	28.391975, -16.626993	No effects	Road TF-5 Kp. 44.6	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	26 October, 2019	28.1585, -16.638	No effects	Road TF-21 Kp. 68.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	6 April, 2019	28.3731, -16.7339	No effects	Road TF-42 Kp. 1.77	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	16 February, 2019	28.3097, -16.5027	No effects	Road TF-24 Kp. 36	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2019	1 January, 2019	28.3714, -16.7307	No effects	Road TF-42 Kp. 1.37	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2018	23 November, 2018	28.5636, -16.221	No effects	Road El Cardonal	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2018	23 November, 2018	28.5608, -16.2225	No effects	Street Lomo La Chanca, Taganana	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2018	23 November, 2018	28.5451, -16.2036	No effects	Road TF-134 Kp. 0.25	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2018	23 November, 2018	28.3657, -16.7698	No effects	Road TF-421 Kp. 5.8	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2018	18 November, 2018	28.3907, -16.5586	No effects	Road TF-333 Kp. 1.3	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2018	18 September, 2018	28.39343, -16.634788	No effects	Road TF-5 Kp. 45.6	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2018	24 August, 2018	28.501174, -16.423029	No effects	Playa de la Arena (beach)	0	0	0	Breakage of safety nets and fences.	Evacuation of the beach, establishment of a security perimeter, removal of fallen blocks, cleaning and repair of safety nets and fences.	None.	Europa Press (25 August, 2018) IGME (2020)
Rock fall 2018	18 February, 2018	28.393311, -16.635387	No effects	Coast of San Juan de la Rambla, between Las Aguas and La Rambla El Rosario	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2017	29 November, 2017	28.4897, -16.2631	No effects	Dam Los Campitos	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)

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Rock fall 2017	19 October, 2017	28.260715, -16.392248	No effects	Santa Lucía - Los Barrancos cave, Road TF-616 number 96	0	0	0	Damage to roofs of houses.	The City Council recommends vacating the homes. However, two years later, Town Council was trying to evict the neighbors, but they refused. Already in 2020, the City Council signs a decree to start the works of cleaning and stabilization of the slope, forcing the neighbors to vacate their homes.	None.	Medina (10 December, 2019) Medina (17 January, 2020)
Rock fall 2017	15 August, 2017	28.3768, -16.7247	No effects	Av. Marítima 17-31 Icod de los Vinos	0	1	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2017	29 July, 2017	28.393015, -16.629755	No effects	Road TF-5 Kp. 45	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	2 December, 2016	28.42449, -16.47922	No effects	Street Tosca Barrios in El Farrobillo	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	14 November, 2016	28.2563, -16.6227	No effects	Teide cable car parking	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	27 October, 2016	28.417134, -16.519495	No effects	Bollullo beach, in La Orotava	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	19 October, 2016	28.3954, -16.6571	No effects	Road TF-5 Kp. 47.8	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	25 July, 2016	28.5407, -16.2	No effects	General road TF-12 Kp. 5 - 6, to Taganana	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	12 July, 2016	28.36546, -16.88325	No effects	Road TF-445 Kp.4 Punta de Teno	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	6 March, 2016	28.5422, -16.2199	No effects	Road TF-12 Kp. 12.1, between El Bailadero and Las Casas de la Cumbre	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	24 February, 2016	28.393015, -16.629755	No effects	Road TF-5 Kp. 45	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	22 February, 2016	28.393275, -16.63987	No effects	Road TF-5 Kp. 46.1	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	21 February, 2016	28.393334, -16.635238	No effects	Road TF-5 Kp. 70.6	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	21 February, 2016	28.39334, -16.635199	No effects	Road TF-5 Kp. 45.6	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	21 February, 2016	28.412599, -16.529209	No effects	Road TF-31 Kp. 73.2	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	21 February, 2016	28.2845, -16.3849	No effects	Highway TF-1 Kp. 25.2	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	21 February, 2016	28.533937, -16.355936	No effects	Road TF-13 Tejina	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	20 February, 2016	28.4391, -16.4715	No effects	Road TF-5 Kp. 25.7	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)

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Rock fall 2016	18 February, 2016	28.259, -16.606	No effects	Road TF-21 of Las Cañadas del Teide	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	18 February, 2016	28.21823, -16.62765	No effects	Road TF-21 of Las Cañadas del Teide	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	18 February, 2016	28.210301, -16.640619	No effects	Road TF-21 of Las Cañadas del Teide, Kp. 49.36	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	14 February, 2016	28.0701, -16.726	No effects	Highway TF-1 Kp. 74	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	14 February, 2016	28.533939, -16.355941	No effects	Road TF-13 Tejina	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	11 January, 2016	28.1833, -16.4295	No effects	Highway TF-1 km 37,5, Tejina	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2016	11 January, 2016	28.533948, -16.355957	No effects	Road TF-13 Tejina	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	9 December, 2015	28.38468, -16.35514	No effects	Highway TF-1 Kp. 13	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	1 November, 2015	28.5737, -16.18882	No effects	Road TF-134 between Benijo and Almáciga.	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	31 October, 2015	28.5427, -16.205	No effects	General road TF-12 to Taganana	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	31 October, 2015	28.5328, -16.1982	No effects	General road TF-12 to Taganana	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	30 October, 2015	28.36481, -16.87955	No effects	Road TF-445 Punta de Teno	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	30 October, 2015	28.533848, -16.355765	No effects	Road TF-13 Tejina	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	30 October, 2015	28.50413, -16.38279	No effects	Road El Boquerón and street Zoilo Miranda	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	26 October, 2015	28.1284, -16.714	No effects	Barranco del Infierno (ravine)	1	4	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	16 October, 2015	28.4844, -16.23961	No effects	Anaga Avenue, highway TF-11 between Santa Cruz de Tenerife and San Andrés	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	10 October, 2015	28.532115, -16.353214	No effects	Road TF-13 Tejina	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	2 June, 2015	28.472434, -16.449917	No effects	Coast of El Puertito (El Sauzal)	0	1[pp]	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	13 May, 2015	28.41004, -16.56641	No effects	Cave of the harbor of Santa Cruz	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2015	10 March, 2015	28.53199, -16.35333	No effects	Road TF-13 Tejina	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2014	30 November, 2014	28.393616, -16.634232	No effects	Road TF-5 Kp. 45.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)

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Rock fall 2014	23 November, 2014	28.393382, - 16.630492	No effects	Road TF-5 Kp. 45.1	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2014	19 November, 2014	28.5412, - 16.2002	No effects	General road TF-12 Kp. 6, to Taganana	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2014	10 October, 2014	28.39179, - 16.6244	No effects	Road TF-5 Kp. 44.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2014	17 February, 2014	28.36196, - 16.89209	No effects	Road TF-445 Punta de Teno	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2014	29 January, 2014	28.50105, - 16.42292	No effects	La Arena beach, in Mesa del Mar	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2013	16 December, 2013	28.25902, - 16.60567	No effects	Road TF-21 of Las Cañadas del Teide	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2013	12 December, 2013	28.259923, - 16.818688	No effects	Road TF-82 Kp. 29.1	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2013	3 December, 2013	28.2953, - 16.4103	No effects	General road of the South TF-28	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2013	3 December, 2013	28.5031, - 16.1947	No effects	Highway TF-11 San Andrés	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2013	3 December, 2013	28.216274, - 16.62636	No effects	Road TF-21 of Las Cañadas del Teide, Kp. 47.68	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2013	2013 (exact date unknown)	28.4154, - 16.5396	No effects	Martiánez ravine	0	0	0	Direct damages	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2012	14 November, 2012	28.393015, - 16.629755	No effects	Road TF-5 Kp. 45	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2012	7 November, 2012	28.393015, - 16.629755	No effects	Road TF-5 Kp. 45	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2012	7 November, 2012	28.392581, - 16.627852	No effects	Road TF-5 Kp. 44.7	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Flow 2012	7 November, 2012	28.391822, - 16.626758	No effects	Road TF-5 Kp. 44.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Flow 2012	7 November, 2012	28.3937, - 16.6457	No effects	Road TF-5 Kp. 46.3 - 47.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2012	31 October, 2012	28.4833, - 16.24147	No effects	Anaga Avenue, highway TF-11 between Santa Cruz de Tenerife and San Andrés	0	1	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	A.H. (2 June, 2015) IGME (2020)
Rock fall 2012	2 June, 2012	28.393938, - 16.633492	No effects	Road TF-5 Kp. 45.4	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2012	9 April, 2012	28.393987, - 16.633111	No effects	Road TF-5 Kp. 45.3	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2012	28 February,	28.393302, - 16.630375	No effects	Road TF-5 Kp. 45	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)

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	2012										
Rock fall 2011	11 October, 2011	28.393273, -16.630331	No effects	Road TF-5 Kp. 45.05	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Collapse 2011	8 September, 2011	28.409592, -16.566978	No effects	Cave of the harbor of Santa Cruz	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	21 August, 2011	28.4166, -16.5362	No effects	Road TF-31 northeast of Puerto de la Cruz	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	4 July, 2011	28.3777, -16.7221	No effects	San Marcos beach, Camino de las Barandas, Icod de los Vinos	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	5 June, 2011	28.2605, -16.3936	No effects	Santa Lucía - Los Barrancos cave	0	0	Counted but not reported.	Damage to house roof tiles.	Approximately 17 days after the incident, clean-up work was carried out by a company contracted for this purpose by the Güímar City Council.	None.	Chijeb (23 June, 2011) IGME (2020)
Rock fall 2011	3 June, 2011	28.392922, -16.637425	No effects	Road TF-5 Kp. 45.7	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	30 May, 2011	28.39179, -16.6244	No effects	Road TF-5 Kp. 44.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	23 April, 2011	28.3792, -16.7242	No effects	San Marcos beach, Icod de los Vinos	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	9 April, 2011	28.394019, -16.644729	No effects	Road TF-5 Kp. 46.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	20 March, 2011	28.394041, -16.644644	No effects	Road TF-5 Kp. 46.5	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	15 March, 2011	28.4433, -16.2901	No effects	Street Chafira 60, Moraditas de Taco	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	9 February, 2011	28.393459, -16.6306	No effects	Road TF-5 Kp. 45	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	31 January, 2011	28.5683, -16.2094	No effects	Road TF-134 Almáciga	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	31 January, 2011	28.5464, -16.2405	No effects	Road TF-136 through Roque Negro	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	31 January, 2011	28.3787, -16.36853	No effects	Street la Guancha 45-59	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	31 January, 2011	28.5753, -16.1799	No effects	Road to the Draguillo	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	31 January, 2011	28.3767, -16.5881	No effects	Road TF-342 in Realejo Alto	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	31 January, 2011	28.504368, -16.378463	No effects	Road TF-156 Kp. 3	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2011	31 January, 2011	28.39345, -16.63472	No effects	Road TF-5 Kp. 45.6	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2010	29 November, 2010	28.392321, -16.620936	No effects	Road TF-5 Kp. 44	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2010	28 April, 2010	28.4021, -16.3229	No effects	Colón Avenue, Radazul Bajo	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2010	9 February, 2010	28.218216, -16.627642	No effects	Road TF-21 of Las Cañadas del Teide	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall	9 February,	28.210279, -	No effects	Road TF-21 of	0	0	0	No damages.	Not reported. Probably removal of fallen blocks	None.	IGME (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
2010	2010	16.640758		Las Cañadas del Teide, Kp. 49.36					and cleaning of the area.		
Rock fall 2010	1 February, 2010	28.5402, -16.2482	No effects	Road TF-136 36-36, through Roque Negro	0	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2010	February, 2010	28.5353, -16.2383	No effects	Road TF-12 La Panaderita, through Las Casas de las Cumbres	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2009	1 November, 2009	28.2474, -16.8406	No effects	Santiago del Teide beach, Los Gigantes Cliff	2	Reported but not counted.	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	EFE (2 November, 2009) IGME (2020)
Rock fall 2009	7 October, 2009	28.247293, -16.840505	No effects	Los Gigantes cliff beach	2	Not counted but reported	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	Información (2009)
Landslide and Rock fall 2009	August, 2009	28.1339, -16.7058	No effects	Barranco del Infierno (ravine)	1	Not reported	Not reported	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2007	27 January, 2007	28.50209, -16.19604	No effects	Highway TF-11 Kp. 2.6 San Andrés	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2006	6 August, 2006	28.28914, -16.86264	No effects	Masca beach	1	2	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 2001	23 December, 2001	28.1331, -16.7107	No effects	Barranco del Infierno (ravine)	1	Counted but not reported.	Not reported	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 1996	11 March, 1996	28.50066, -16.20143	No effects	Highway TF-11 San Andrés	1	0	0	Direct damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Landslide 1996	11 March, 1996	28.4587, -16.2594	No effects	Street Núñez de Balboa 5, Santa Cruz de Tenerife	2	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Landslide 1996	26 January, 1996	28.363, -16.7678	No effects	Road TF-421 2-2 El Tanque	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 1987	December, 1987	28.48217, -16.2403	No effects	Anaga Avenue 13, highway TF-11 between Santa Cruz de Tenerife and San Andrés	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall 1987	November, 1987	28.48445, -16.24149	No effects	Street Pista Militar 82-84	0	0	0	No damages.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall/Landslide 1947	27 January, 1947	28.482075, -16.396715 (aprox.)	Storm Landslide	Tacoronte	5	0	0	A house destroyed.	On the same day of the incident, the neighborhood and the authorities began the work of cleaning up and digging up the bodies.	The landslide was triggered by a rain and wind storm.	IGN (2020)
Landslide 1941	7 July 1941	Old massif to the NE of Santa Cruz de Tenerife	Freak wave Landslide Tsunami Flooding	Santa Cruz de Tenerife and San Andrés	0	1	Not reported.	Inundation of the littoral of Santa Cruz de Tenerife and San Andrés, affecting the Island Council building, the Maritime Avenue, breaking the door of an office and inundating the Navy Command	Not reported.	The waves surpassed heights of 2 m in the Cabildo building and 6 m in the Navy Command.	Galindo et al. (2021)
Rock fall ??	??	28.57088, -16.30798	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.57103, -16.31004	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.571, -16.31183	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.57117, -16.31437	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.57069, -16.31425	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Rock fall ??	??	28.57013, -16.3132	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56995, -16.31408	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56894, -16.31375	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56846, -16.31076	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56782, -16.31093	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56748, -16.30937	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56746, -16.30844	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56627, -16.30675	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56571, -16.30637	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56574, -16.30539	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.56211, -16.33068	Allegedly without effect.	La Hoya	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.558169, -16.332365	Allegedly without effect.	Hoya las Colmenas cliff	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.4414, -16.2955	Allegedly without effect.	Taco mountain, abandoned quarry	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	The Rock fall occurred in an abandoned quarry.	IGME (2020)
Rock fall ??	??	28.4854, -16.2809	Allegedly without effect.	Carmona ravine, Valle Jiménez	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.4843, -16.2824	Allegedly without effect.	Guerra ravine, Valle Jiménez	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.4793, -16.2889	Allegedly without effect.	Tabares ravine, San Cristóbal de La Laguna	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.4771, -16.2877	Allegedly without effect.	Guerra mountain, Valle Tabares	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.4786, -16.2873	Allegedly without effect.	Guerra mountain, Valle Tabares	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.381, -16.463	Allegedly without effect.	Track in the north of La Orotava	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.502906, -16.380815	Allegedly without effect.	De Guerra Mountain, Street Zoilo Miranda	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.533633, -16.355354	Allegedly without effect.	Road TF-13 Tejina	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.5601, -16.2811	Allegedly without effect.	Road TF-145, Las Carboneras to Chinamada	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall ??	??	28.54538, -16.35031	Allegedly without effect.	Road TF-13 Urbanization Porlier	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Landslide ??	??	28.54601, -16.34871	Allegedly without effect.	Agricultural field on the Bajamar trail	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Landslide ??	??	28.54589, -16.34862	Allegedly without effect.	Agricultural field on the Bajamar trail	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Landslide	??	28.55577, -	Allegedly without	Morro Mountain	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks	None.	IGME (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
??		16.31433	effect.						and cleaning of the area.		
Rock fall ??	??	28.55737, - 16.31543	Allegedly without effect.	Las Cuevas ravine	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.561192, - 16.332291	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.561072, - 16.332277	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.560995, - 16.332269	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.560732, - 16.332248	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.560629, - 16.332252	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.560476, - 16.332255	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.560247, - 16.33225	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.560084, - 16.332237	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.559354, - 16.332343	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.559129, - 16.332352	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.558994, - 16.332338	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.558843, - 16.332323	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55847, - 16.332377	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.558283, - 16.332442	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.557979, - 16.332628	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55766, - 16.332889	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.557595, - 16.332955	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.557185, - 16.333355	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.556827, - 16.33441	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.556851, - 16.33437	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55633, - 16.33522	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55633, - 16.33522	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55633, - 16.33522	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55617, - 16.33548	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55603, - 16.33559	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55526, - 16.33598	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55542, - 16.33823	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)

Event	Date	Location	Cascading effects/hazards	Main affected areas	Fatalities	Injuries	Displacements	Economic, social and natural losses	Management and resilient measures	Observations	References
Rock fall / Flow ??	??	28.555502, -16.338411	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.555699, -16.338729	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.555747, -16.33887	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.555803, -16.339055	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.555817, -16.339271	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.555817, -16.339503	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.555817, -16.3397	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55577, -16.34021	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55577, -16.34021	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55577, -16.34021	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.5558, -16.340621	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.55599, -16.341086	Allegedly without effect.	El Arenal beach	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
Rock fall / Flow ??	??	28.53973, -16.33984	Allegedly without effect.	Porlier ravine trail	0	0	0	Not reported.	Not reported. Probably removal of fallen blocks and cleaning of the area.	None.	IGME (2020)
TSUNAMIS											
Tsunami 1969	28 February 1969	South of the Gorringe Bank	Distal earthquake Tsunami Flooding	Santa Cruz de Tenerife	Not reported.	Not reported.	Not reported.	Not reported.	Not reported.	The tsunami was recorded by tide gauges.	Galindo et al. (2021)
Tsunami 1941	7 July 1941	Santa Cruz	Freak wave Landslide Tsunami Flooding	Santa Cruz de Tenerife and San Andrés	0	1	Not reported.	Inundation of the littoral of Santa Cruz de Tenerife and San Andrés, affecting the Island Council building, the Maritime Avenue, breaking the door of an office and inundating the Navy Command	Not reported.	The waves surpassed heights of 2 m in the Cabildo building (around 200 m from the coast) and 6 m in the Navy Command (around 250 m from the coast).	Galindo et al. (2021)
Tsunami 1911	15 November, 1911	Undetermined	Probably a submarine earthquake Tsunami	La Orotava	0	0 (Mules pulling a cart were swept away by the water and almost drowned)	0	Minor damage to the quay, where water washed away several bales of bananas, some cement barrels and a mule cart	Not reported.	It is said that when the sea was fairly calm, three large waves came in succession. It is believed that they may have been caused by an earthquake at sea	Galbis (1940)
Tsunami 1761	31 March 1761	SW of Iberia	Distal earthquake Tsunami Flooding	Northern coasts of Tenerife.	Not reported.	Not reported.	Not reported.	No severe damages, flooding of buildings and houses.	Not reported.	Similar effects of the previous one. Results of a recent model of the 1761 tsunami propose wave heights along the northern coast of Tenerife smaller than 0.3 m.	Galindo et al. (2021)
Tsunami 1755	1 November, 1755	SW of Iberia	Distal earthquake Tsunami Flooding	All the coasts of Tenerife, but especially the northern coast.	Not reported.	Not reported.	Not counted but reported.	No severe damages, flooding of buildings and houses.	The inhabitants of Bajamar, Tejina and other localities fled when they saw how the sea retreated leaving a large dry strip of at least 1.4 km.	The sea withdrew in Tenerife and Gran Canaria more than 1 km, later returning inland leaving a flooded distance from the coast of around another 1 km.	Galindo et al. (2021)

Table 18. Summary Table With Results Obtained From the Pyroclastic Density Current (PDC) Simulations. Data is Extracted From and Should Be Complemented With Map Scenarios Shown in Figs. S2 to S15.

PDC simulations					
Collapse equivalent angle (a_c)	**Collapse equivalent height (H_c)**	**Maximum length reached on land (km)**	**Direction of maximum length**	**Extension (km^2)**	**Affected areas**
4º	**2,000 m**	60.4	NE	2,034.38	The whole island of Tenerife
	3,000 m	60.4	NE	2,034.38	The whole island of Tenerife
7º	**2,000 m**	46.30	NE	1,876.39	The whole island of Tenerife except the north of Santa Cruz de Tenerife, Tegueste and San Cristóbal de la Laguna municipalities.
	3,000 m	54.40	NE	1,975.61	The whole island of Tenerife except the north of Santa Cruz de Tenerife municipality.
11º	**2,000 m**	29.30	NE, S	1,597.51	The whole island of Tenerife except the northeastern municipalities and two small regions in the southern coast of Arona and in the west of Buenavista del Norte.
	3,000 m	34.40	NE	1,682.93	The whole island of Tenerife except the northeastern municipalities.
15º	**2,000 m**	21.20	NE, SW, NW	1,025.51	The northern municipalities of Tenerife, from Los Silos to La Orotava, the western municipalities, and the north of the southern and eastern municipalities.
	3,000 m	25.00	E, SE, SW	1,406.19	The northern municipalities of Tenerife, from the east of Buenavista del Norte to Santa Úrsula, the western and eastern municipalities and the northern half of the southern municipalities.
19º	**2,000 m**	16.50	NE, NW	533.22	The northern municipalities of Tenerife, from Garachico to Los Realejos, and the central part of the island, covering the north of the western, southern and eastern municipalities.
	3,000 m	19.40	NE, SW, NW	880.52	The northern municipalities of Tenerife, from the east of Los Silos to La Orotava, almost all the western municipalities and the north of the southern and eastern municipalities.
23º	**2,000 m**	13.20	N	300.97	Just beyond the limits of Las Cañadas caldera and almost all the extension of the northern municipalities from Icod de los Vinos to Los Realejos.
	3,000 m	15.70	NE, NW	526.69	The northern municipalities of Tenerife, from Garachico to Los Realejos, and the central part of the island, covering the north of the western, southern and eastern municipalities.
27º	**2,000 m**	9.90	N, NW	185.62	Las Cañadas caldera and the north of the northern municipalities from Icod de los Vinos to Los Realejos.
	3,000 m	12.80	N	327.54	Just beyond the limits of Las Cañadas caldera and almost all the extension of the northern municipalities from Icod de los Vinos to Los Realejos.

Table 19. Summary Table With Maximum Expected Peak Ground Acceleration (PGA) Values Obtained From Seismic Simulations for an Epicenter Located North of the Mt Teide Summit.

Epicenter 1 (northern slope of Teide)				
		Pétursson and Vogfjörd (2009)	**Ágústsson et al. (2008)**	**Beauducel et al. (2004)**
Depth = 0 km	**Mw = 5**	0,10 g	0,61 g	0,12 g
	Mw = 6	0,19 g	3,04 g	0,48 g
	Mw = 7	0,29 g	11,99 g	1,95 g
Depth = 1,8 km	**Mw = 5**	0,10 g	0,61 g	0,12 g
	Mw = 6	0,19 g	3,04 g	0,48 g
	Mw = 7	0,29 g	11,99 g	1,95 g
Depth = 3,6 km	**Mw = 5**	0,10 g	0,61 g	0,12 g
	Mw = 6	0,19 g	3,04 g	0,48 g
	Mw = 7	0,29 g	11,99 g	1,95 g

Table 20. Summary Table With Maximum Expected Peak Ground Acceleration (PGA) Values Obtained From Seismic Simulations for an Epicenter Located at the Crater of Teide.

Epicenter 2 (crater of Teide)				
		Pétursson and Vogfjörd (2009)	**Ágústsson et al. (2008)**	**Beauducel et al. (2004)**
Depth = 0 km	**Mw = 5**	0,10 g	0,67 g	0,12 g
	Mw = 6	0,20 g	3,35 g	0,49 g
	Mw = 7	0,28 g	13,21g	2,01g
Depth = 2,5 km	**Mw = 5**	0,10 g	0,67 g	0,12 g
	Mw = 6	0,20 g	3,35 g	0,49 g
	Mw = 7	0,28 g	13,21 g	2,01 g
Depth = 5 km	**Mw = 5**	0,10 g	0,67 g	0,12 g
	Mw = 6	0,20 g	3,35 g	0,49 g
	Mw = 7	0,28 g	13,21 g	2,01 g

Table 21. Summary Table With the Factors of Safety (FS) Obtained From the Slope Stability Static Analysis for Model 1.

Model 1 (with alteration zones)	
Analysis method	**Factor of Safety**
Bishop simplified	1.281
Janbu Generalised	1.259
Morgenstern-Price	1.311

Table 22. Summary Table With the Factors of Safety (FS) Obtained From the Slope Stability Static Analysis for Model 2.

Model 2 (without alteration zones)	
Analysis method	**Factor of Safety**
Bishop simplified	1.334
Janbu Generalised	1.334
Morgenstern-Price	1.361

Table 23. Summary Table With the Factors of Safety (FS) Obtained for Each Value of kh Tested During the Slope Stability Pseudo-Static Analysis for Model 1.

Model 1 (with alteration zones)																							
Analysis method	k_h																						
	0.03	0.04	0.06	0.07	0.1	0.12	0.13	0.14	0.15	0.16	0.18	0.19	0.2	0.22	0.26	0.28	0.29	0.32	0.33	0.48	0.49	1.00	1.11
Bishop simplified	1.185	1.156	1.102	1.076	1.007	0.966	0.946	0.928	0.910	0.892	0.859	0.844	0.829	0.801	0.750	0.727	0.716	0.685	0.675	0.519	0.511	0.283	0.260
Janbu Generalised	1.158	1.129	1.072	1.047	0.978	0.936	0.916	0.896	0.878	0.860	0.827	0.812	0.797	0.768	0.717	0.694	0.684	0.653	0.643	0.531	0.524	0.288	0.264
Morgenstern-Price	1.220	1.192	1.141	1.116	1.052	1.014	0.996	0.979	0.962	0.945	0.915	0.901	0.887	0.861	0.814	0.792	0.780	0.740	0.727	0.569	0.570	0.334	0.307

Table 24. Summary Table With the Factors of Safety (FS) Obtained for Each Value of kh Tested During the Slope Stability Pseudo-Static Analysis for Model 2.

Model 2 (without alteration zones)																						
Analysis method	k_h																					
	0.03	0.04	0.06	0.07	0.1	0.12	0.14	0.15	0.16	0.18	0.19	0.2	0.22	0.26	0.28	0.29	0.32	0.33	0.48	0.49	1.00	1.11
Bishop simplified	1.232	1.201	1.144	1.118	1.044	1.000	0.960	0.941	0.922	0.888	0.871	0.856	0.826	0.772	0.747	0.735	0.691	0.678	0.520	0.512	0.283	0.260
Janbu Generalised	1.226	1.192	1.132	1.105	1.026	0.982	0.940	0.920	0.901	0.866	0.849	0.832	0.800	0.745	0.720	0.708	0.675	0.665	0.533	0.524	0.288	0.264
Morgenstern-Price	1.262	1.233	1.180	1.155	1.084	1.043	1.006	0.988	0.971	0.939	0.924	0.909	0.881	0.817	0.796	0.781	0.741	0.728	0.570	0.570	0.334	0.307

Table 25. Summary Table With the Factors of Safety (FS) Obtained for Each Value of kh Tested During the Slope Stability Pseudo-Static Analysis for Model 1 Bis.

Model 1 Bis																						
Analysis method	k_h																					
	0.03	0.04	0.06	0.07	0.1	0.12	0.14	0.15	0.16	0.18	0.19	0.2	0.22	0.26	0.28	0.29	0.32	0.33	0.48	0.49	1.00	1.11
Bishop simplified	2.195	2.098	1.925	1.848	1.650	1.538	1.440	1.395	1.353	1.273	1.236	1.201	1.137	1.027	0.980	0.958	0.898	0.879	0.663	0.651	0.339	0.307
Janbu Generalised	2.238	2.140	1.966	1.887	1.686	1.572	1.472	1.427	1.382	1.299	1.261	1.225	1.160	1.046	0.997	0.974	0.914	0.895	0.679	0.667	0.345	0.312
Morgenstern-Price	2.188	2.092	1.923	1.848	1.655	1.547	1.451	1.408	1.367	1.292	1.259	1.226	1.166	1.062	1.017	0.996	0.938	0.920	0.719	0.709	0.426	0.395

Annex 5. Supplementary Material 2: Maps

Seismic amplification map of Tenerife (Canary Islands) in terms of the Amplification Factor (Fa) of Borcherdt (1994) for high frequencies (2-10 Hz)

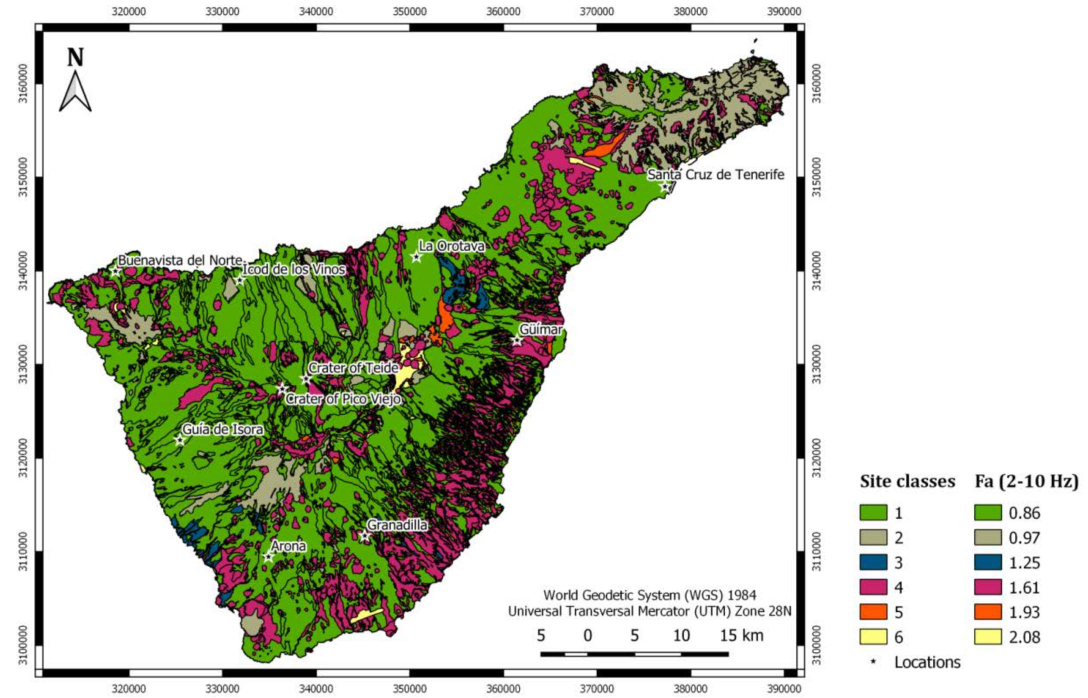

Figure S1. Seismic amplification map of Tenerife (Canary Islands) in terms of the amplification factor (Fa) of Borcherdt (1994) for high frequencies (2-10 Hz).

PDC scenarios

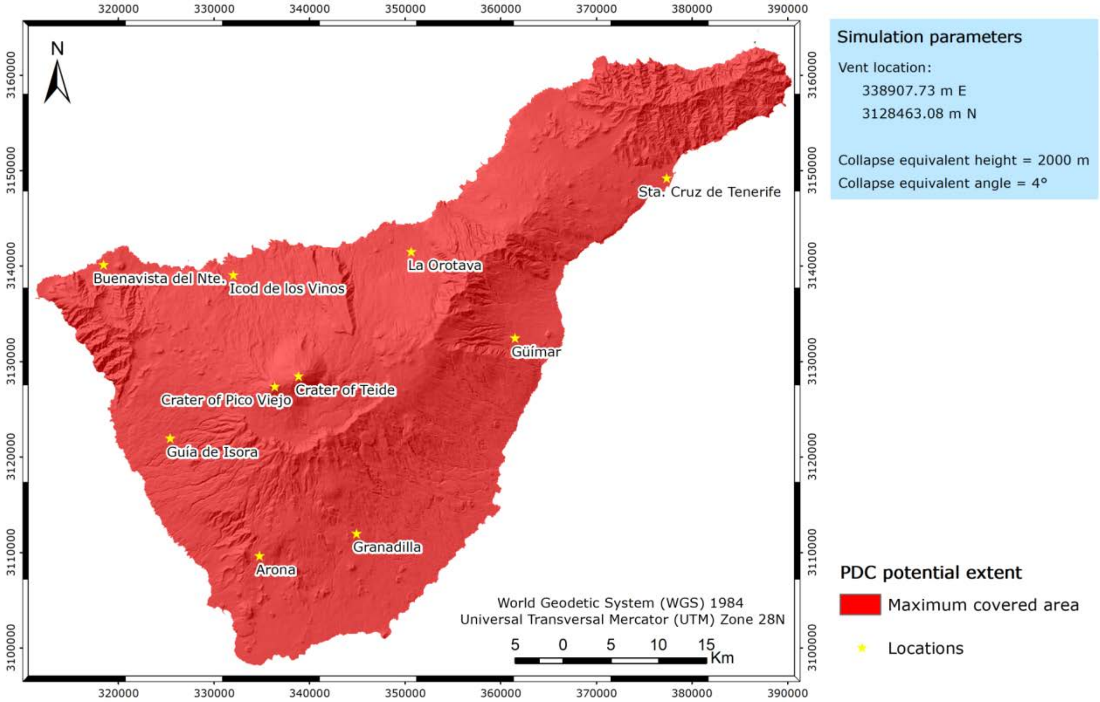

Figure S2. Pyroclastic Density Current (PDC) map scenario considering H_c = 2,000 m and a_c = 4º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

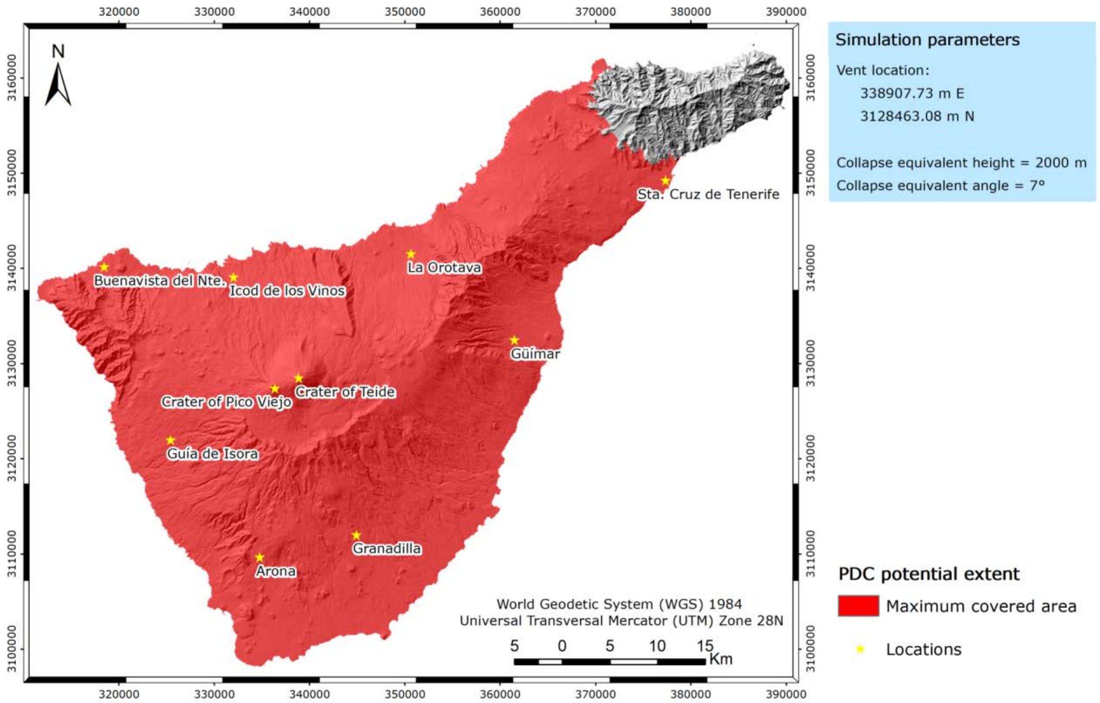

Figure S3. Pyroclastic Density Current (PDC) map scenario considering H_c = 2,000 m and a_c = 7º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

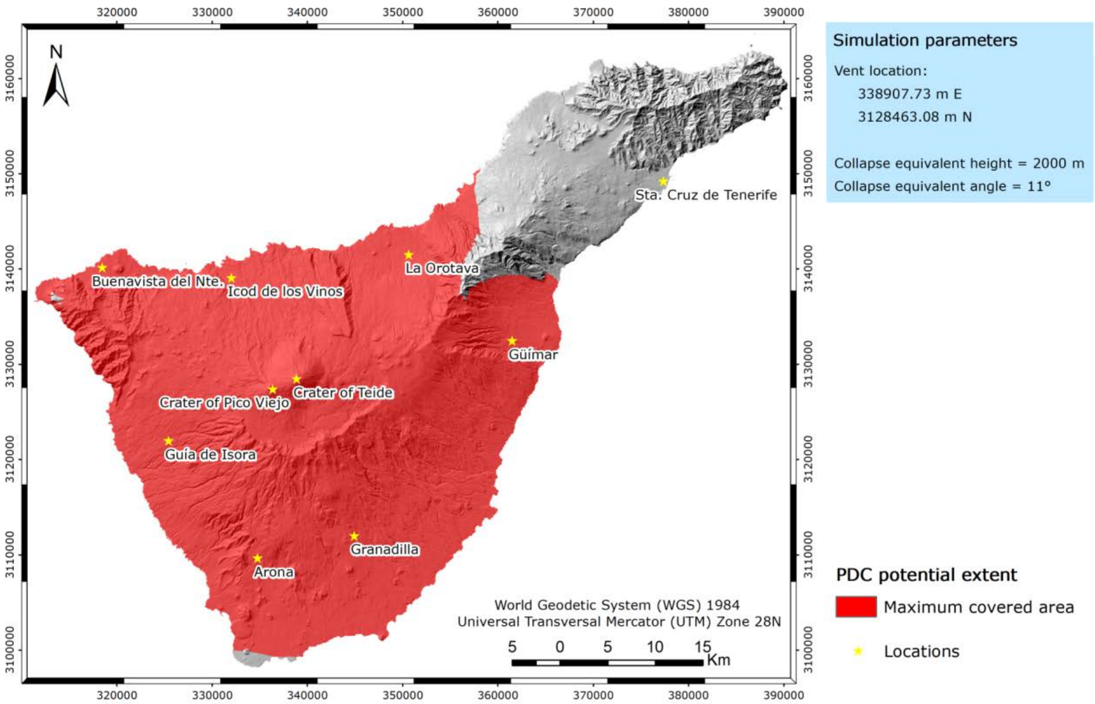

Figure S4. Pyroclastic Density Current (PDC) map scenario considering H_c = 2,000 m and a_c = 11º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

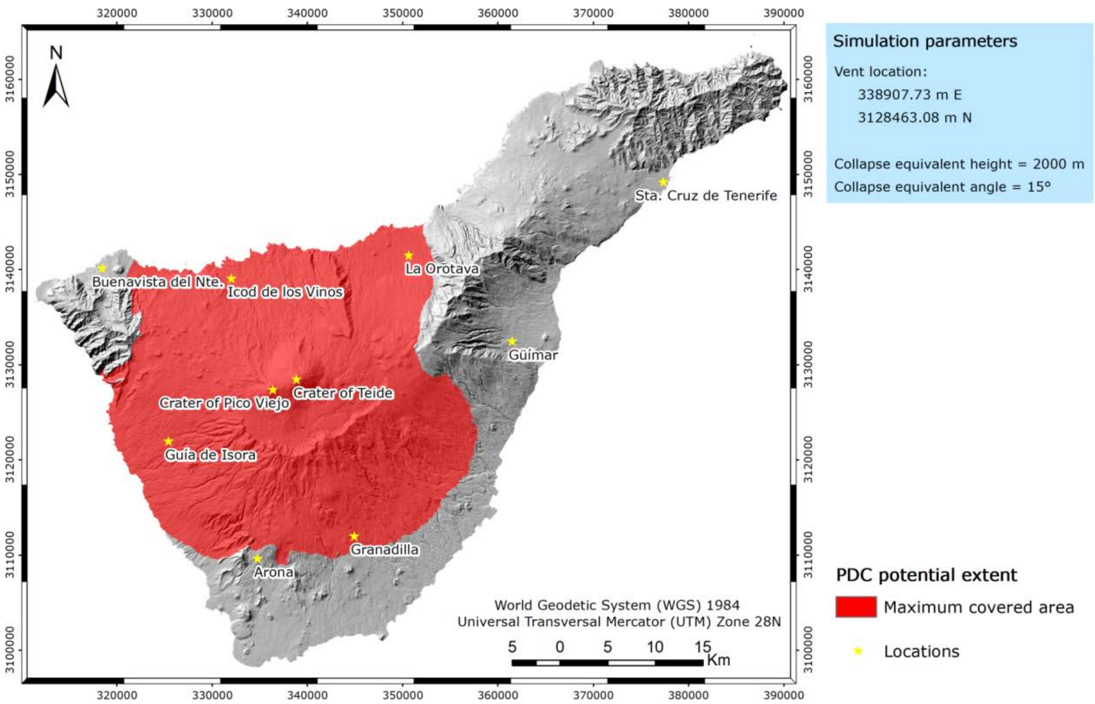

Figure S5. Pyroclastic Density Current (PDC) map scenario considering H_c = 2,000 m and a_c = 15º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

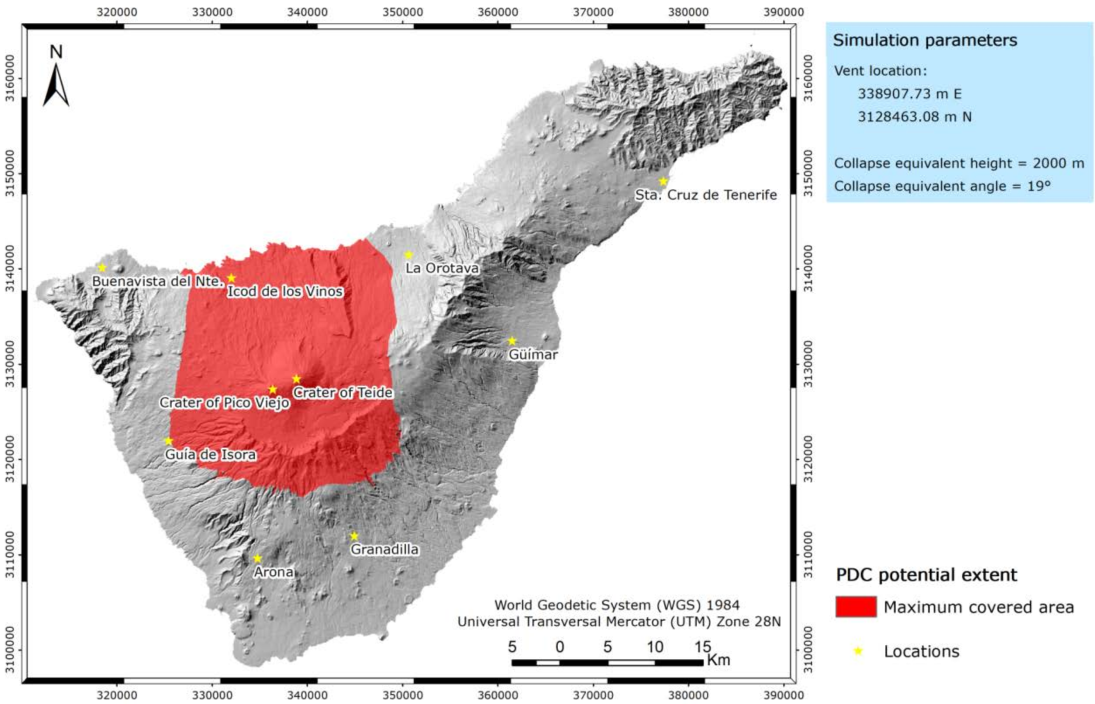

Figure S6. Pyroclastic Density Current (PDC) map scenario considering H_c = 2,000 m and a_c = 19º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

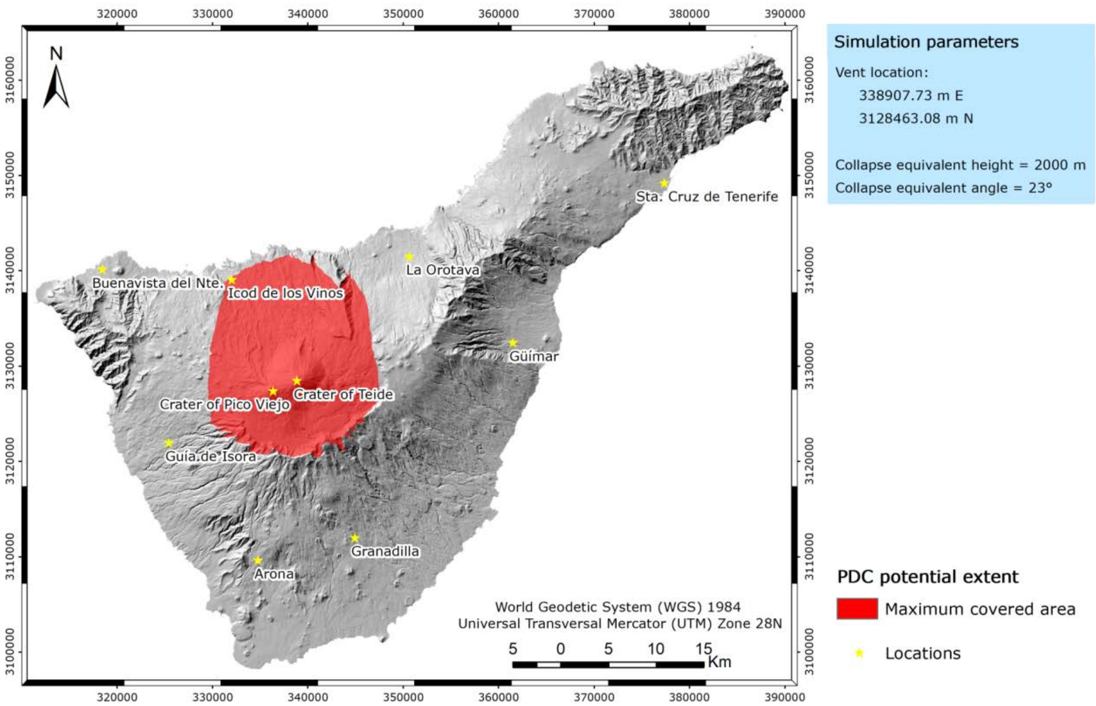

Figure S7. Pyroclastic Density Current (PDC) map scenario considering H_c = 2,000 m and a_c = 23º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

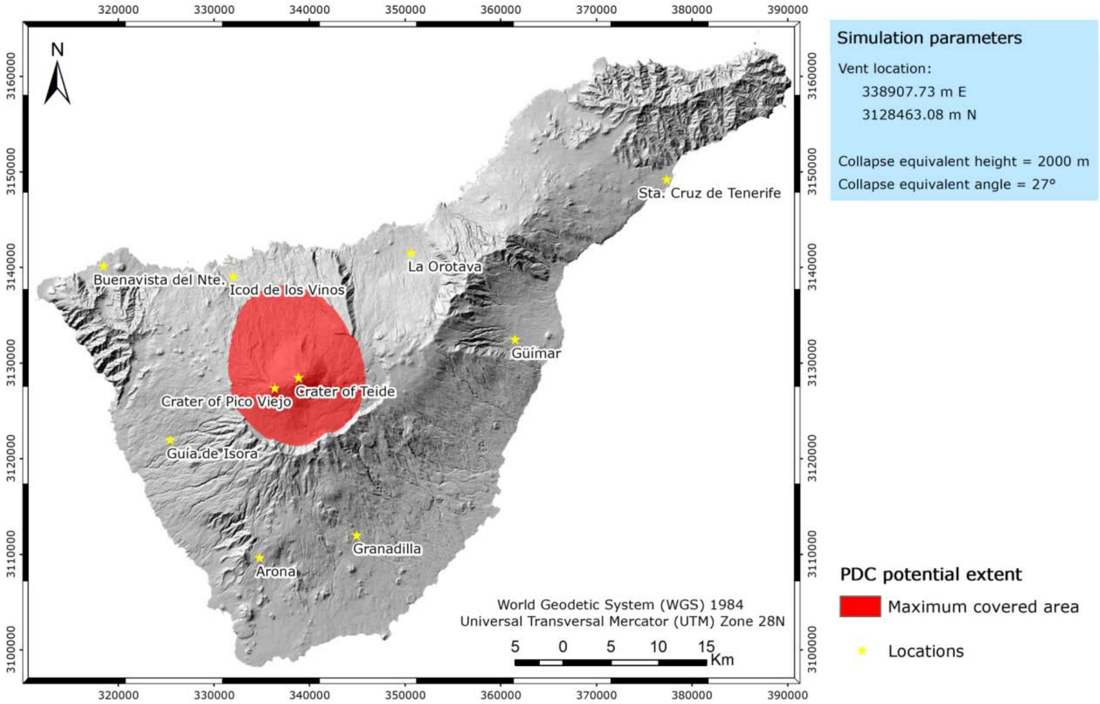

Figure S8. Pyroclastic Density Current (PDC) map scenario considering H_c = 2,000 m and a_c = 27º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

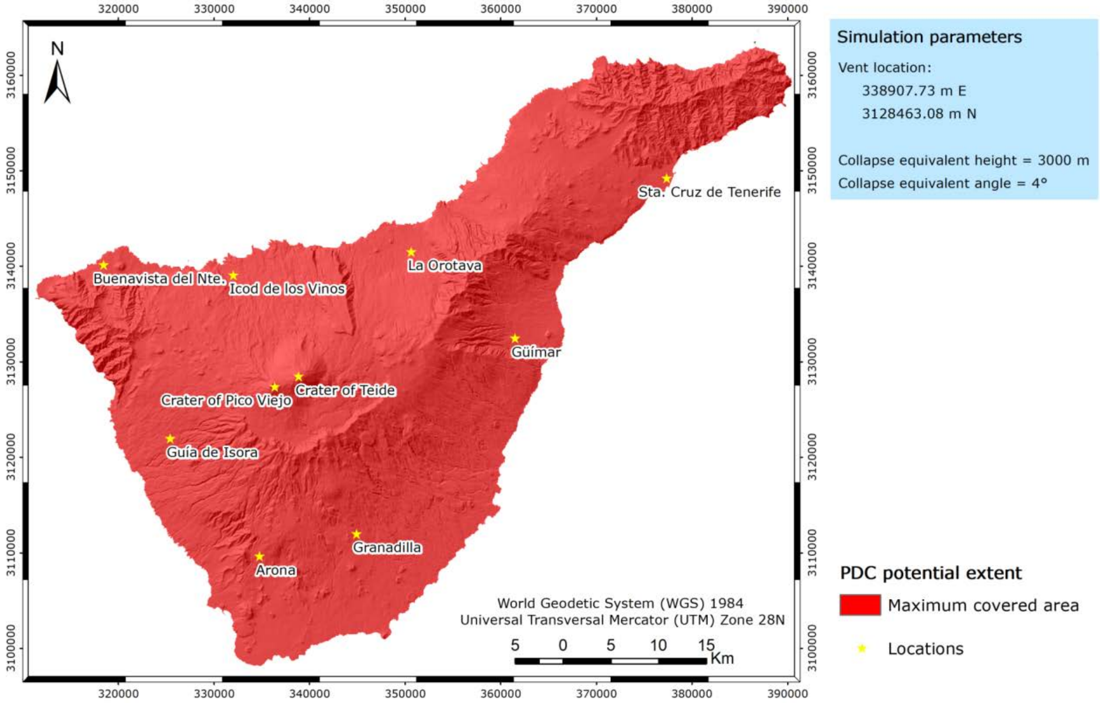

Figure S9. Pyroclastic Density Current (PDC) map scenario considering H_c = 3,000 m and a_c = 4º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

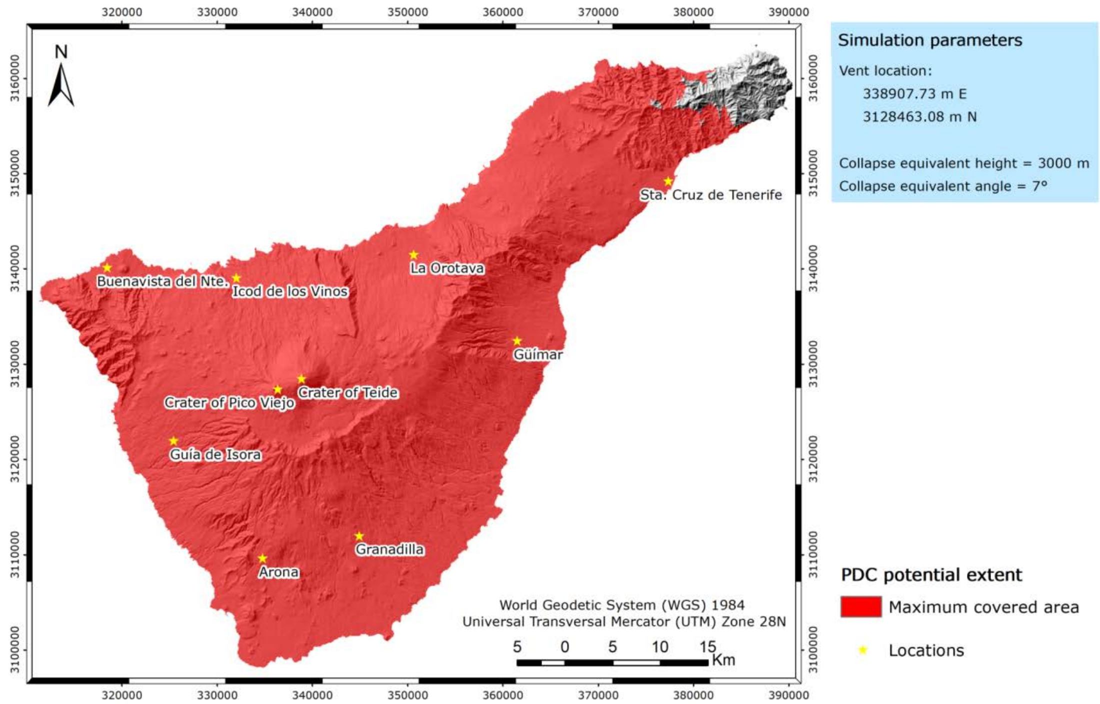

Figure S10. Pyroclastic Density Current (PDC) map scenario considering H_c = 3,000 m and a_c = 7º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

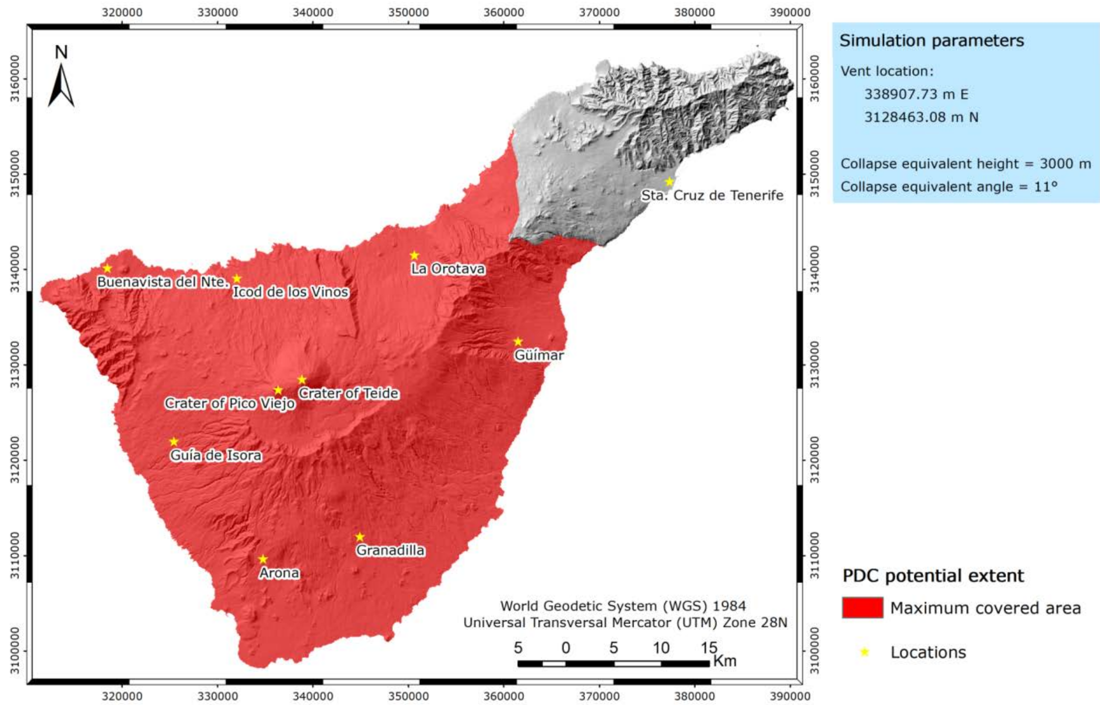

Figure S11. Pyroclastic Density Current (PDC) map scenario considering H_c = 3,000 m and a_c = 11º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

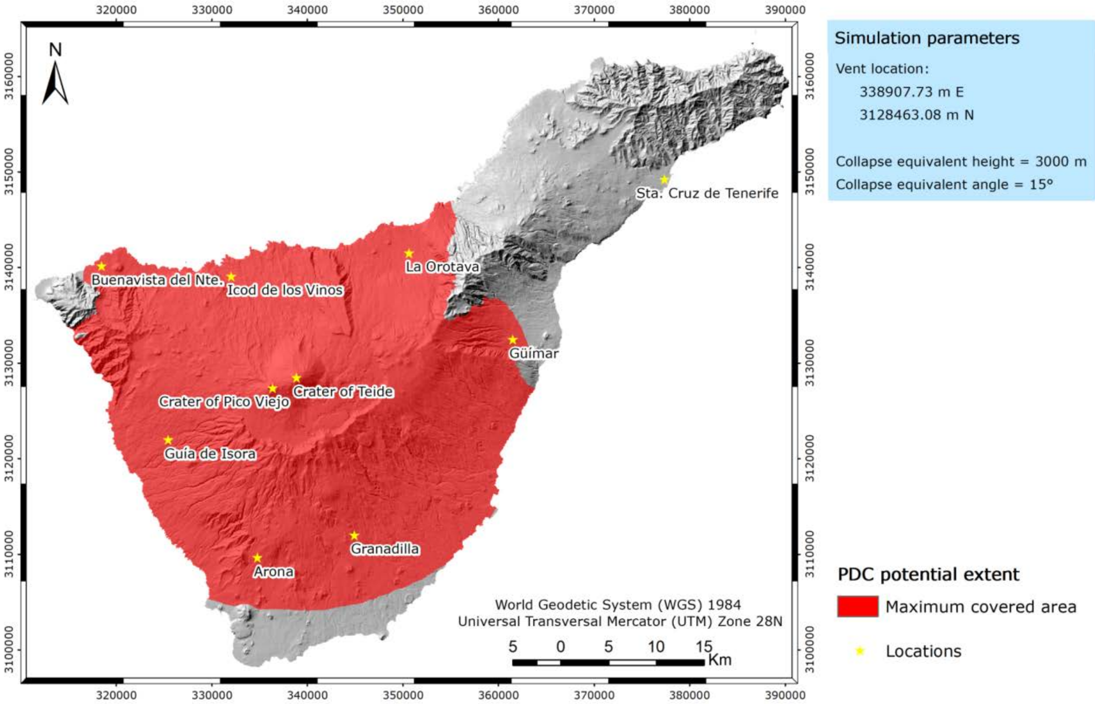

Figure S12. Pyroclastic Density Current (PDC) map scenario considering H_c = 3,000 m and a_c = 15º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

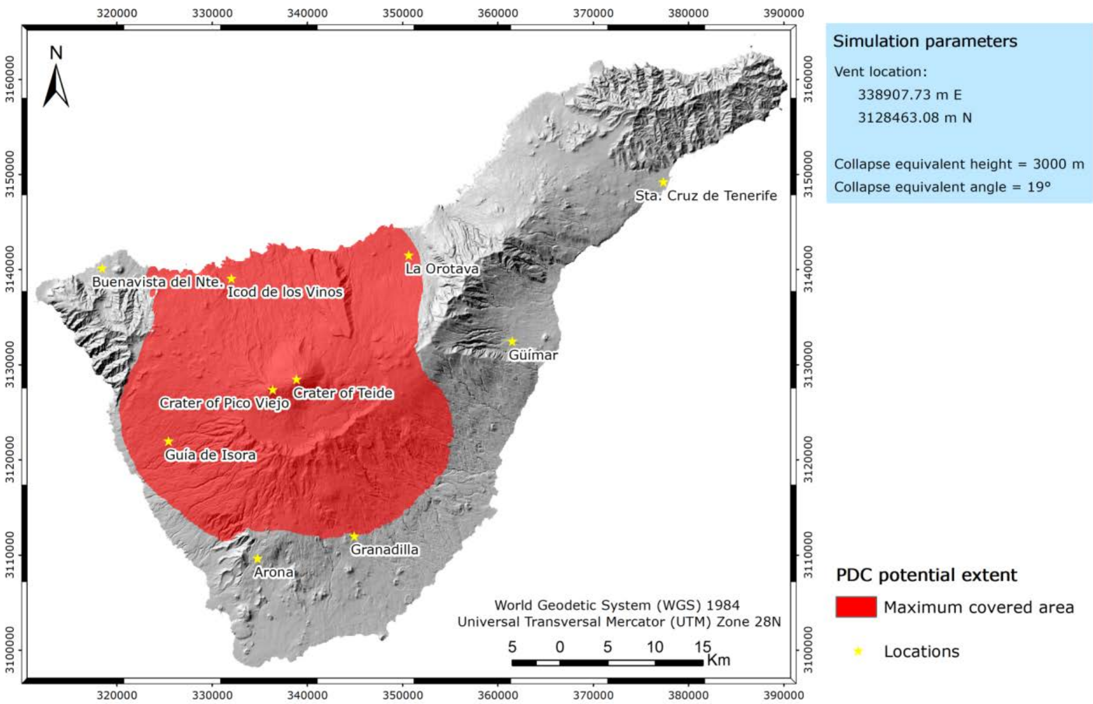

Figure S13. Pyroclastic Density Current (PDC) map scenario considering H_c = 3,000 m and a_c = 19º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

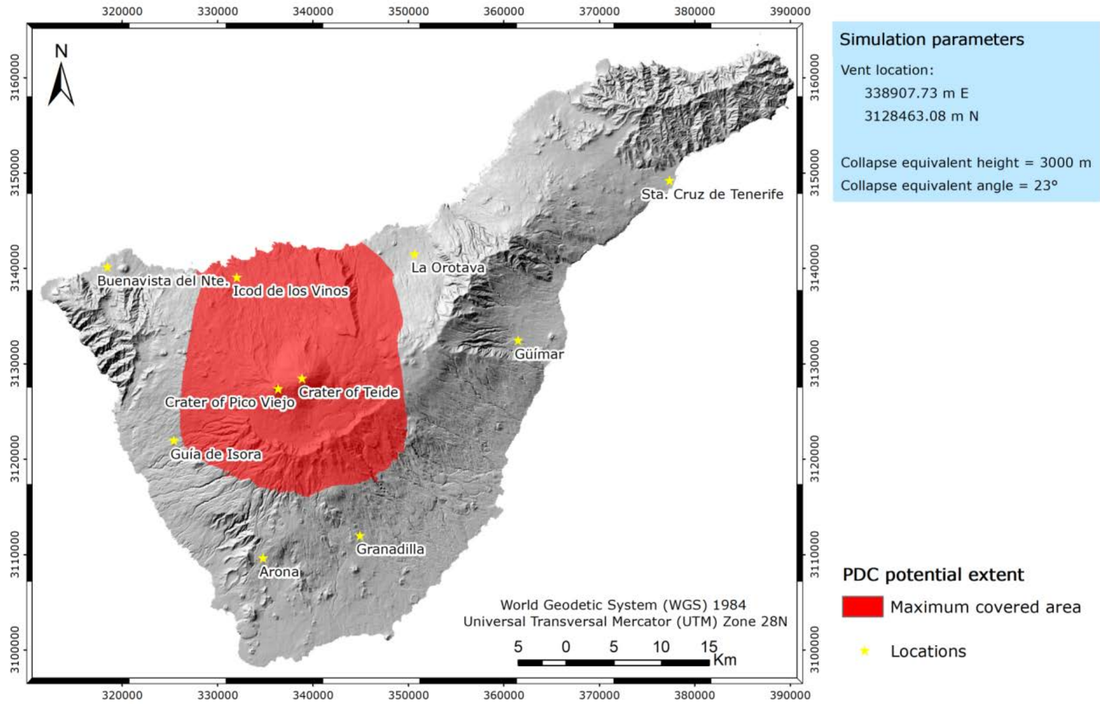

Figure S14. Pyroclastic Density Current (PDC) map scenario considering H_c = 3,000 m and a_c = 23º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

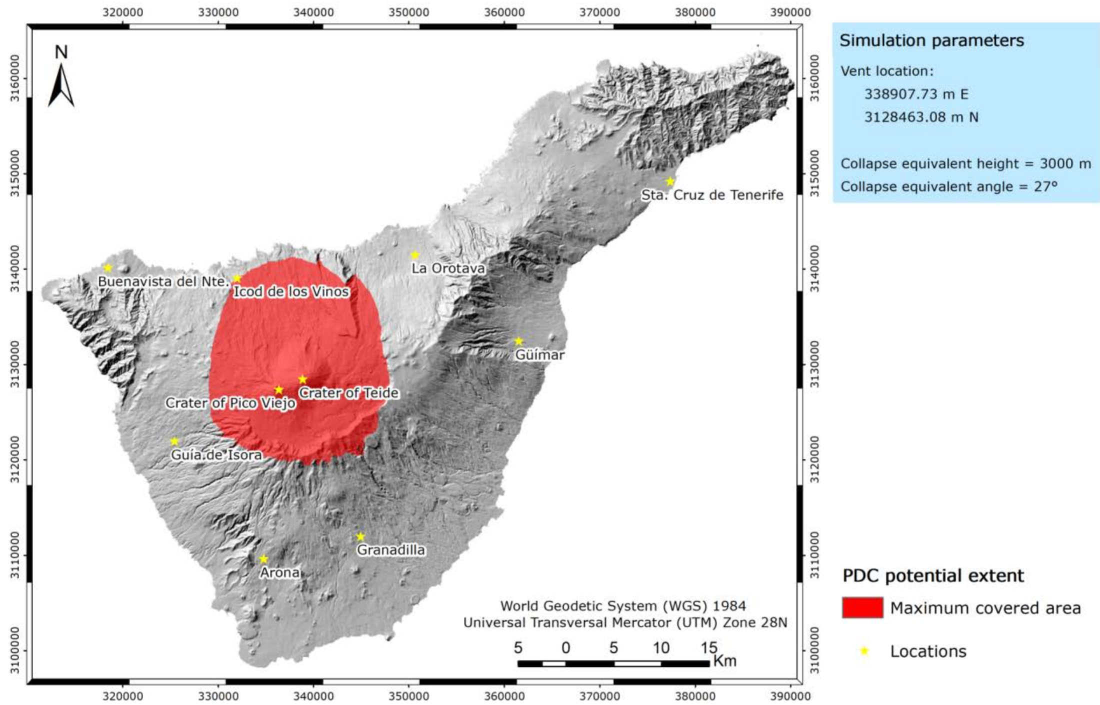

Figure S15. Pyroclastic Density Current (PDC) map scenario considering H_c = 3,000 m and a_c = 27º, for a simulated caldera-forming eruption on Mt Teide, Tenerife (Canary Islands).

PGA scenarios

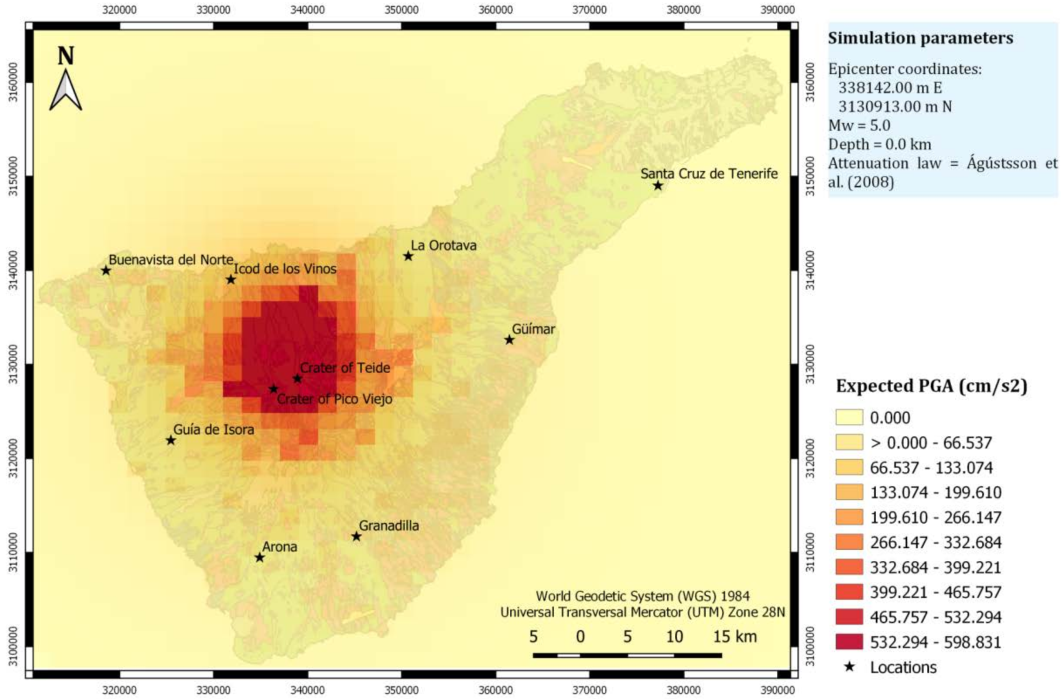

Figure S16. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Ágústsson et al. (2008) attenuation law.

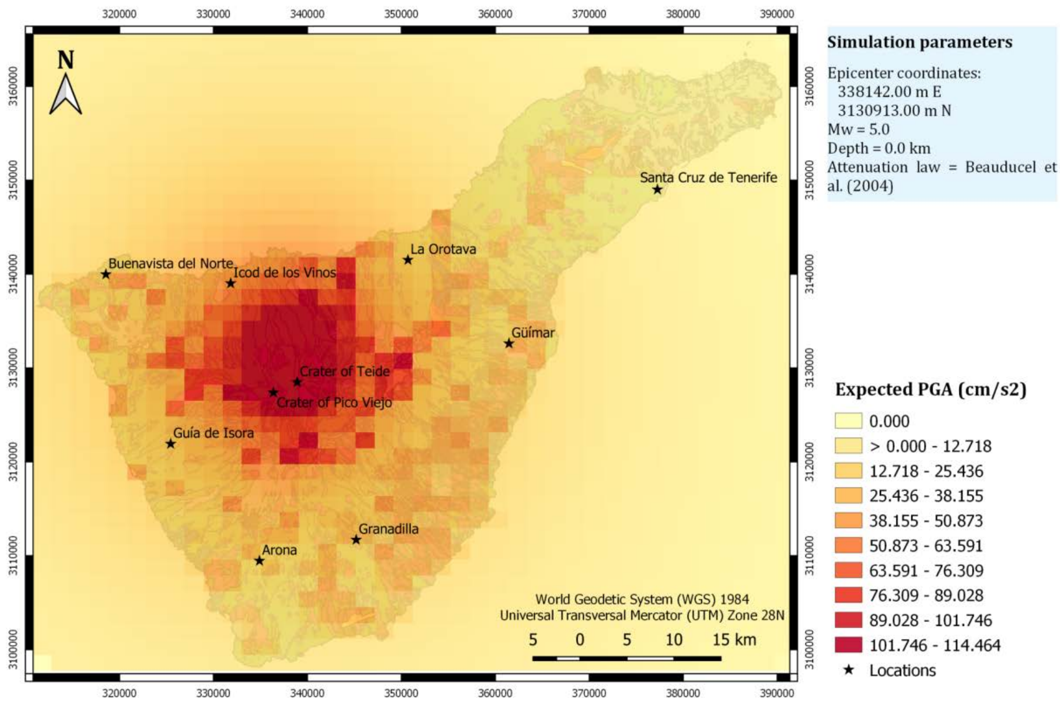

Figure S17. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Beauducel et al. (2004) attenuation law.

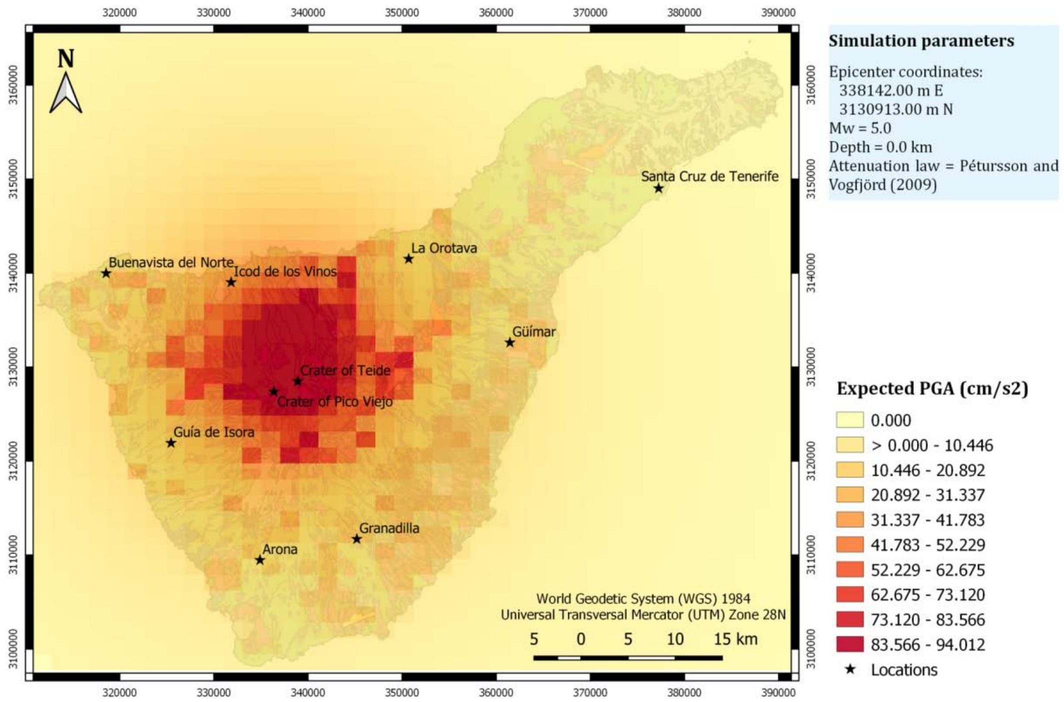

Figure S18. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

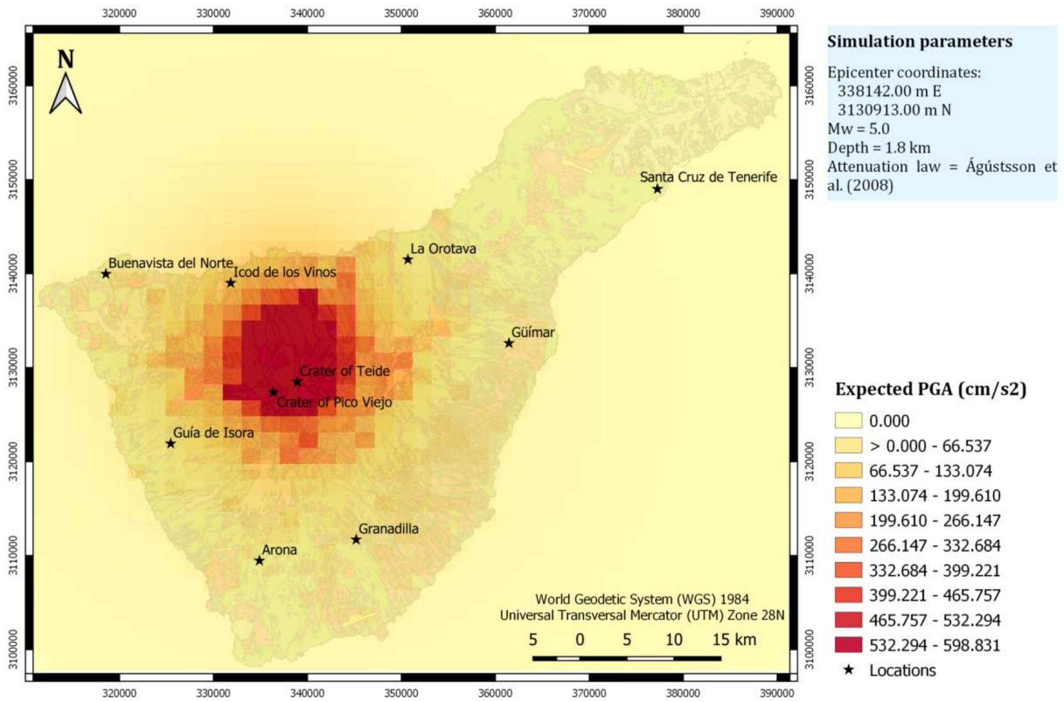

Figure S19. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Ágústsson et al. (2008) attenuation law.

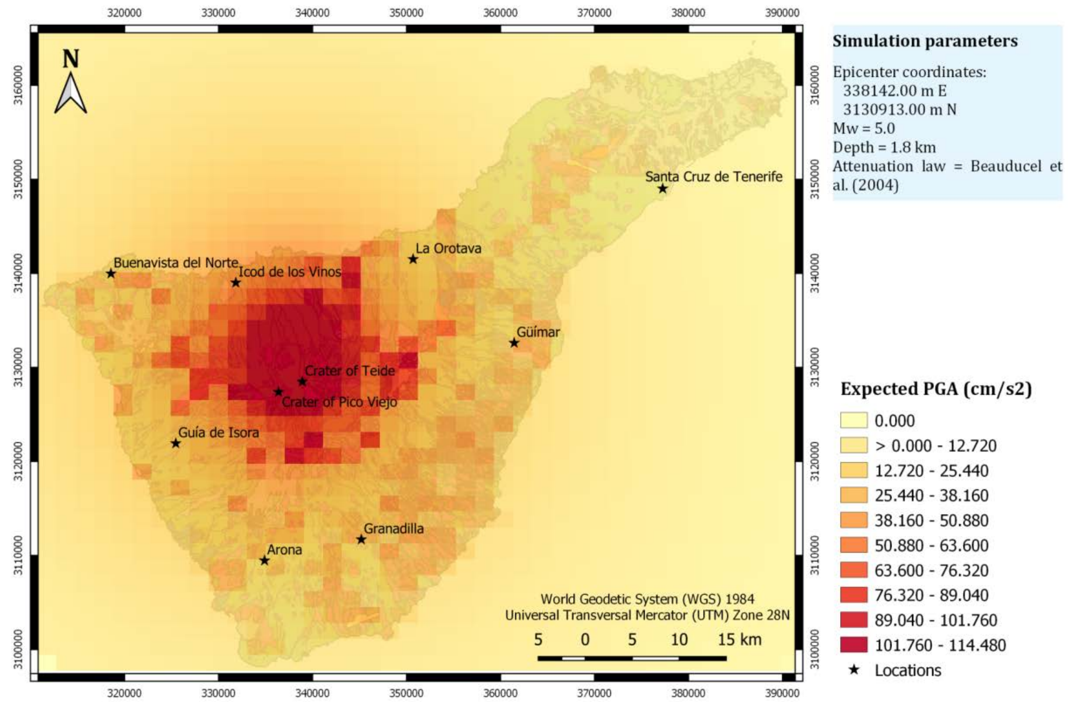

Figure S20. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Beauducel et al. (2004) attenuation law.

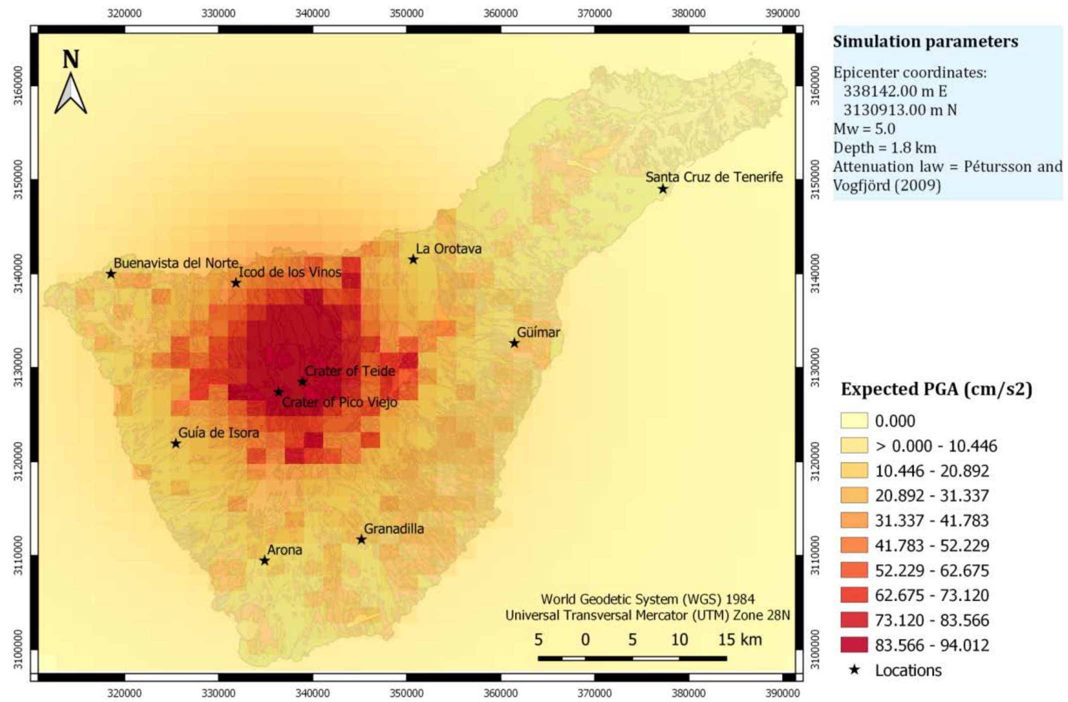

Figure S21. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

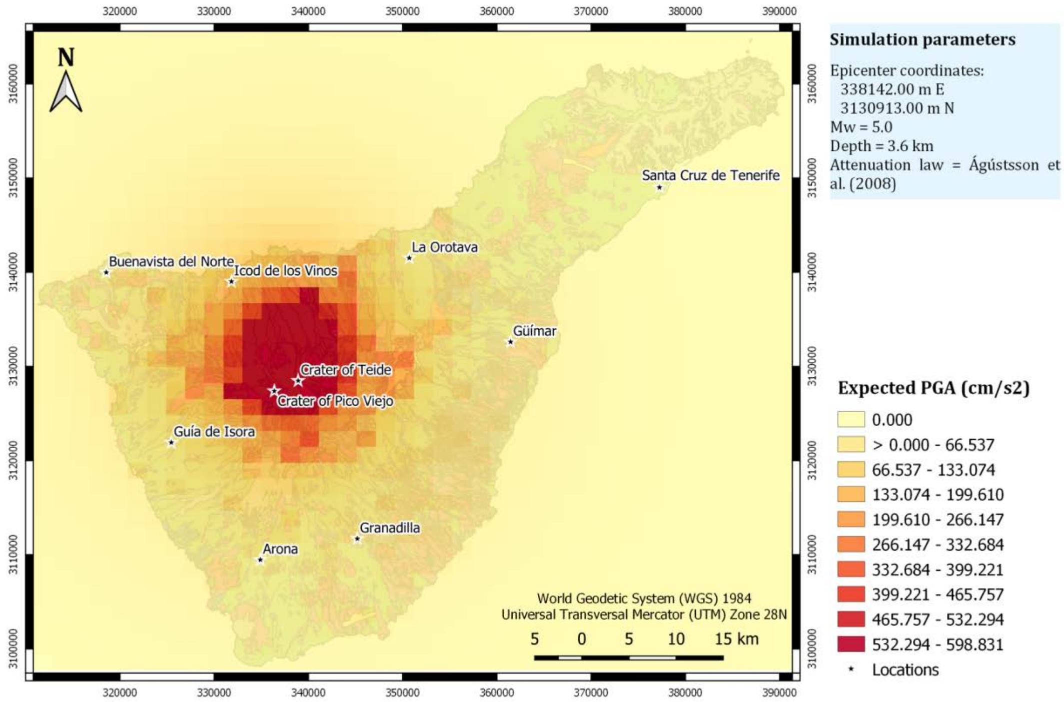

Figure S22. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Ágústsson et al. (2008) attenuation law.

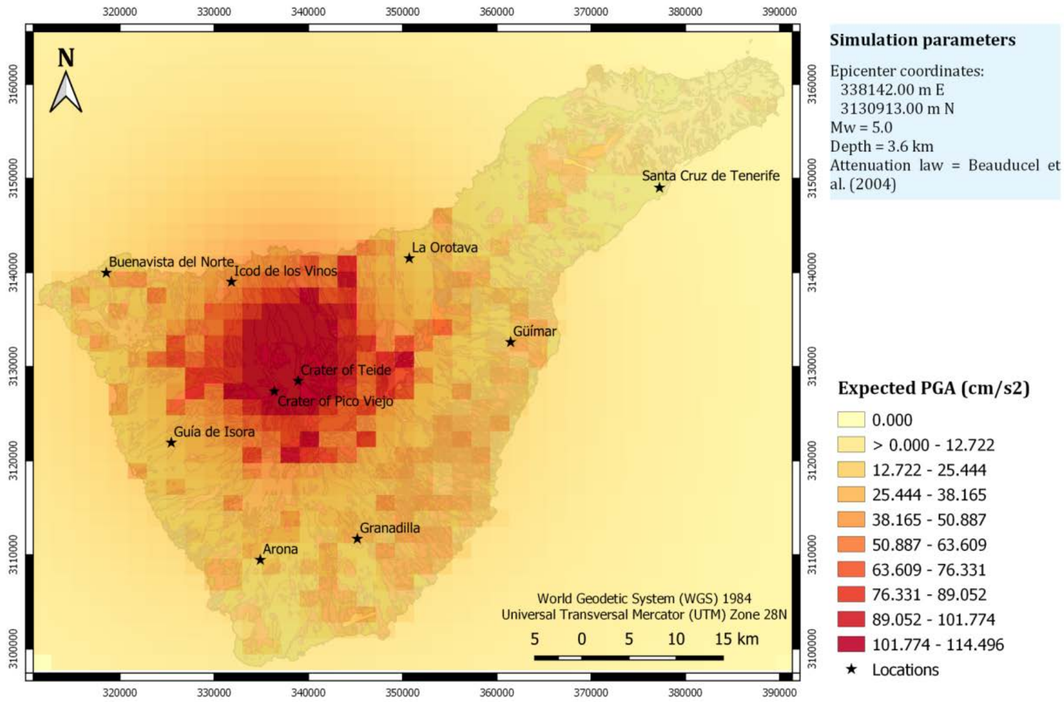

Figure S23. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Beauducel et al. (2004) attenuation law.

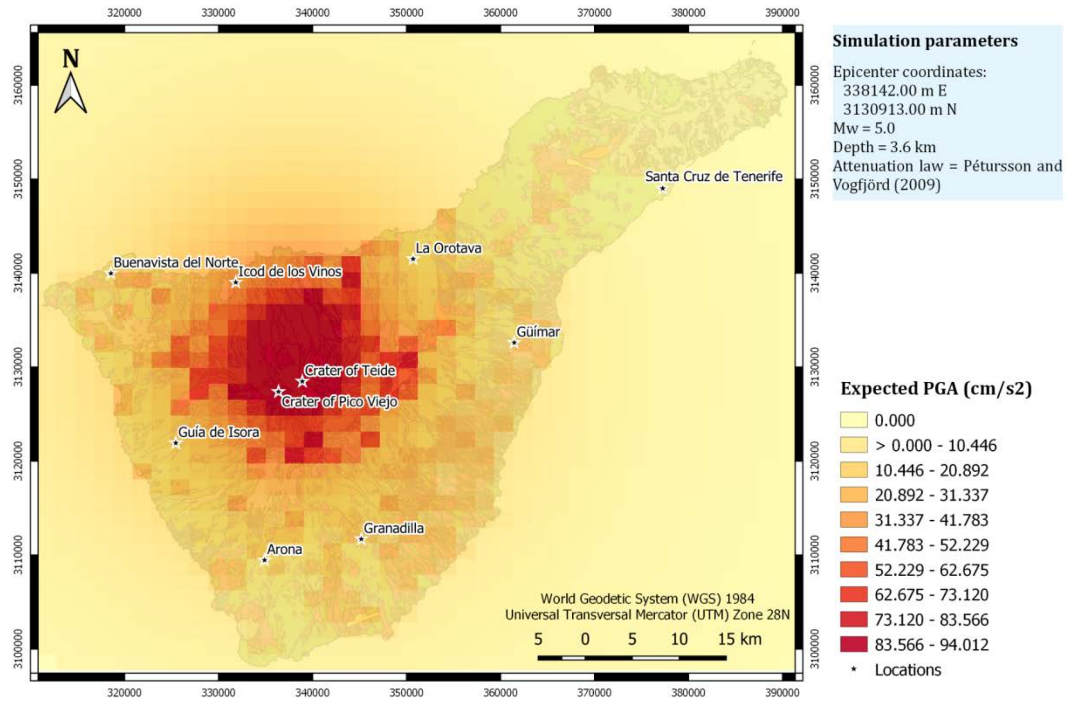

Figure S24. Expected PGA values for a M 5.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

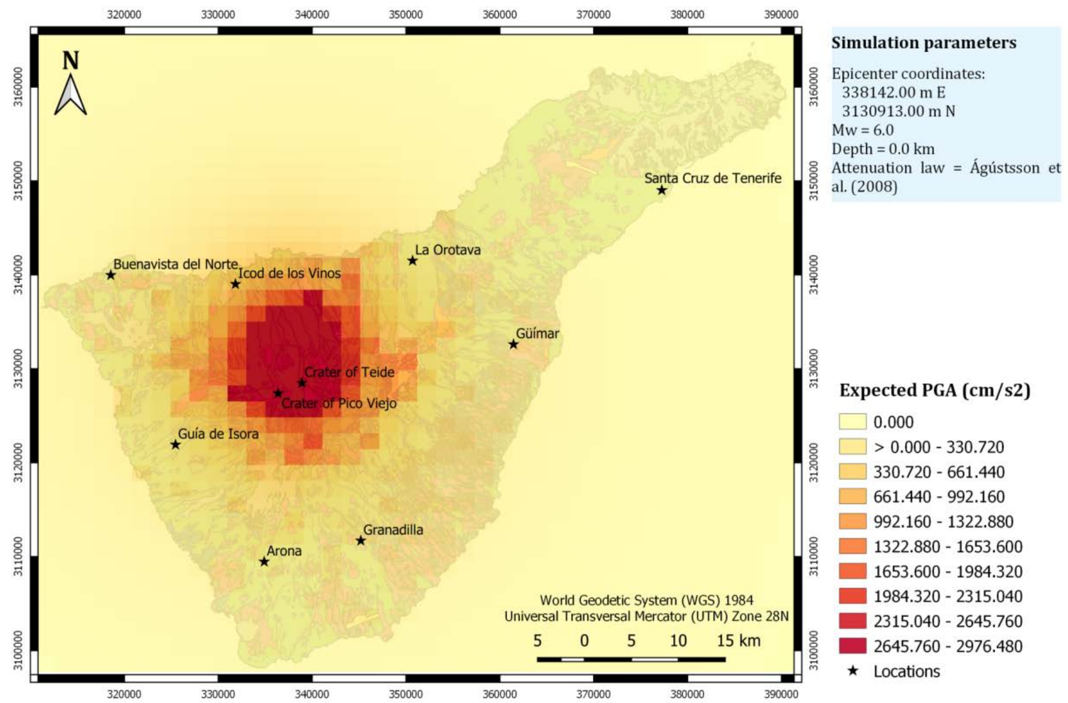

Figure S25. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Ágústsson et al. (2008) attenuation law.

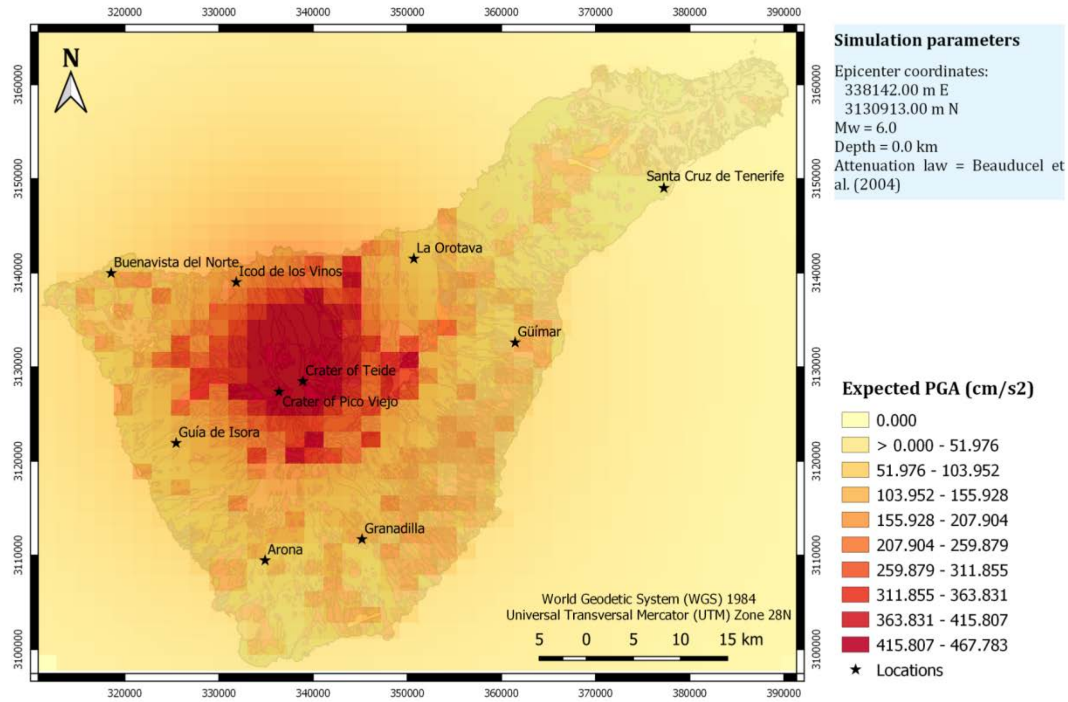

Figure S26. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Beauducel et al. (2004) attenuation law.

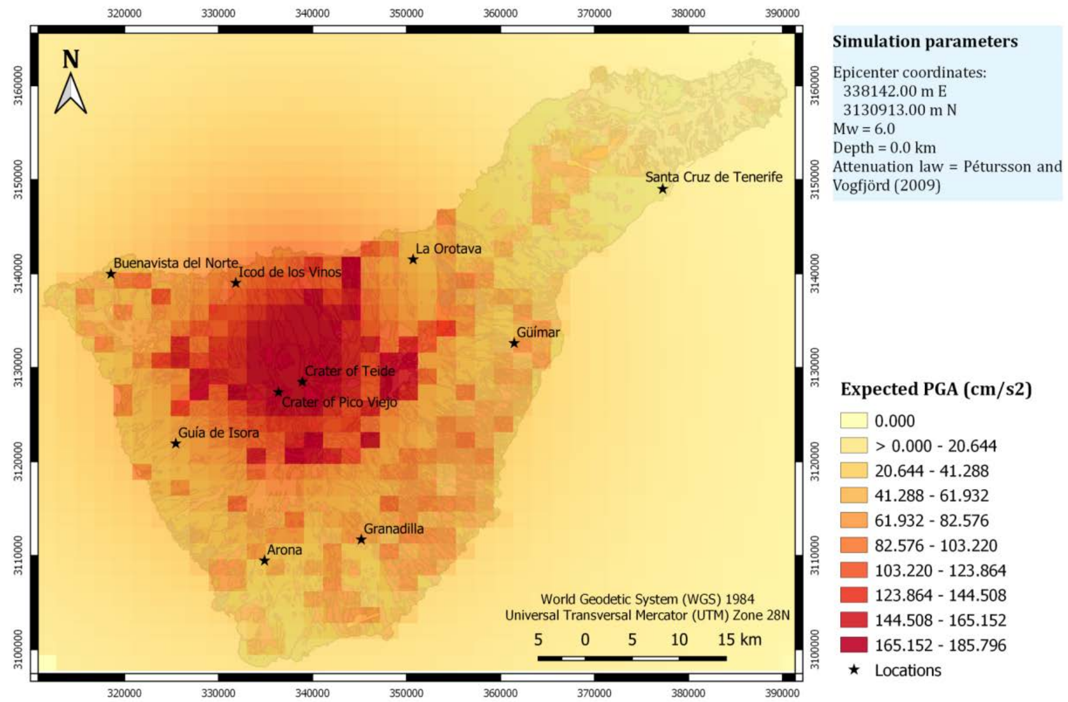

Figure S27. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

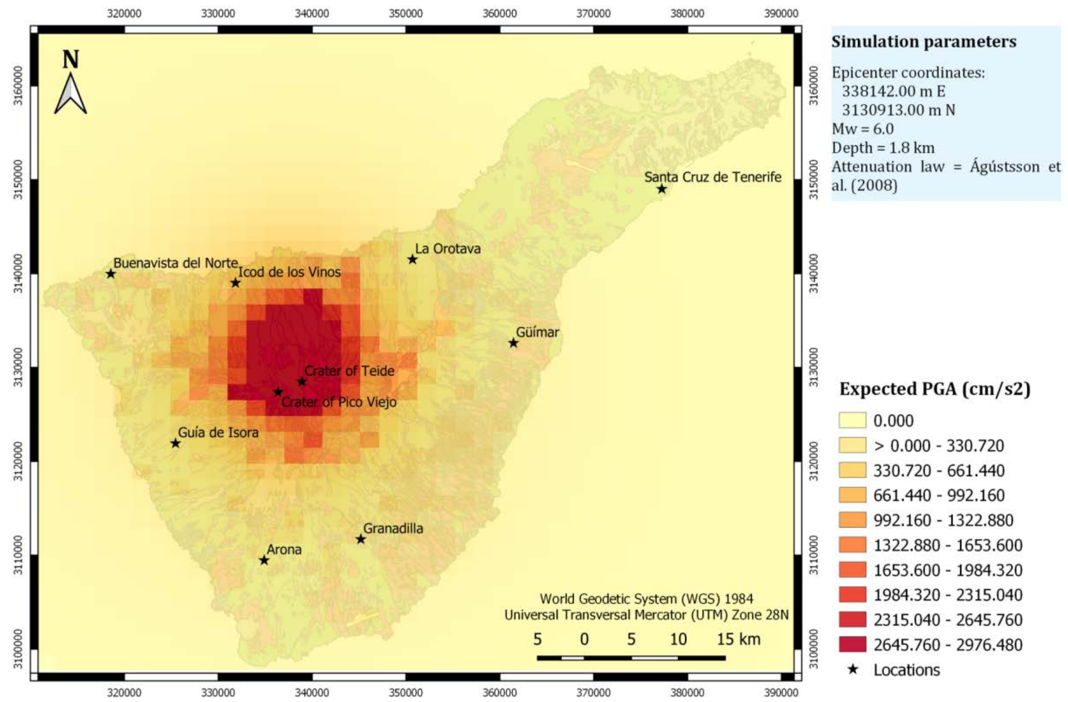

Figure S28. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Ágústsson et al. (2008) attenuation law.

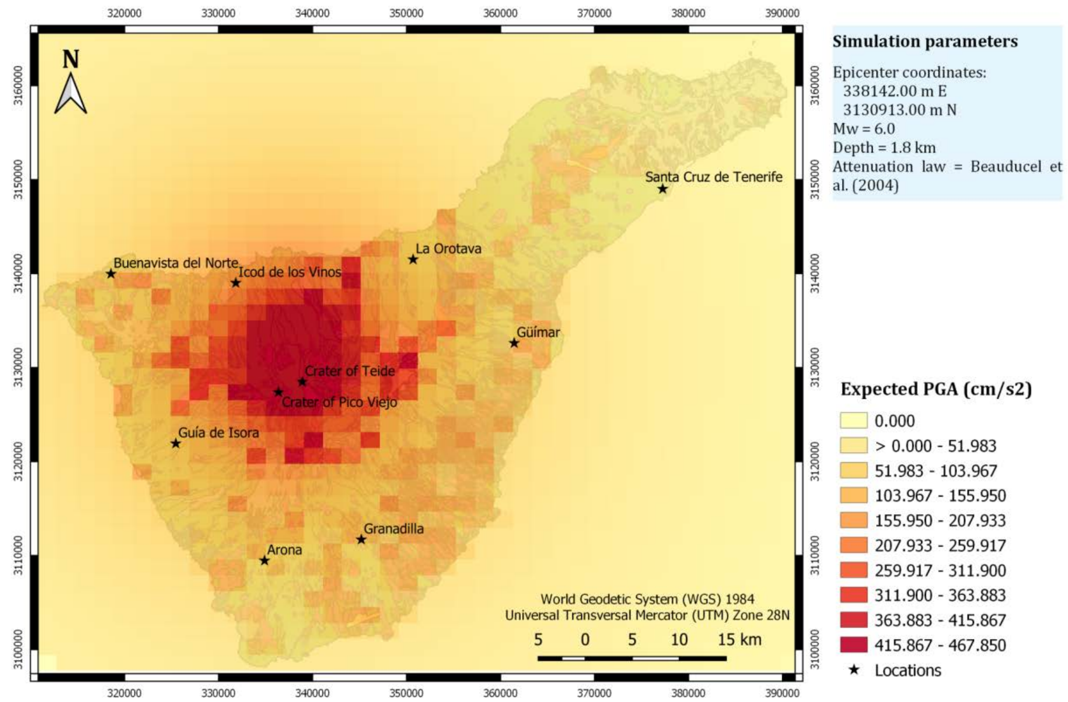

Figure S29. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Beauducel et al. (2004) attenuation law.

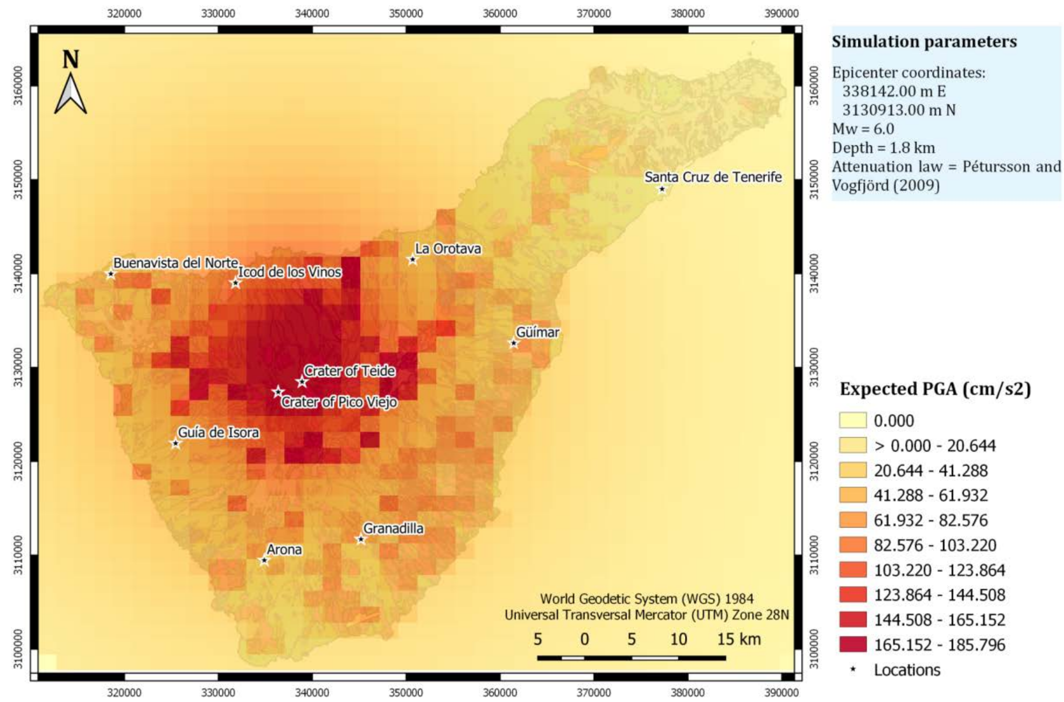

Figure S30. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

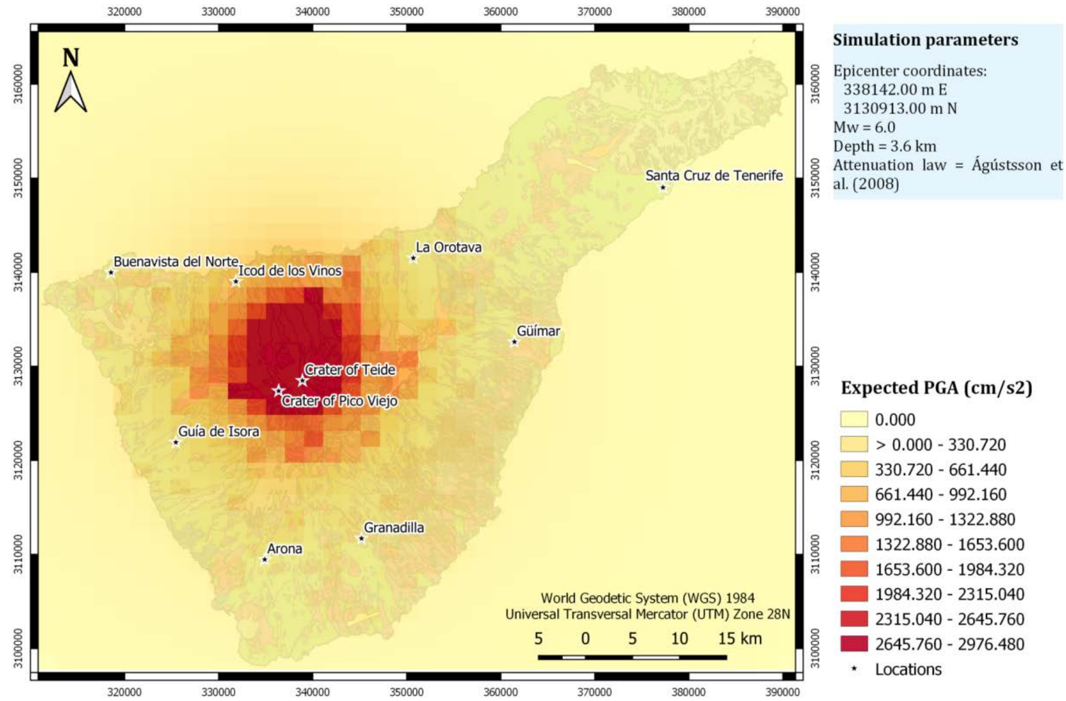

Figure S31. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Ágústsson et al. (2008) attenuation law.

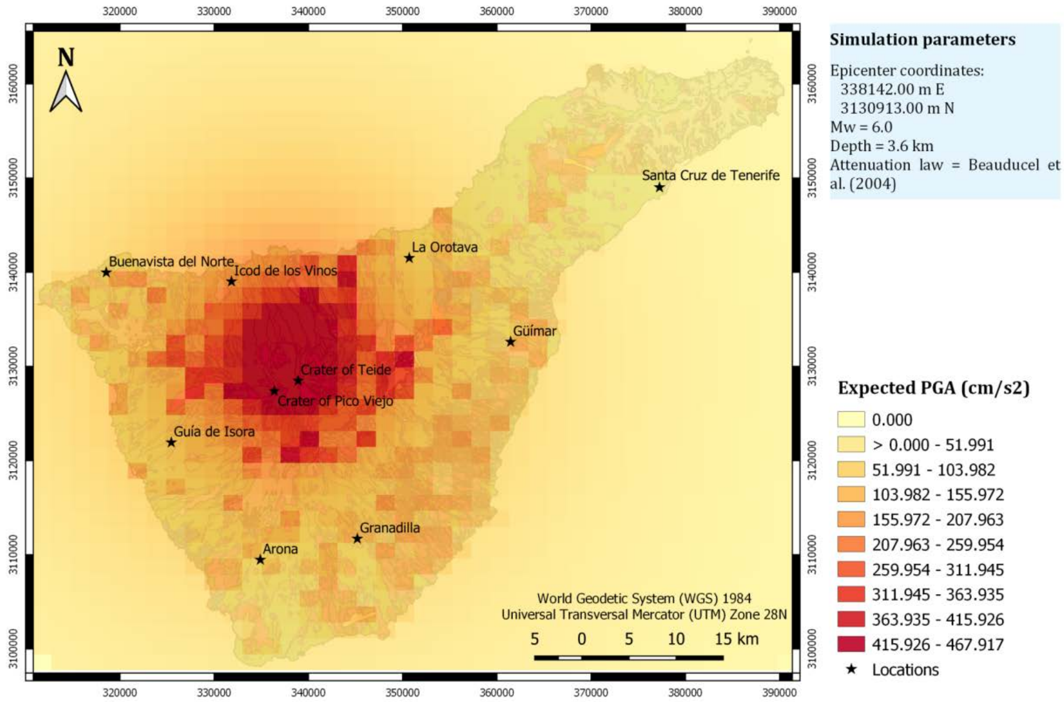

Figure S32. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Beauducel et al. (2004) attenuation law.

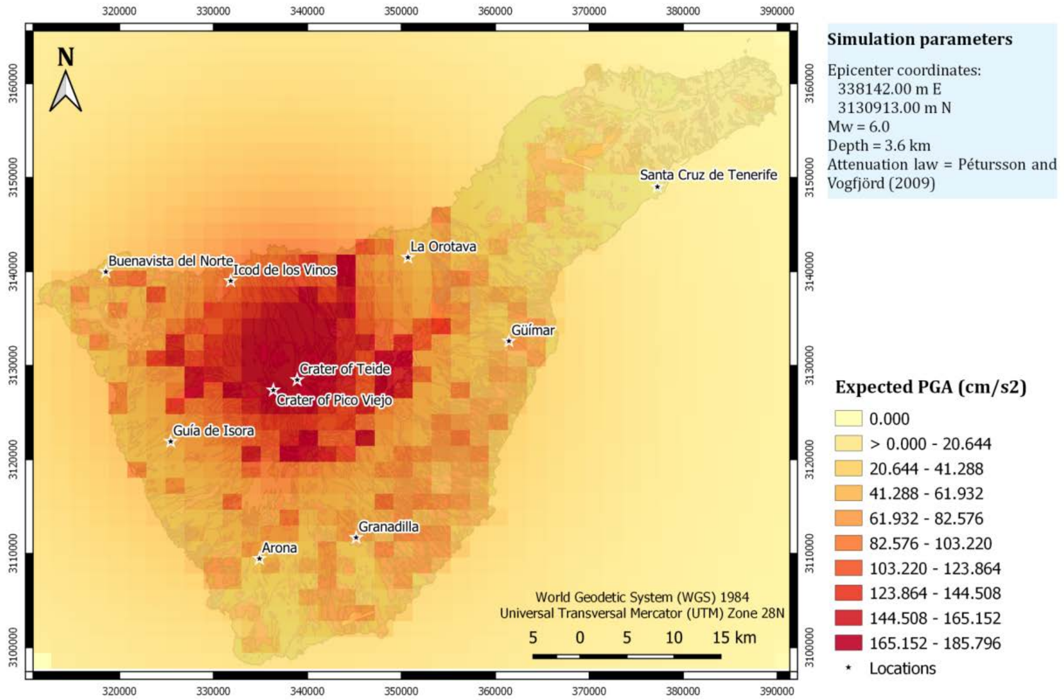

Figure S33. Expected PGA values for a M 6.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

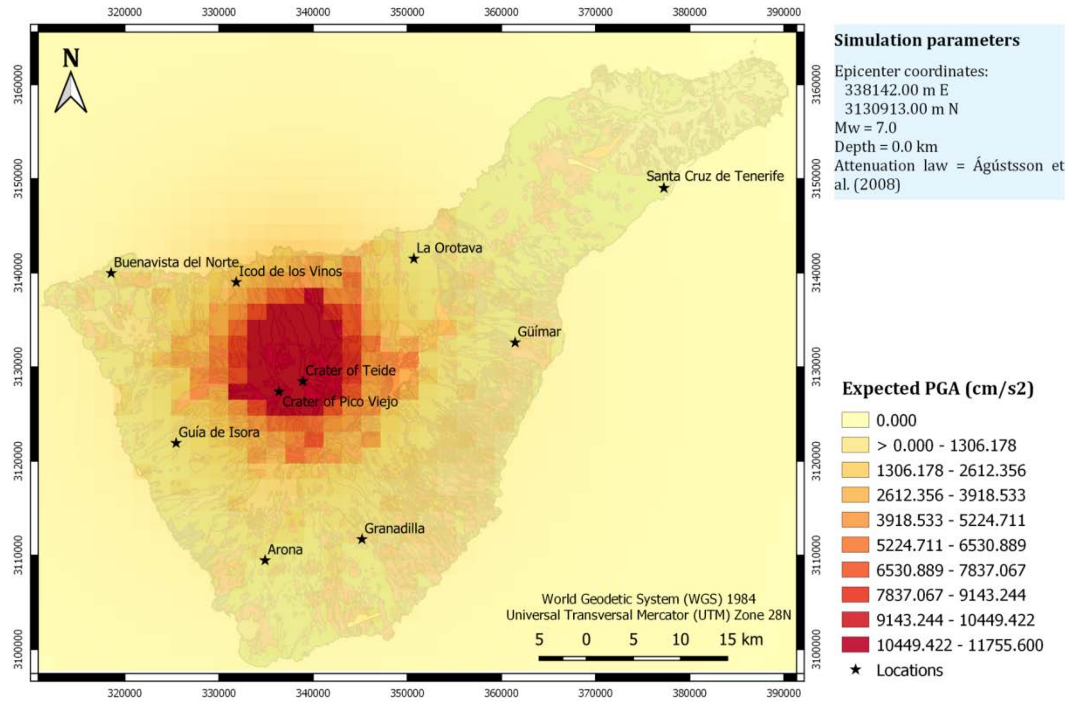

Figure S34. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Ágústsson et al. (2008) attenuation law.

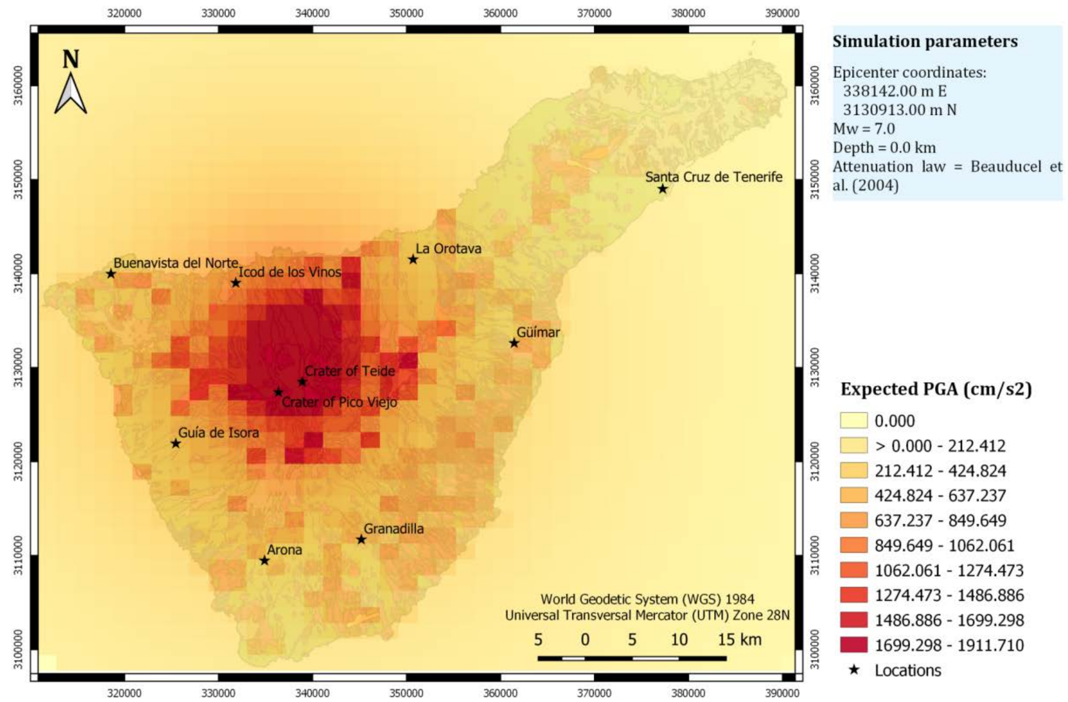

Figure S35. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Beauducel et al. (2004) attenuation law.

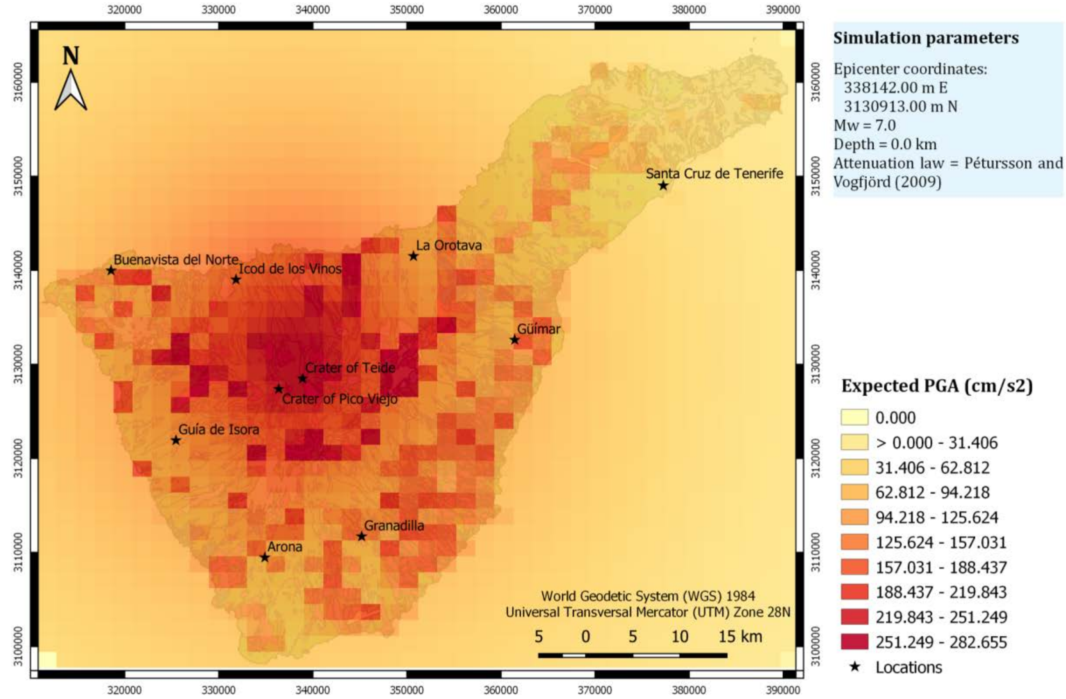

Figure S36. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

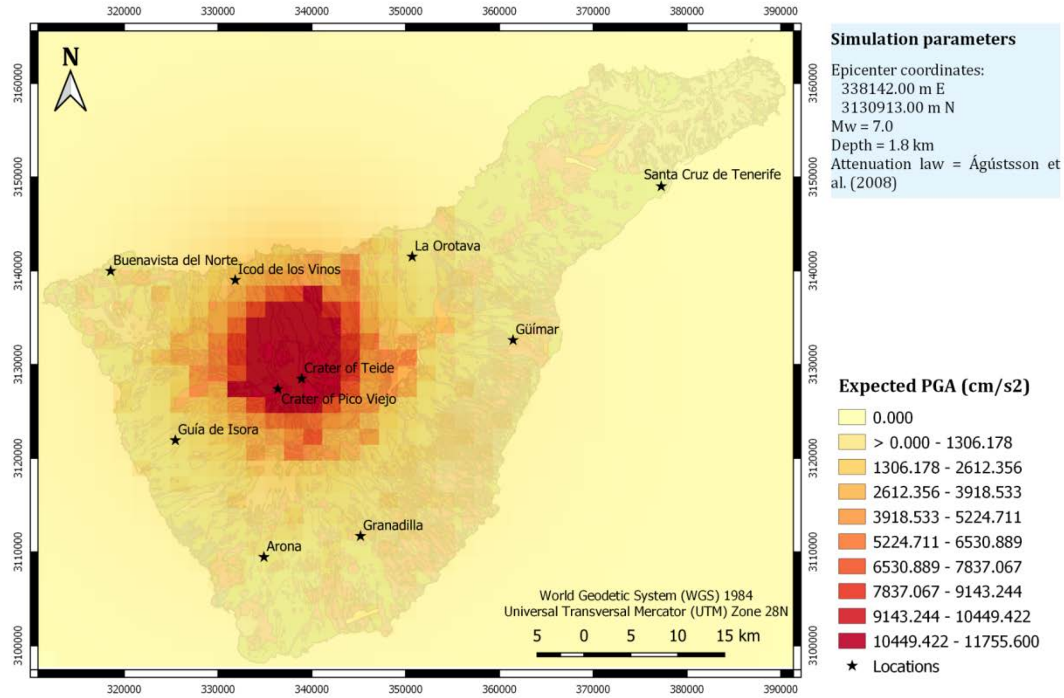

Figure S37. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Ágústsson et al. (2008) attenuation law.

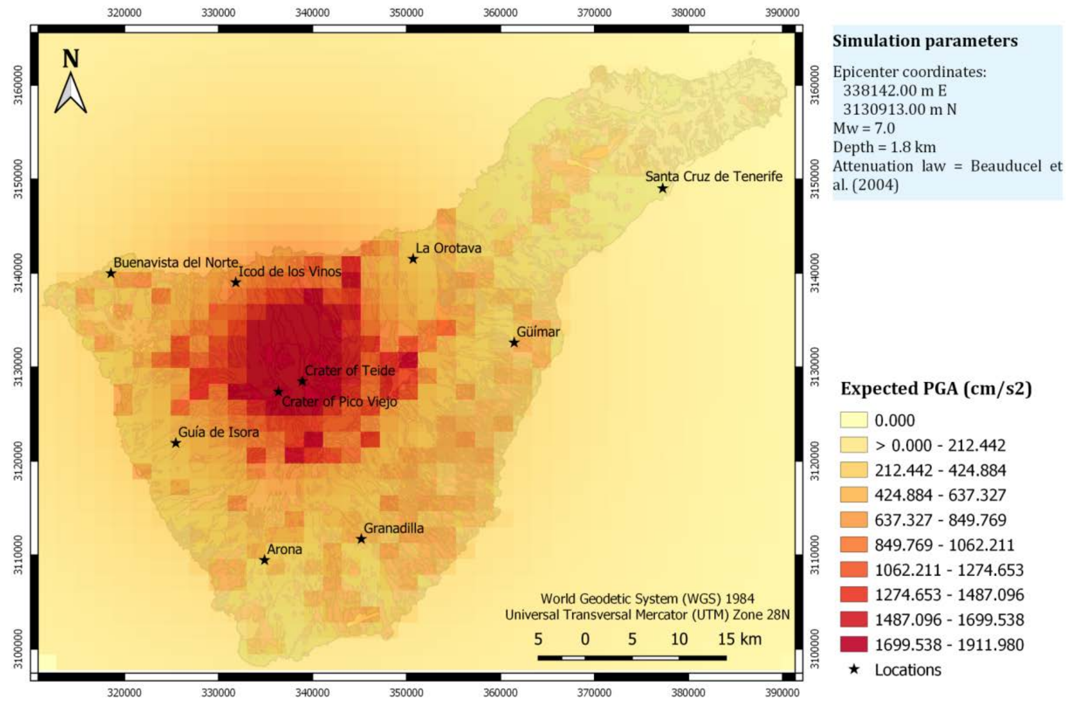

Figure S38. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Beauducel et al. (2004) attenuation law.

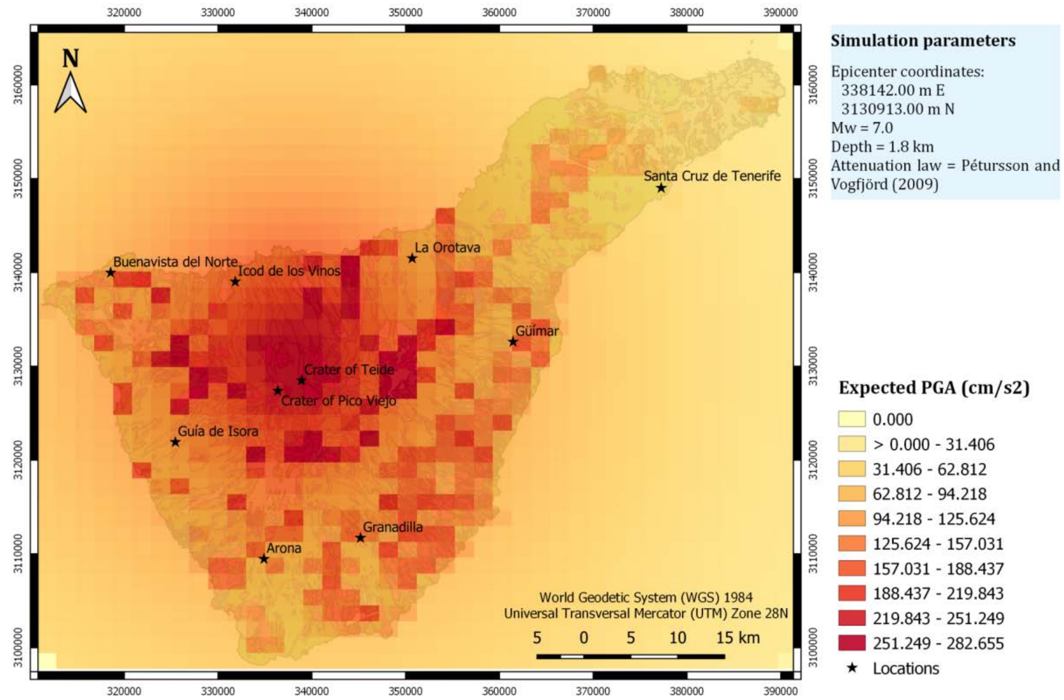

Figure S39. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 1.8 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

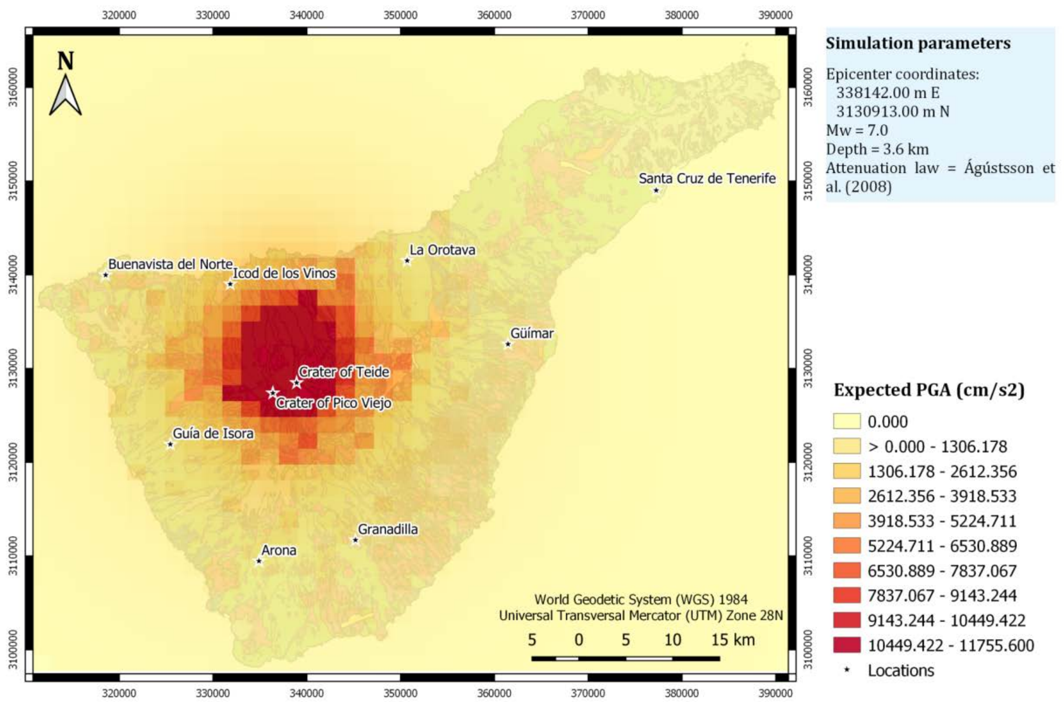

Figure S40. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Ágústsson et al. (2008) attenuation law.

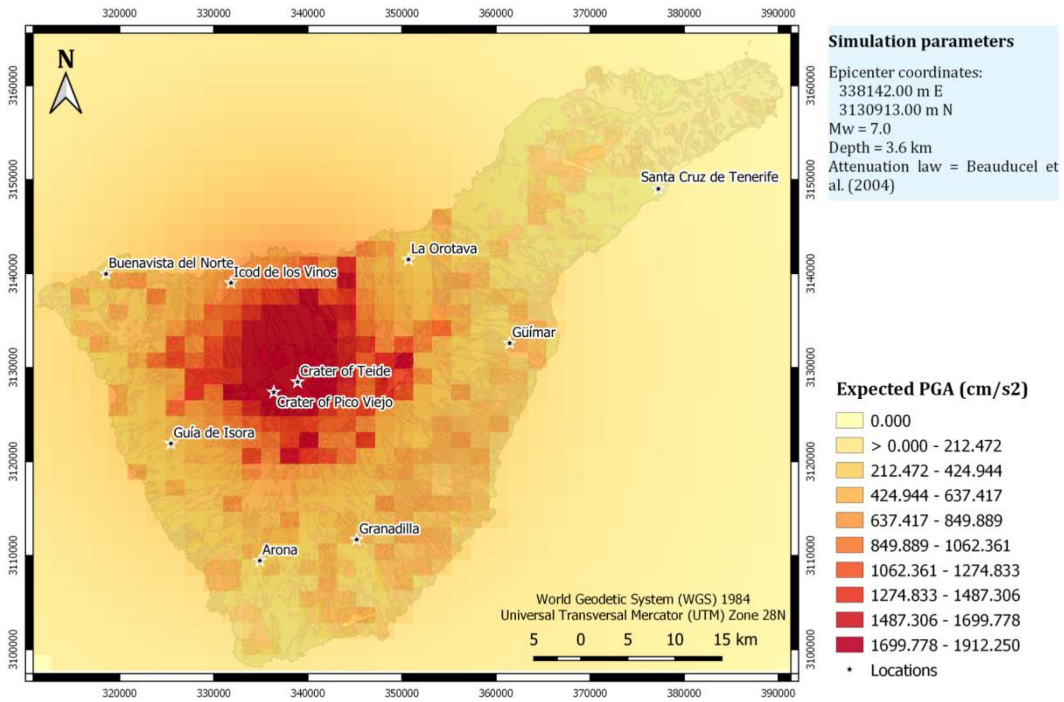

Figure S41. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Beauducel et al. (2004) attenuation law.

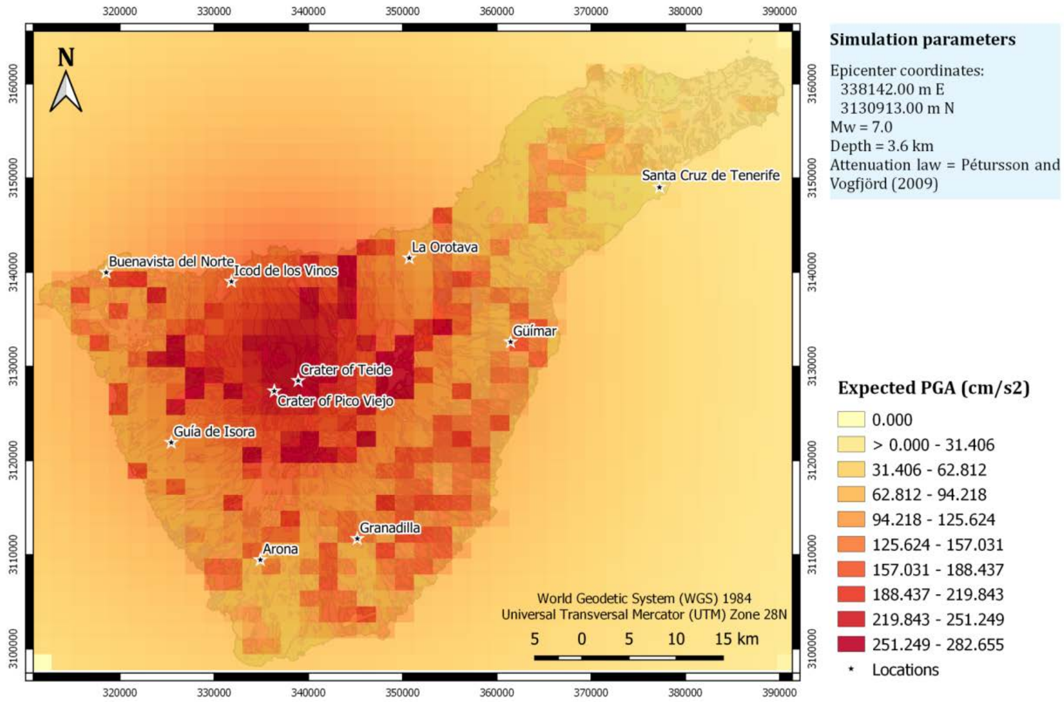

Figure S42. Expected PGA values for a M 7.0 synthetic earthquake located north of the summit of Mt Teide, Tenerife (Canary Islands), at a depth of 3.6 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

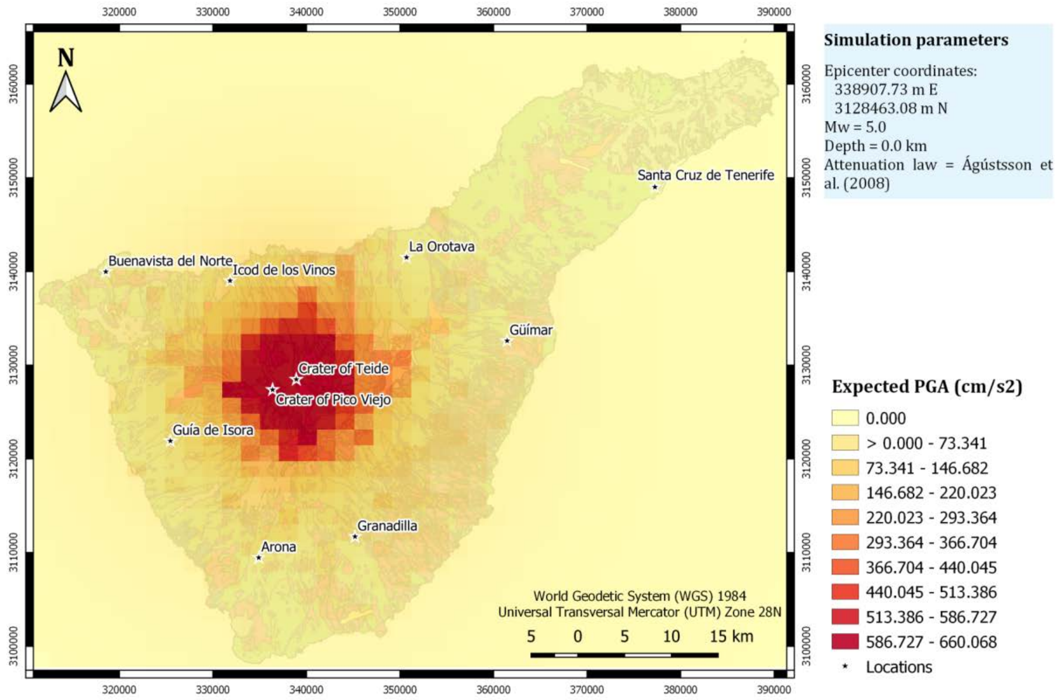

Figure S43. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Ágústsson et al. (2008) attenuation law.

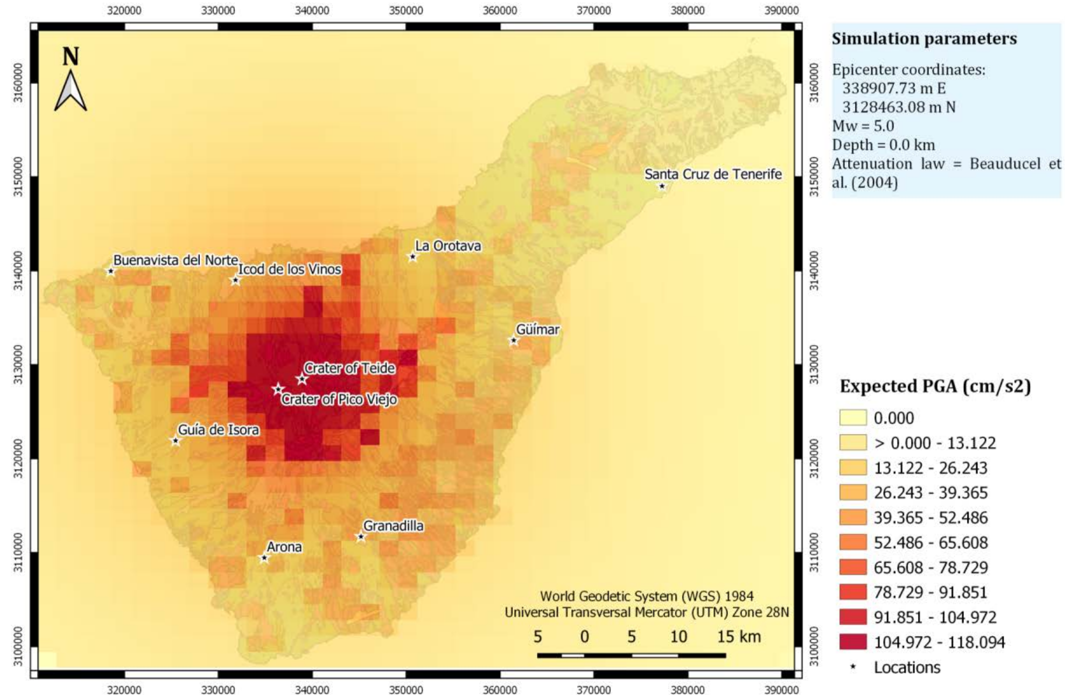

Figure S44. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Beauducel et al. (2004) attenuation law.

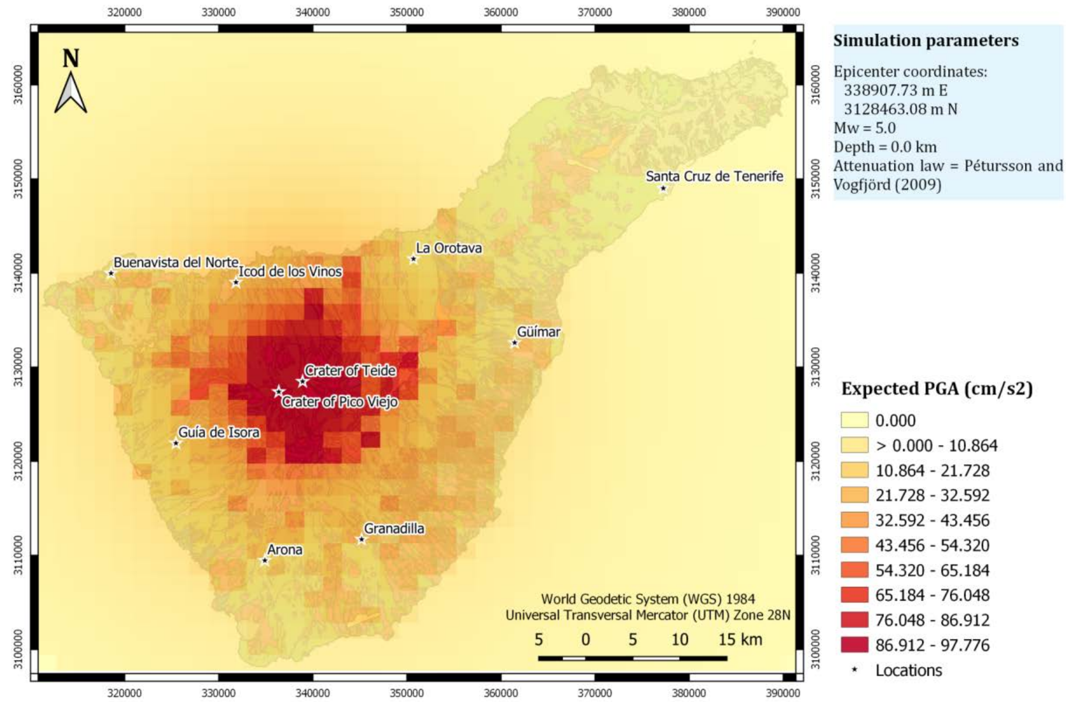

Figure S45. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

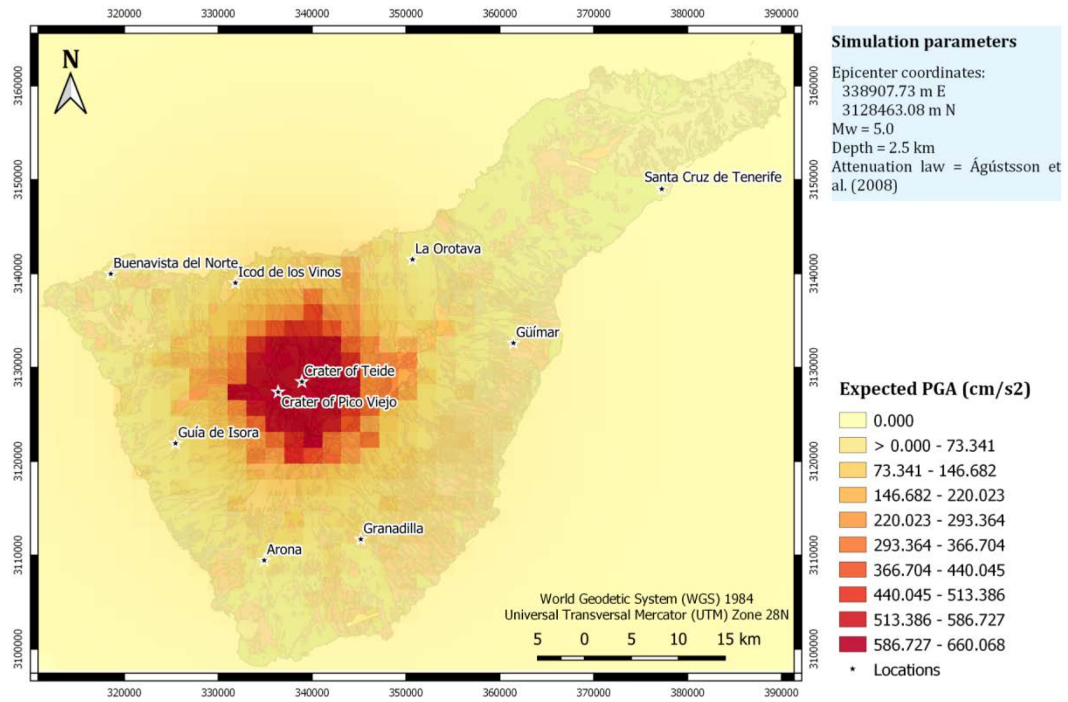

Figure S46. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Ágústsson et al. (2008) attenuation law.

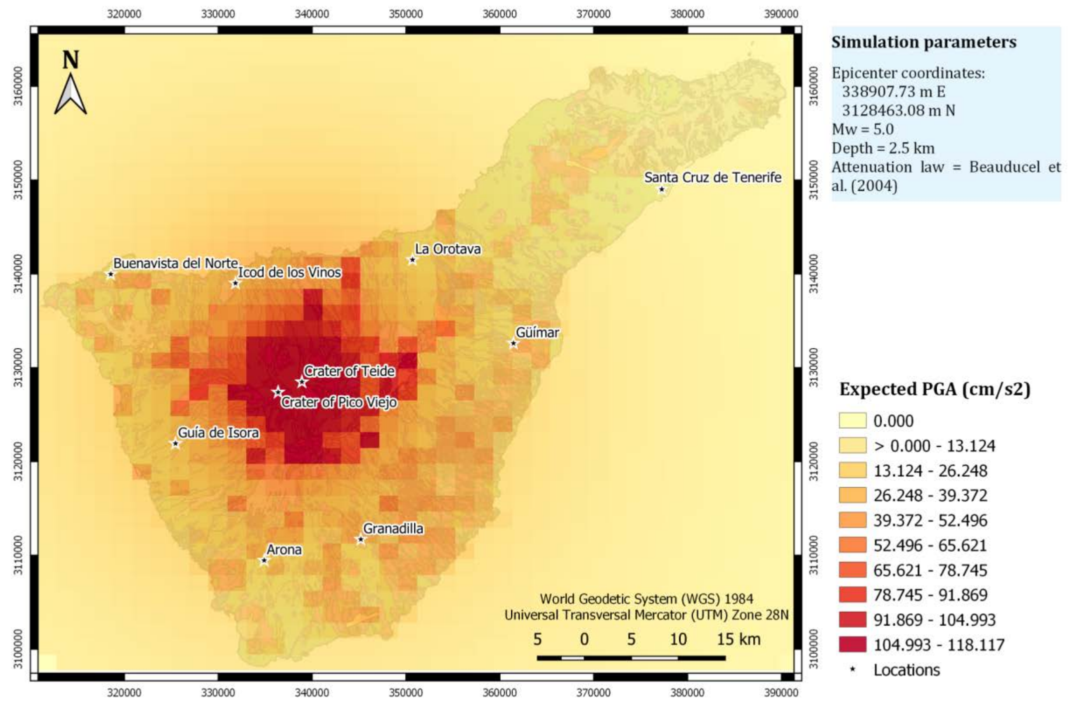

Figure S47. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Beauducel et al. (2004) attenuation law.

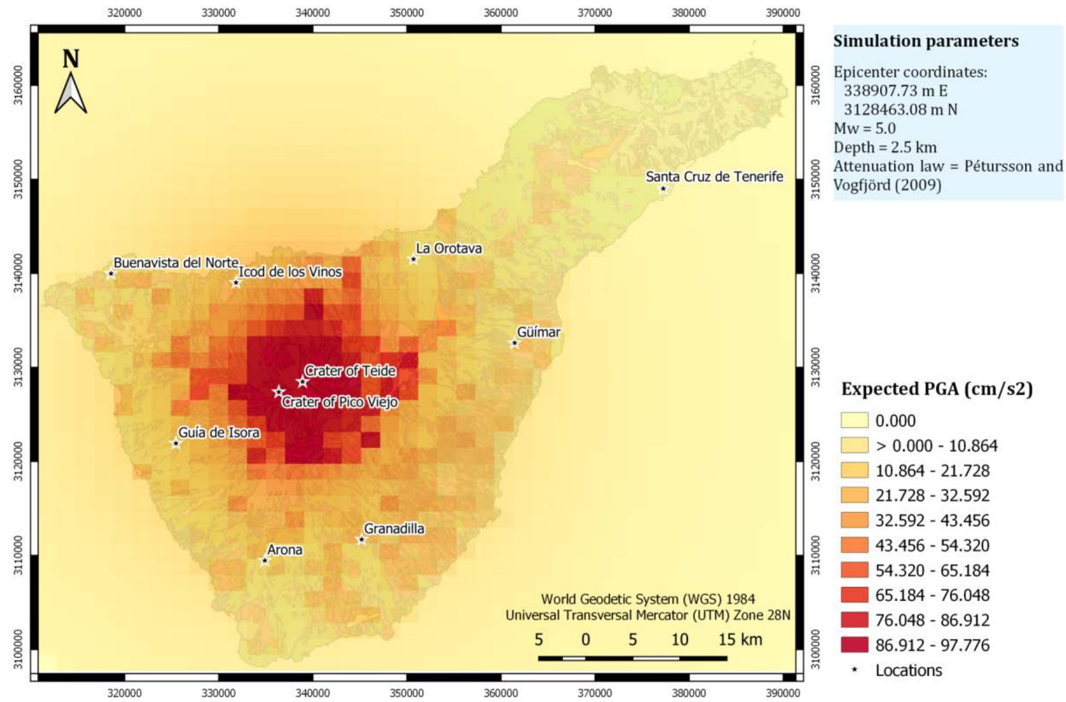

Figure S48. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

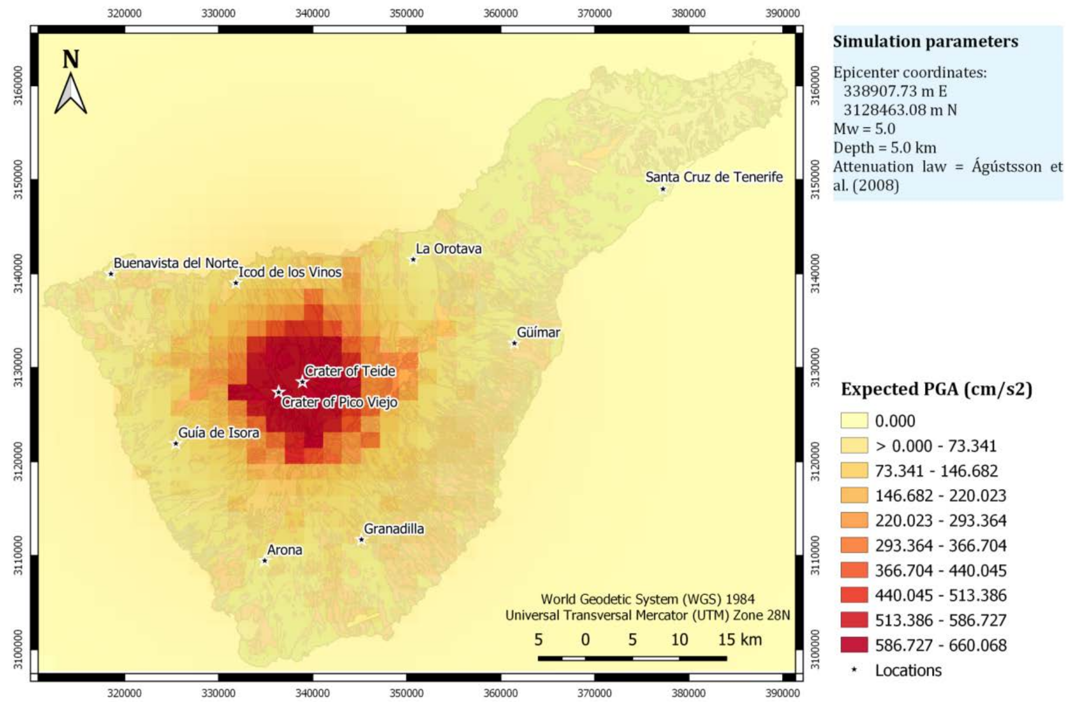

Figure S49. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Ágústsson et al. (2008) attenuation law.

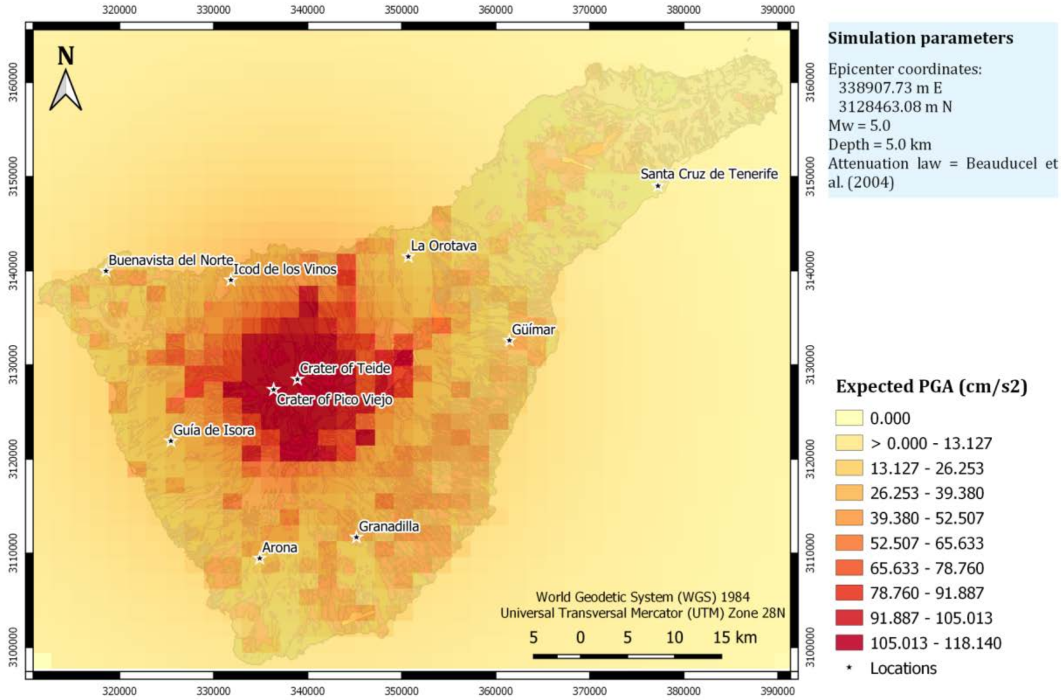

Figure S50. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Beauducel et al. (2004) attenuation law.

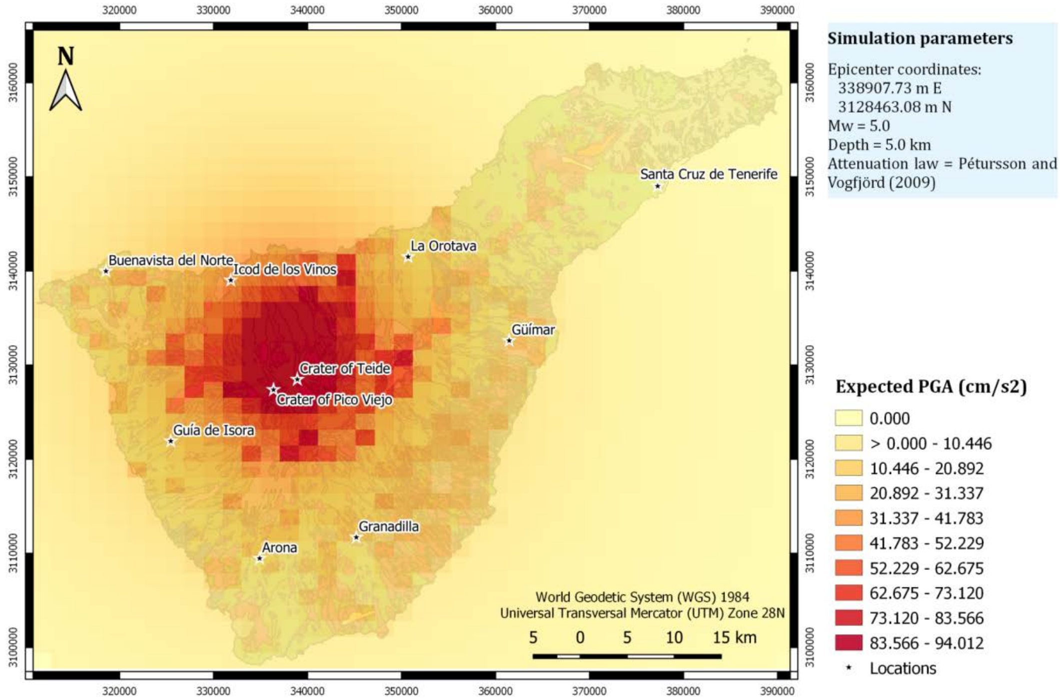

Figure S51. Expected PGA values for a M 5.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

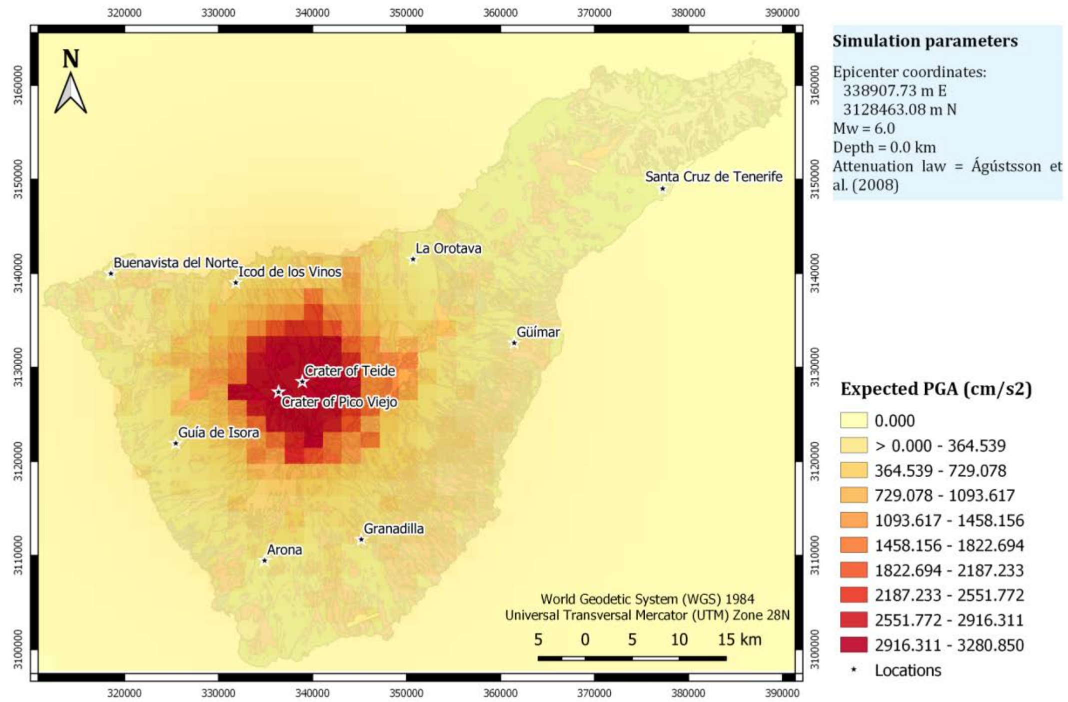

Figure S52. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Ágústsson et al. (2008) attenuation law.

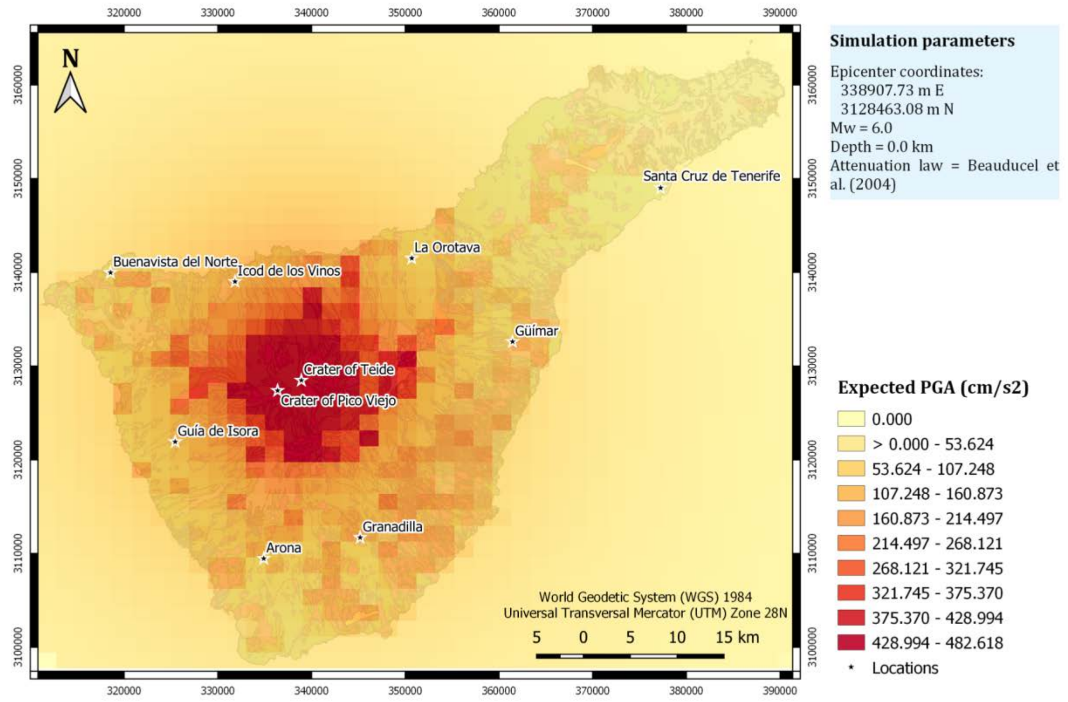

Figure S53. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Beauducel et al. (2004) attenuation law.

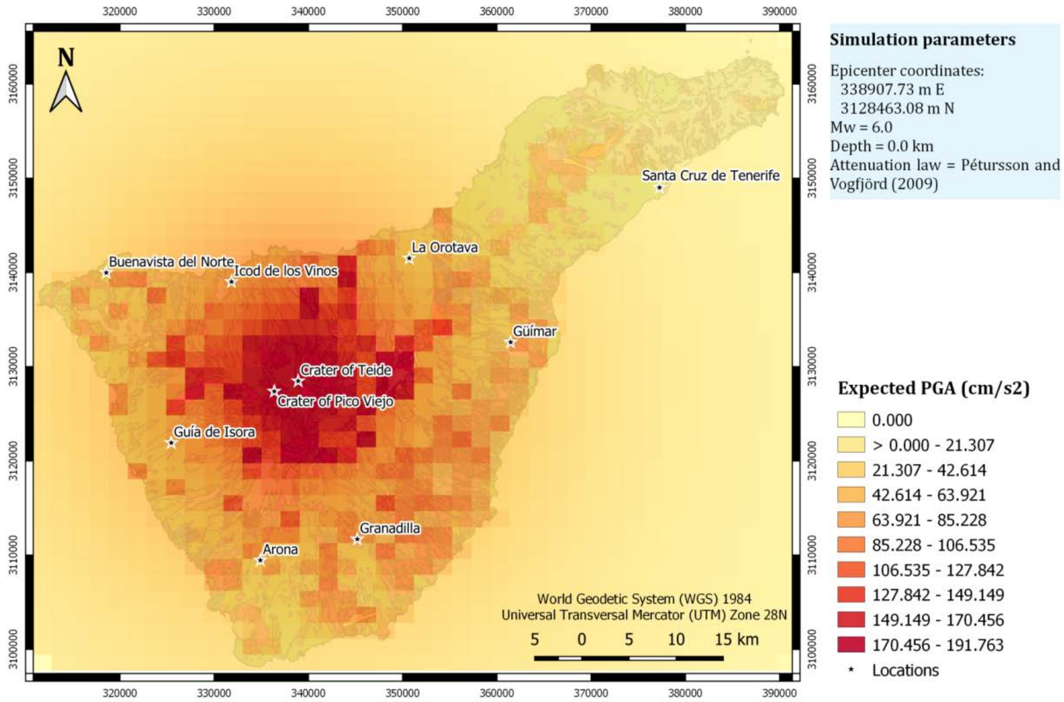

Figure S54. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

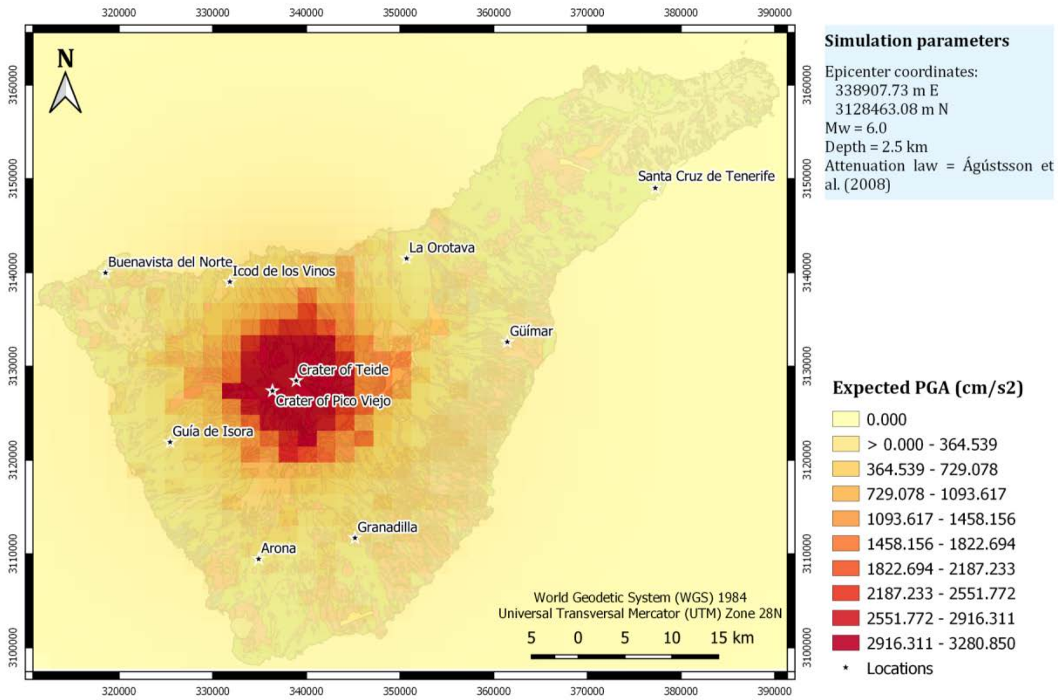

Figure S55. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Ágústsson et al. (2008) attenuation law.

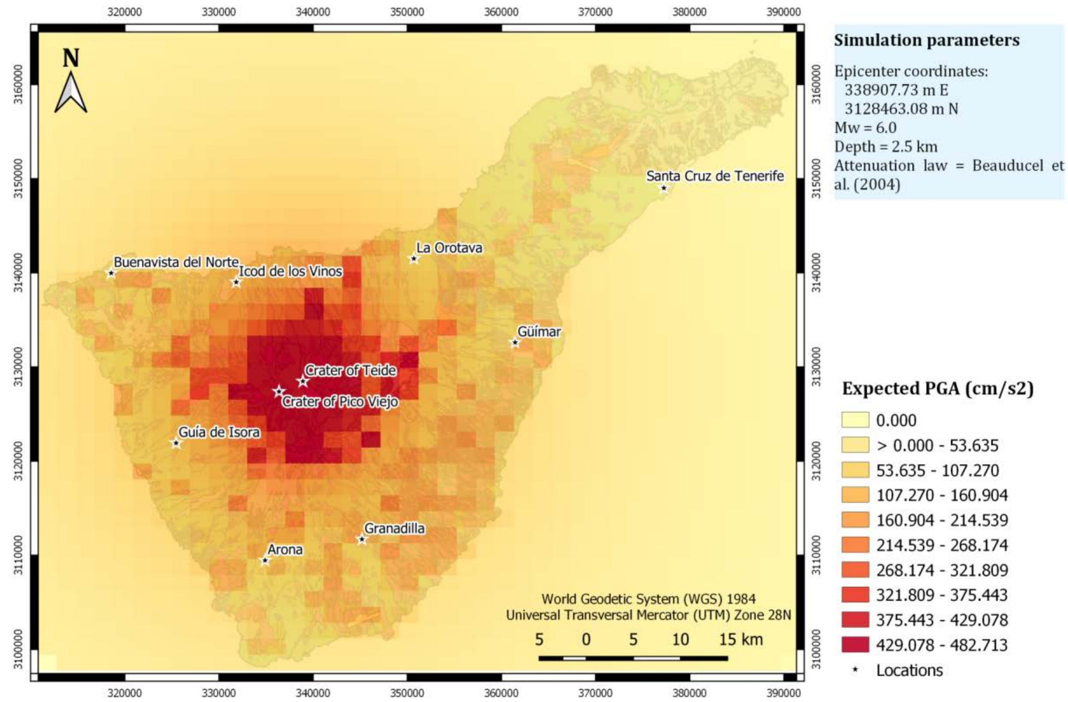

Figure S56. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Beauducel et al. (2004) attenuation law.

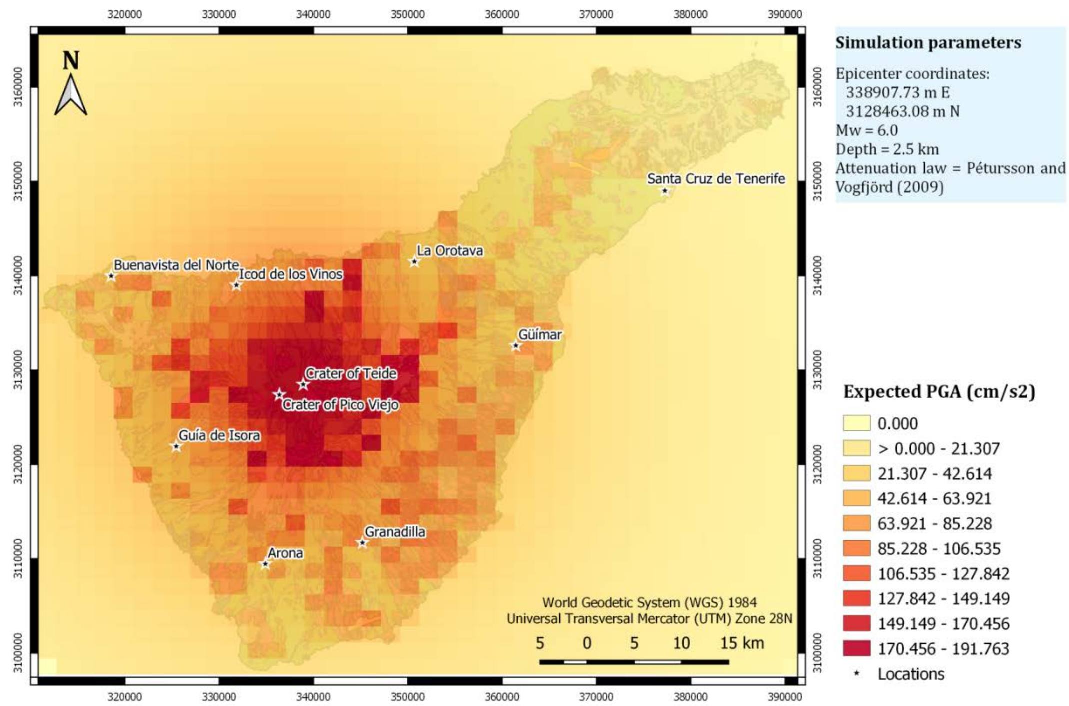

Figure S57. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

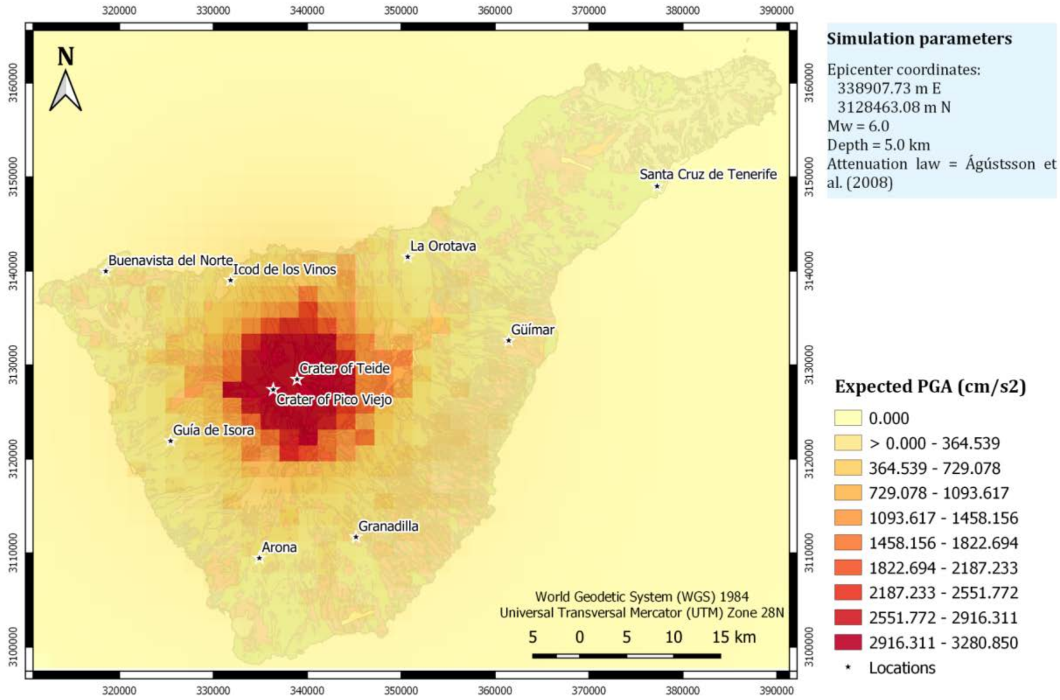

Figure S58. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Ágústsson et al. (2008) attenuation law.

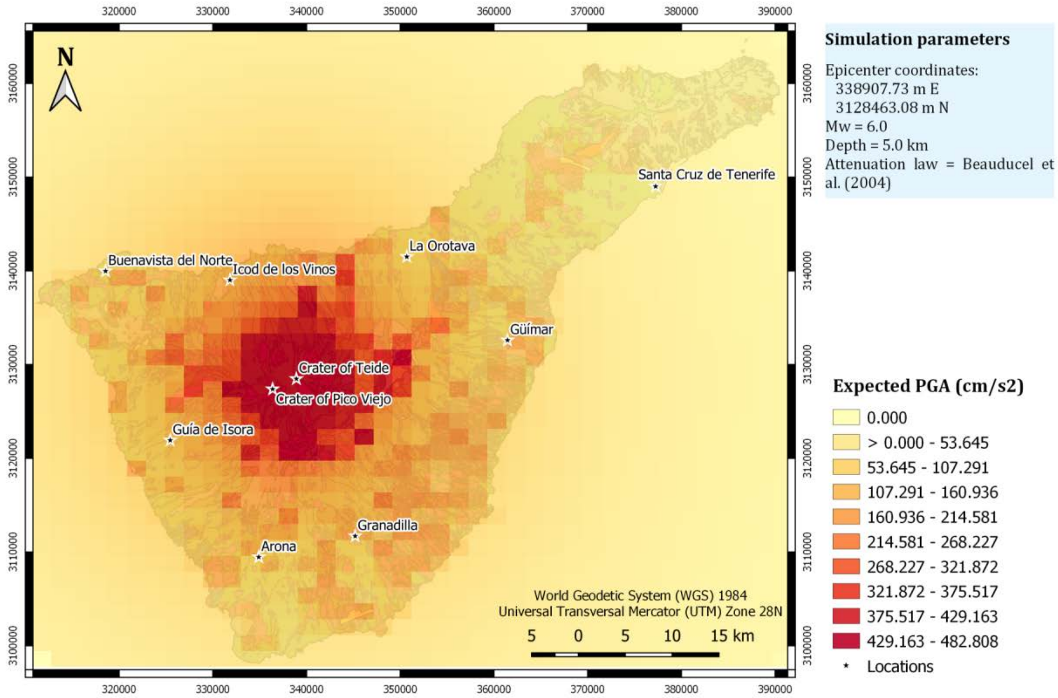

Figure S59. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Beauducel et al. (2004) attenuation law.

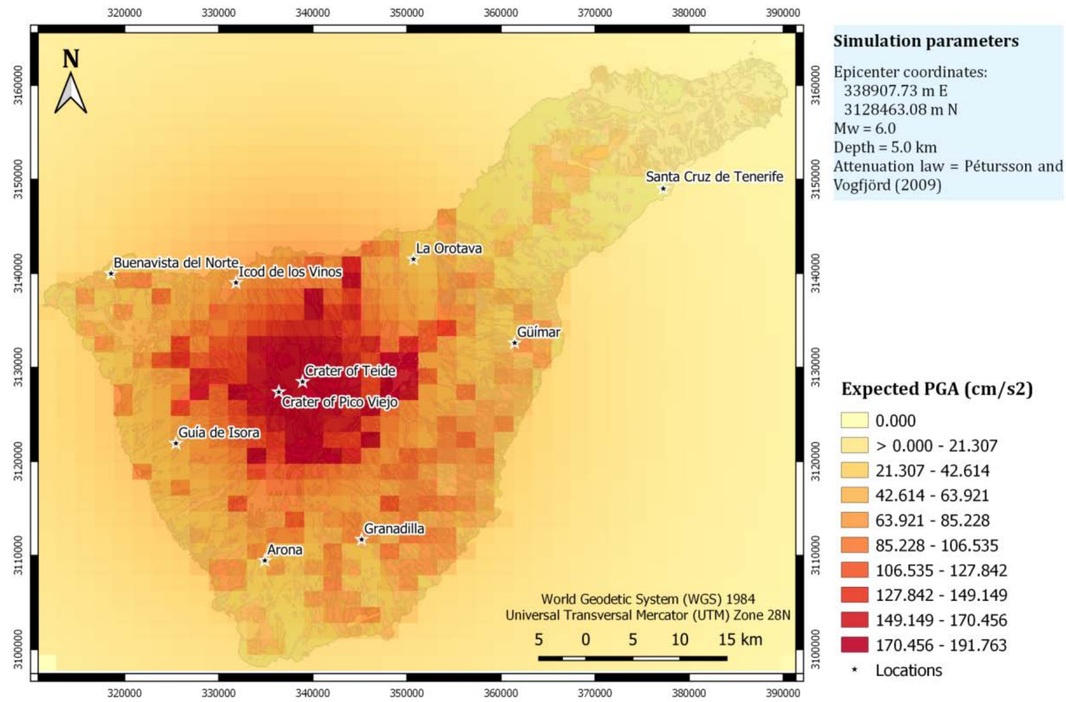

Figure S60. Expected PGA values for a M 6.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

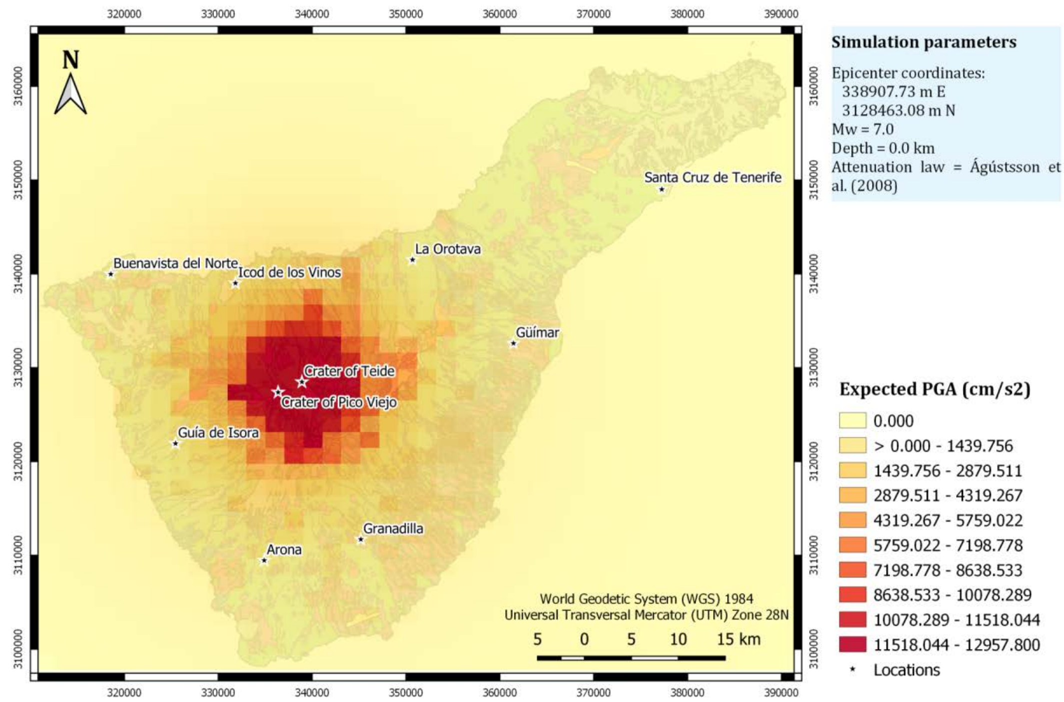

Figure S61. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Ágústsson et al. (2008) attenuation law.

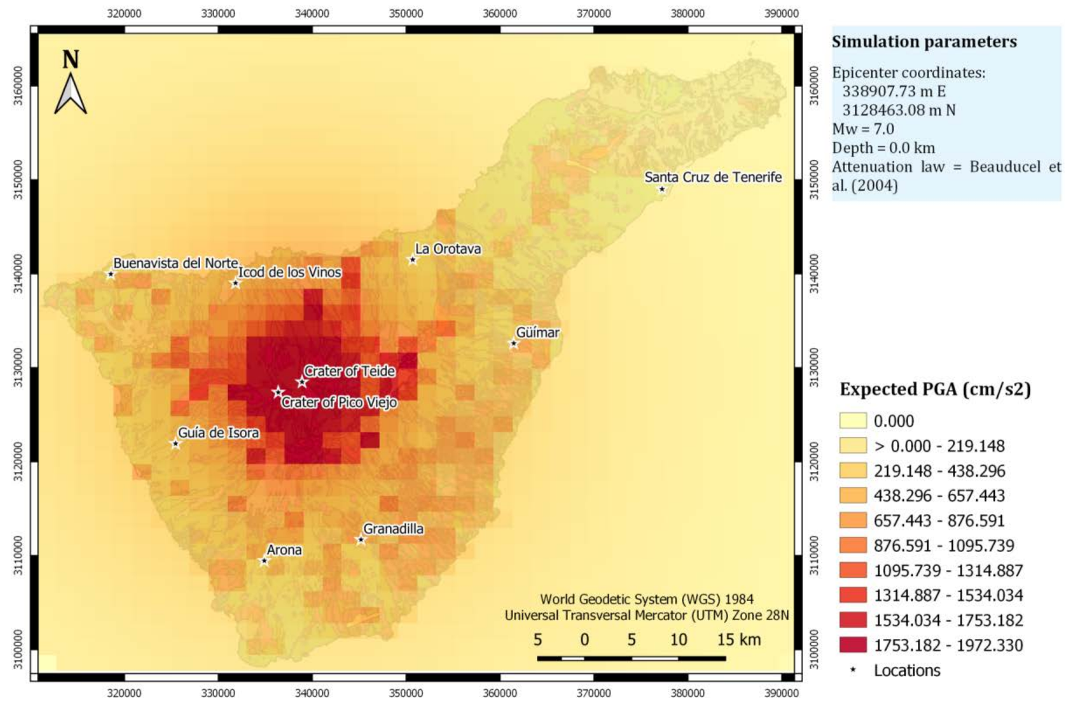

Figure S62. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Beauducel et al. (2004) attenuation law.

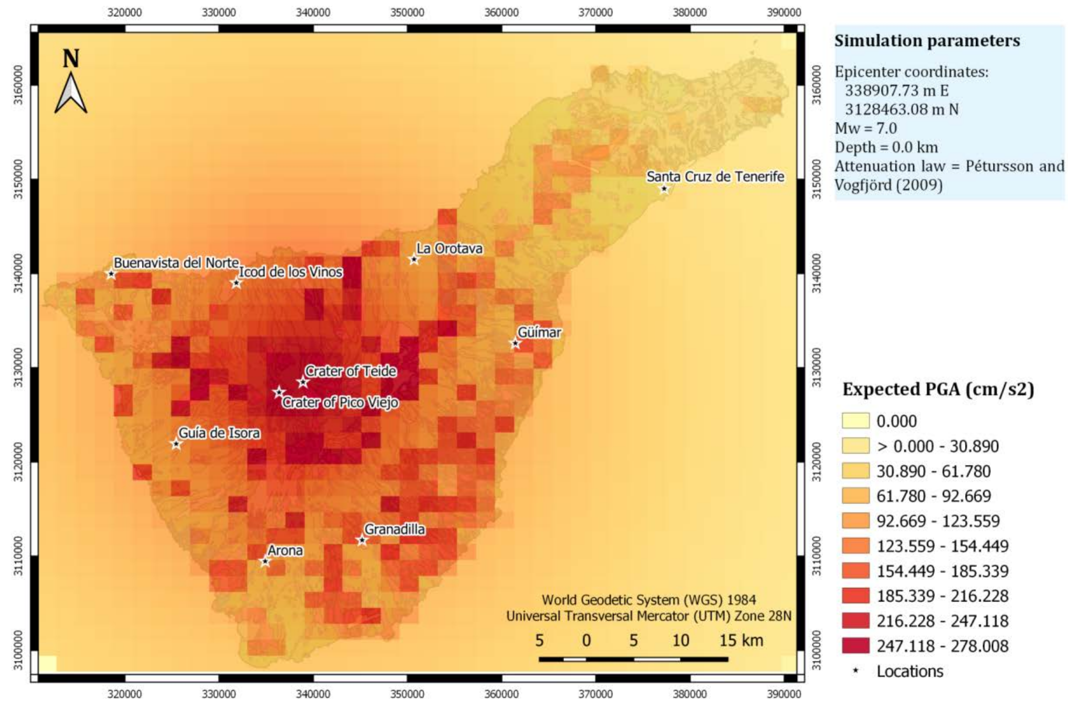

Figure S63. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 0.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

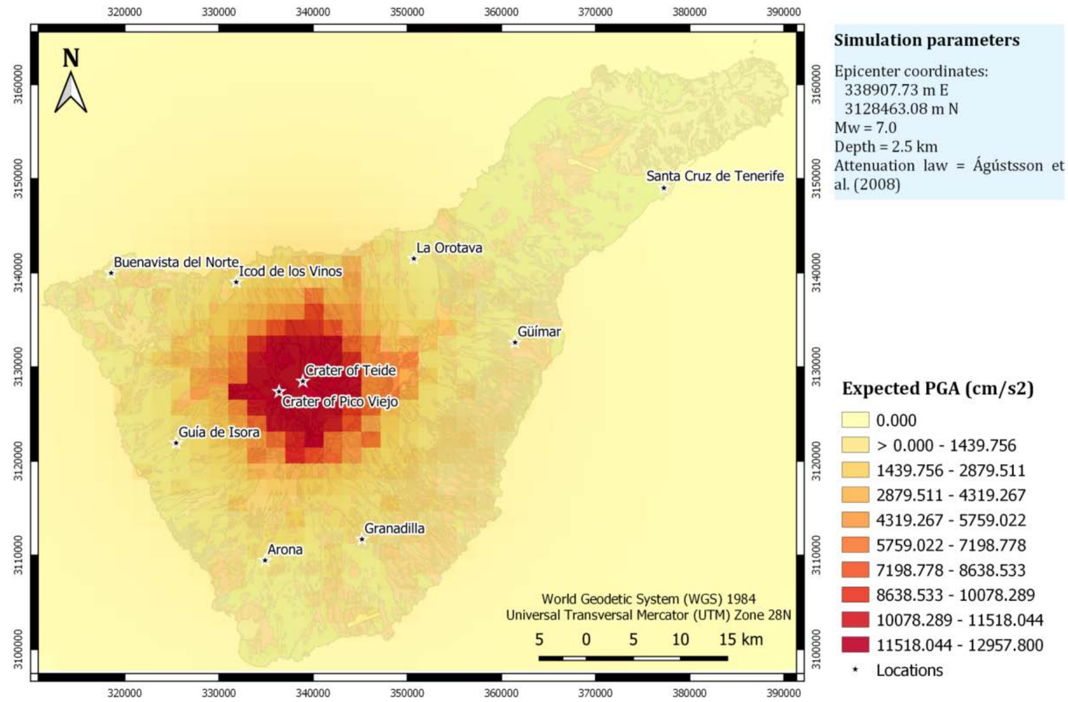

Figure S64. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Ágústsson et al. (2008) attenuation law.

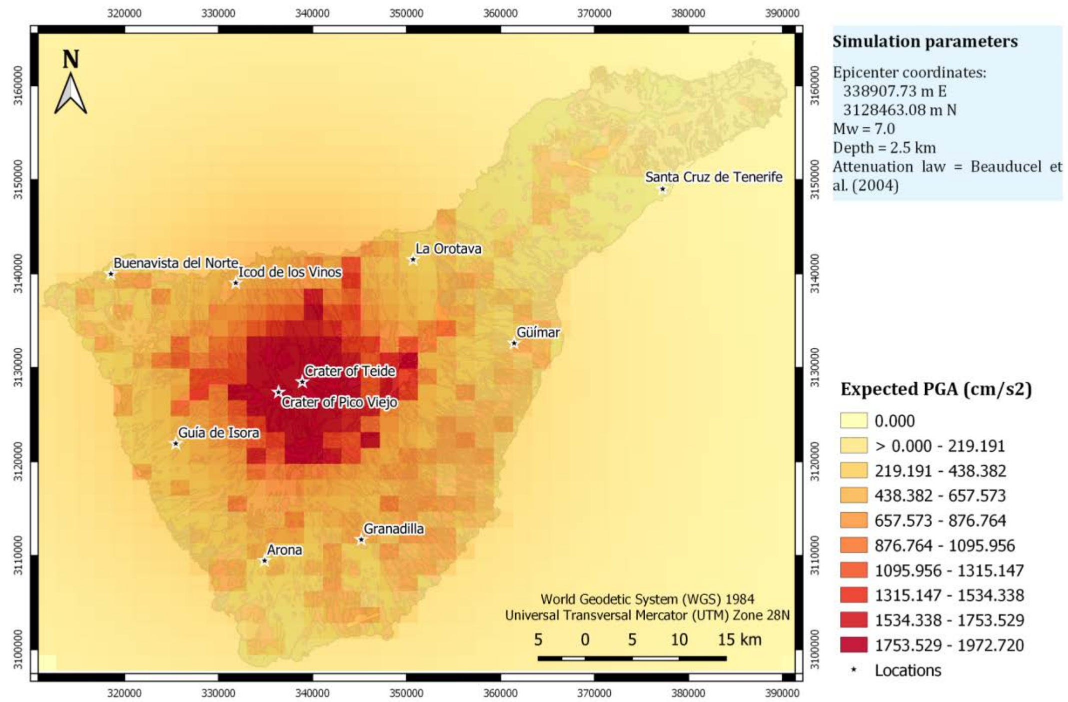

Figure S65. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Beauducel et al. (2004) attenuation law.

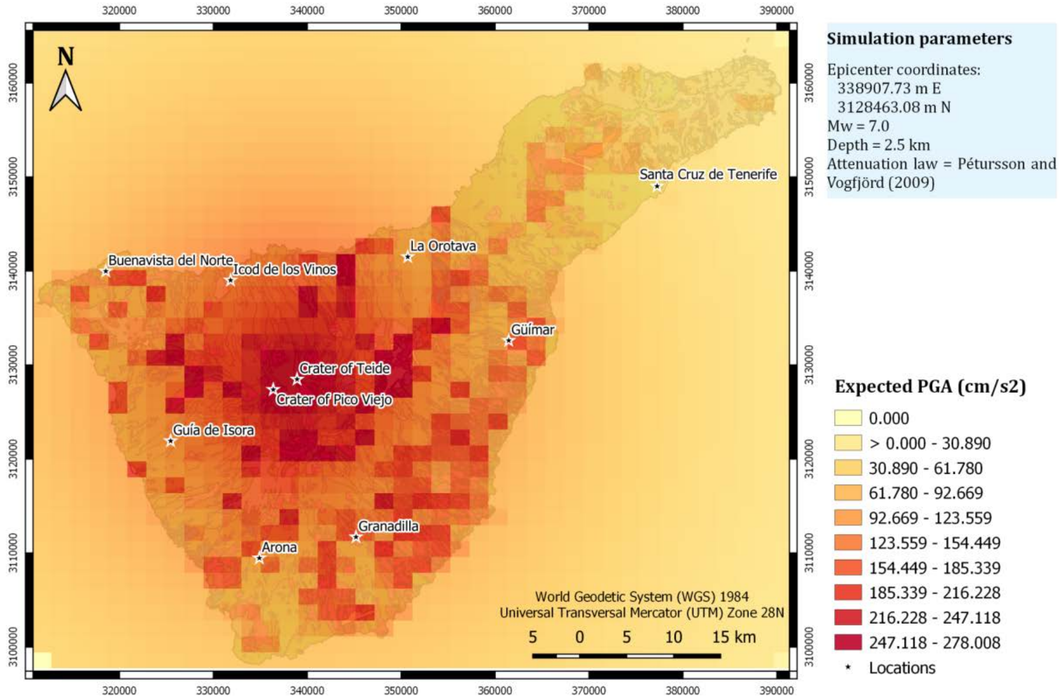

Figure S66. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 2.5 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

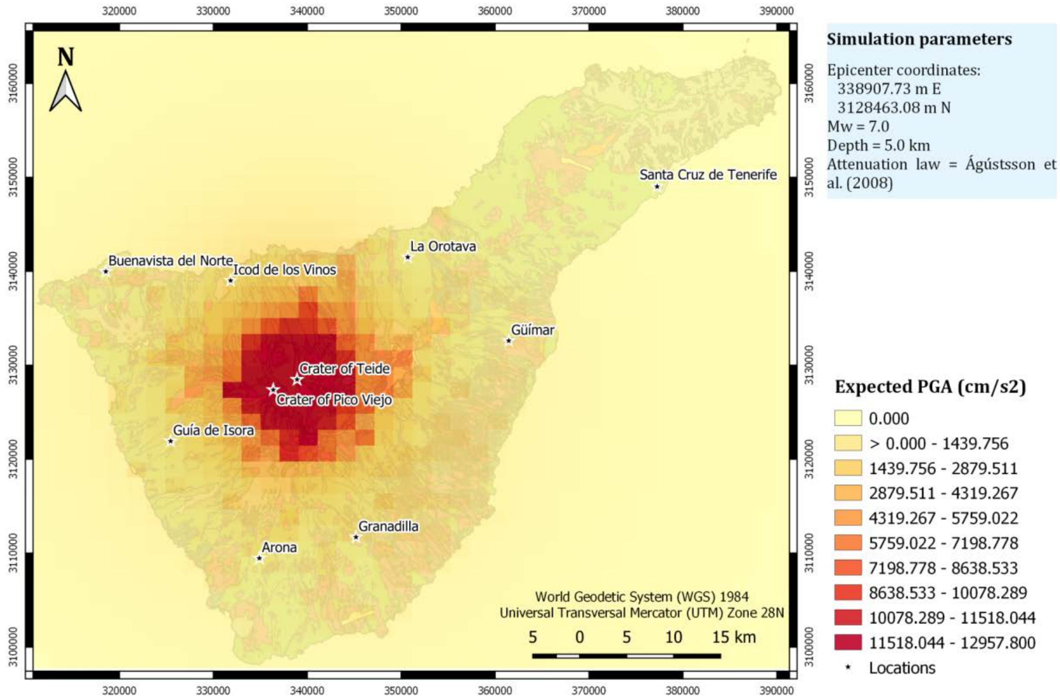

Figure S67. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Ágústsson et al. (2008) attenuation law.

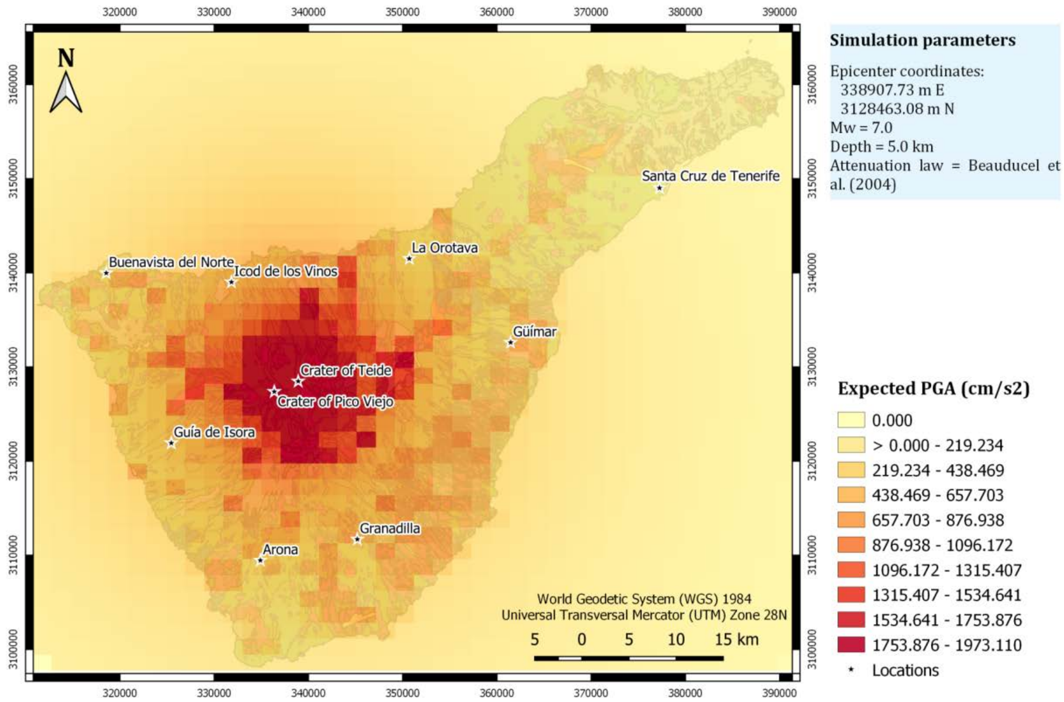

Figure S68. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Beauducel et al. (2004) attenuation law.

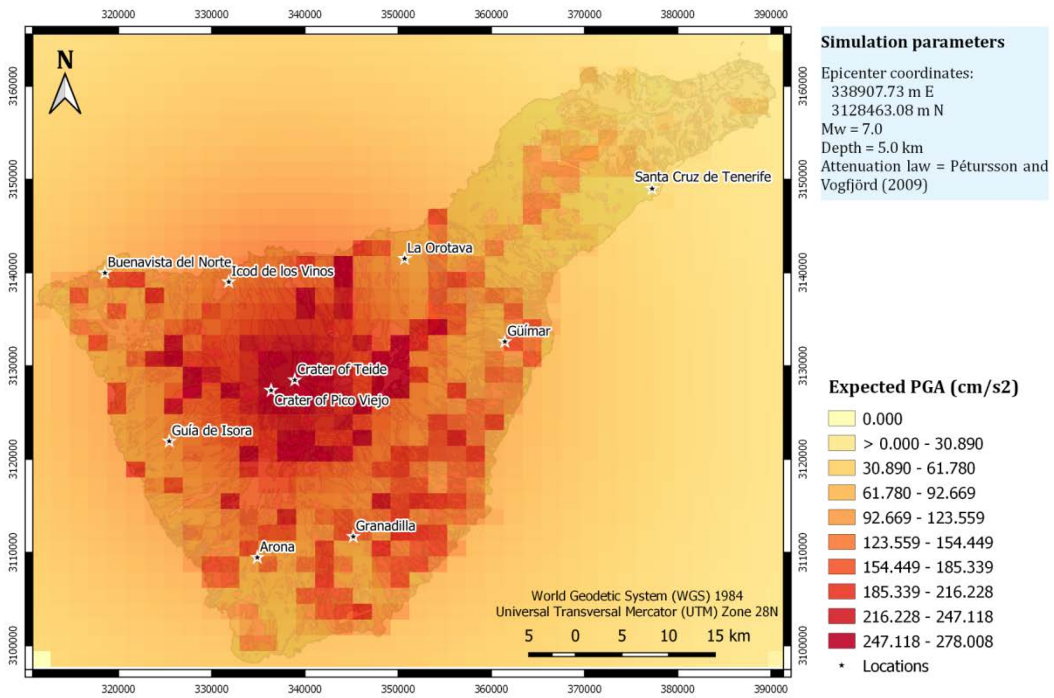

Figure S69. Expected PGA values for a M 7.0 synthetic earthquake located on the crater of Teide, Tenerife (Canary Islands), at a depth of 5.0 km, after applying the Pétursson and Vogfjörd (2009) attenuation law.

Landslide scenarios

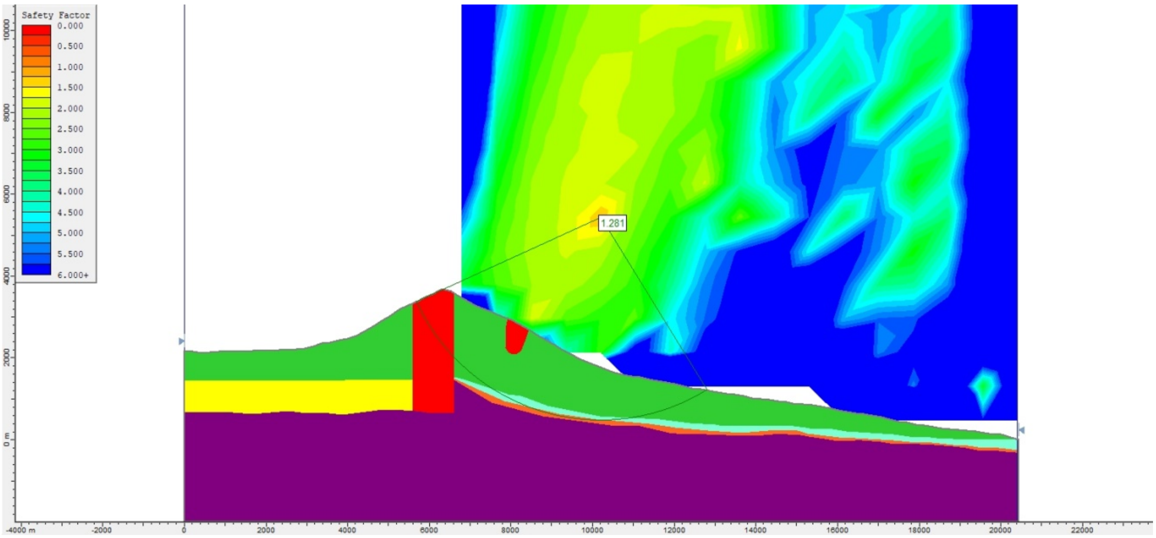

Figure S70. Slope stability static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method.

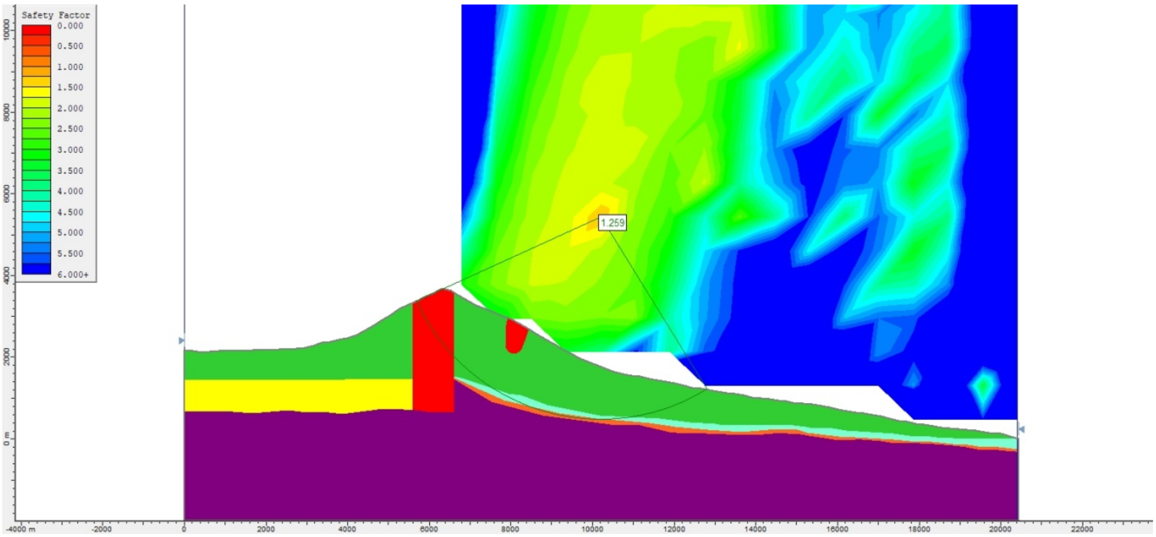

Figure S71. Slope stability static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method.

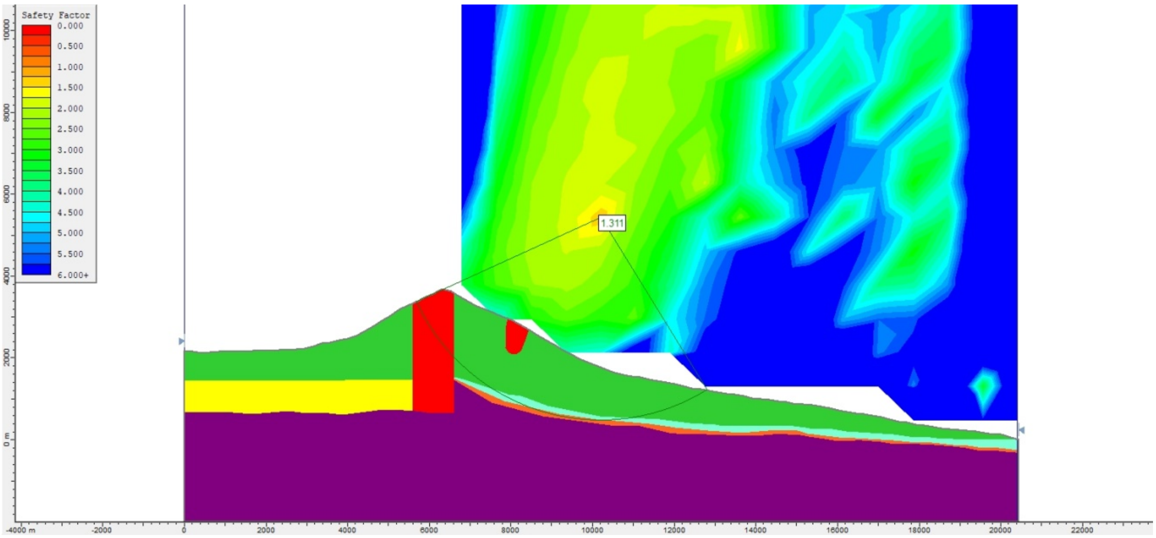

Figure S72. Slope stability static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method.

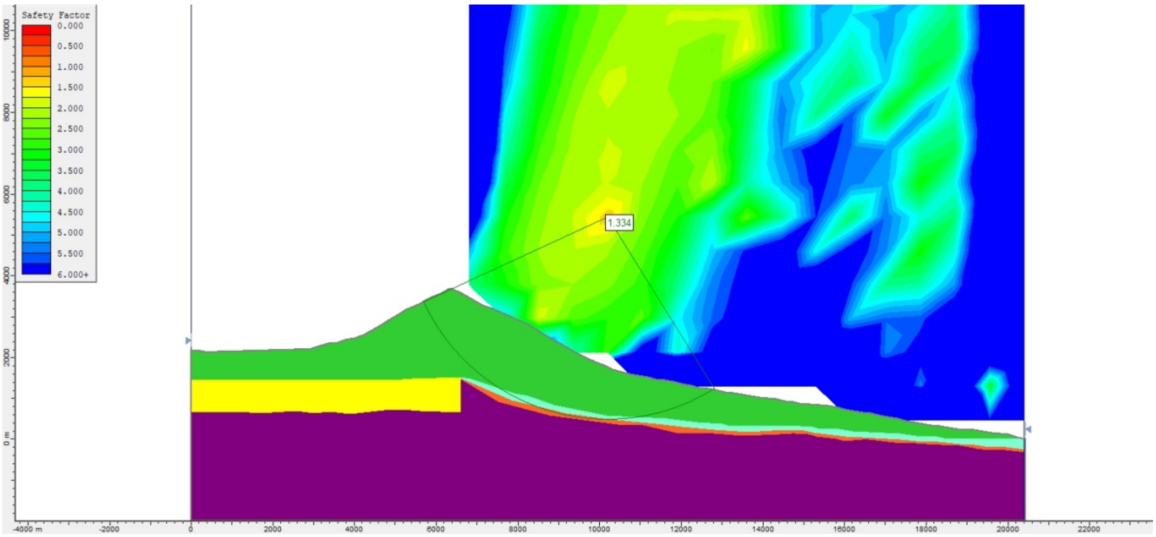

Figure S73. Slope stability static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method.

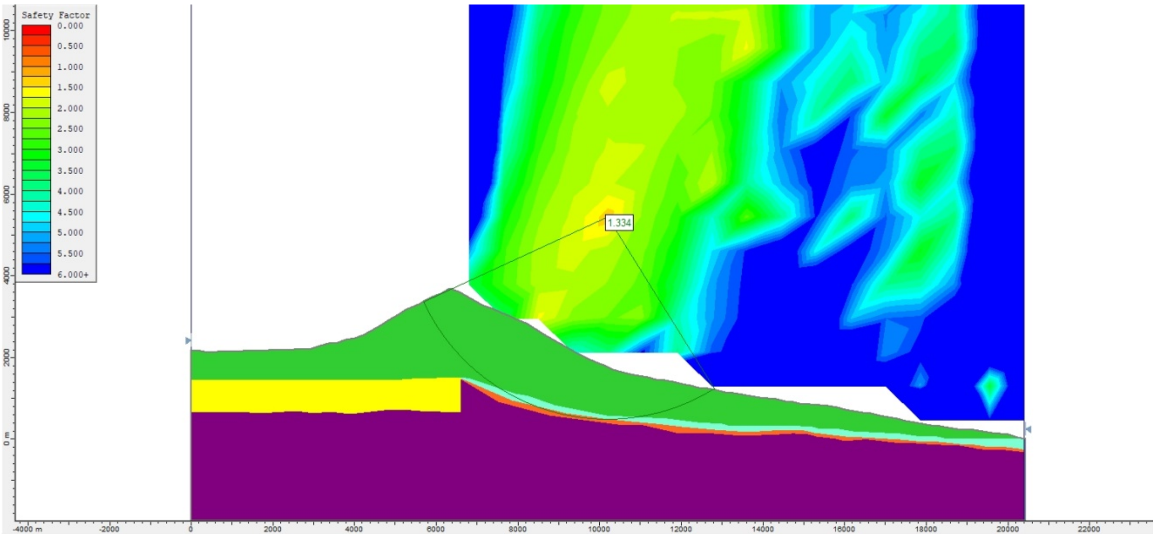

Figure S74. Slope stability static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method.

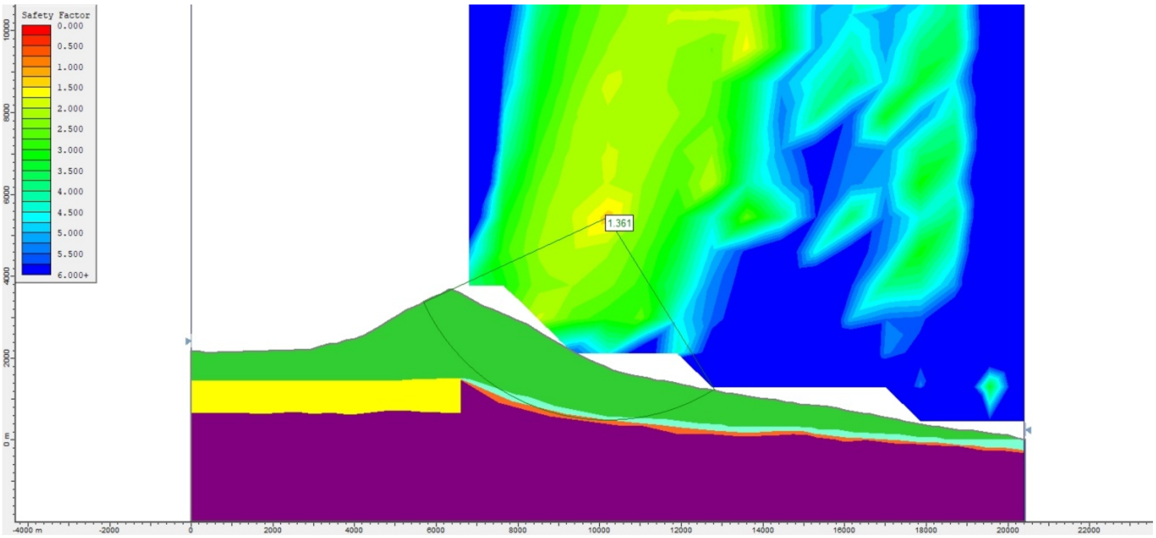

Figure S75. Slope stability static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method.

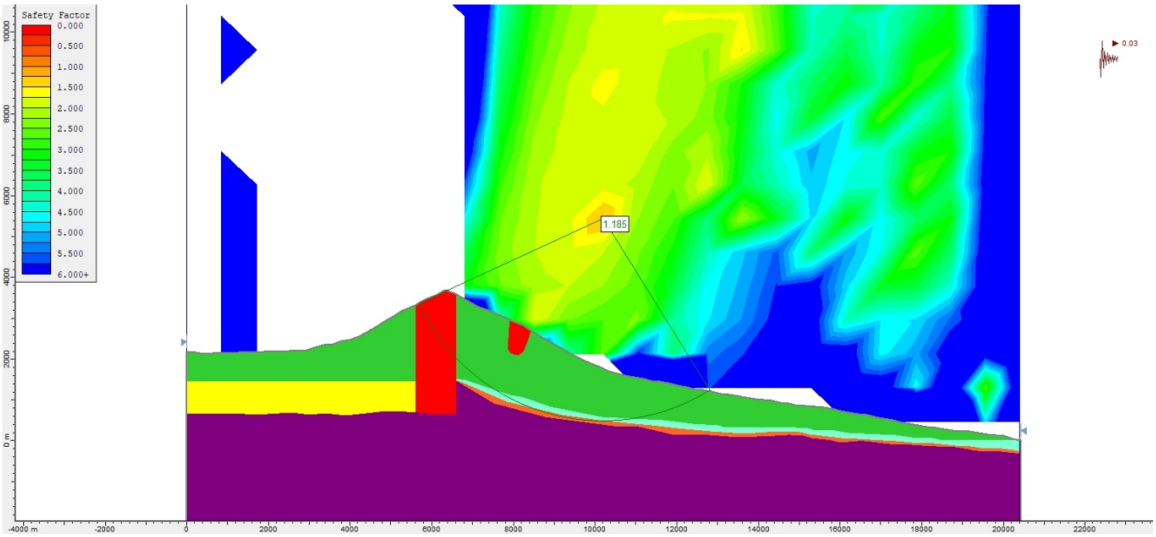

Figure S76. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.03.

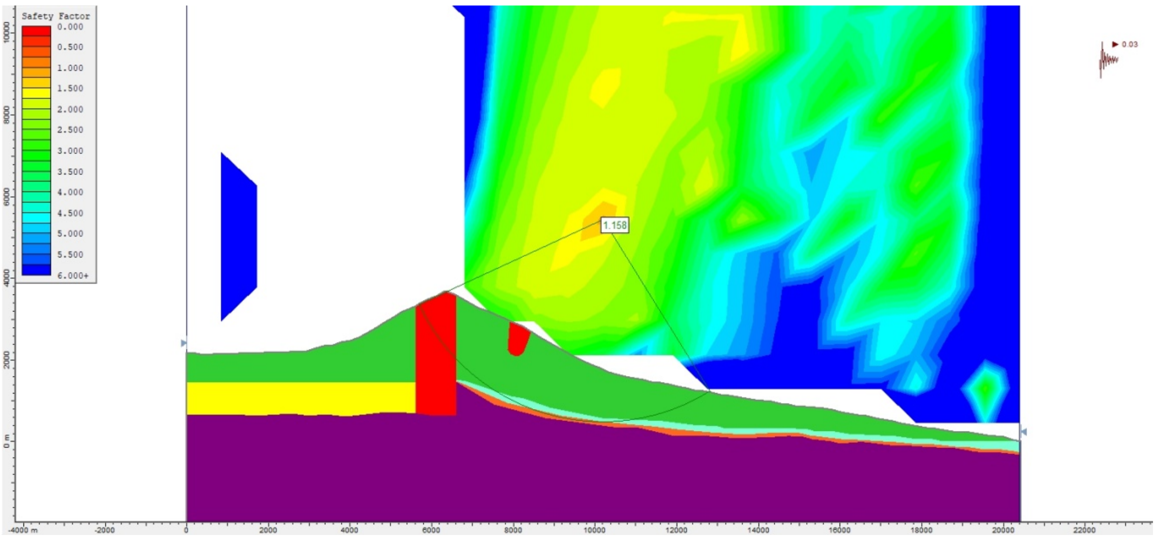

Figure S77. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.03.

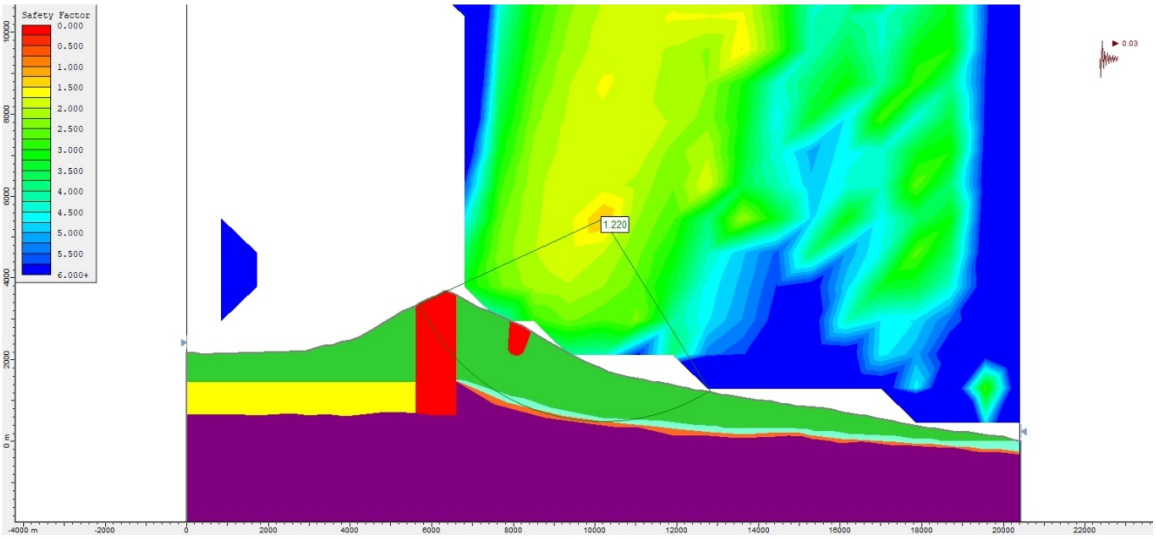

Figure S78. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.03.

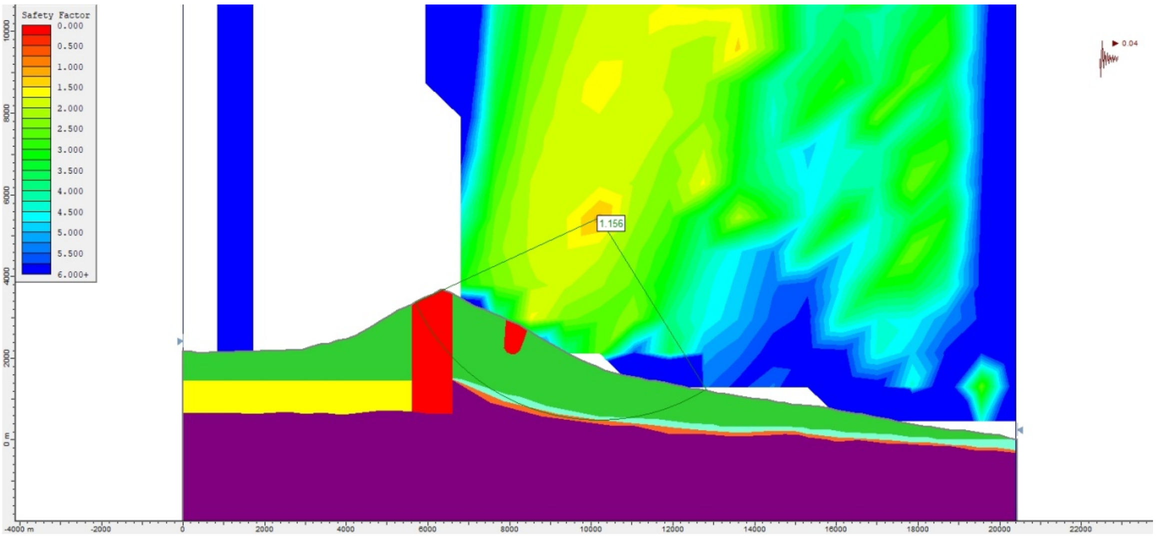

Figure S79. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.04.

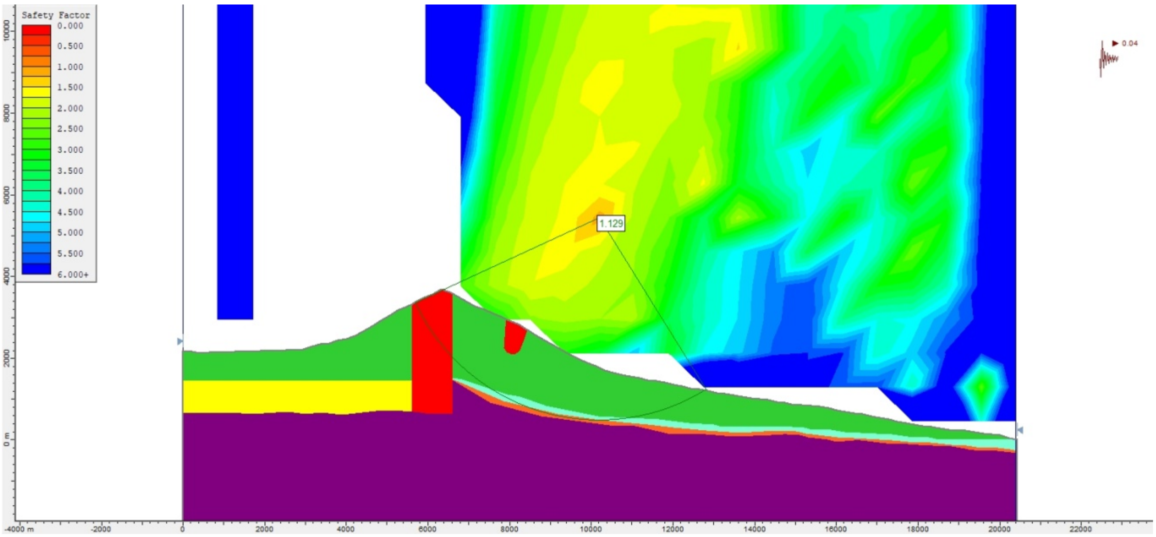

Figure S80. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.04.

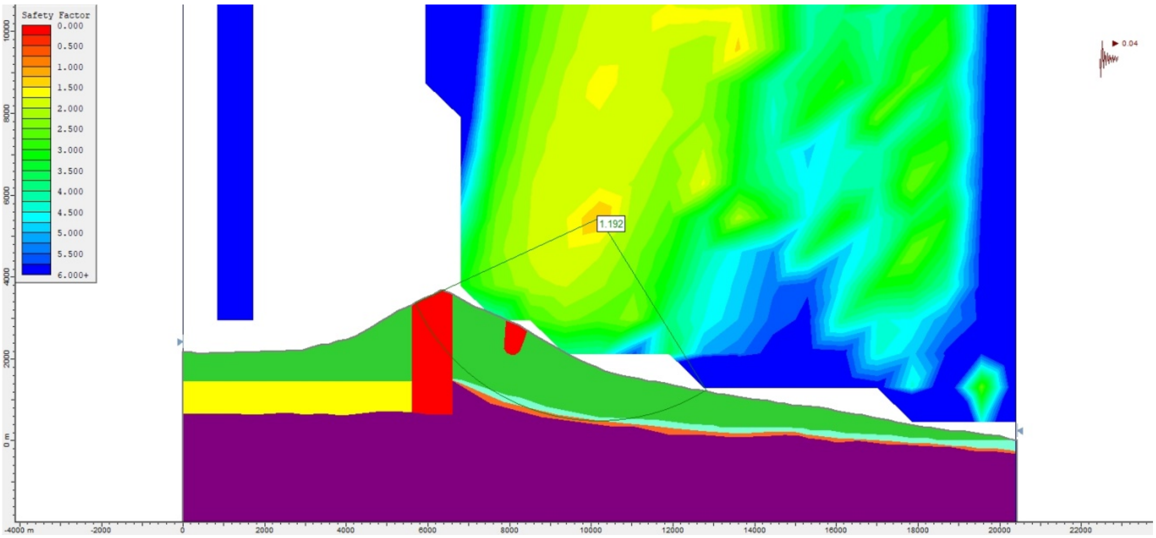

Figure S81. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.04.

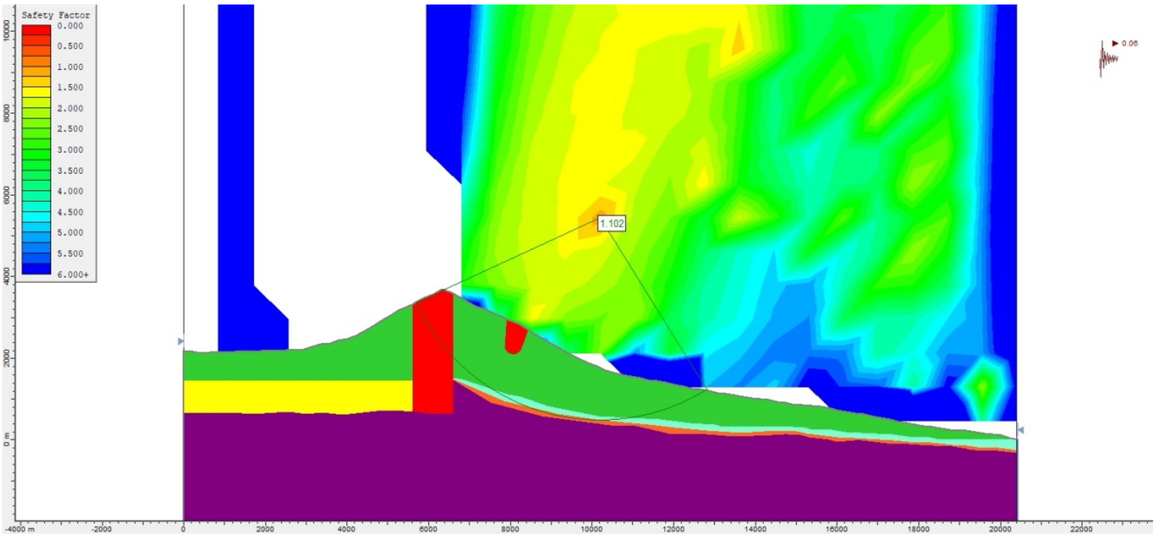

Figure S82. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.06.

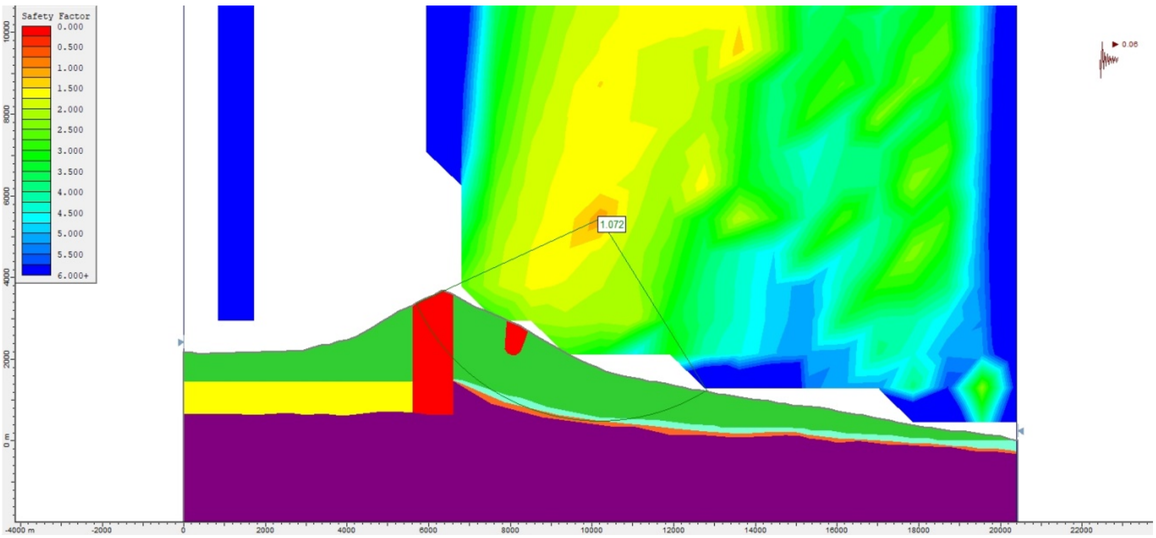

Figure S83. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.06.

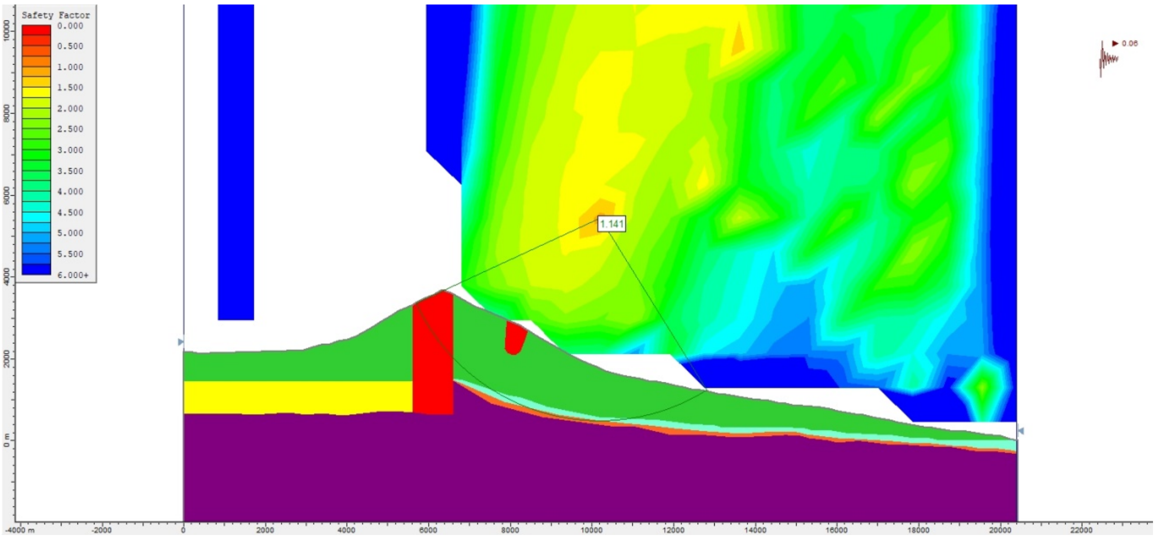

Figure S84. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.06.

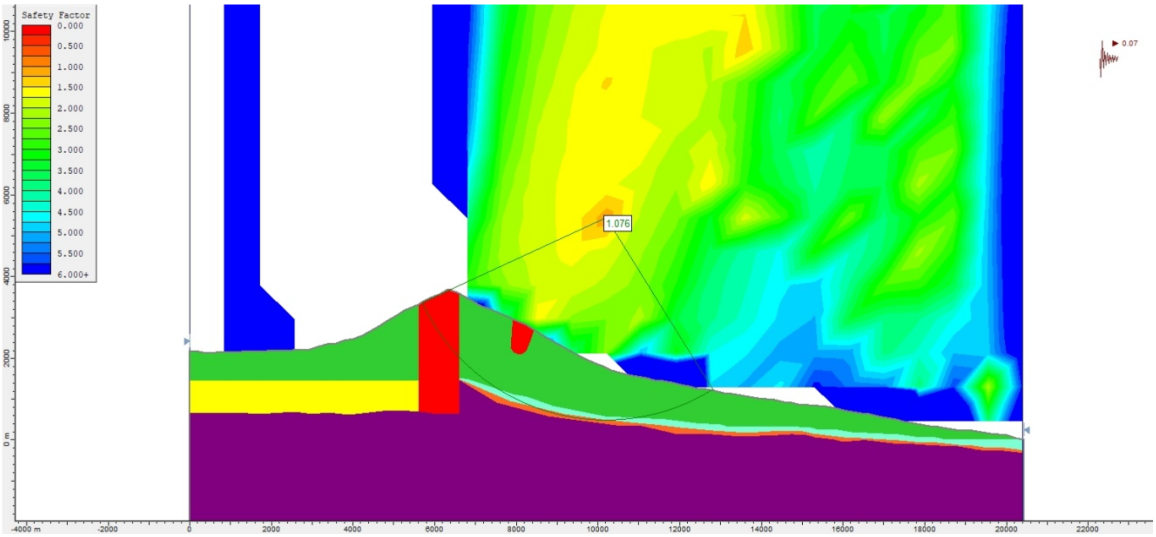

Figure S85. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.07.

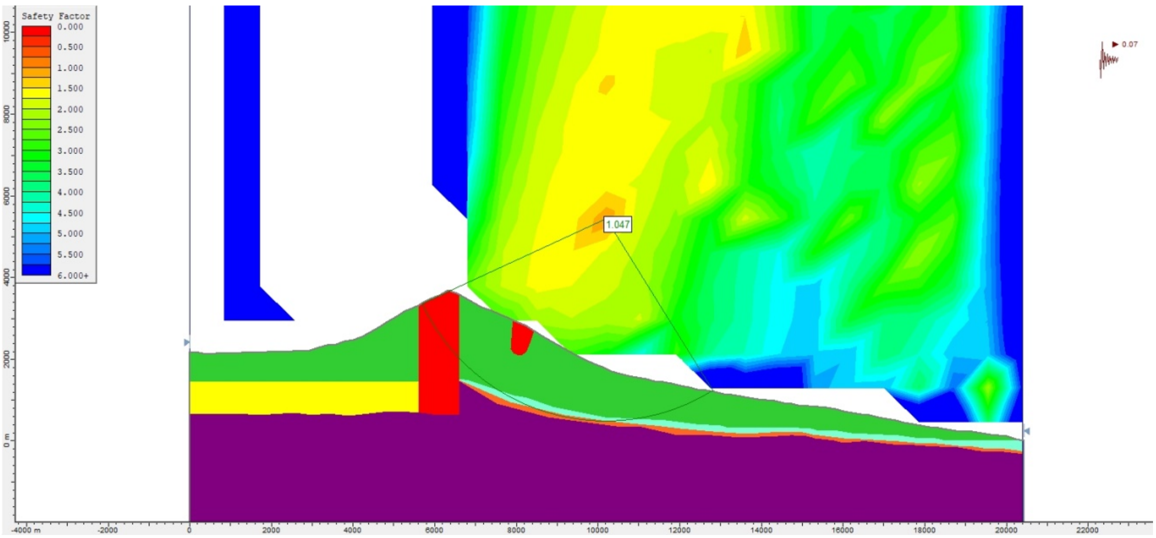

Figure S86. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.07.

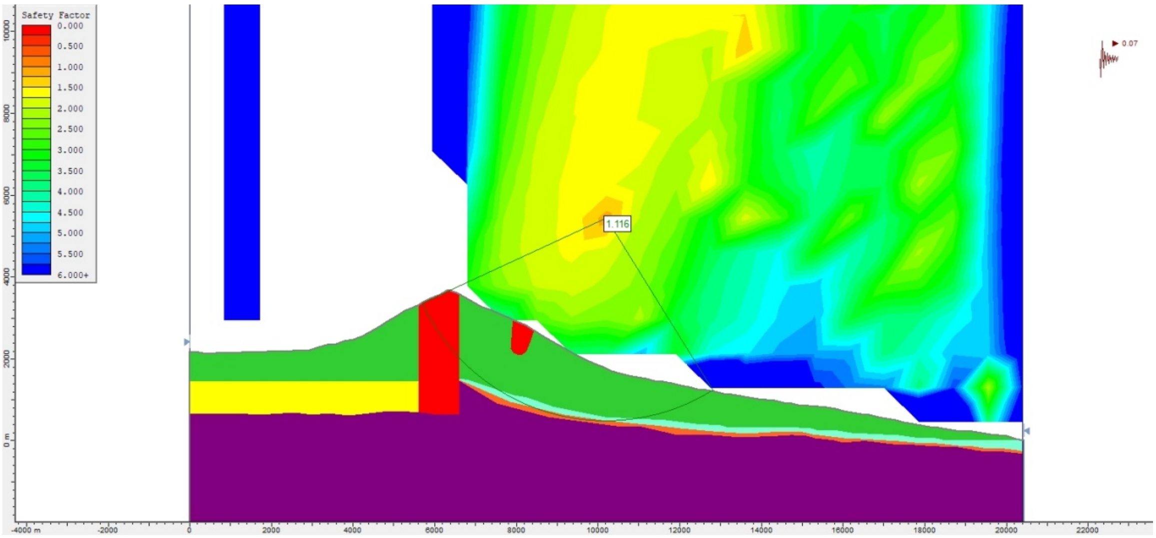

Figure S87. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.07.

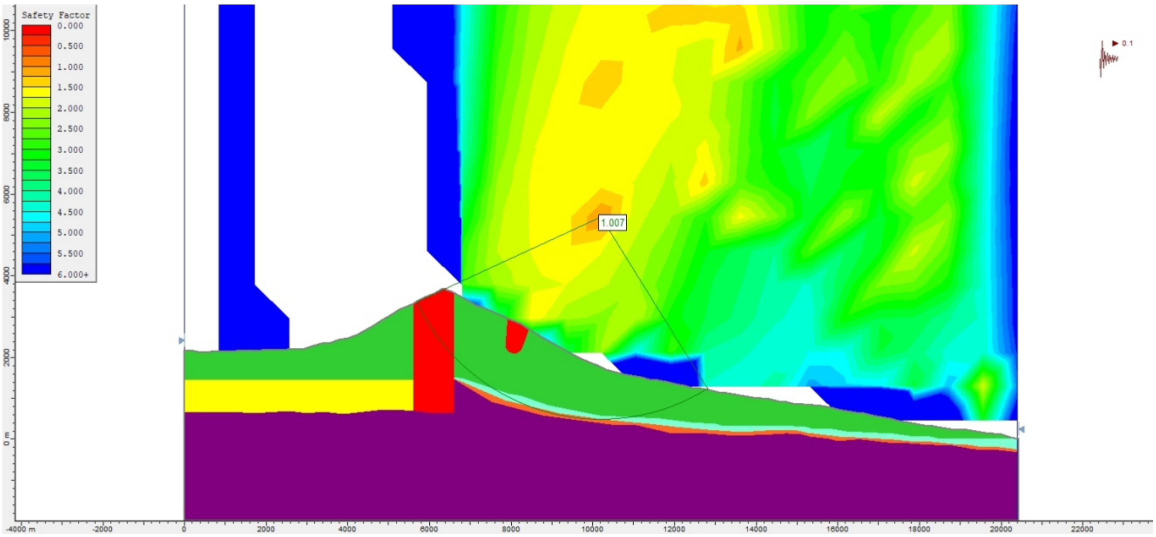

Figure S88. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.10.

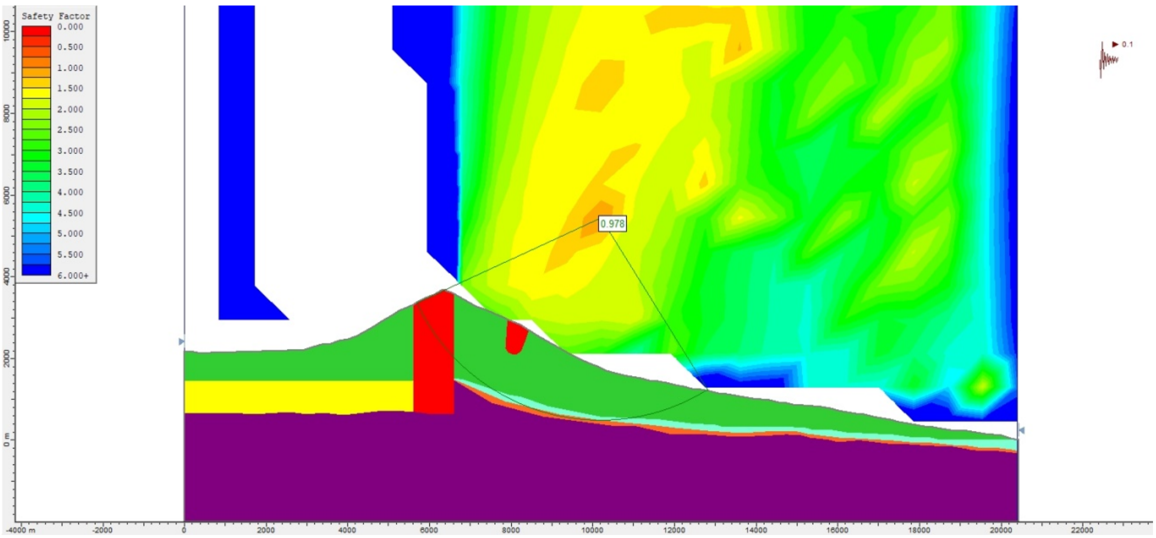

Figure S89. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.10.

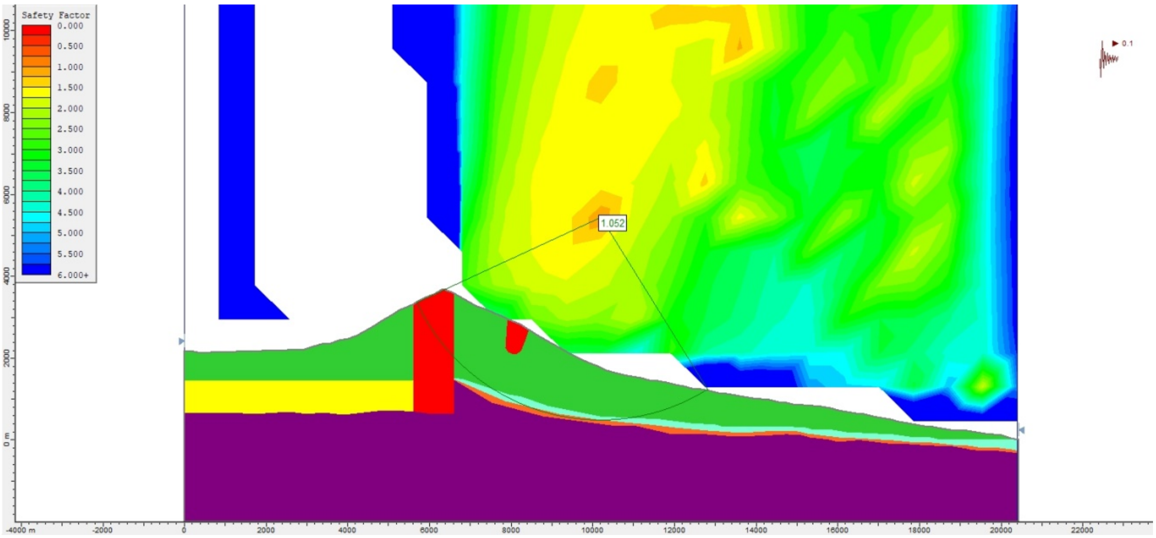

Figure S90. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.10.

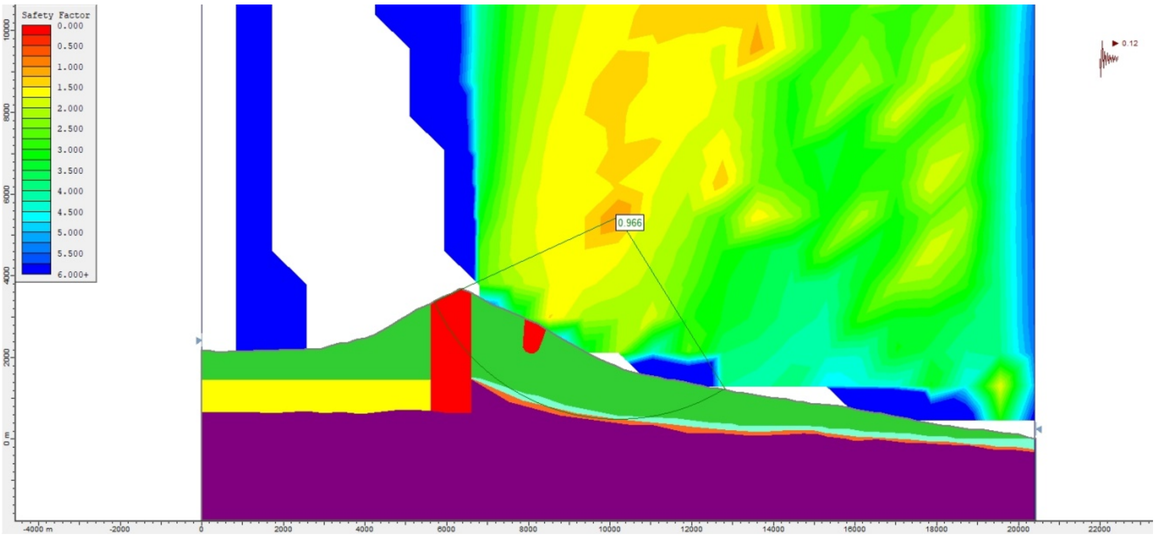

Figure S91. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.12.

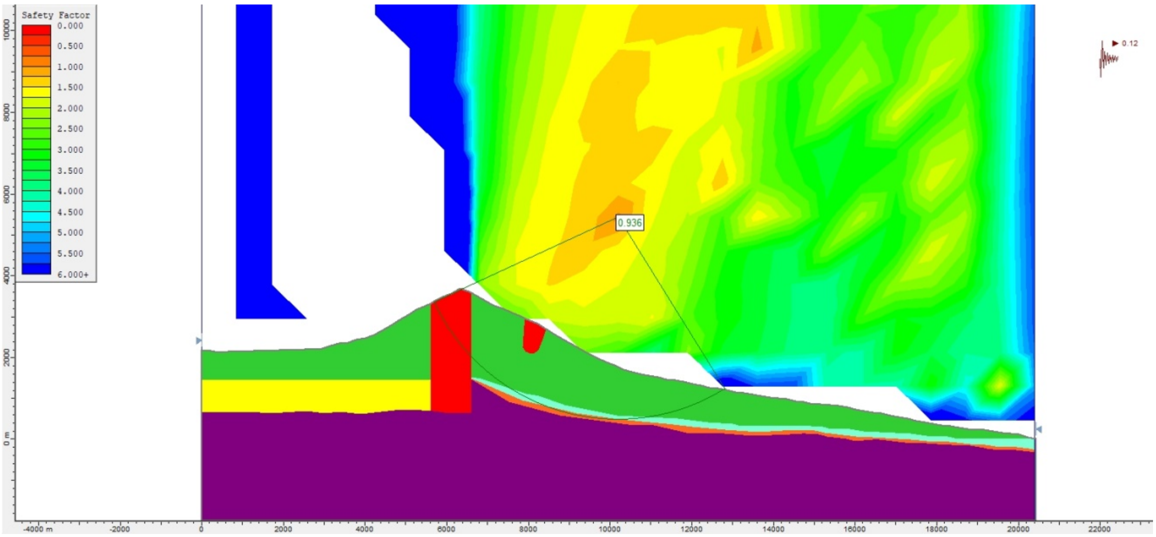

Figure S92. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.12.

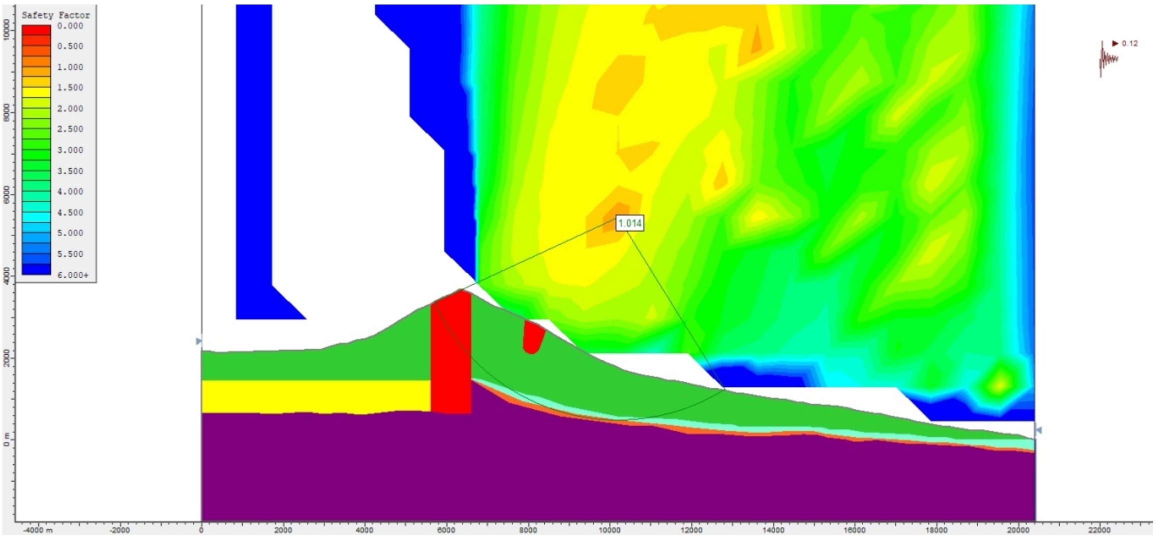

Figure S93. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.12.

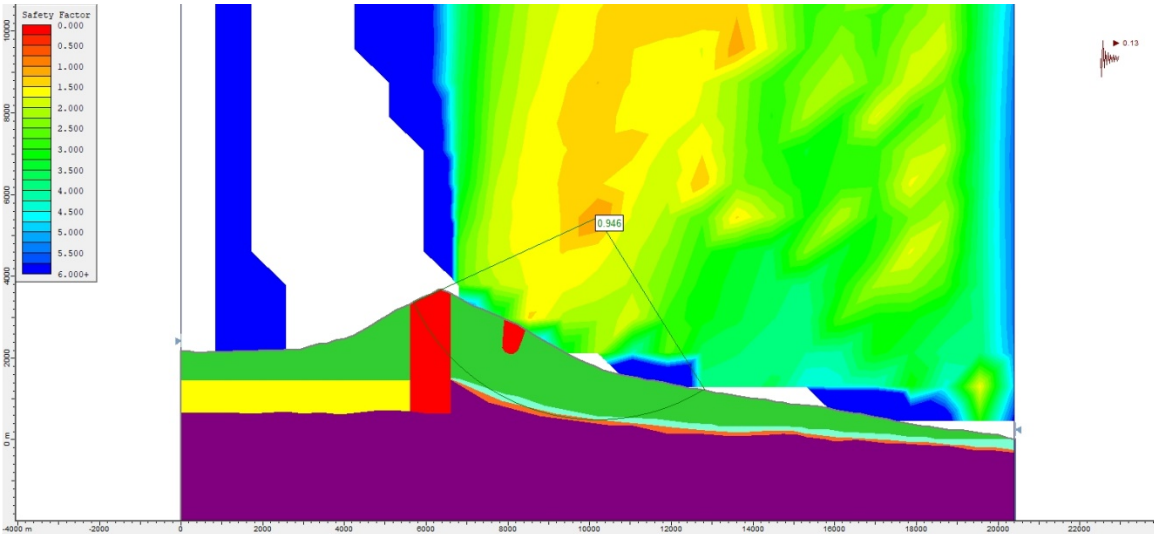

Figure S94. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.13.

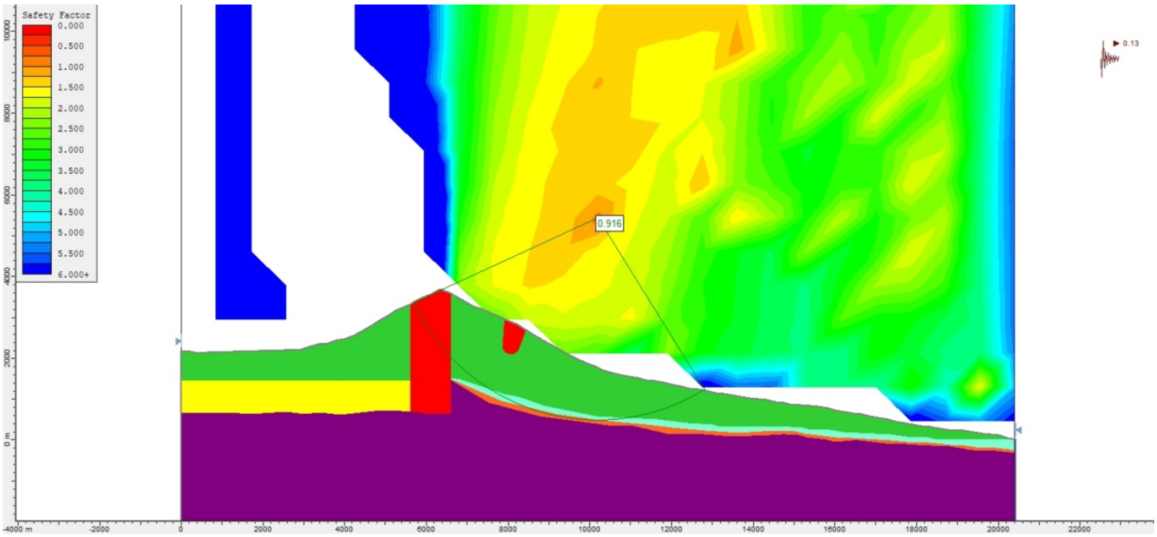

Figure S95. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.13.

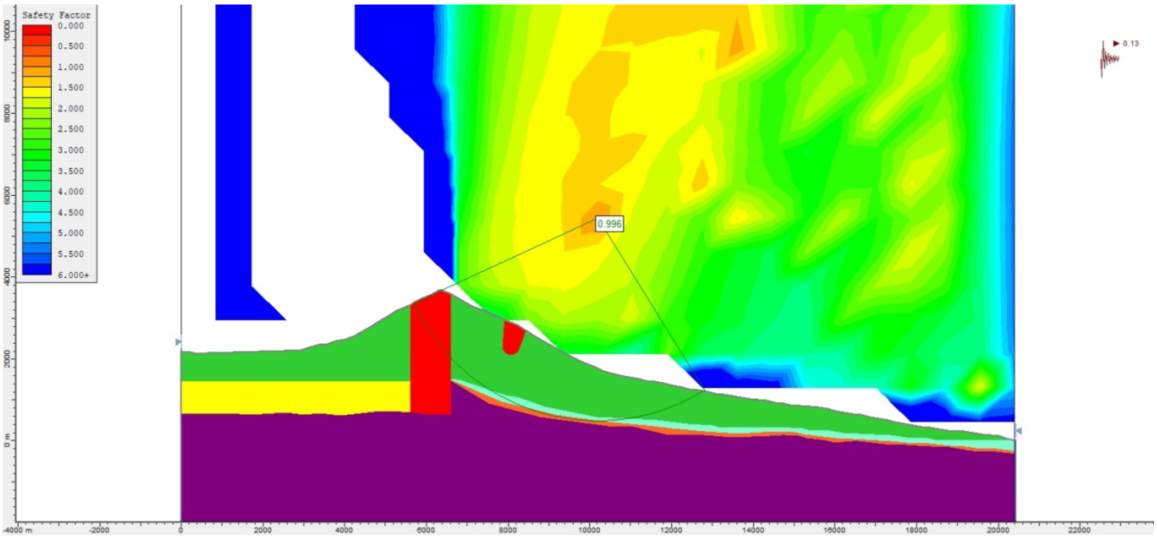

Figure S96. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.13.

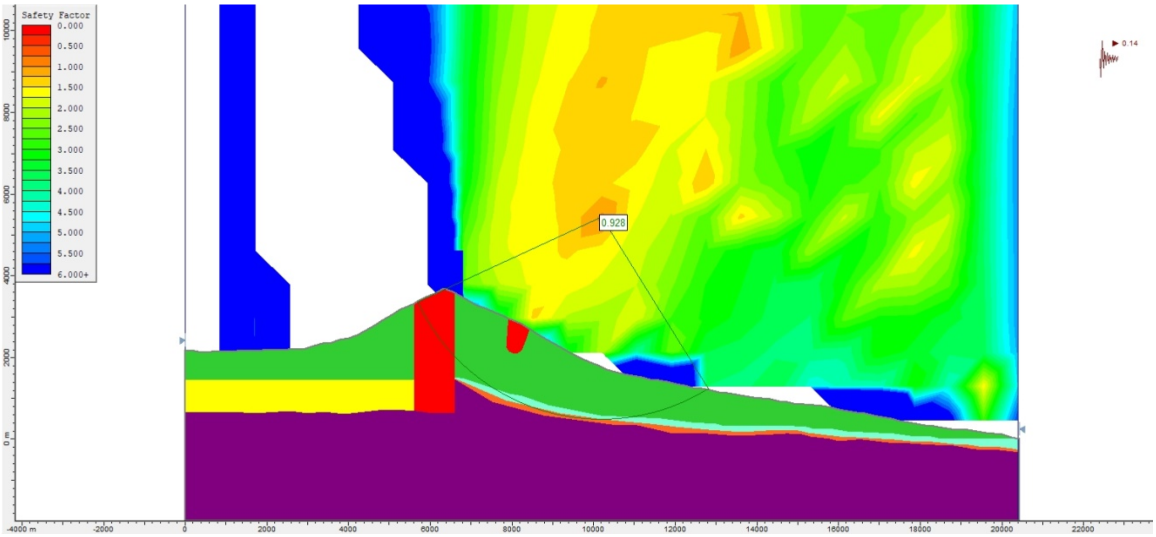

Figure S97. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.14.

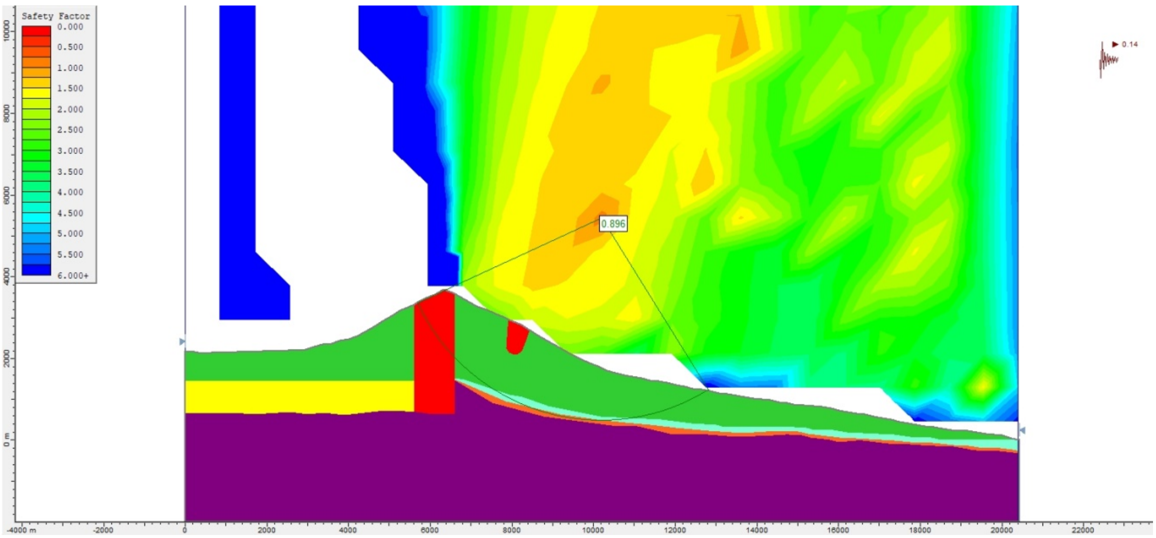

Figure S98. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.14.

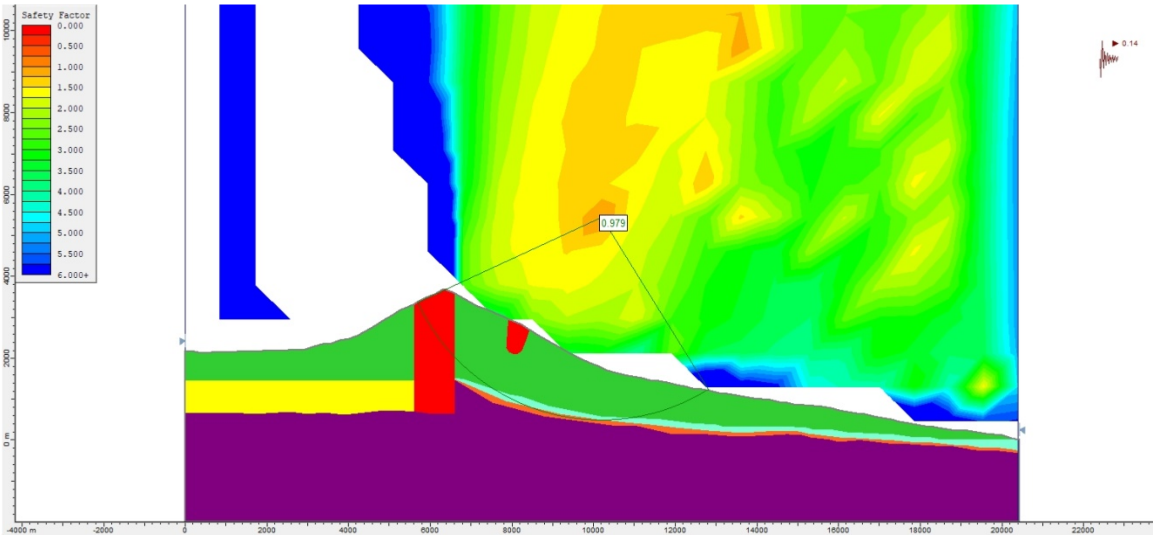

Figure S99. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.14.

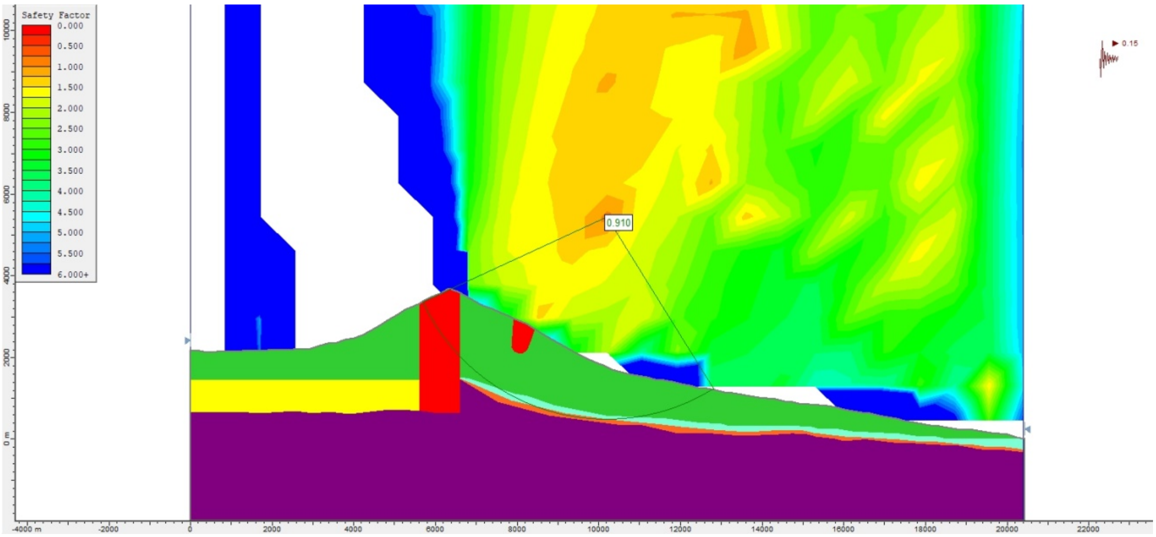

Figure S100. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.15.

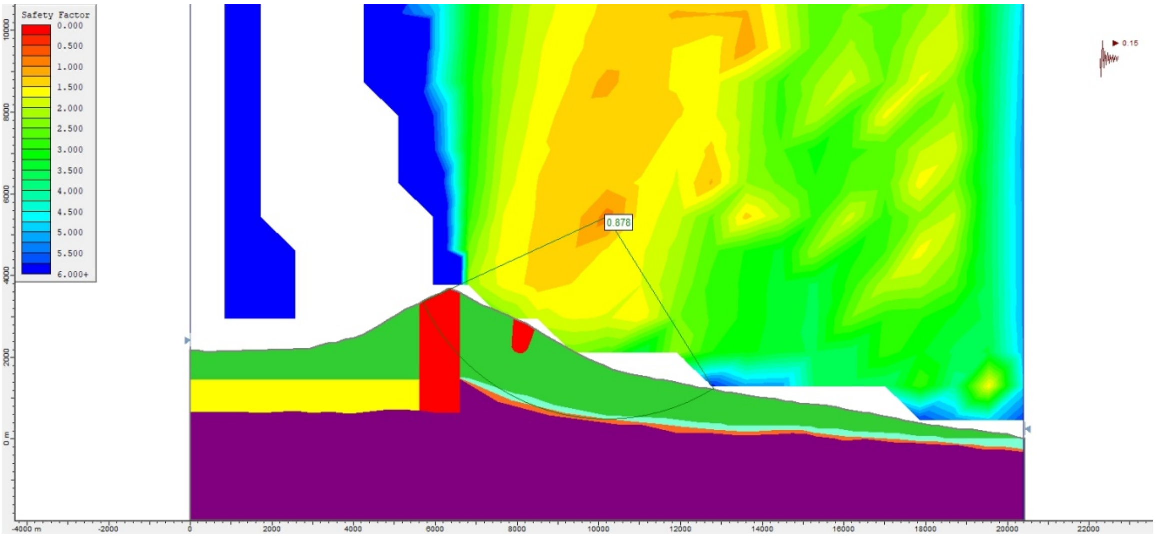

Figure S101. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.15.

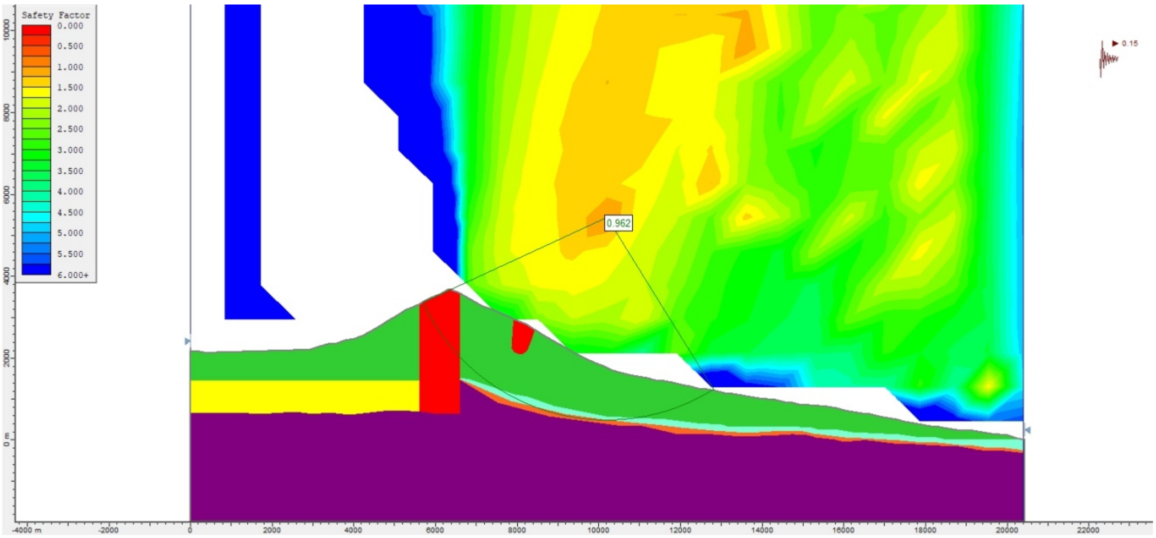

Figure S102. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.15.

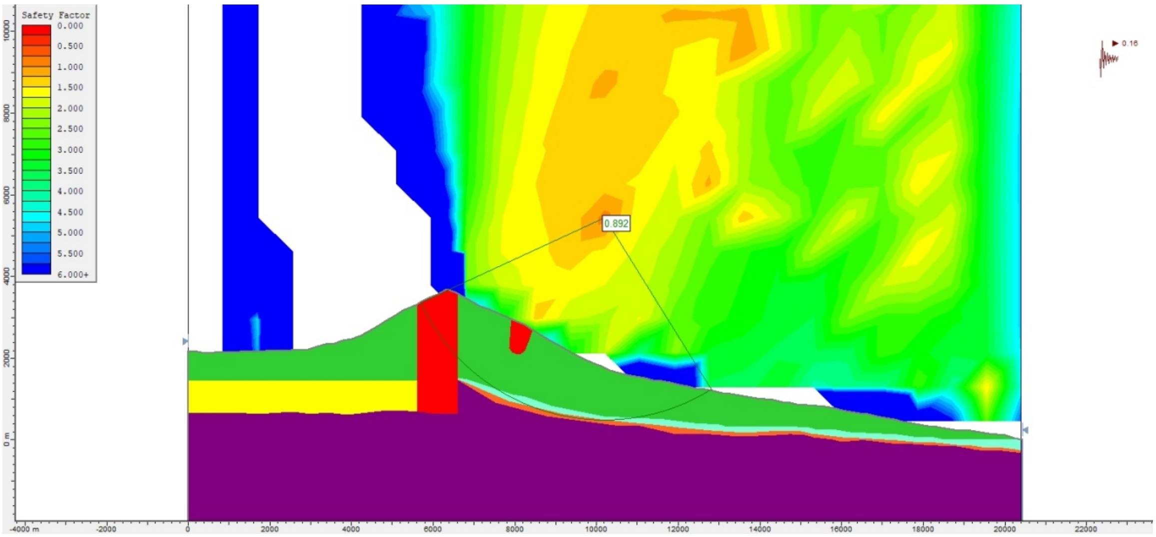

Figure S103. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.16.

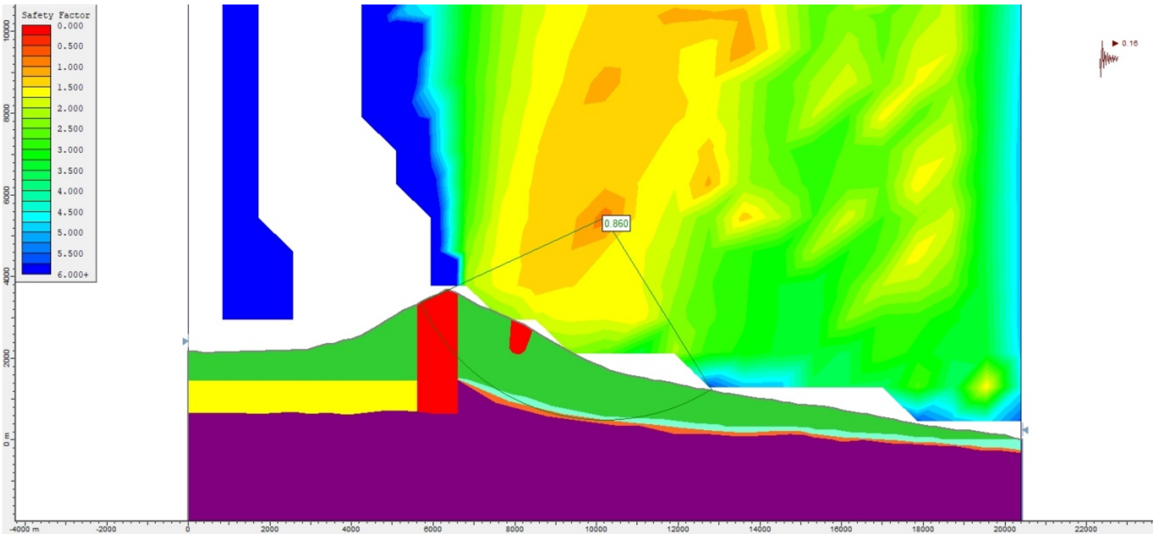

Figure S104. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.16.

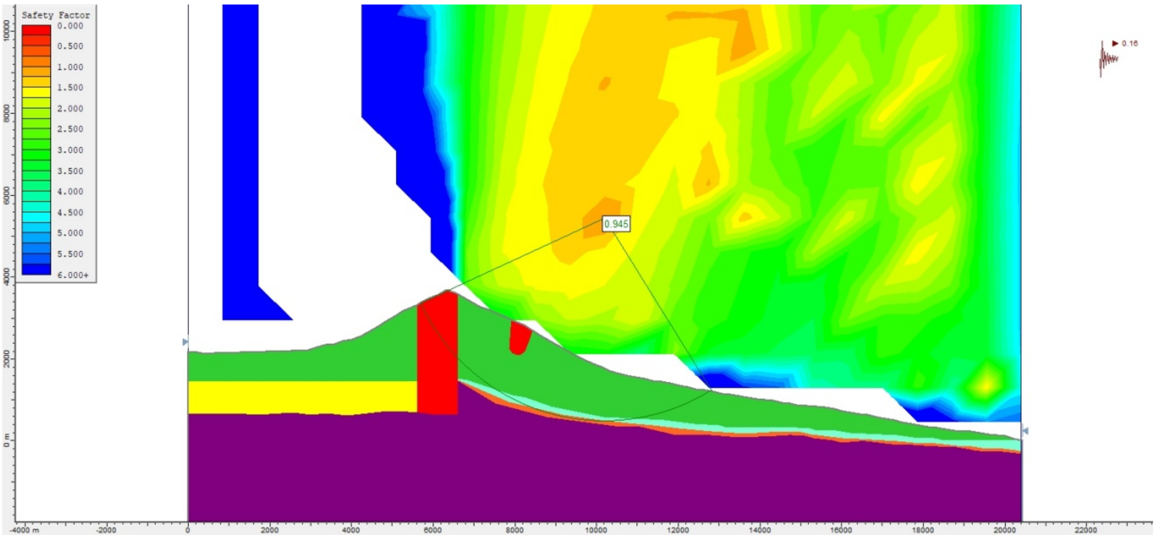

Figure S105. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.16.

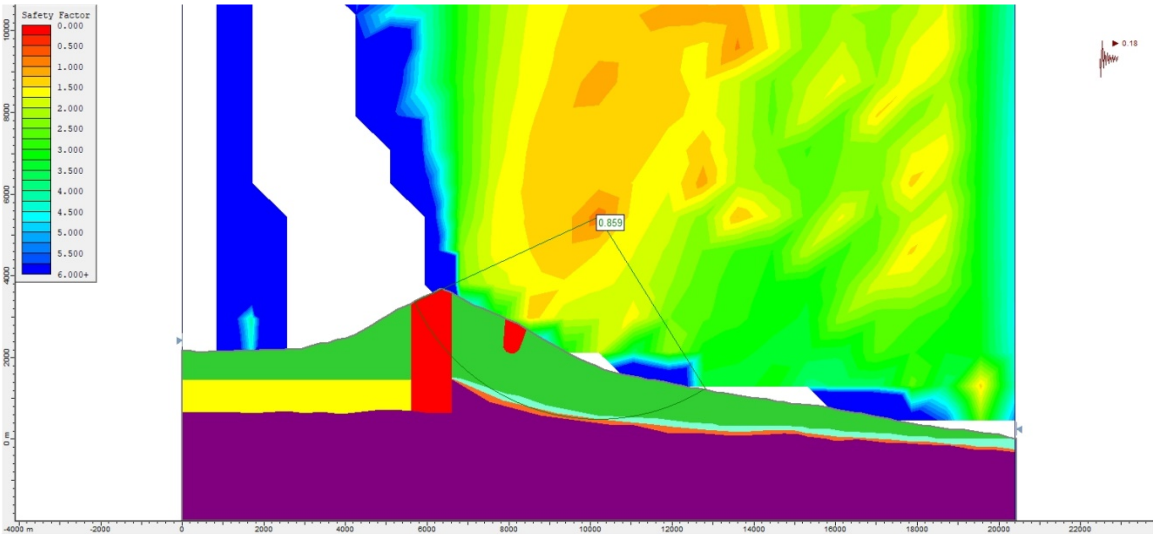

Figure S106. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.18.

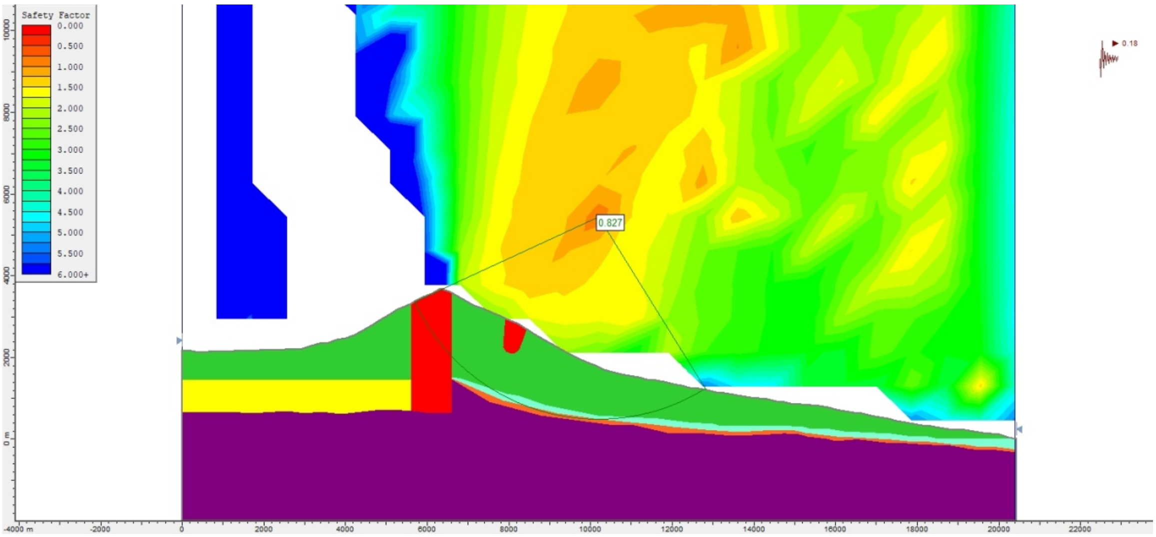

Figure S107. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.18.

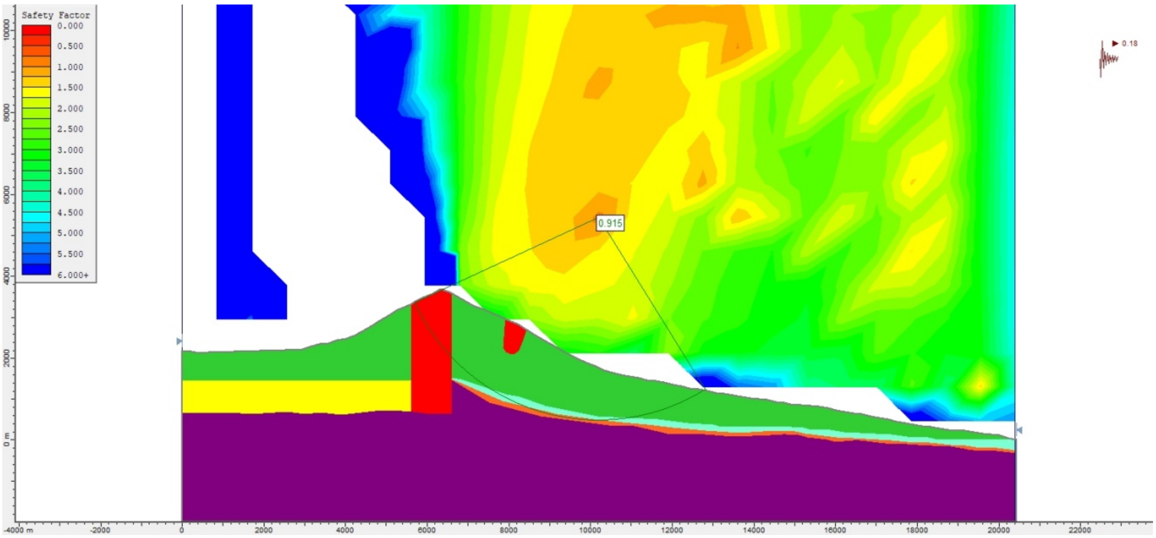

Figure S108. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.18.

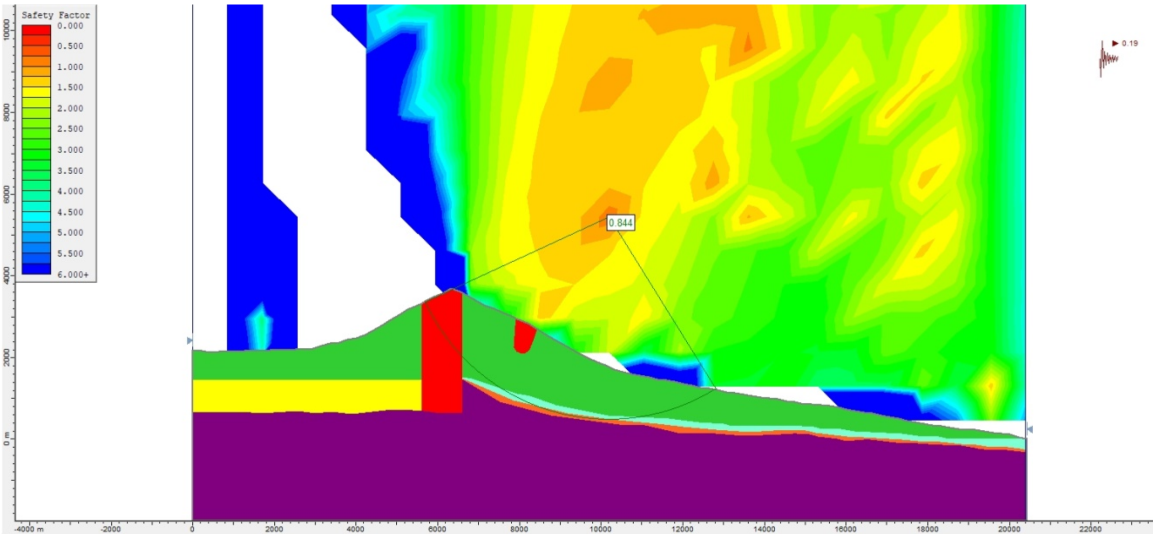

Figure S109. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.19.

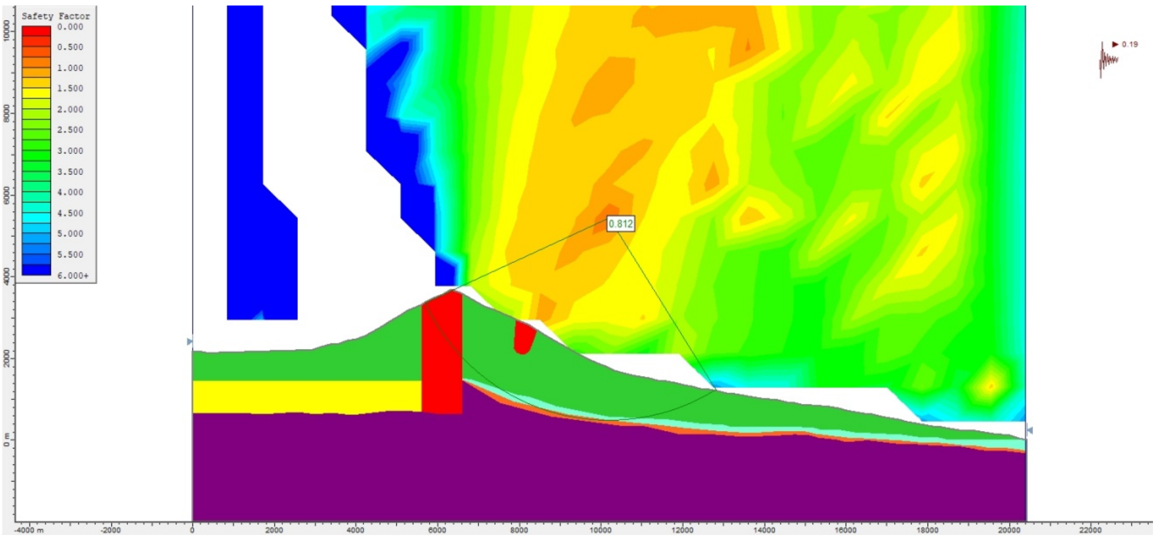

Figure S110. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.19.

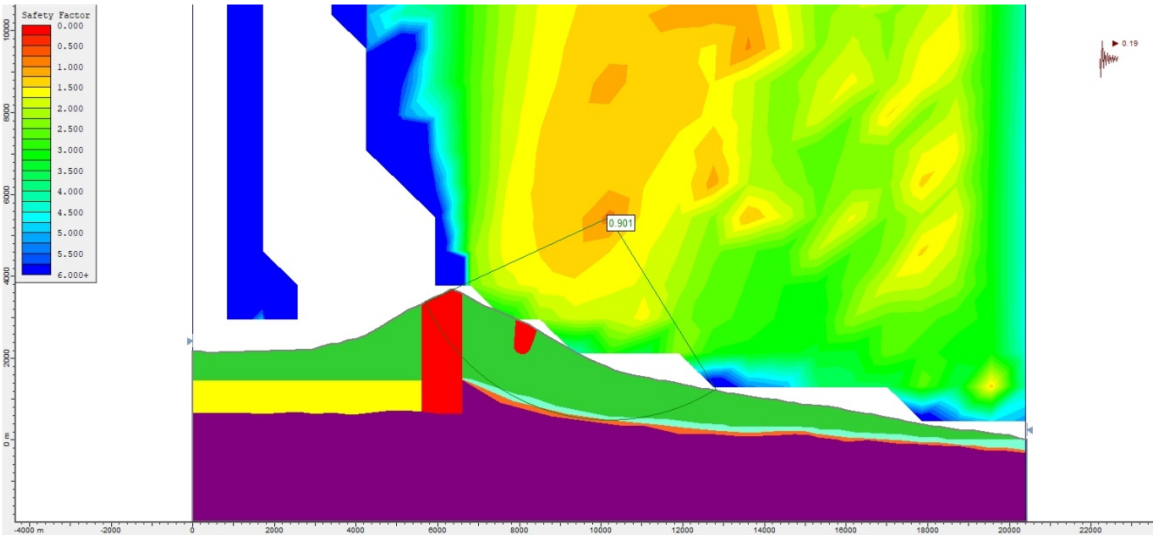

Figure S111. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.19.

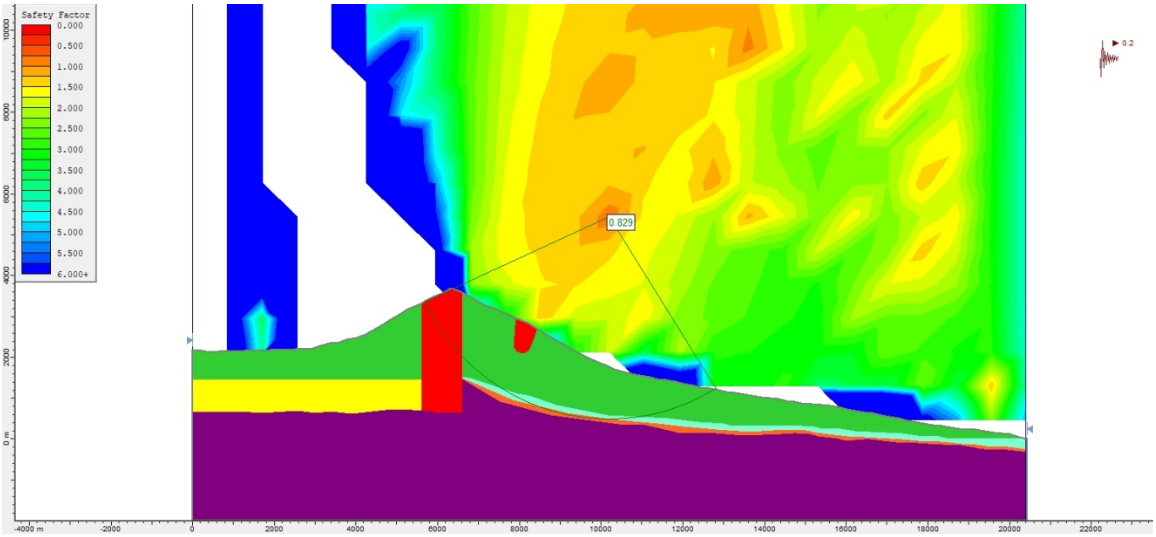

Figure S112. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.20.

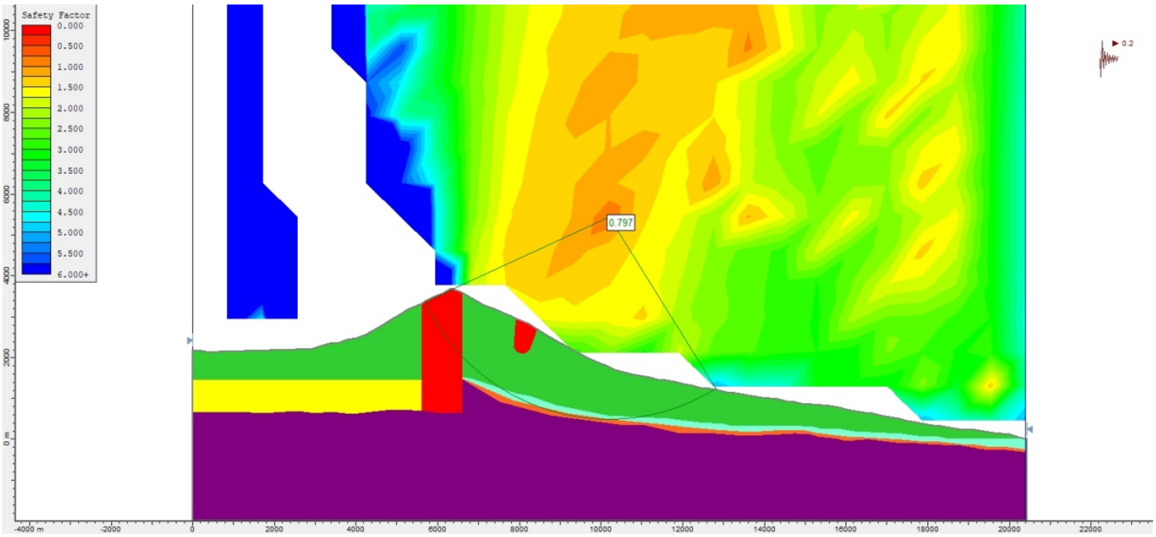

Figure S113. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.20.

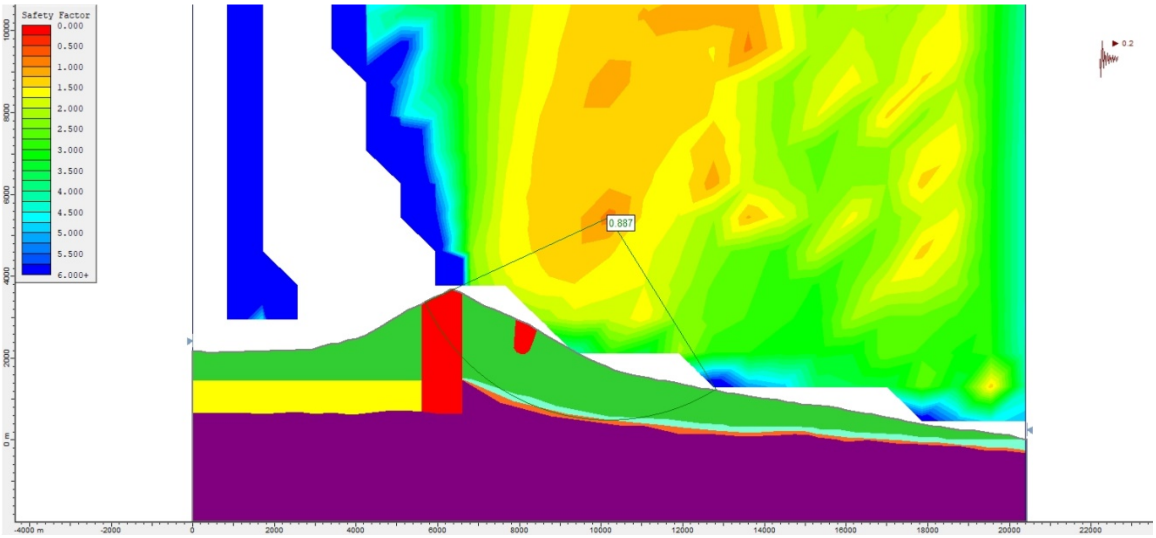

Figure S114. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.20.

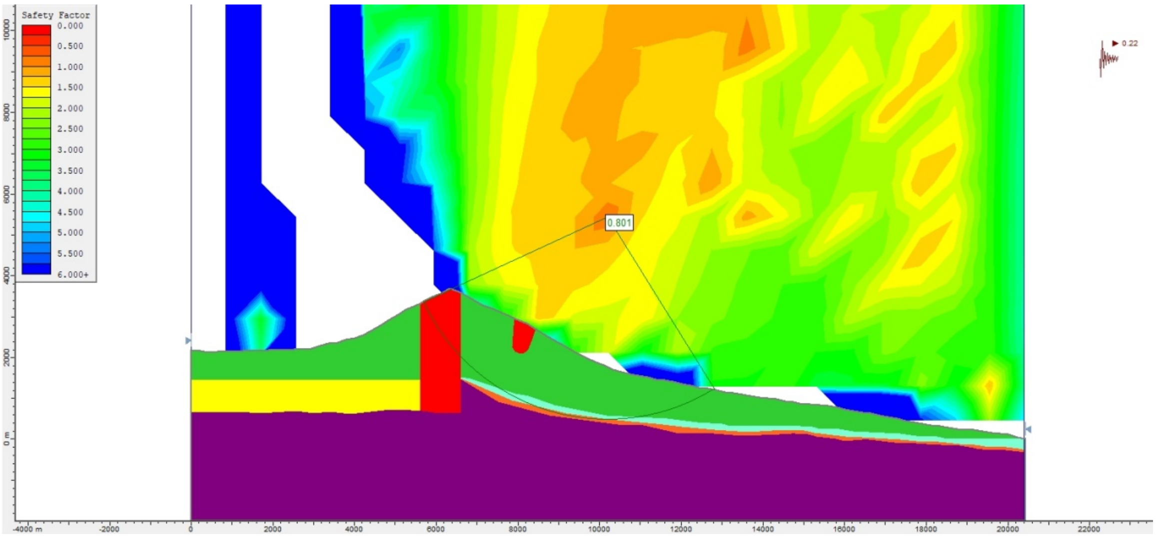

Figure S115. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.22.

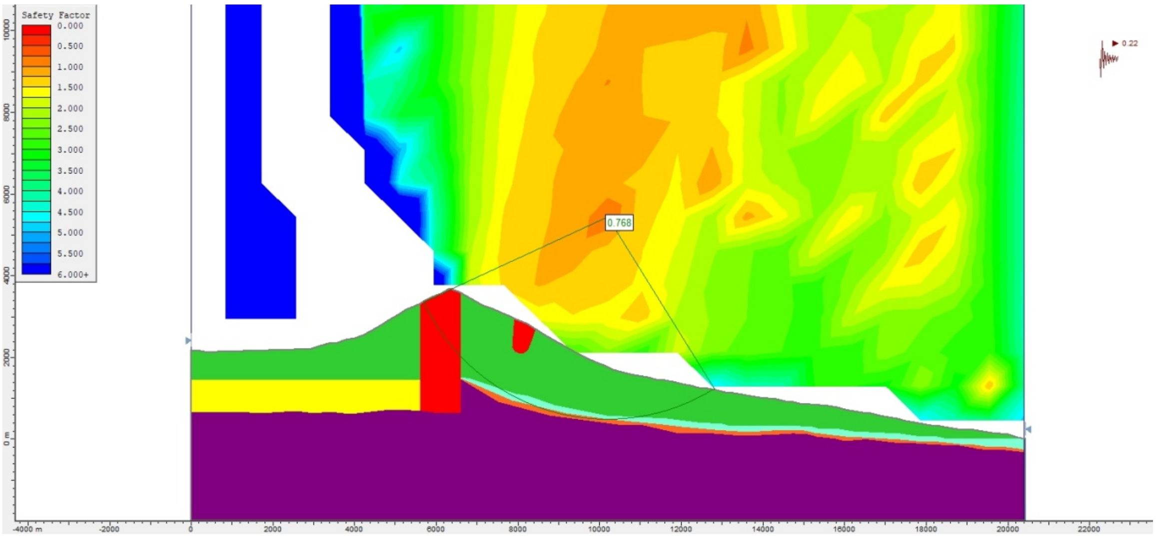

Figure S116. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.22.

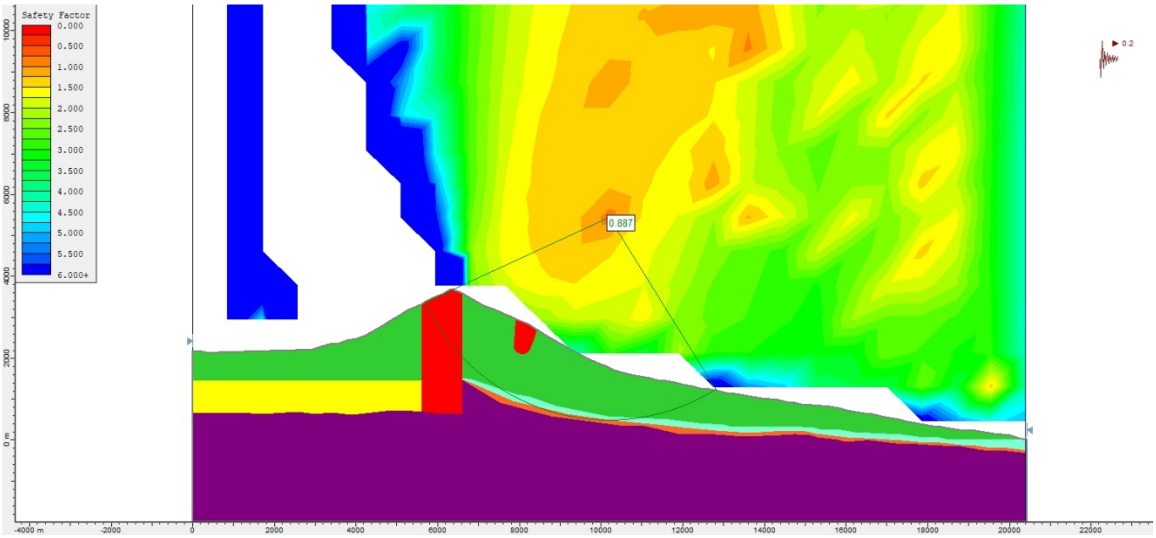

Figure S117. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.22.

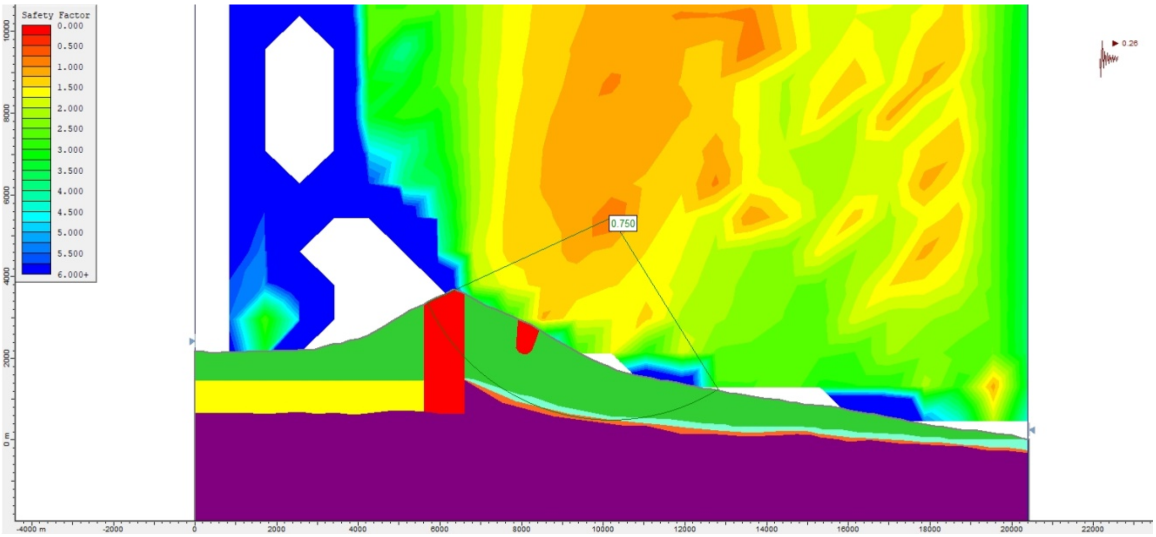

Figure S118. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.26.

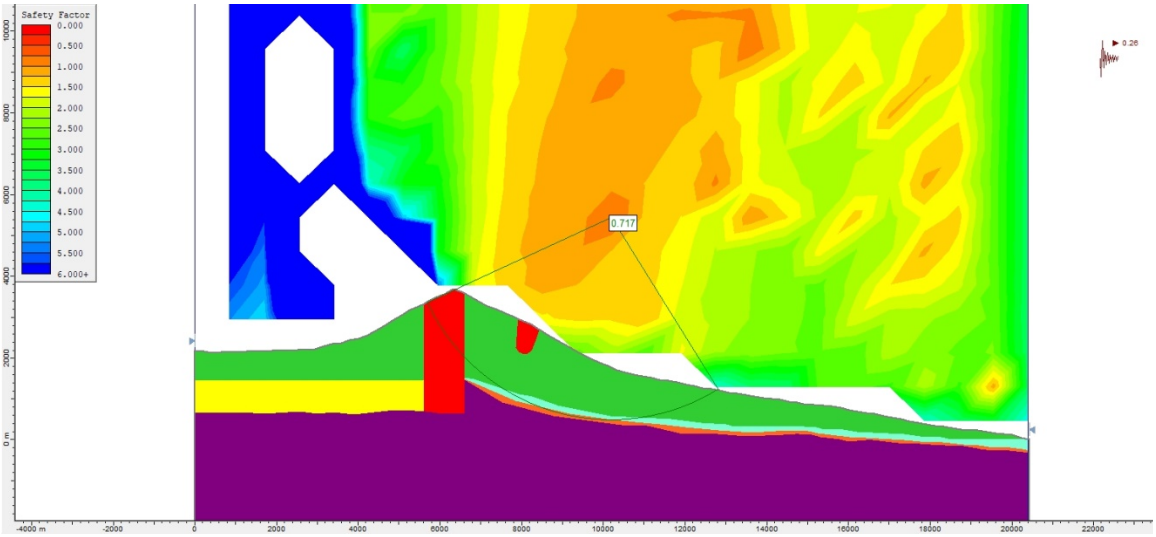

Figure S119. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.26.

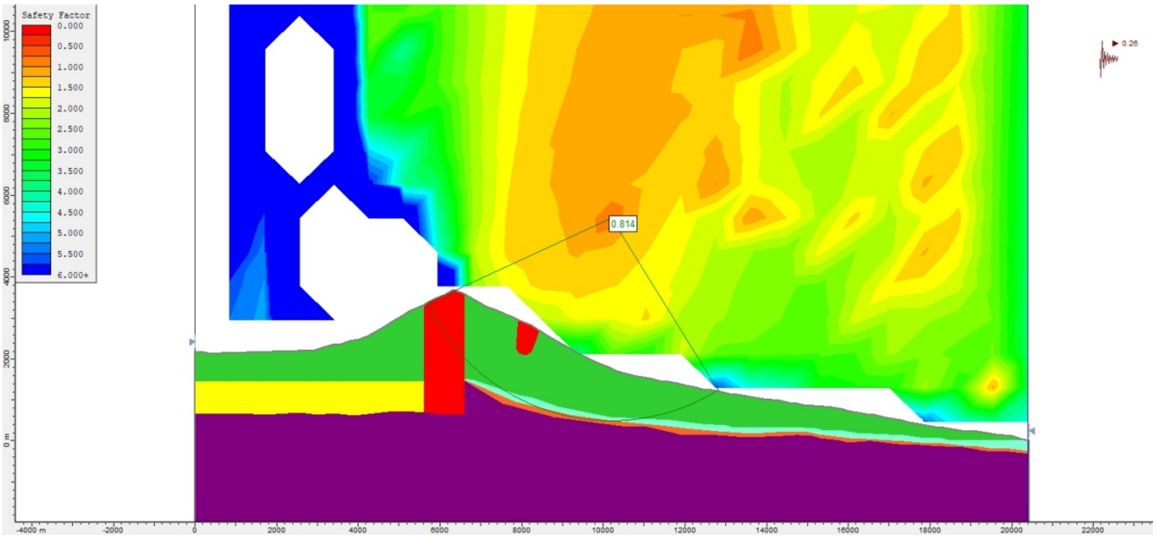

Figure S120. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.26.

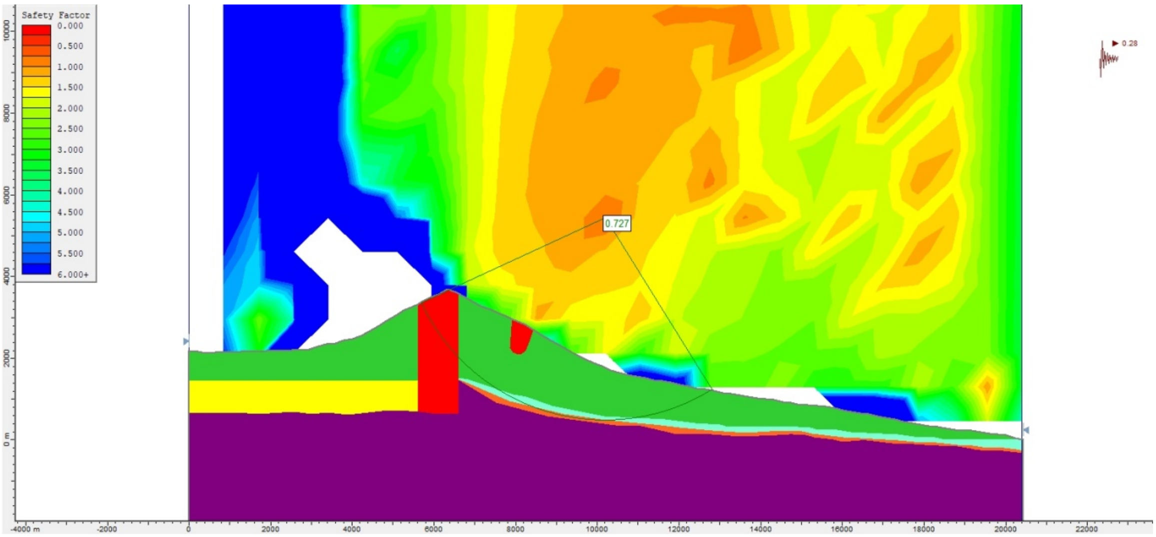

Figure S121. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.28.

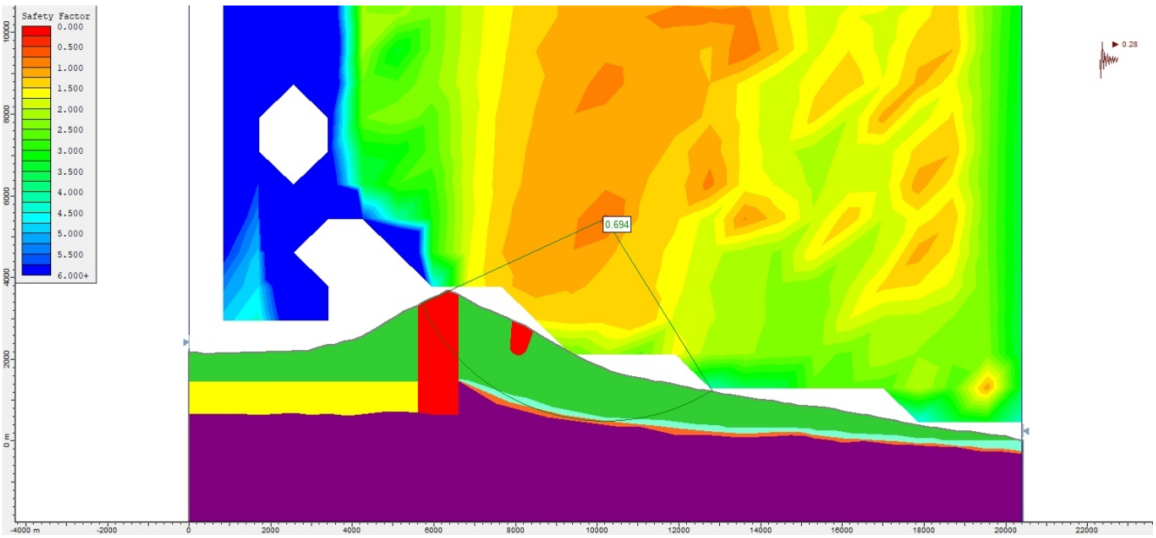

Figure S122. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.28.

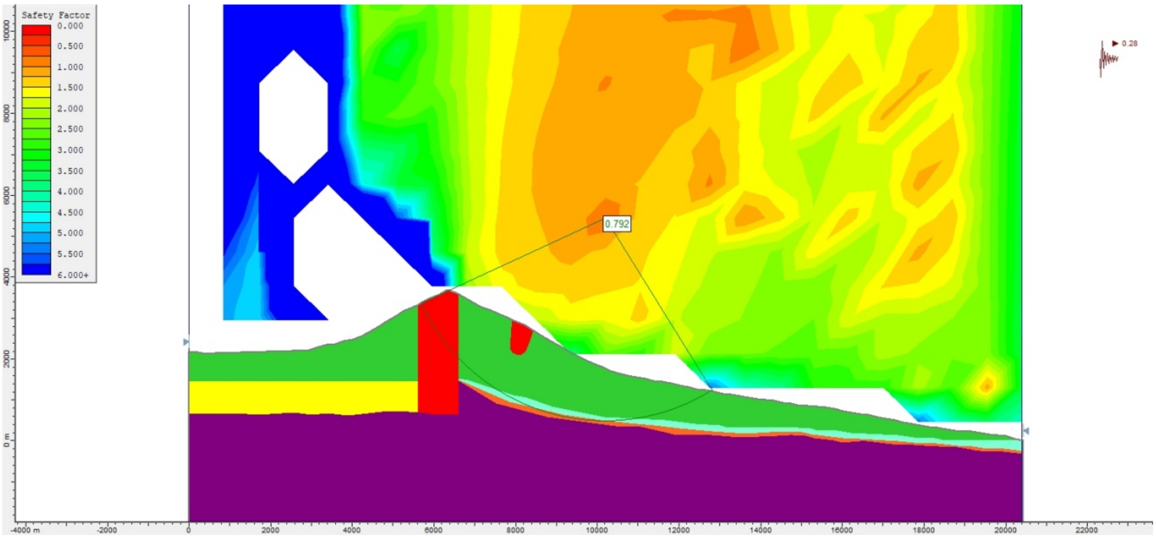

Figure S123. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.28.

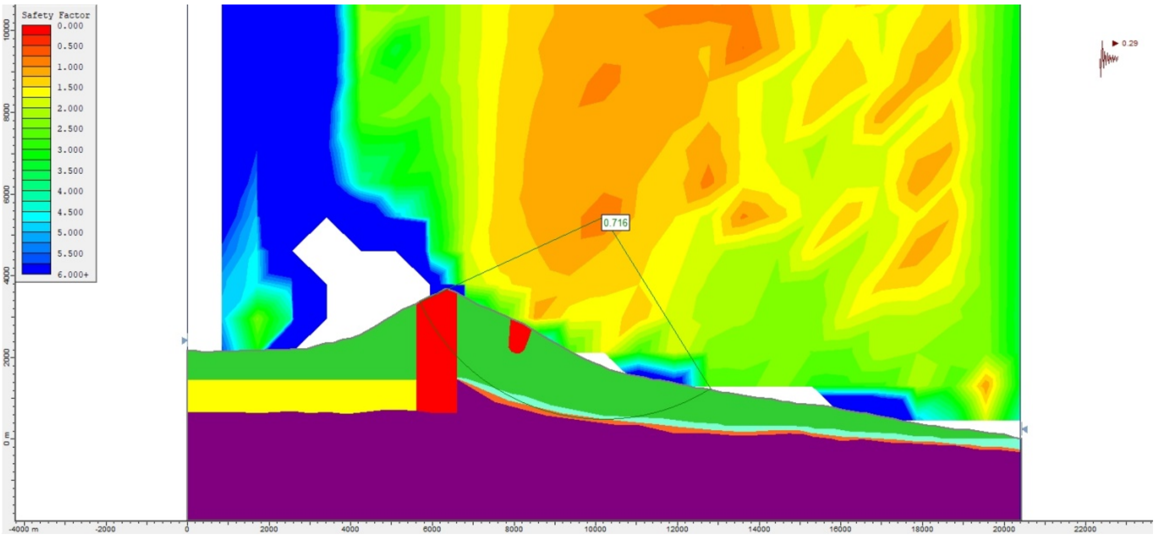

Figure S124. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.29.

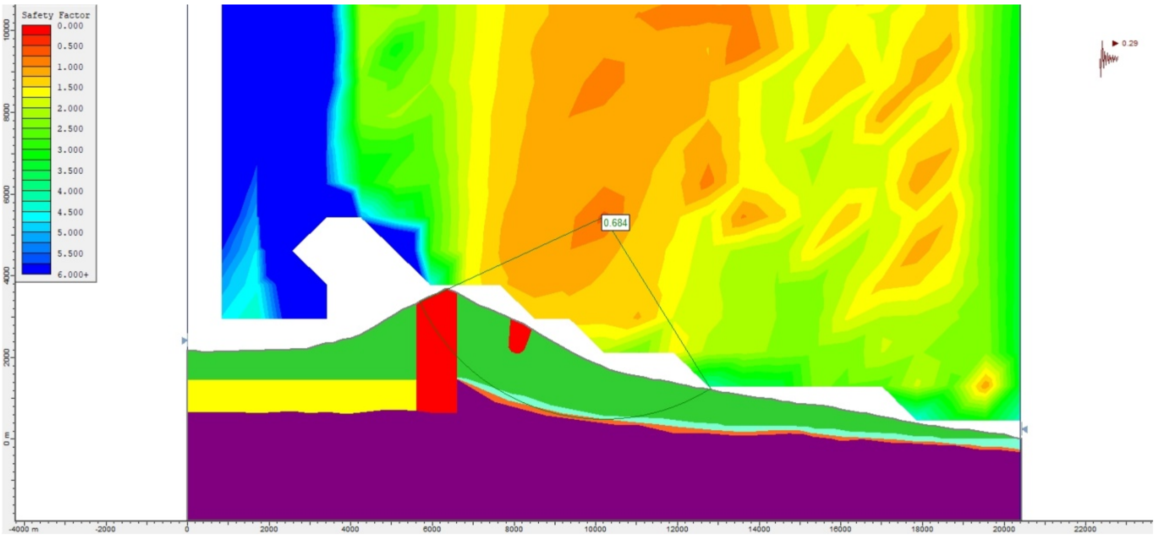

Figure S125. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.29.

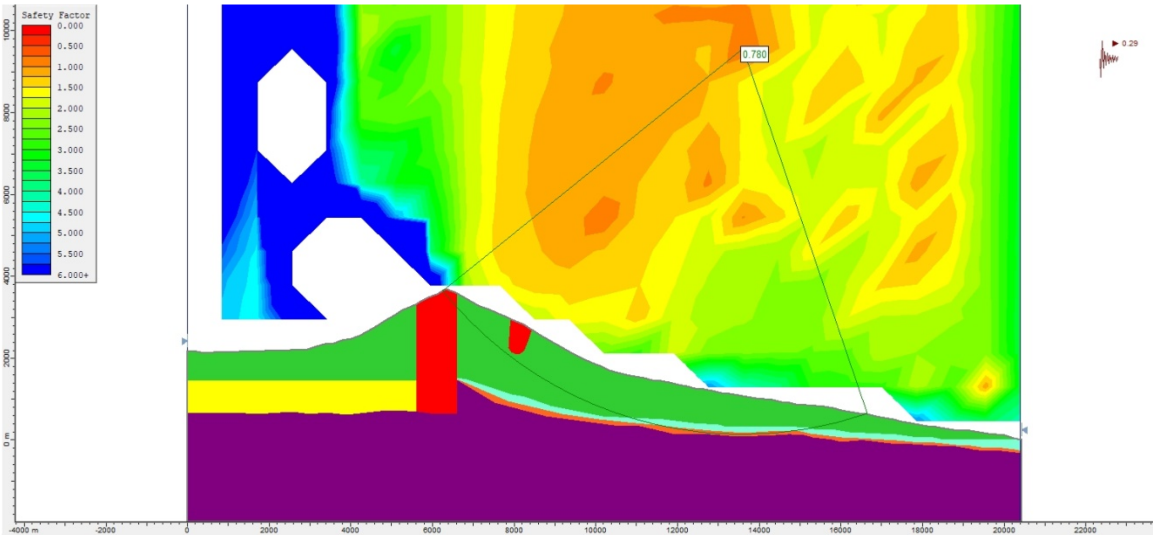

Figure S126. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.29.

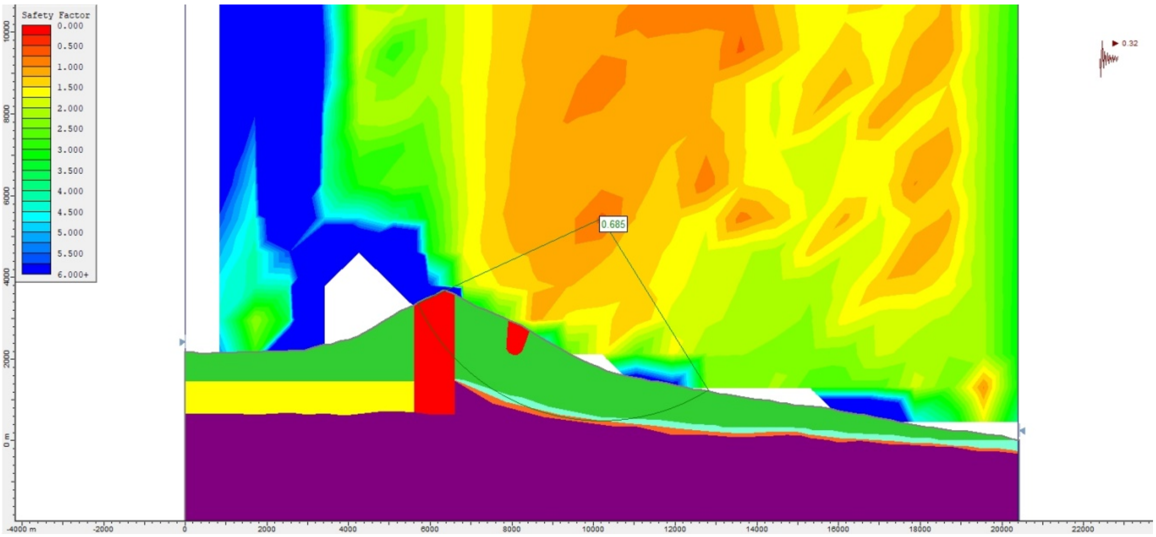

Figure S127. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.32.

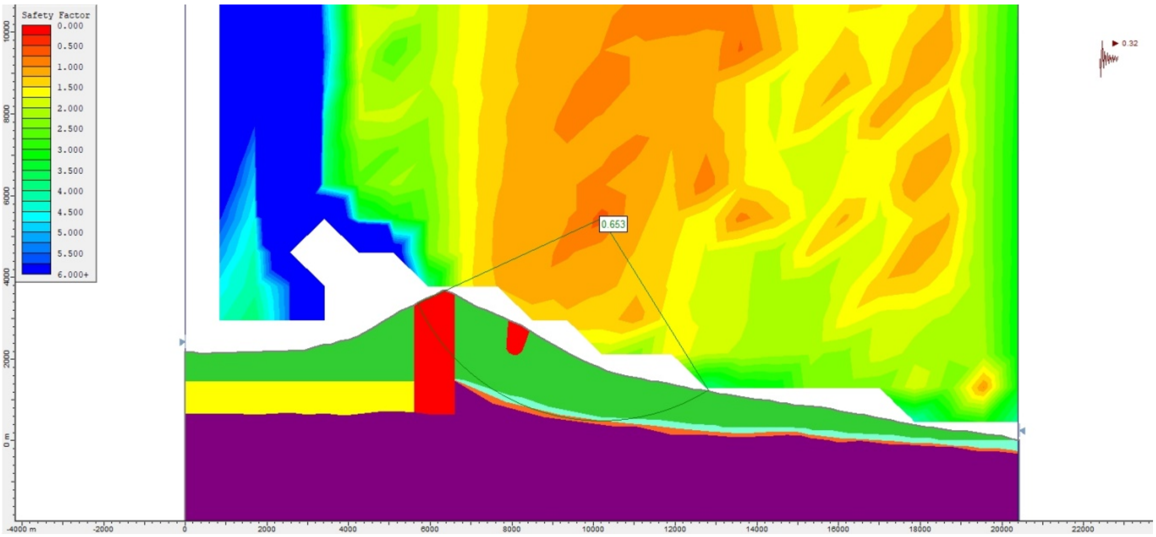

Figure S128. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.32.

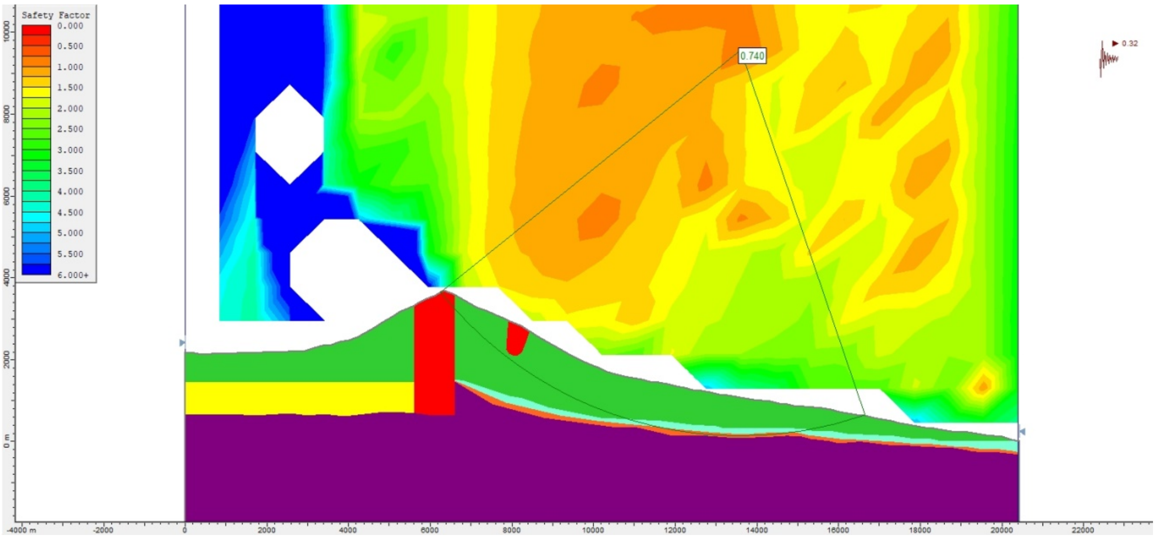

Figure S129. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.32.

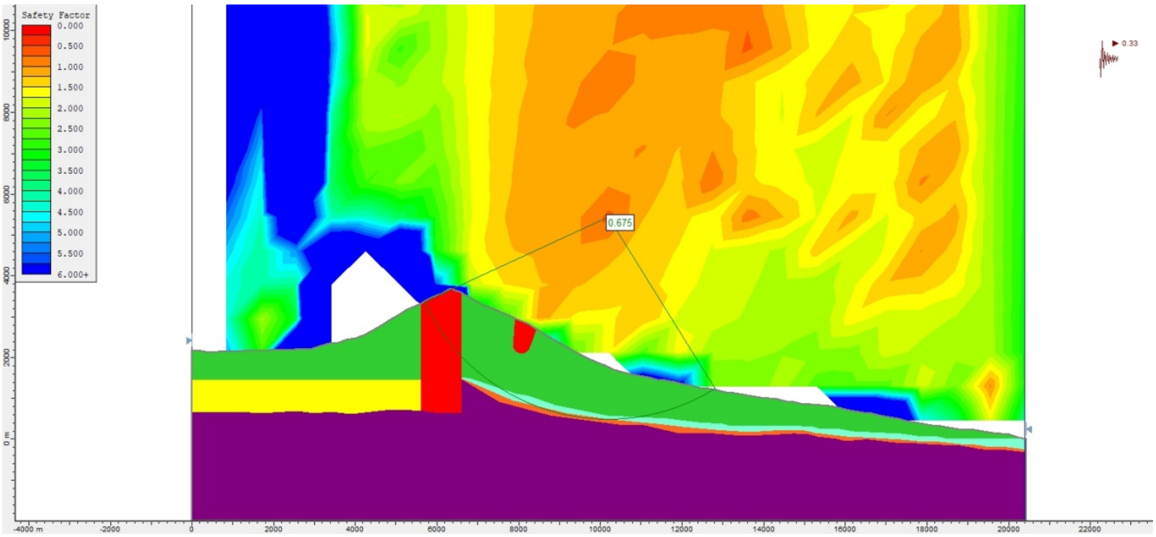

Figure S130. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.33.

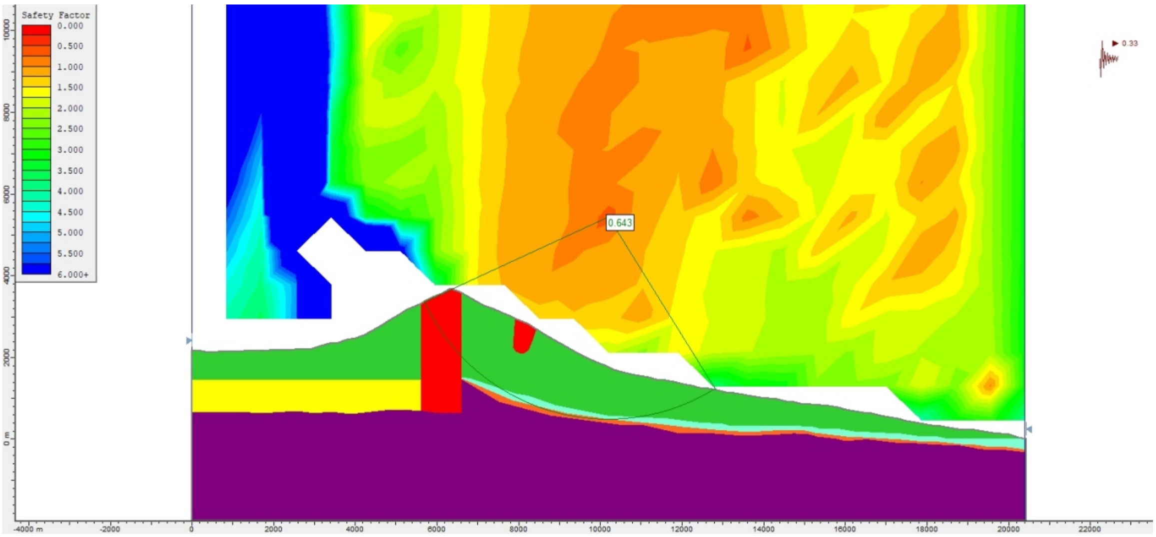

Figure S131. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.33.

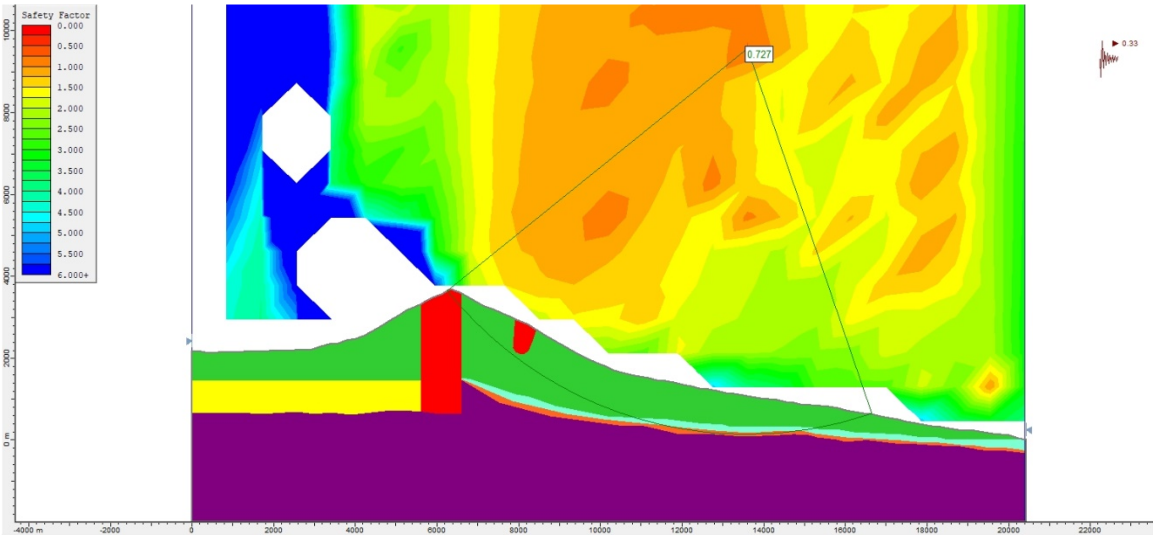

Figure S132. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a $k_h = 0.33$.

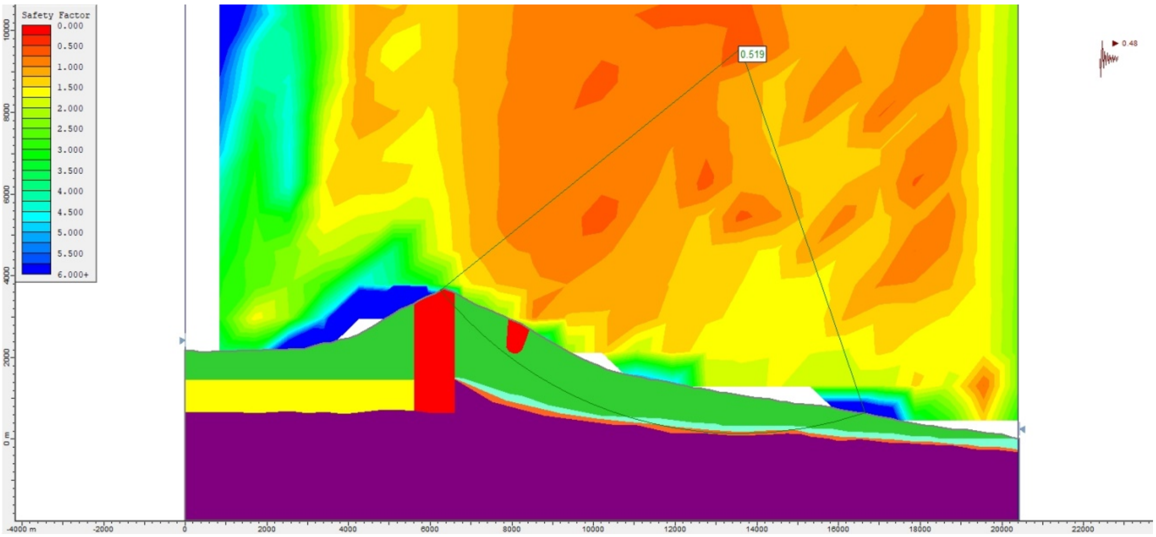

Figure S133. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a $k_h = 0.48$.

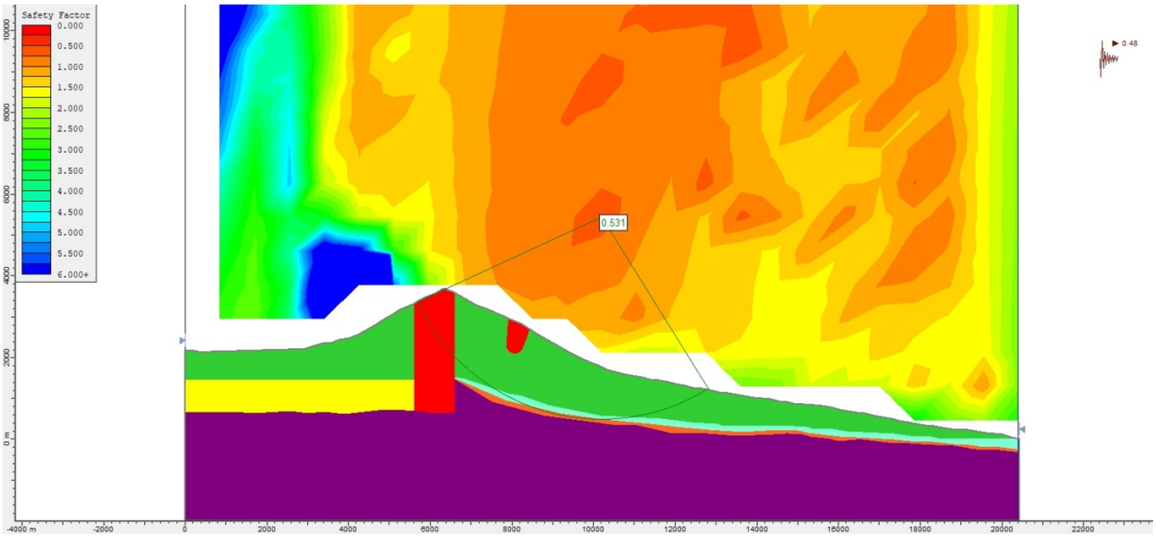

Figure S134. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a $k_h = 0.48$.

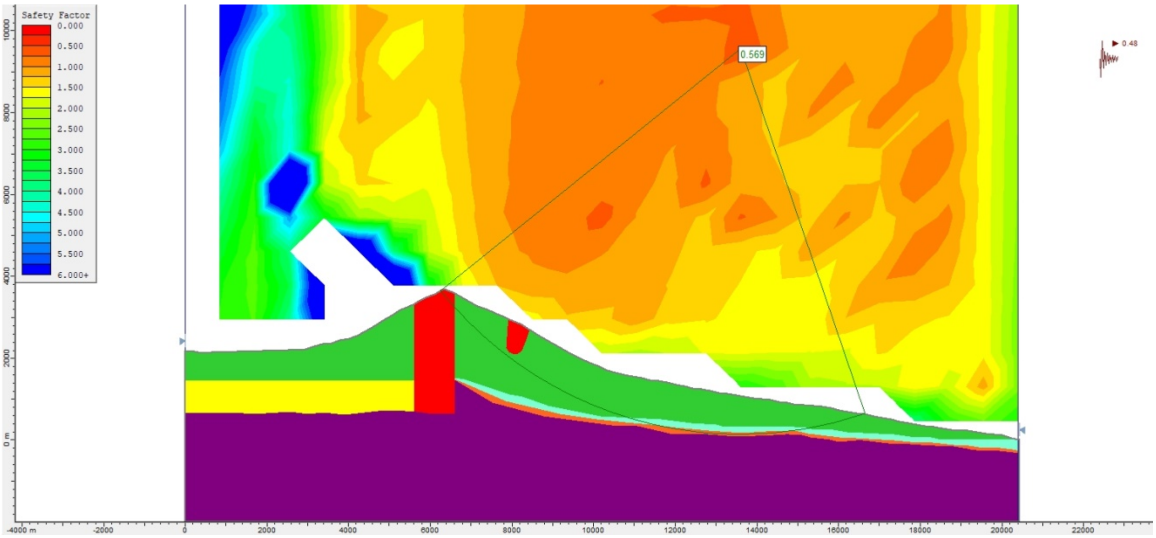

Figure S135. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.48.

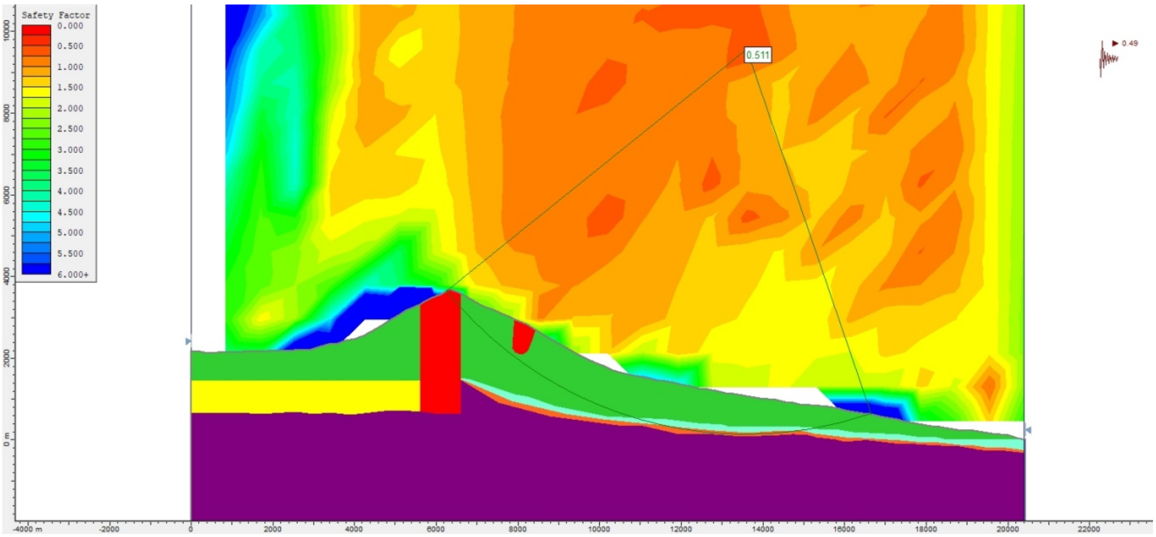

Figure S136. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 0.49.

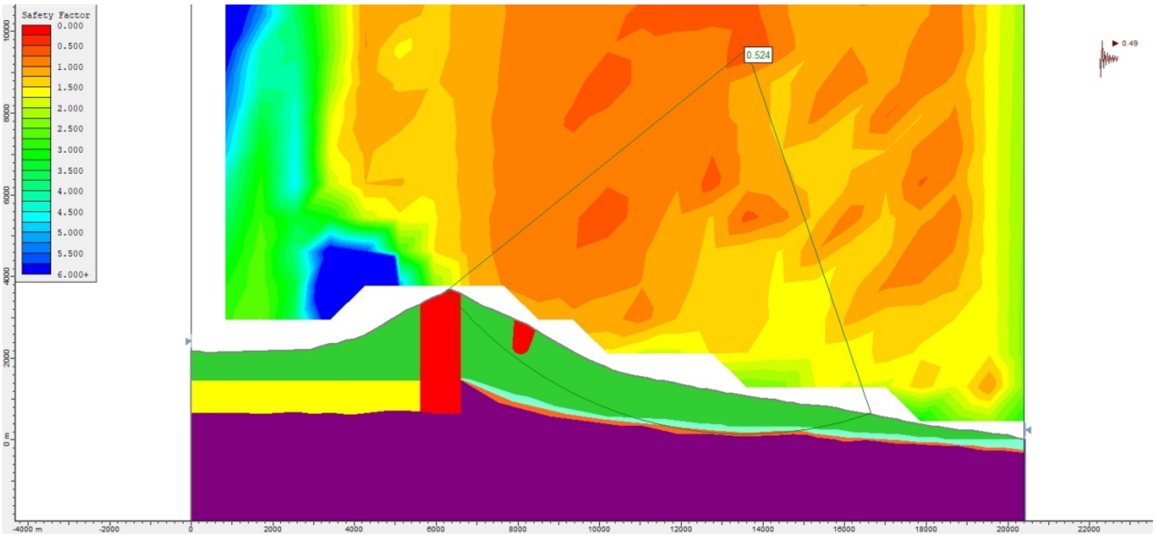

Figure S137. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 0.49.

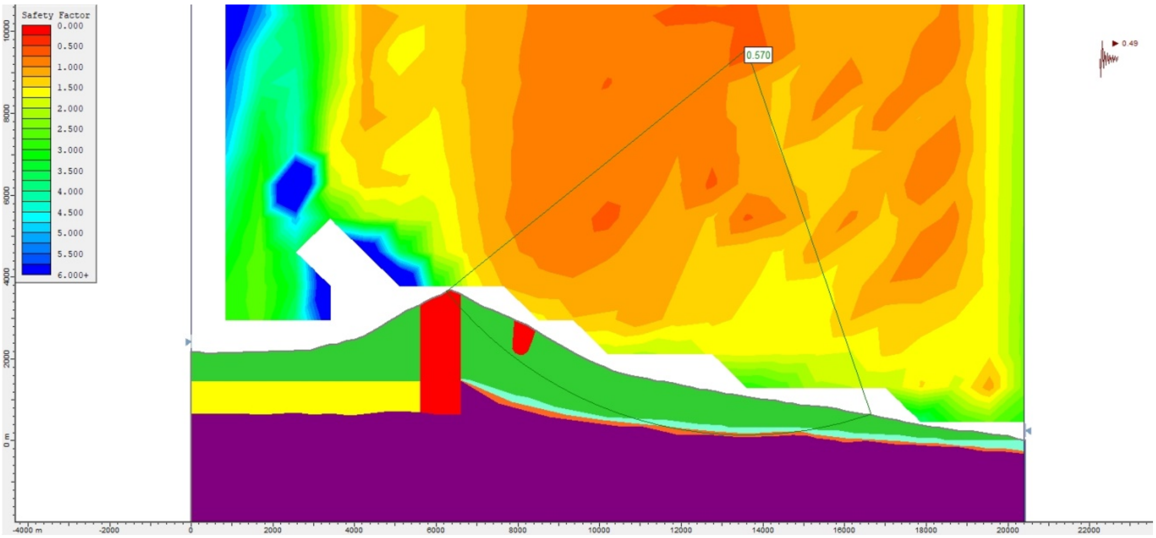

Figure S138. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 0.49.

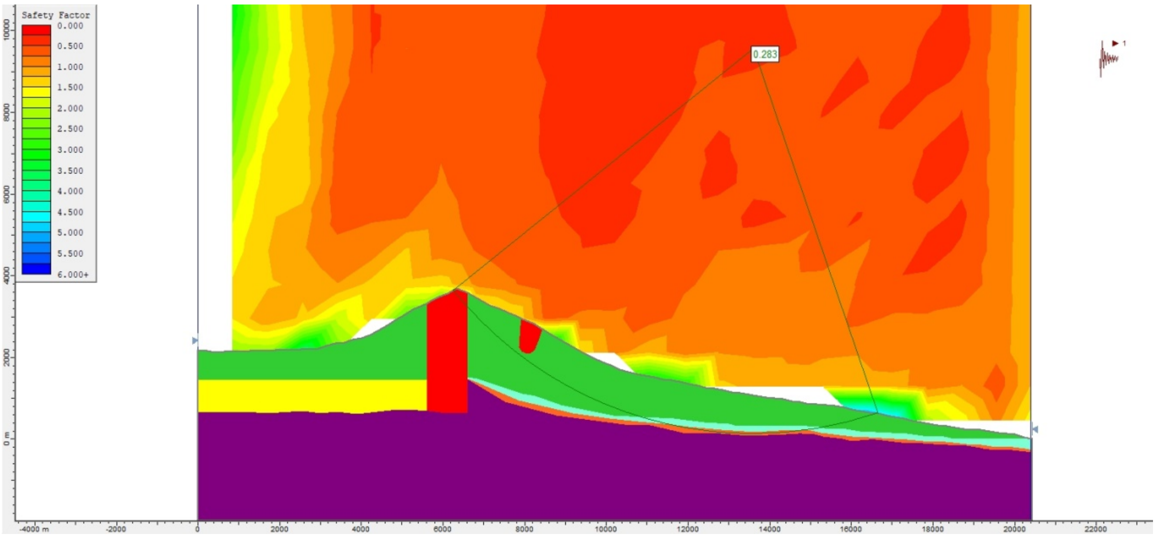

Figure S139. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 1.00.

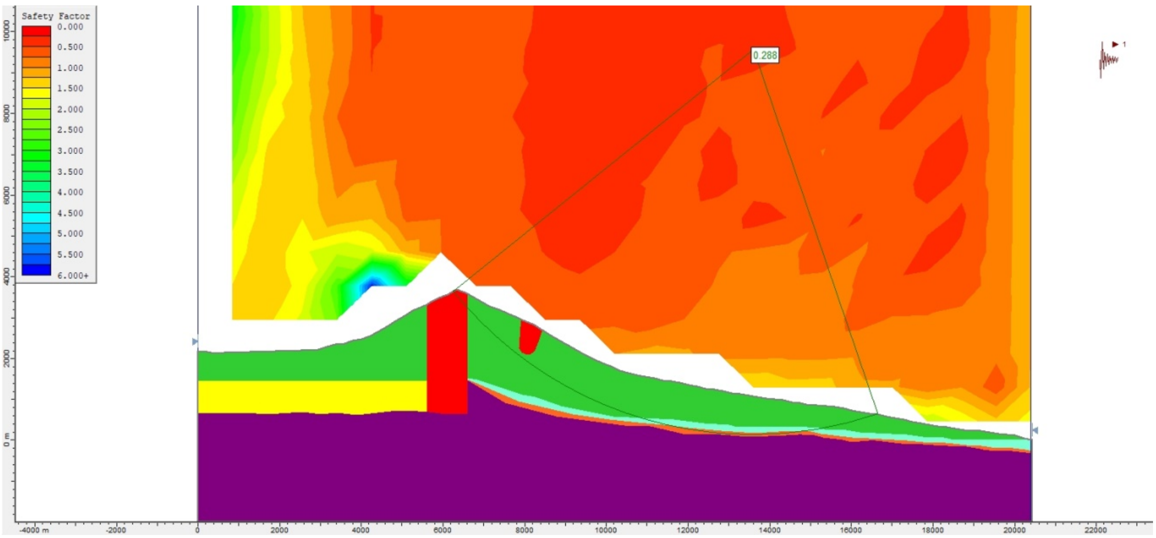

Figure S140. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 1.00.

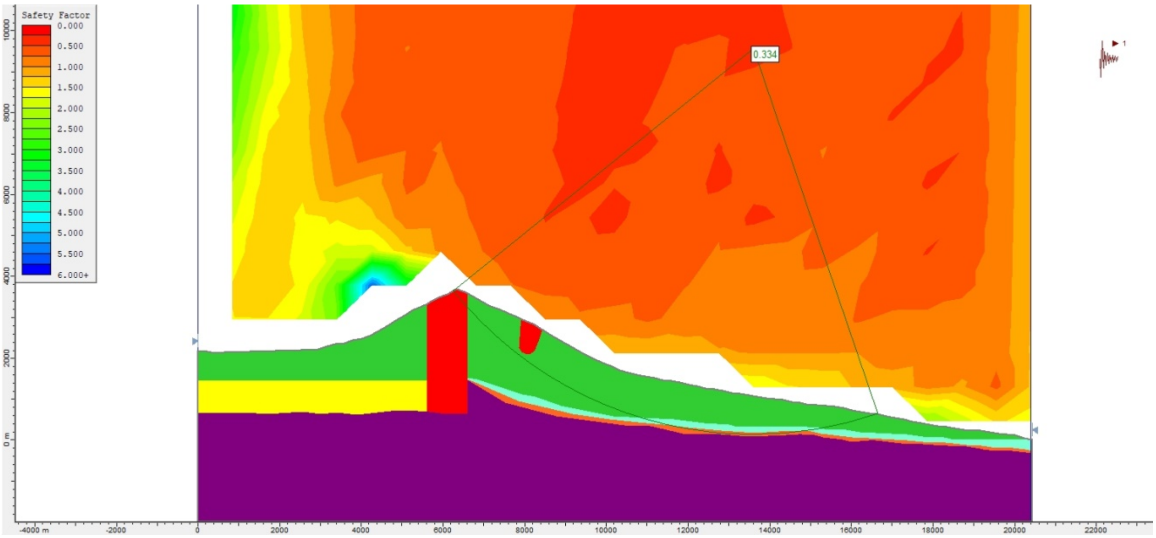

Figure S141. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 1.00.

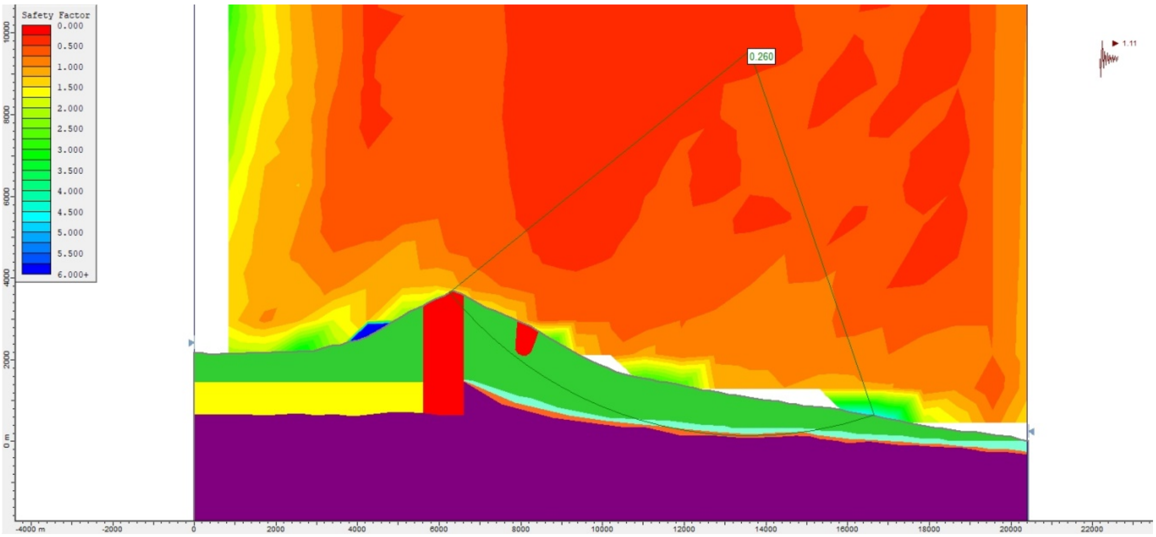

Figure S142. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Bishop simplified method and a k_h = 1.11.

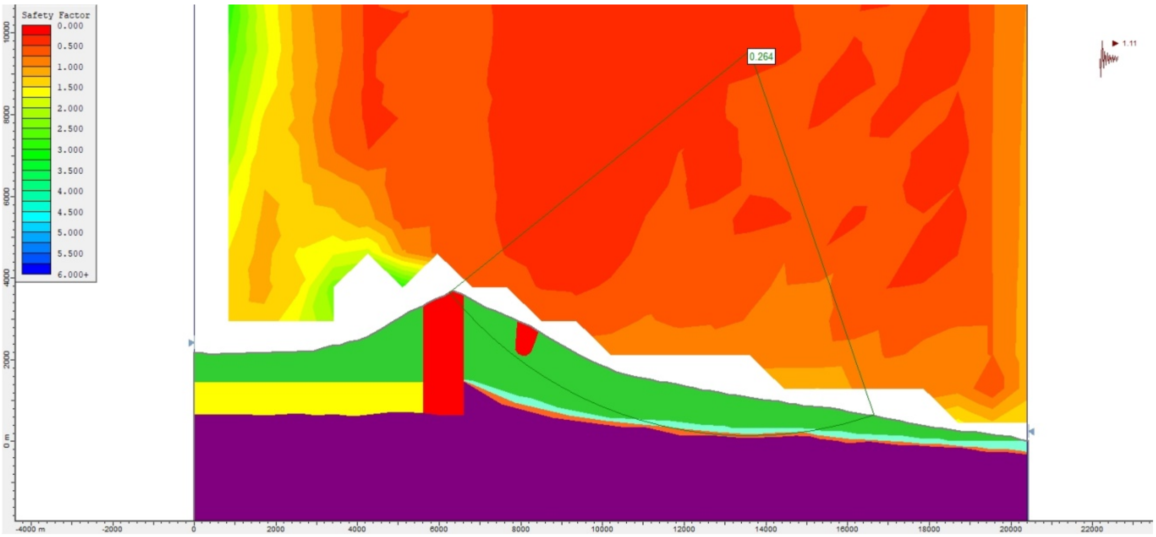

Figure S143. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Janbu Generalised method and a k_h = 1.11.

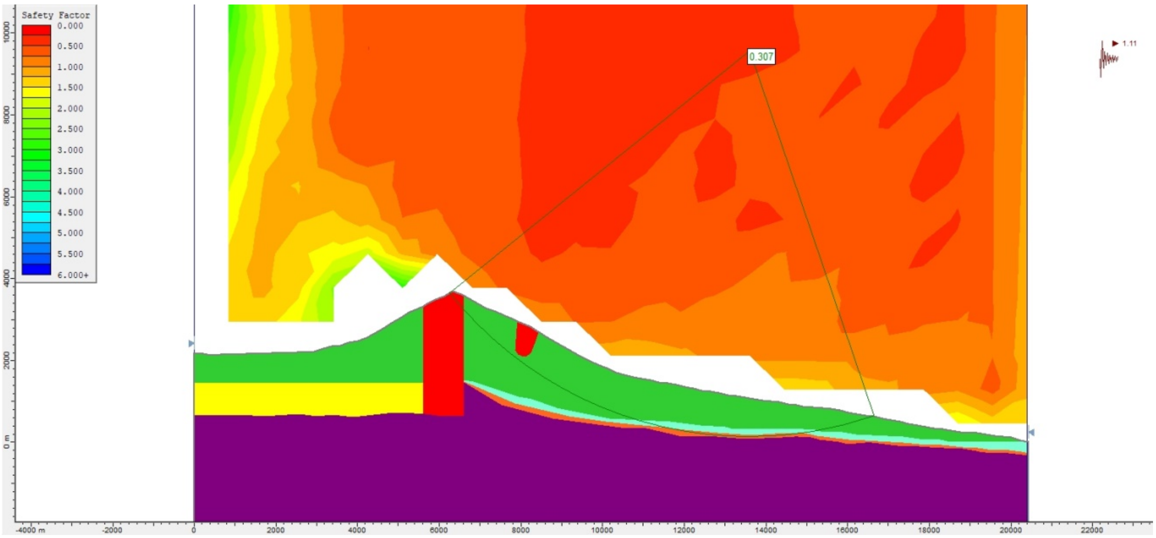

Figure S144. Slope stability pseudo-static analysis for Model 1 (with alteration zones, Figure 4a), using the Morgenstern-Price method and a k_h = 1.11.

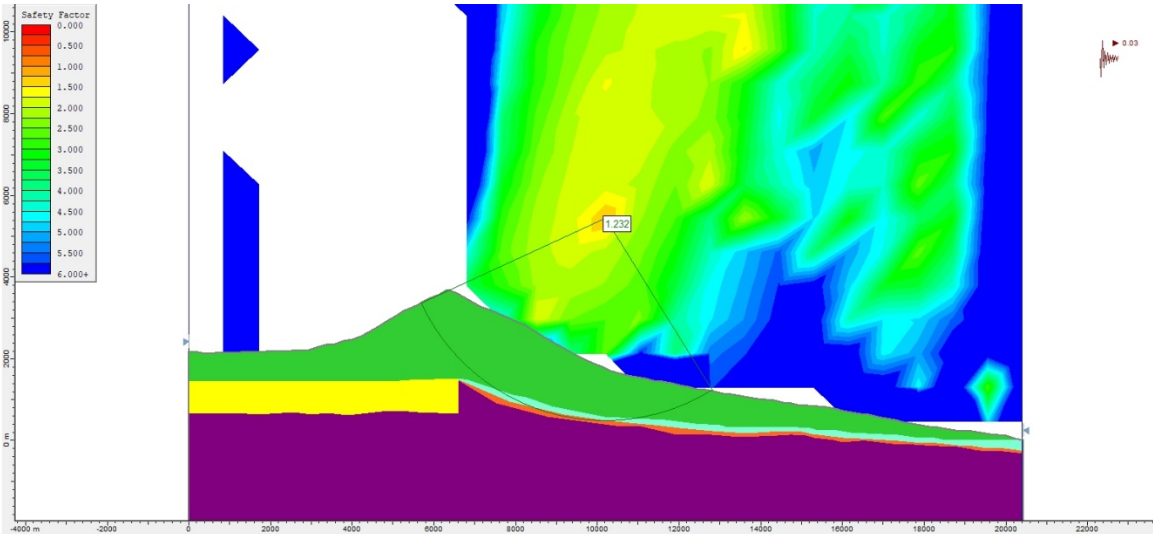

Figure S145. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.03.

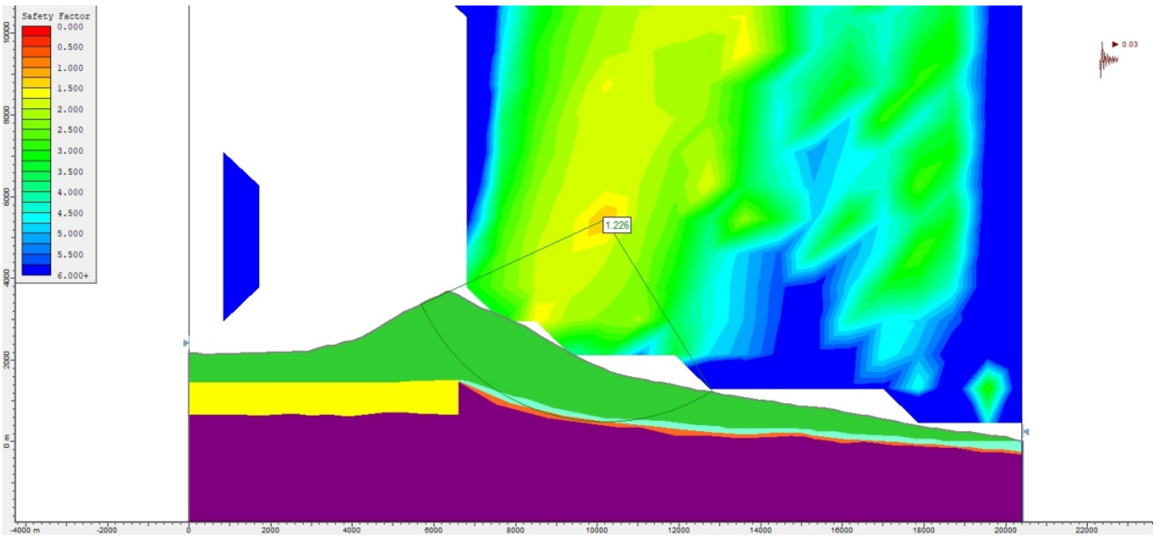

Figure S146. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.03.

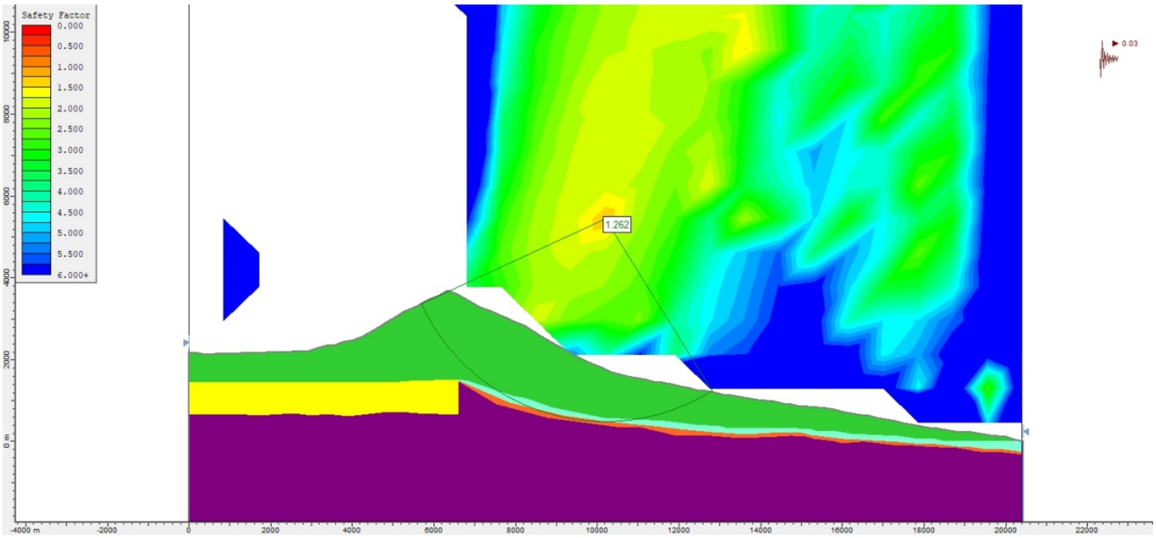

Figure S147. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.03.

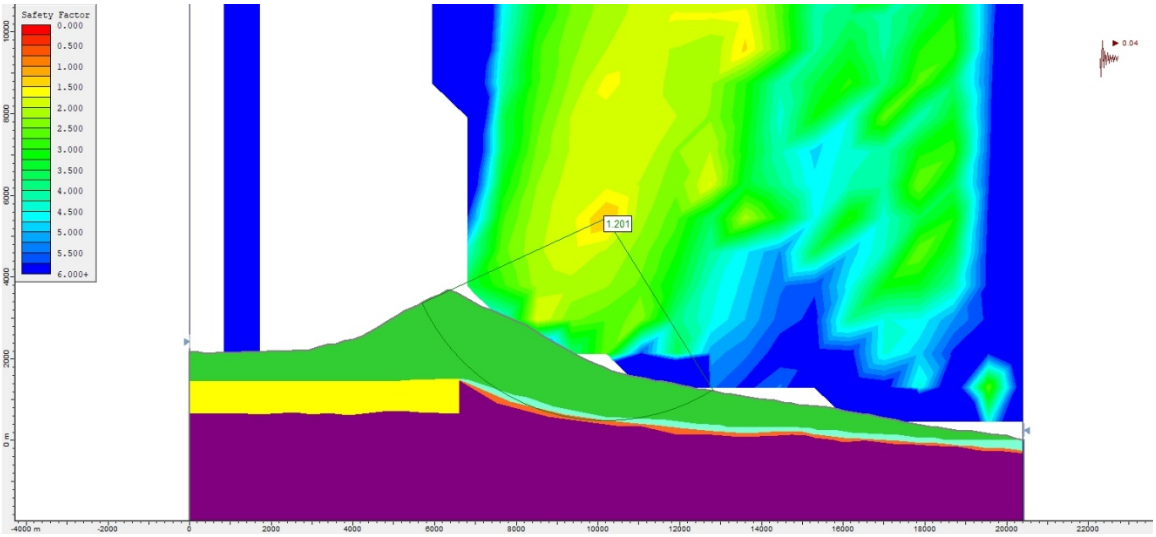

Figure S148. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.04.

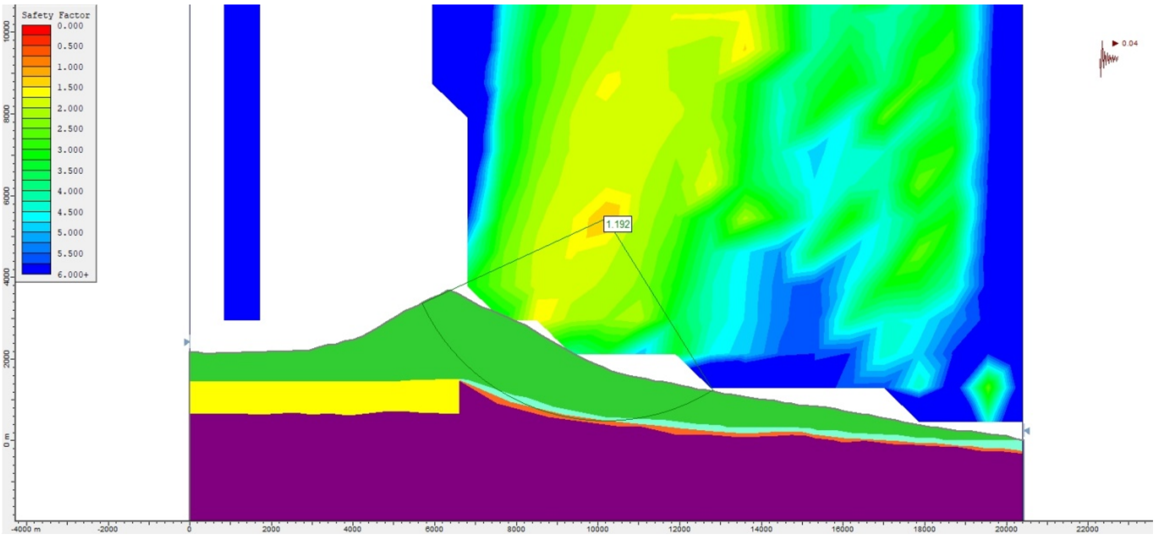

Figure S149. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.04.

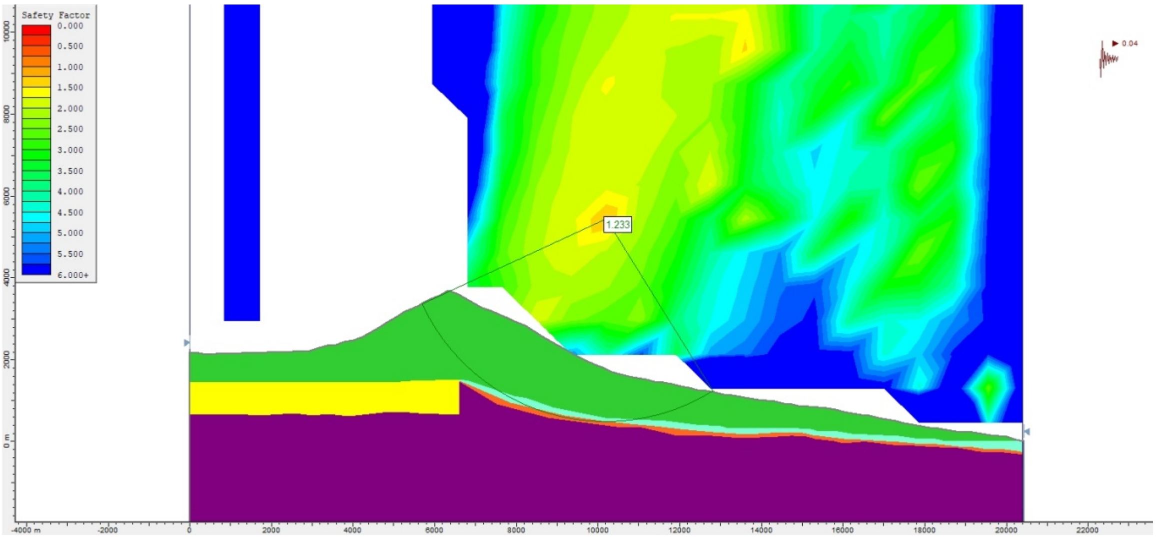

Figure S150. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.04.

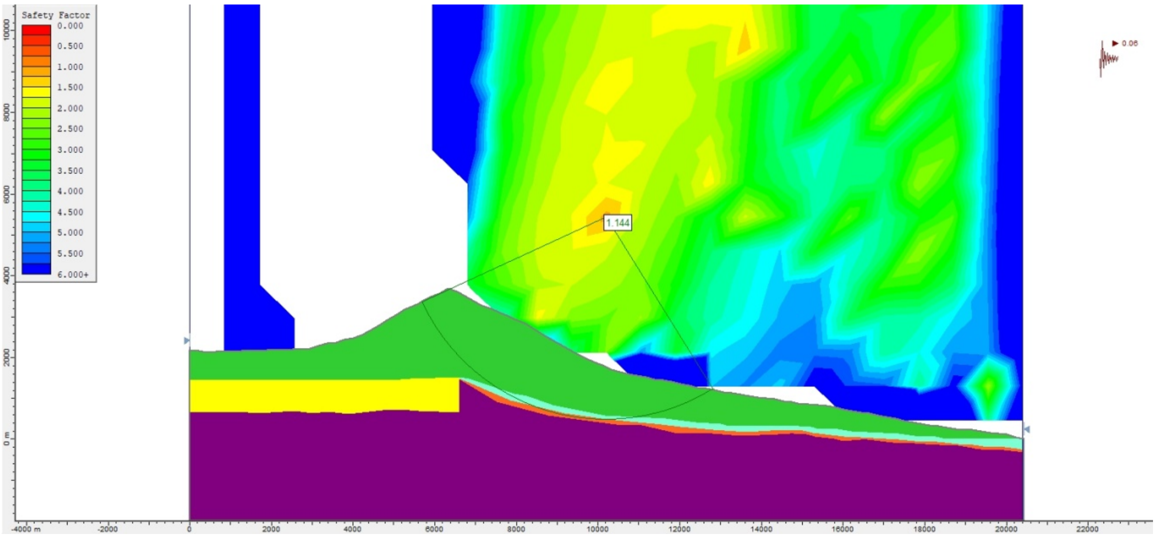

Figure S151. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.06.

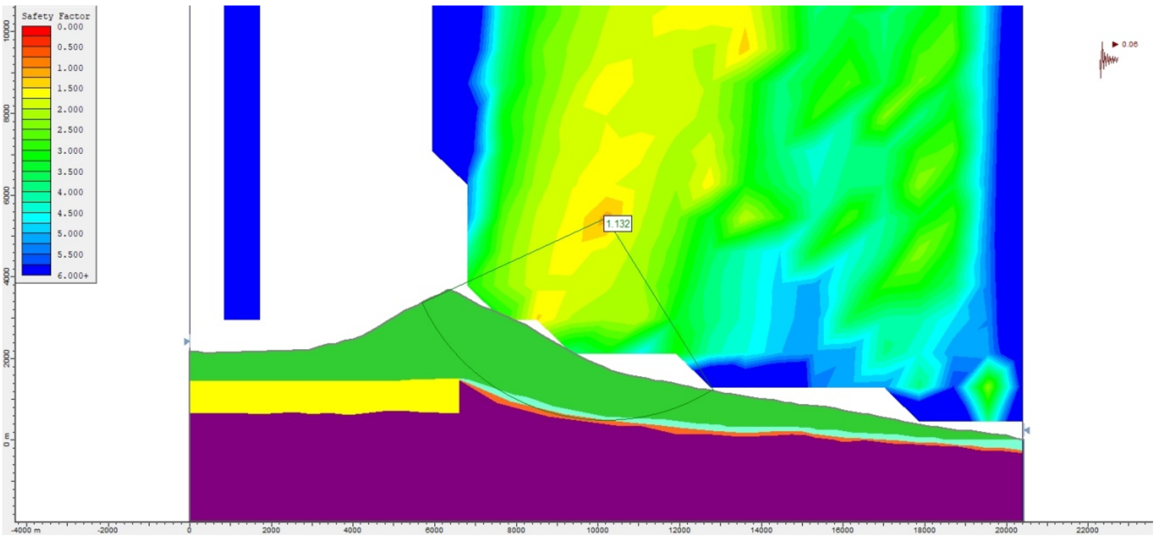

Figure S152. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.06.

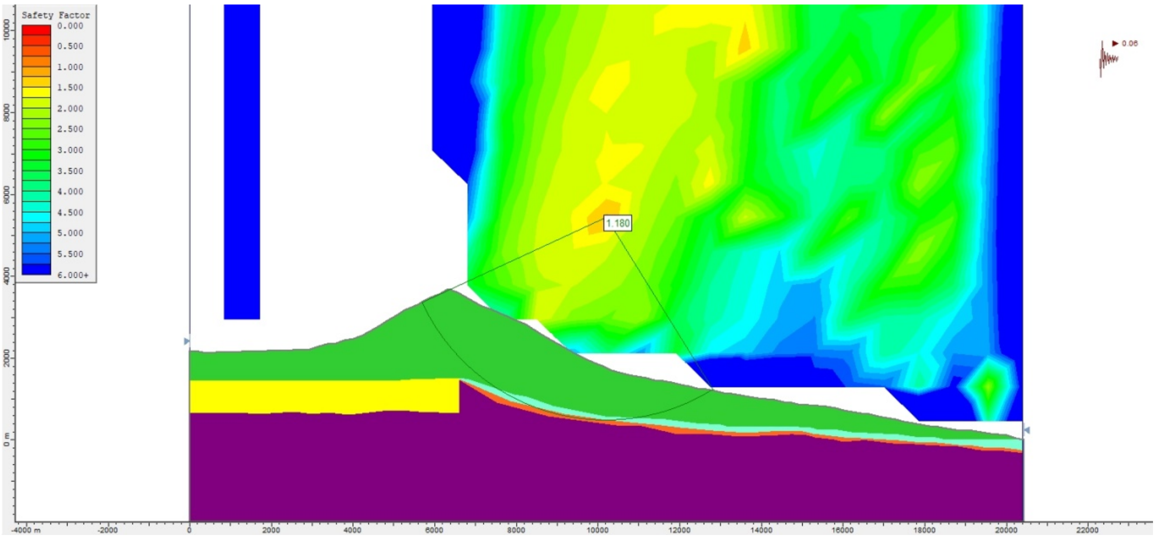

Figure S153. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.06.

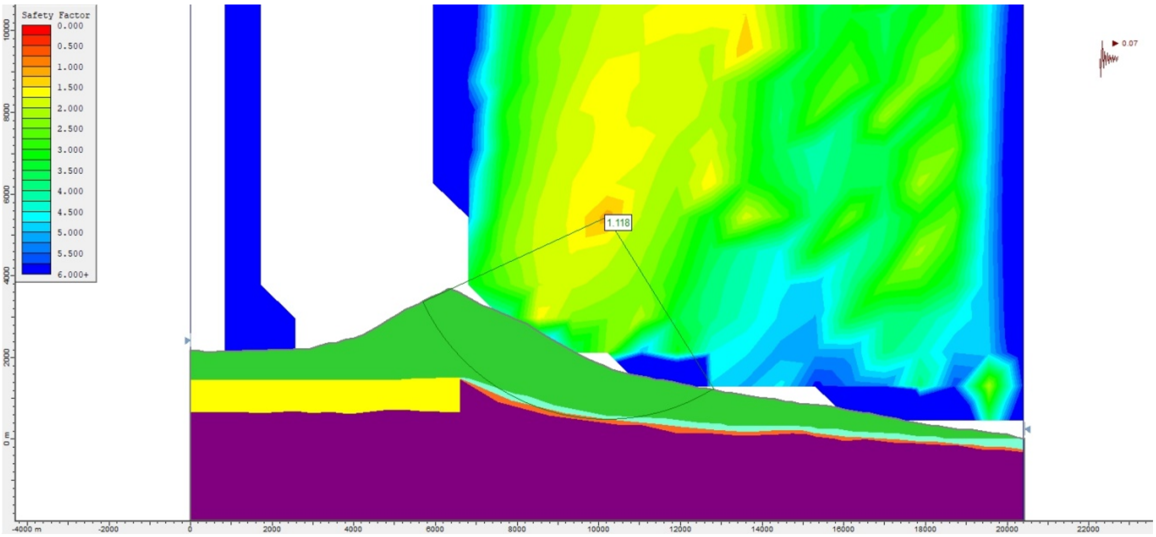

Figure S154. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.07.

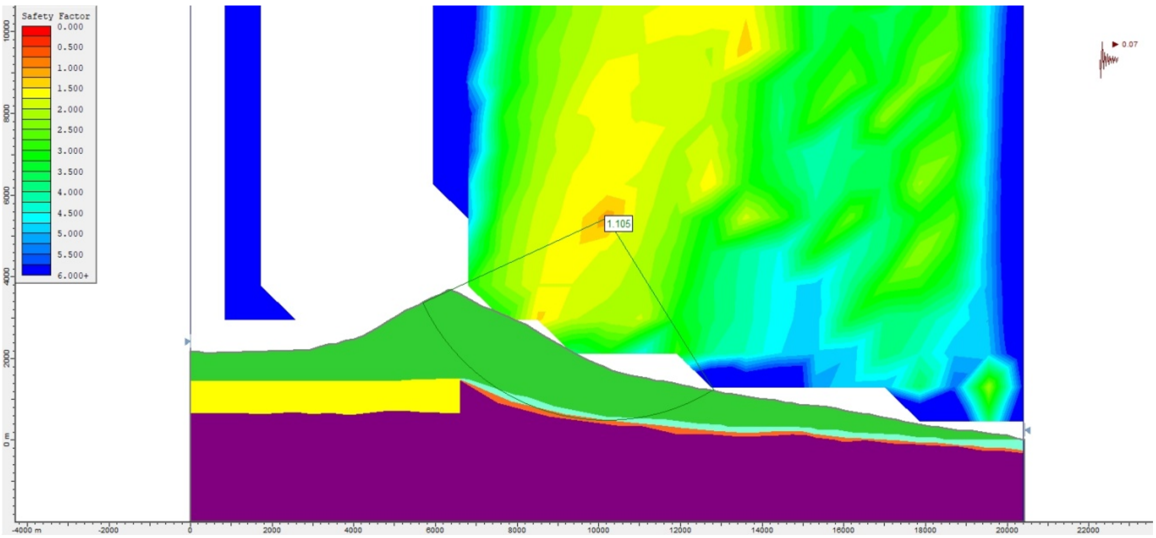

Figure S155. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.07.

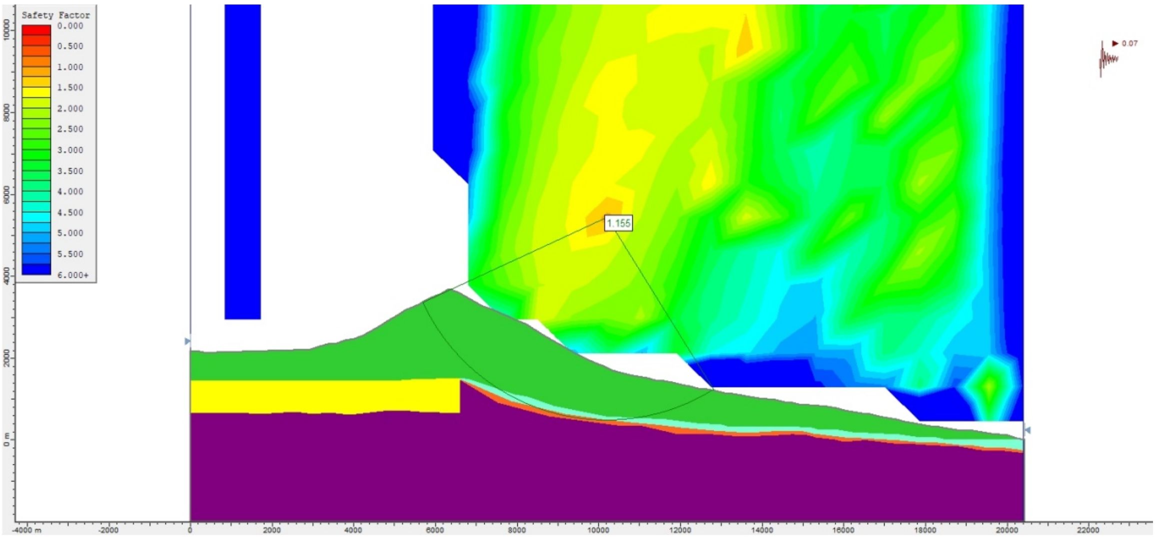

Figure S156. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.07.

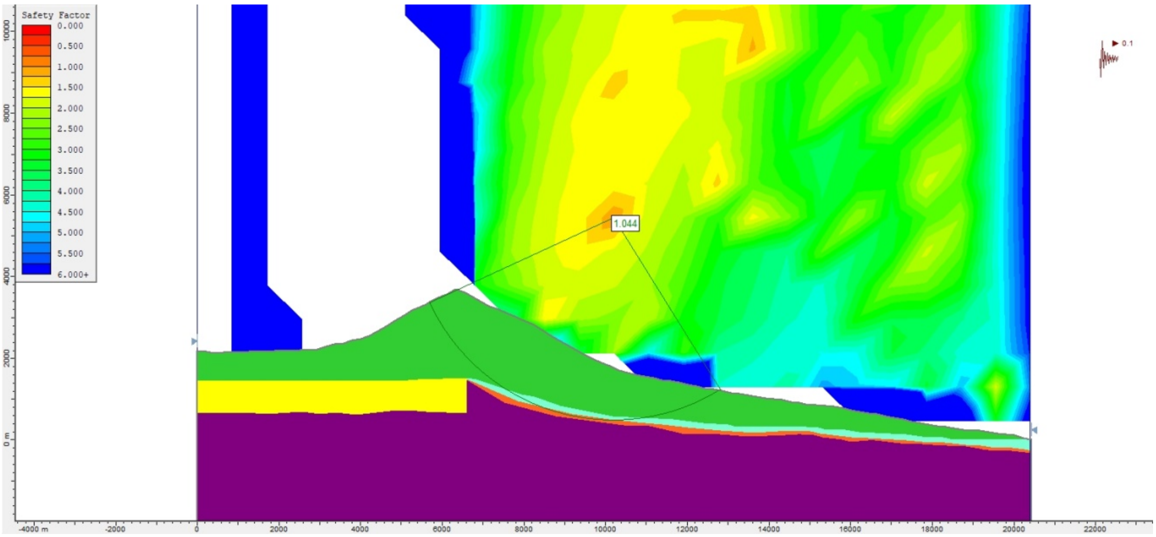

Figure S157. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.10.

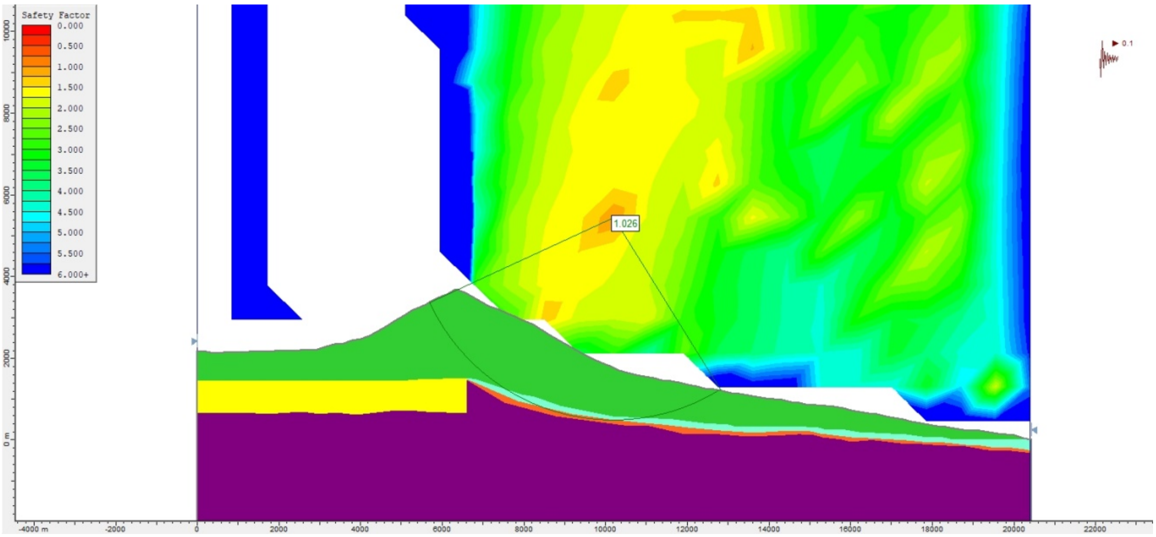

Figure S158. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.10.

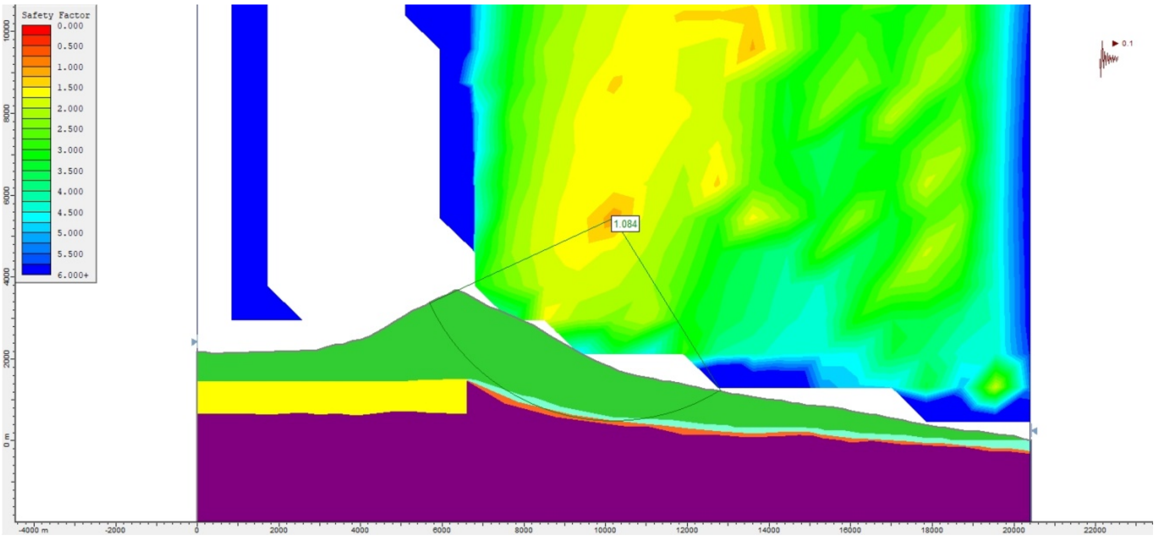

Figure S159. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.10.

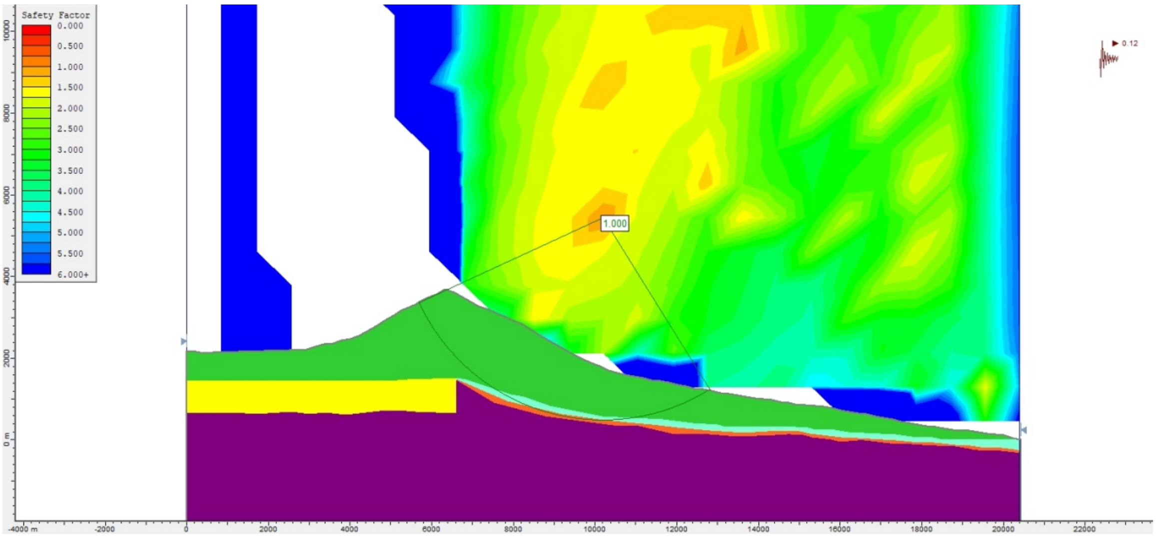

Figure S160. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.12.

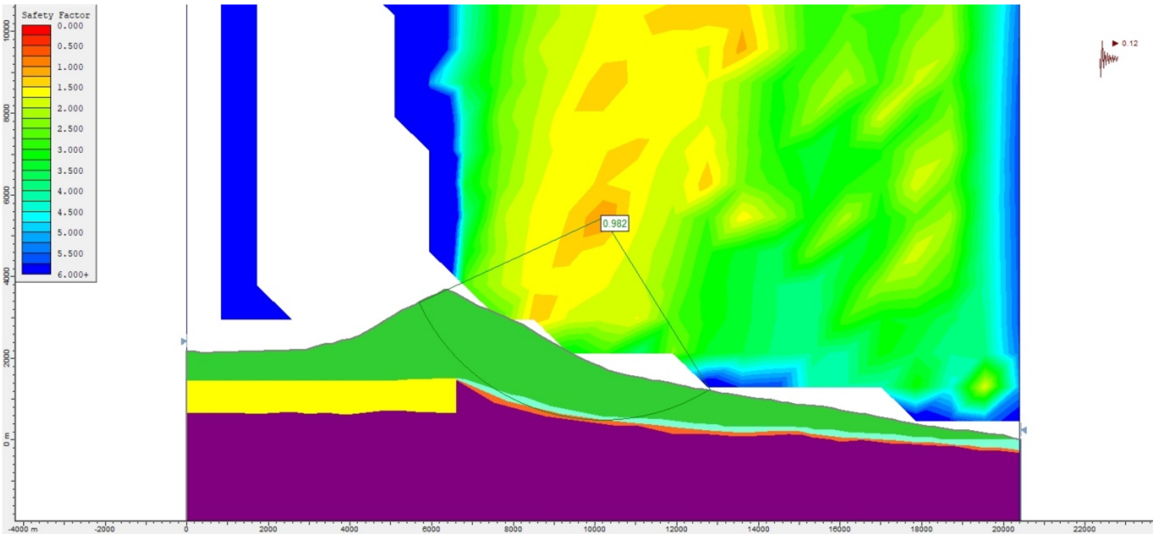

Figure S161. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.12.

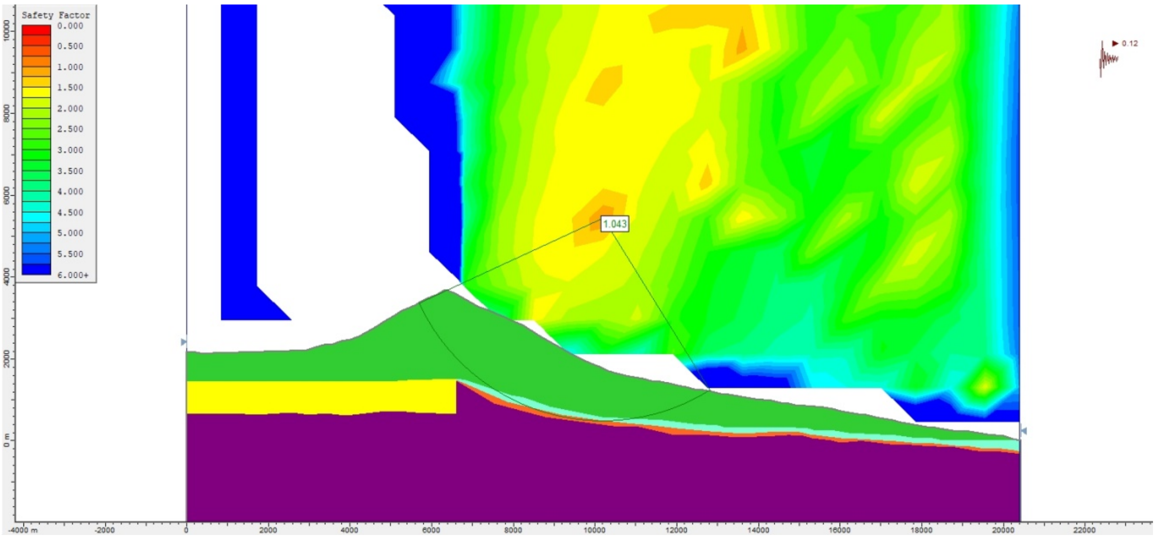

Figure S162. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.12.

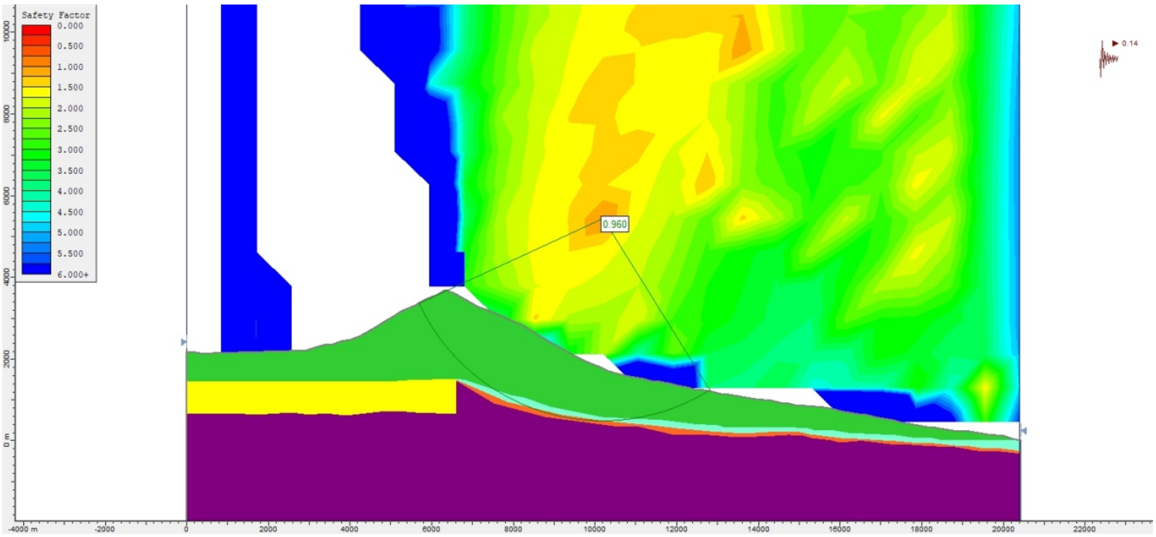

Figure S163. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.14.

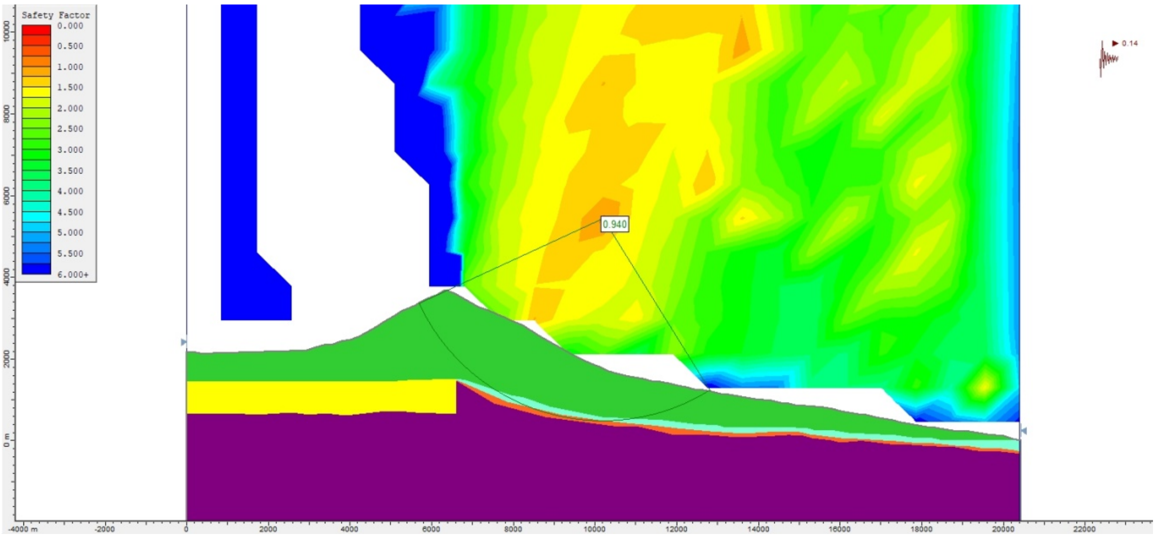

Figure S164. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.14.

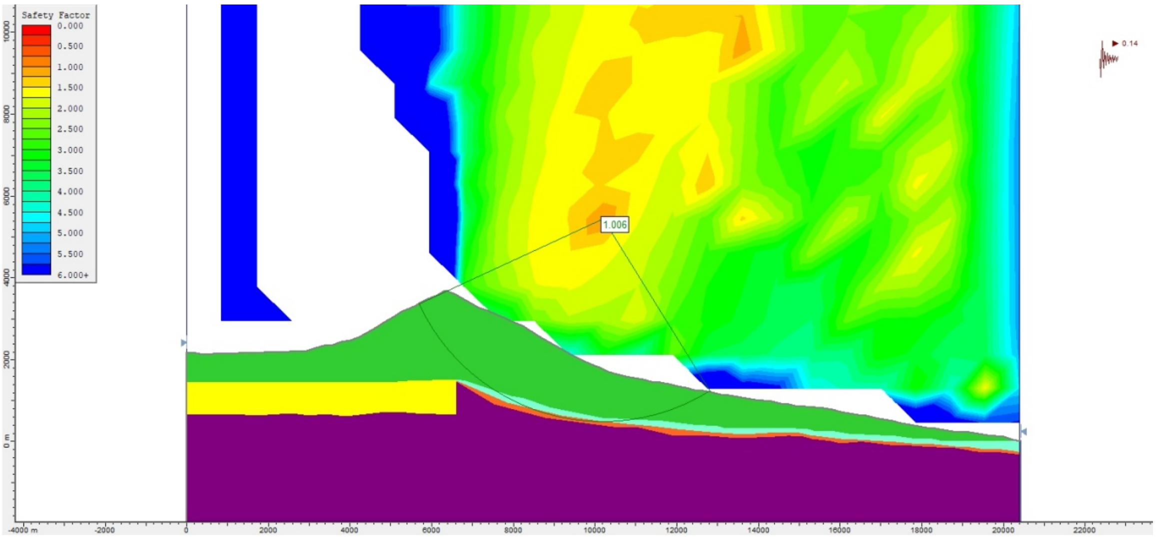

Figure S165. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.14.

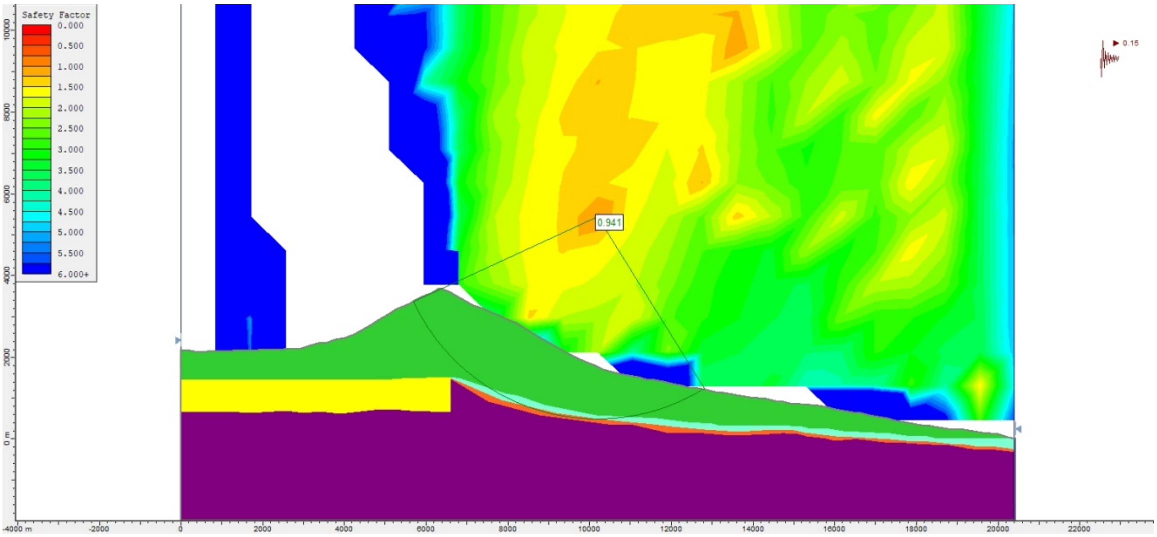

Figure S166. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.15.

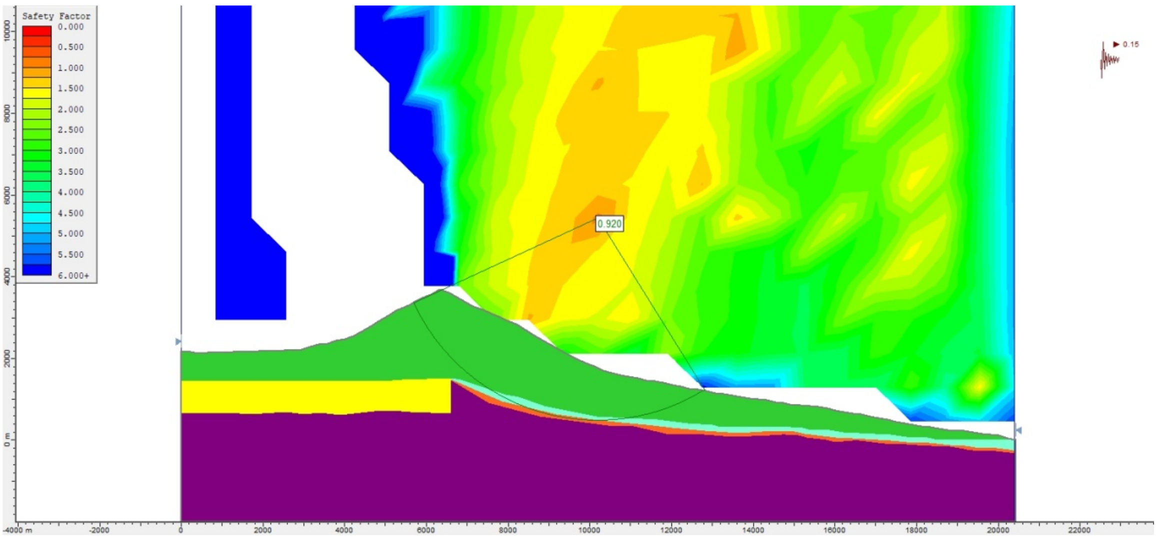

Figure S167. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.15.

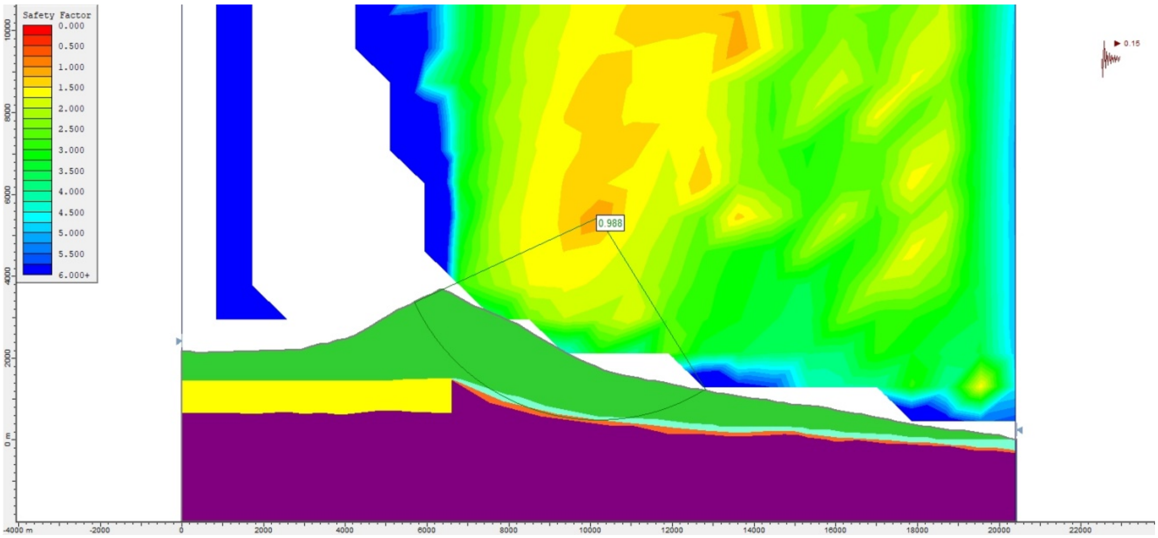

Figure S168. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.15.

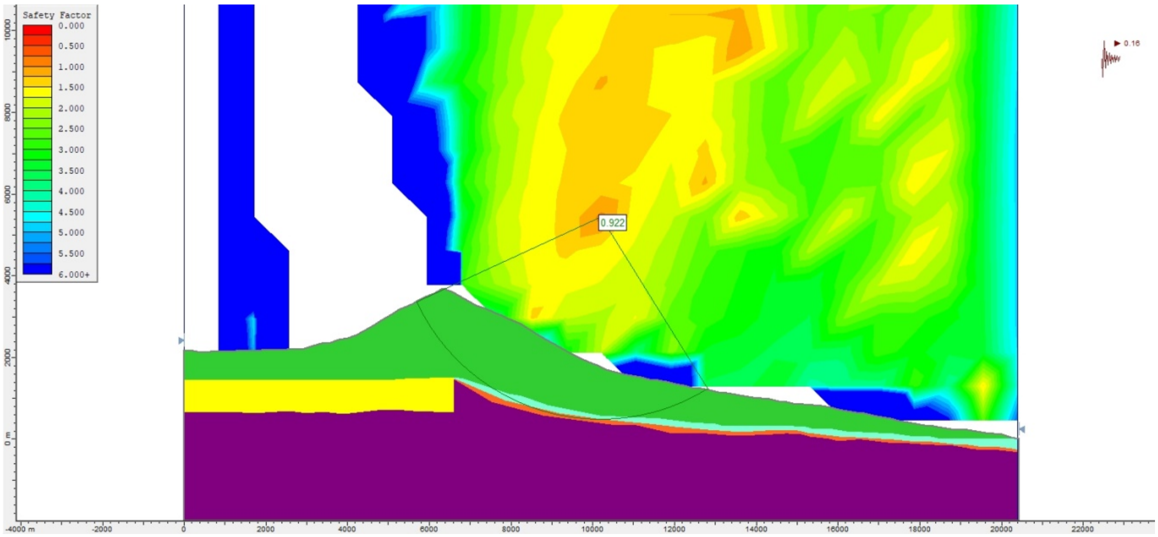

Figure S169. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.16.

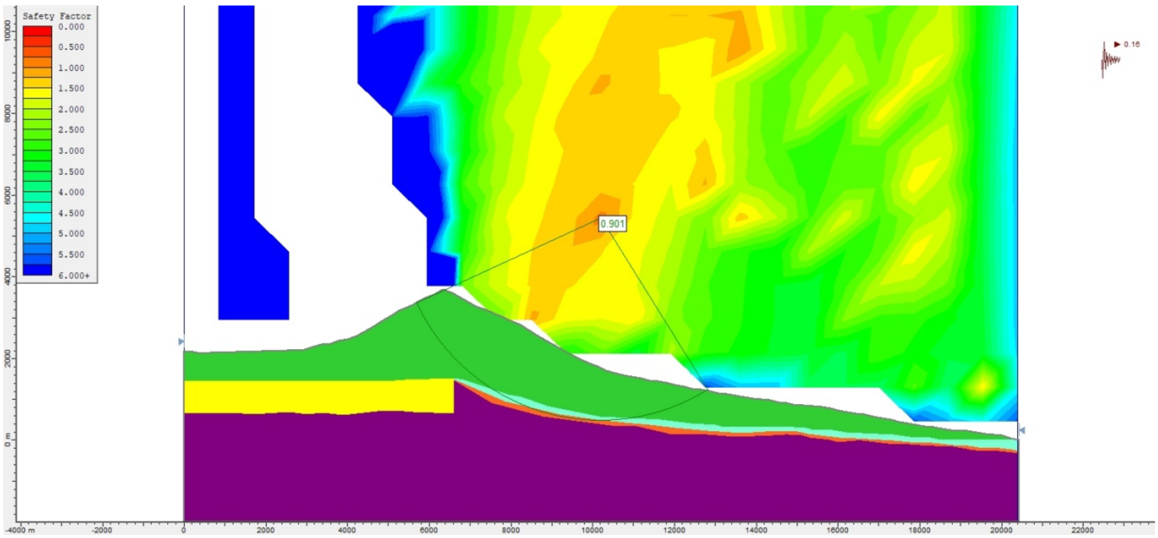

Figure S170. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.16.

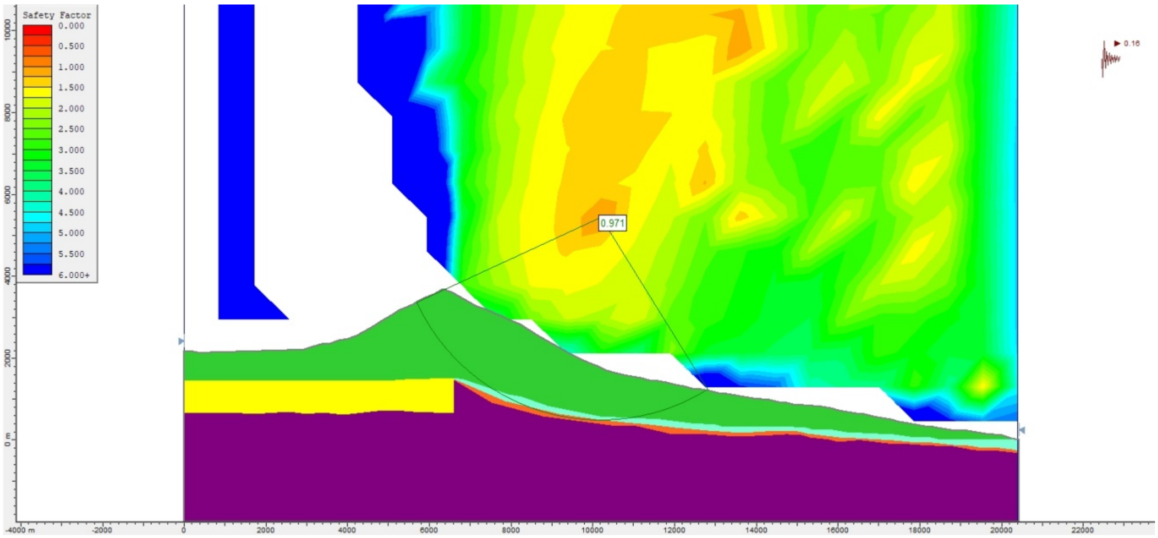

Figure S171. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.16.

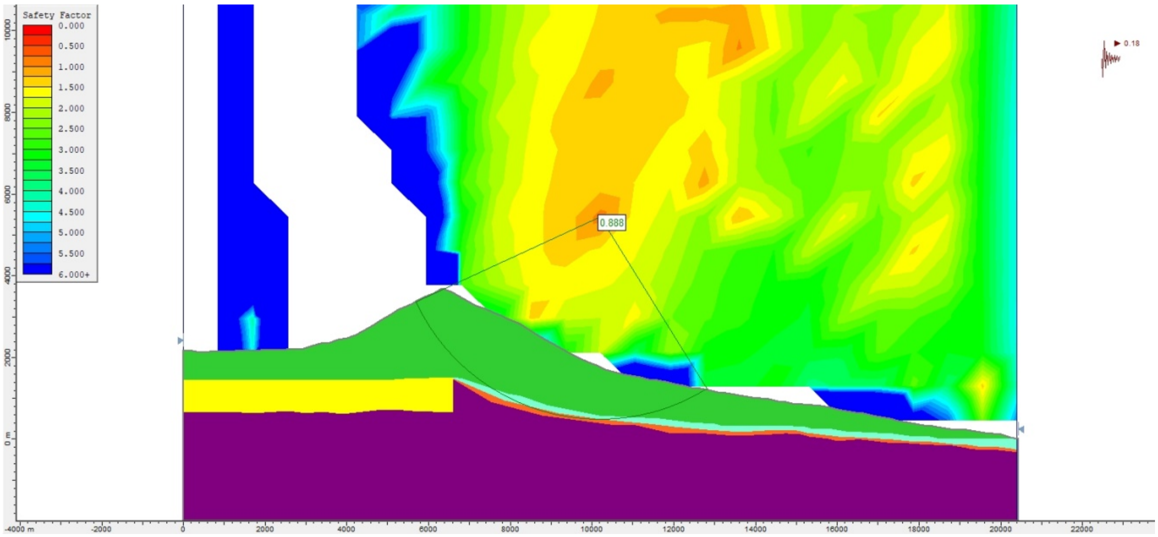

Figure S172. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.18.

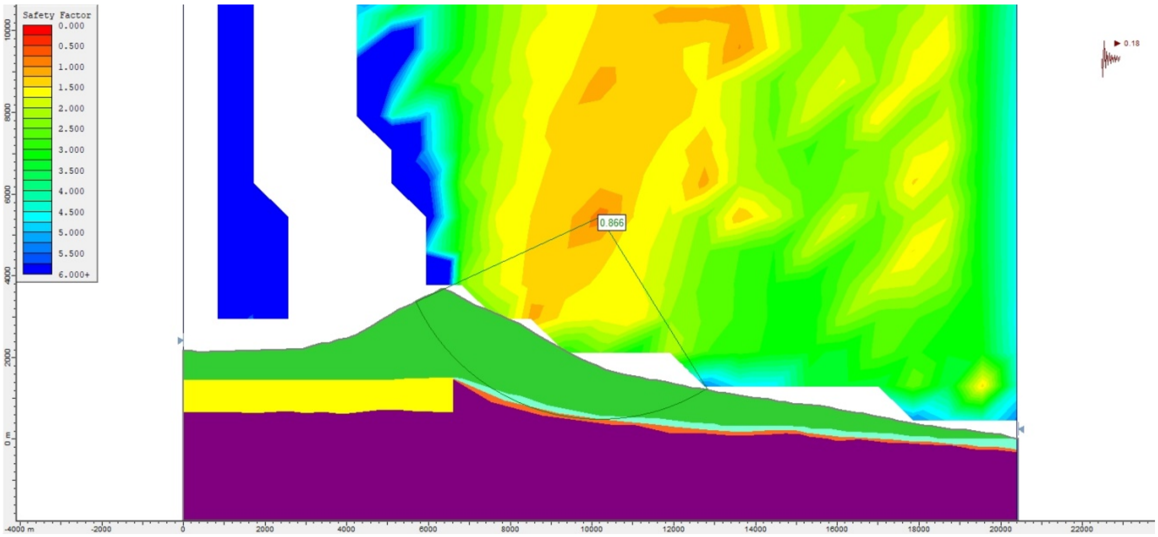

Figure S173. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.18.

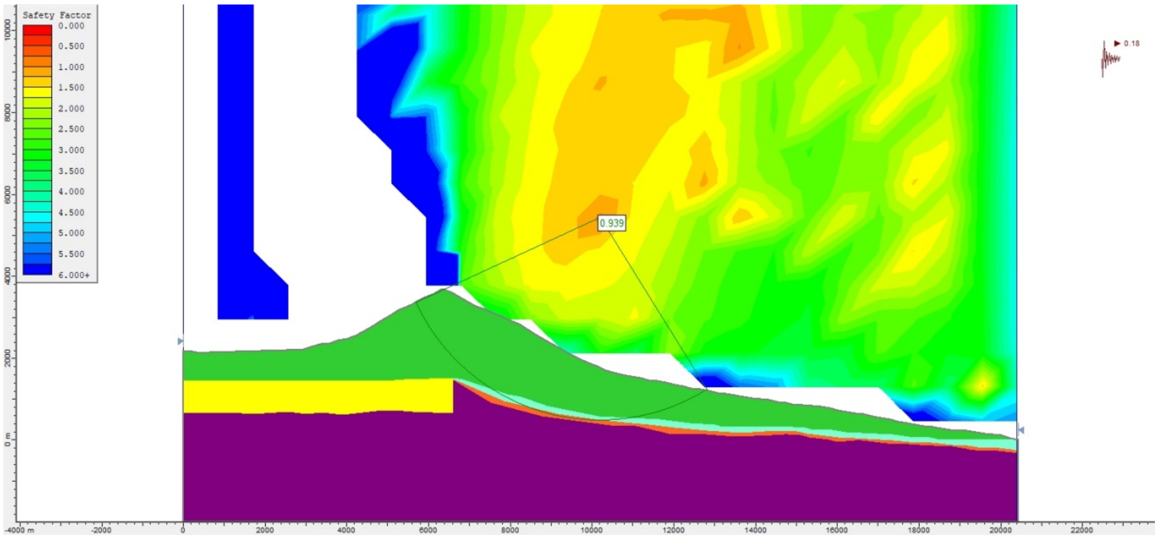

Figure S174. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.18.

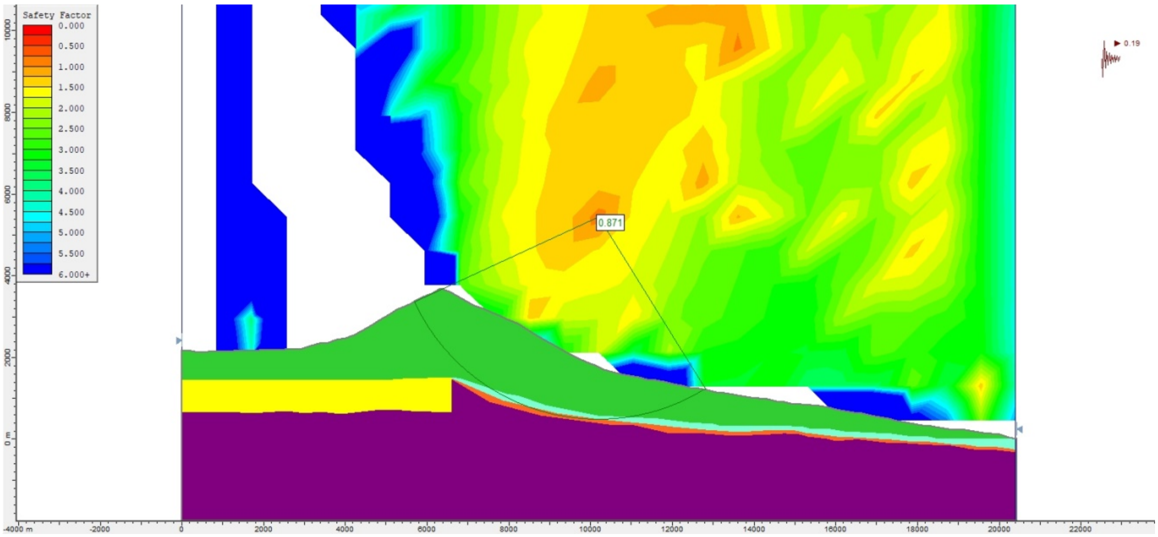

Figure S175. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.19.

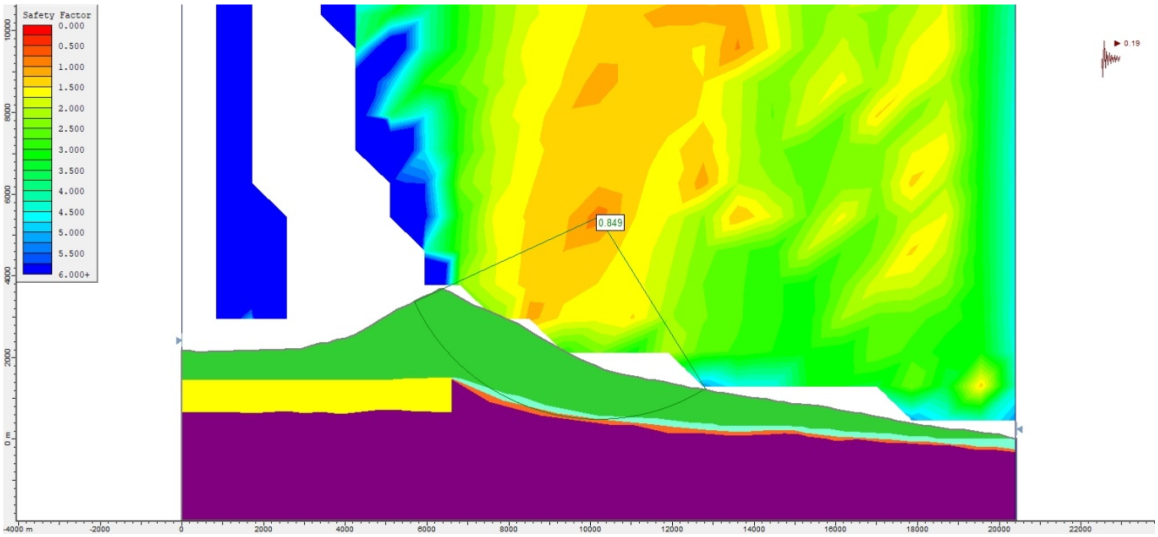

Figure S176. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.19.

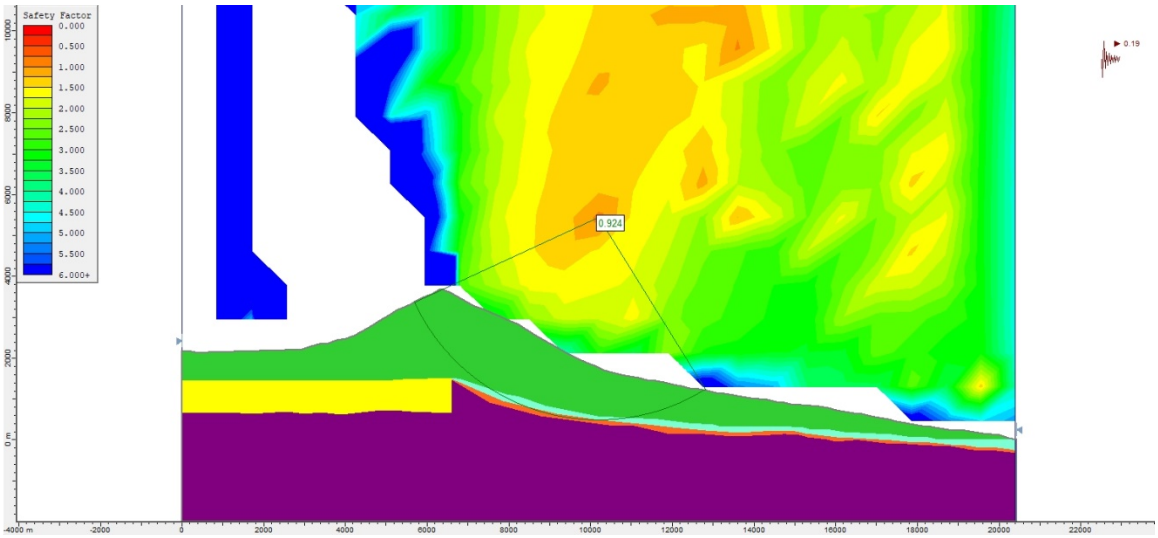

Figure S177. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.19.

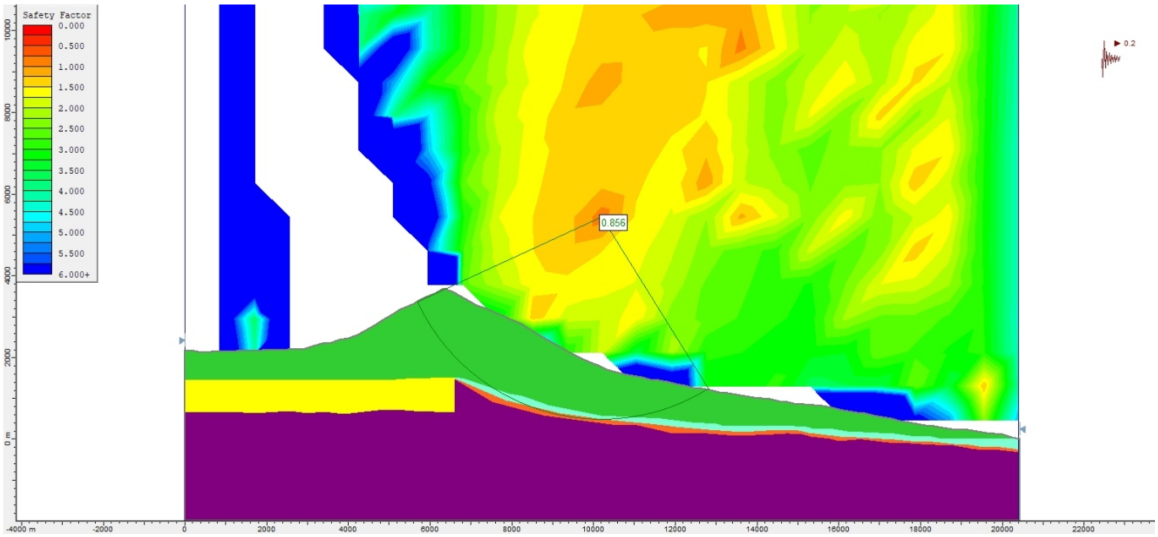

Figure S178. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.20.

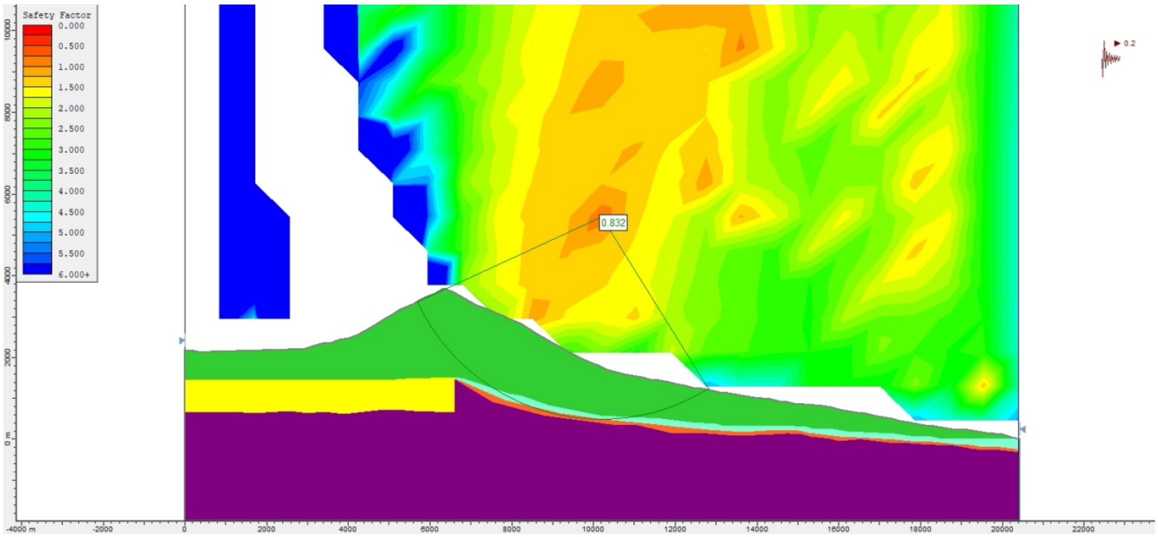

Figure S179. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.20.

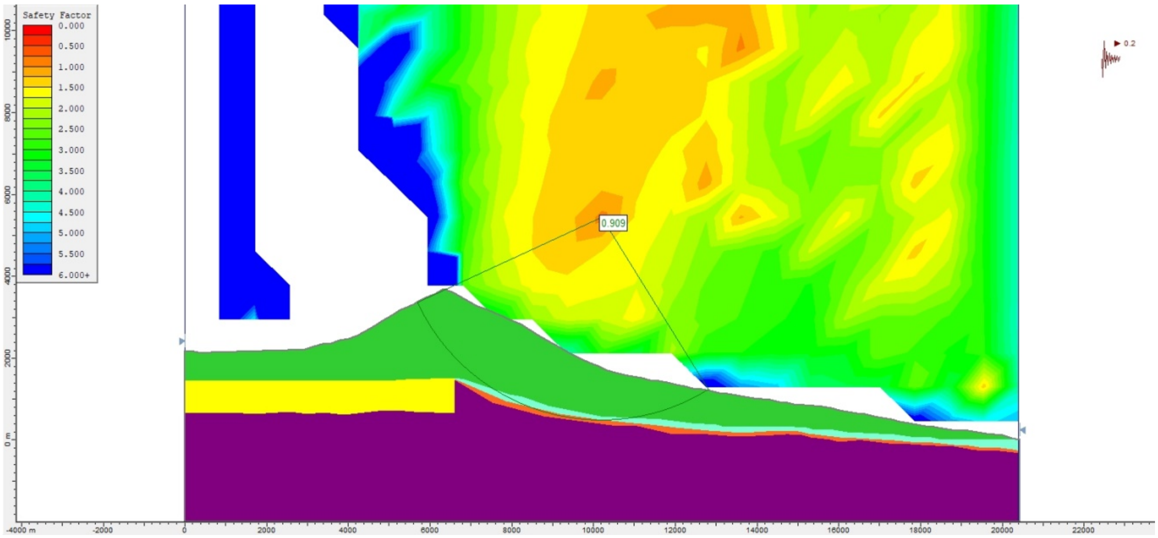

Figure S180. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.20.

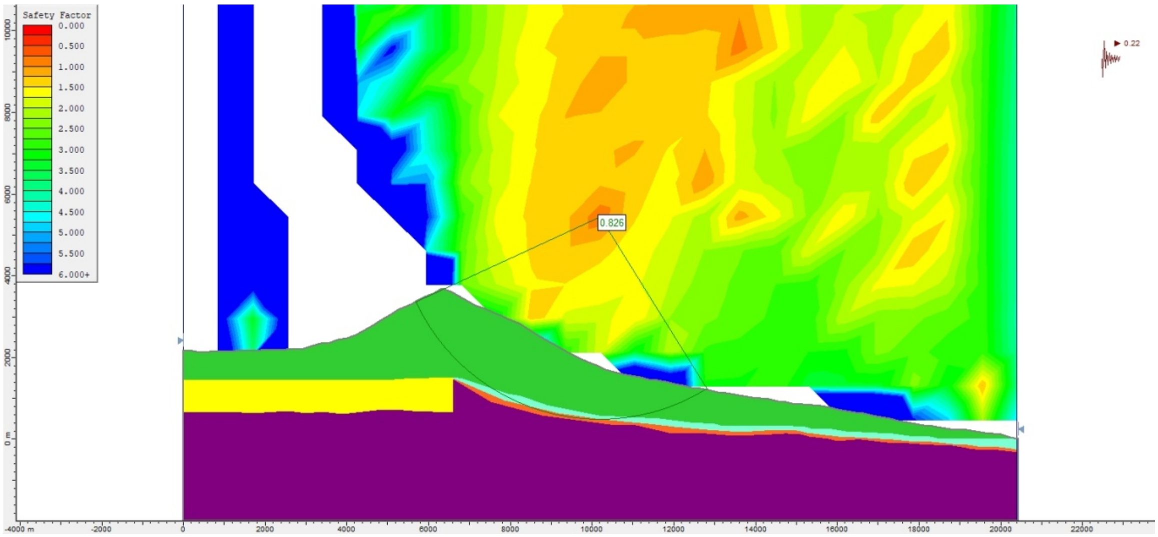

Figure S181. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.22.

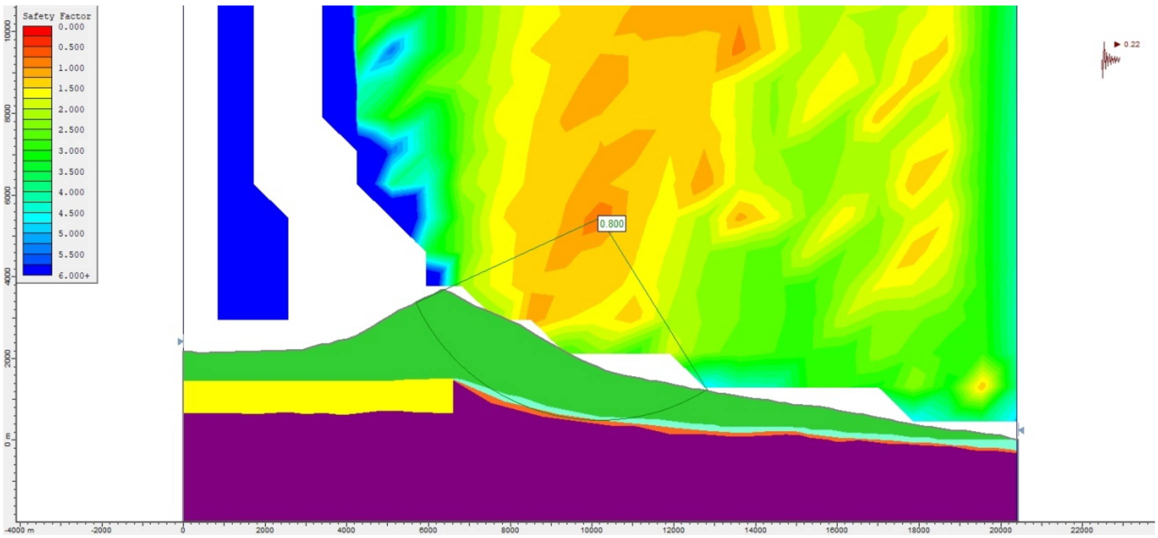

Figure S182. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.22.

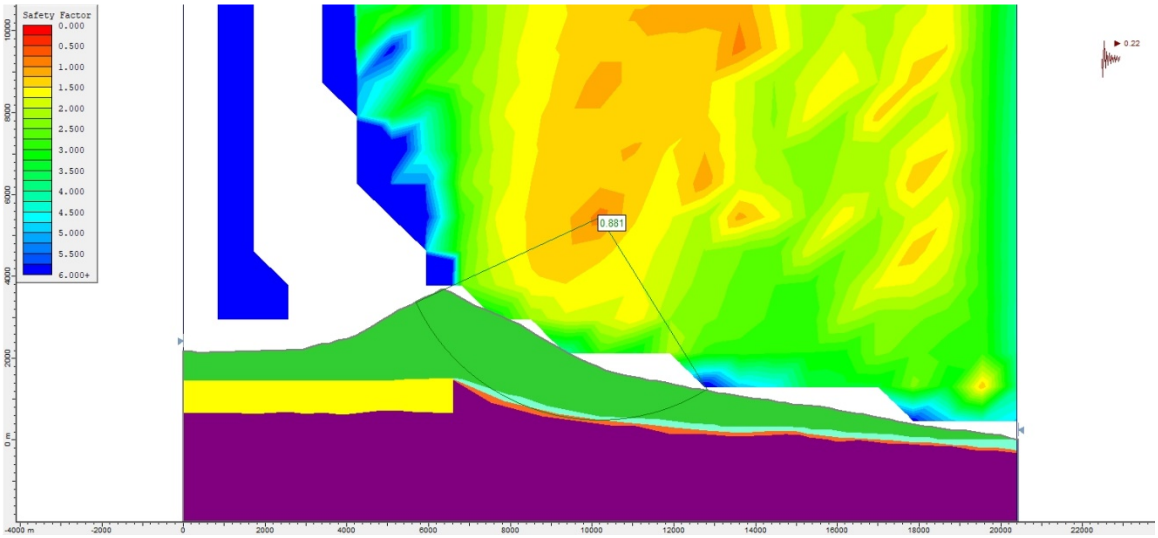

Figure S183. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.22.

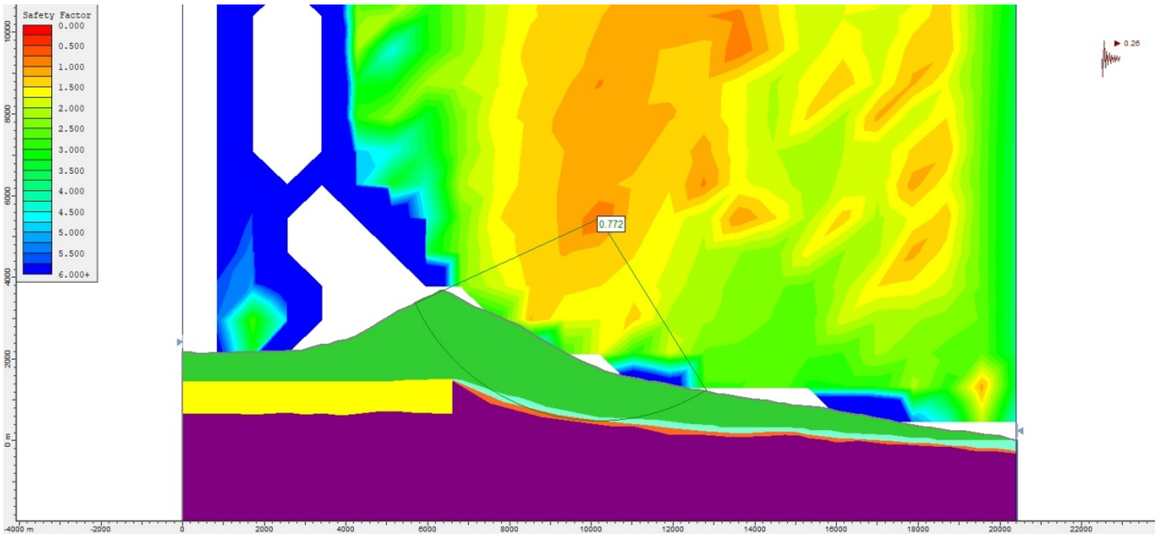

Figure S184. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using Bishop simplified method and a k_h = 0.26.

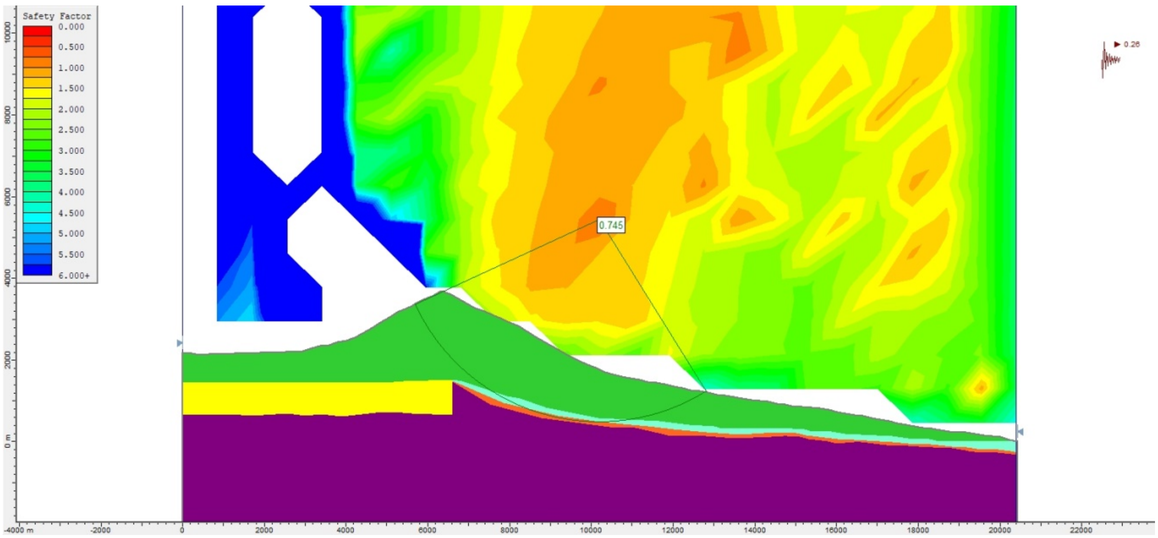

Figure S185. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.26.

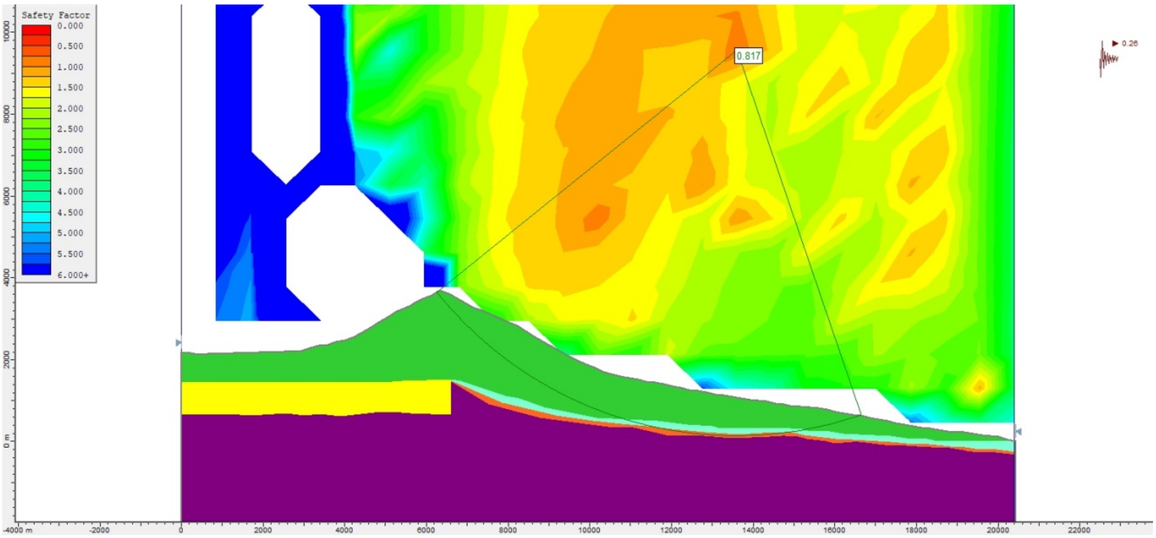

Figure S186. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.26.

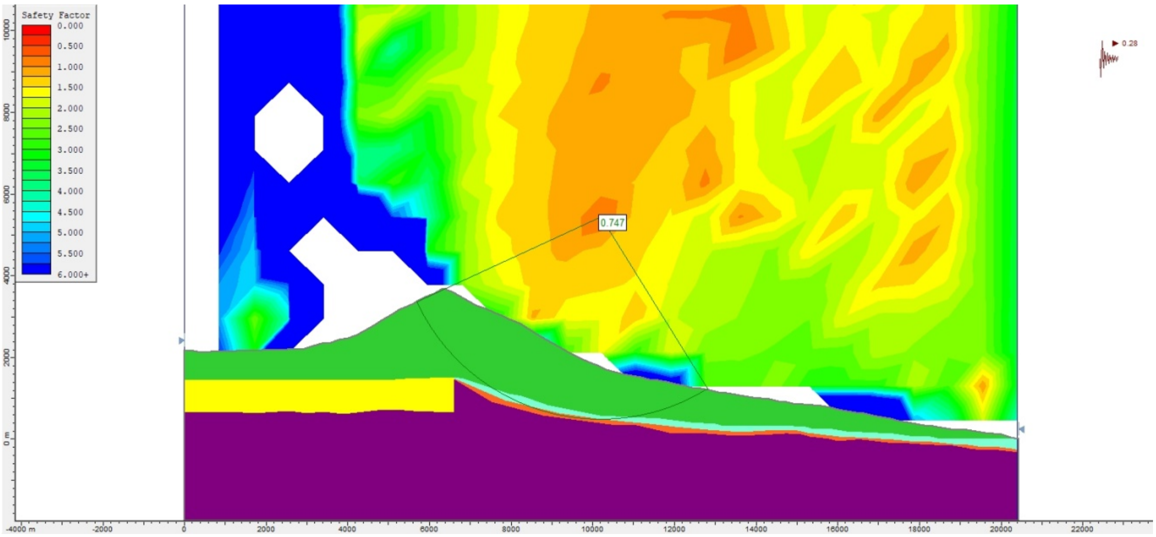

Figure S187. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.28.

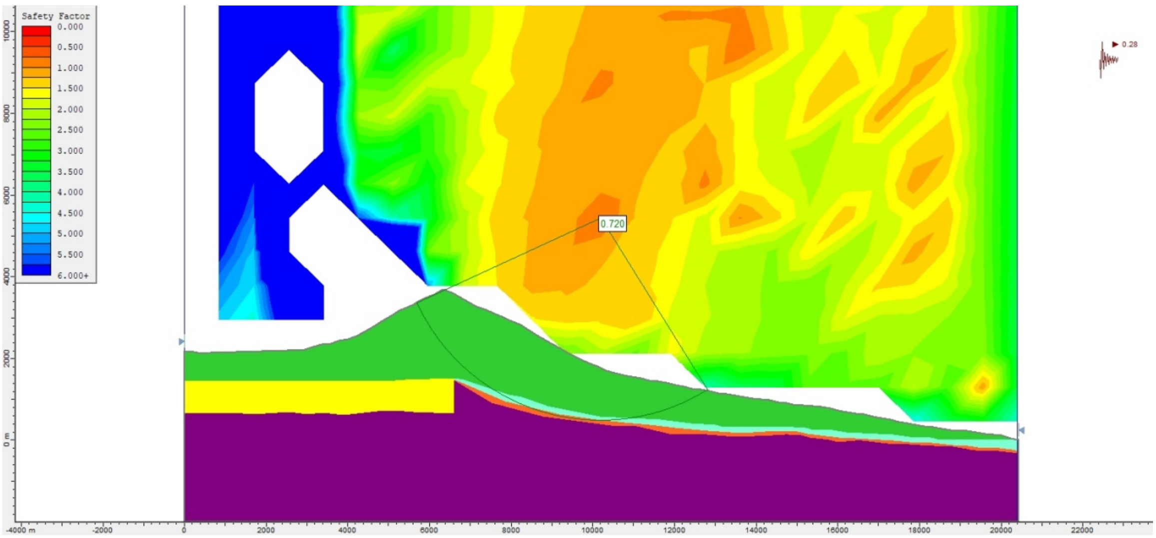

Figure S188. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.28.

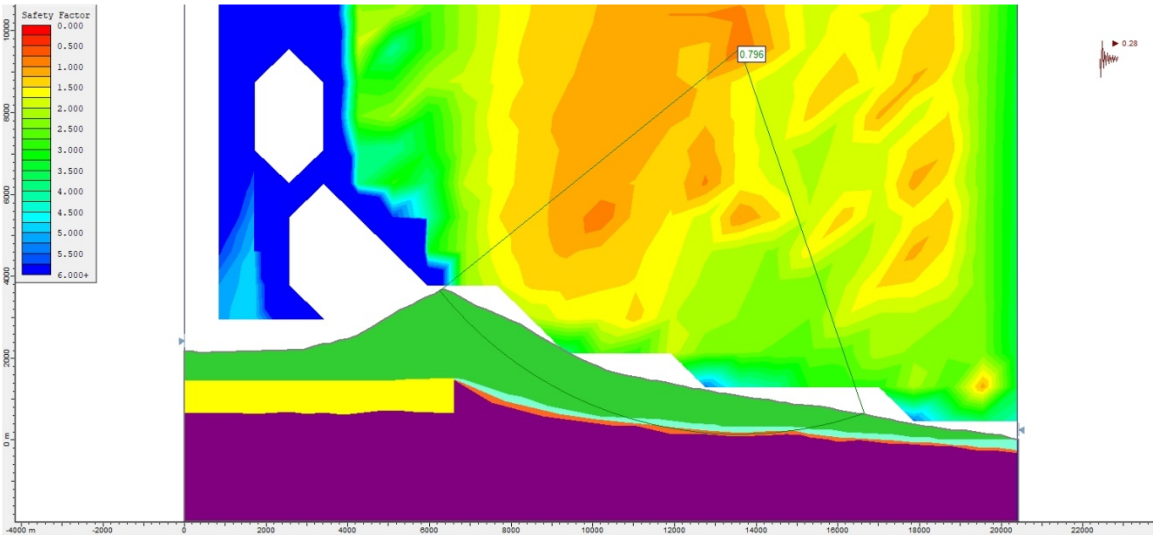

Figure S189. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.28.

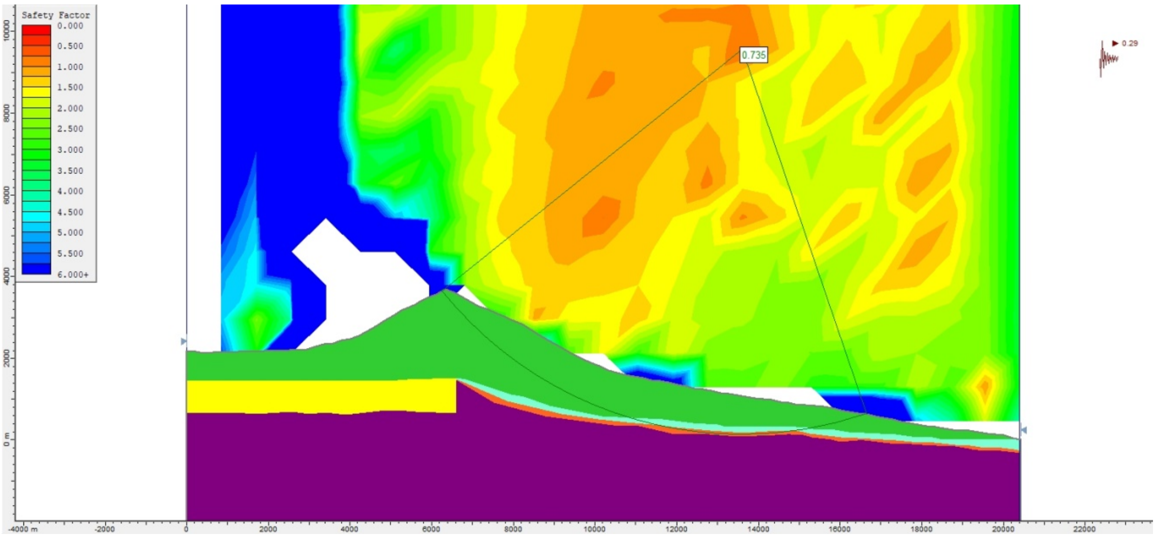

Figure S190. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.29.

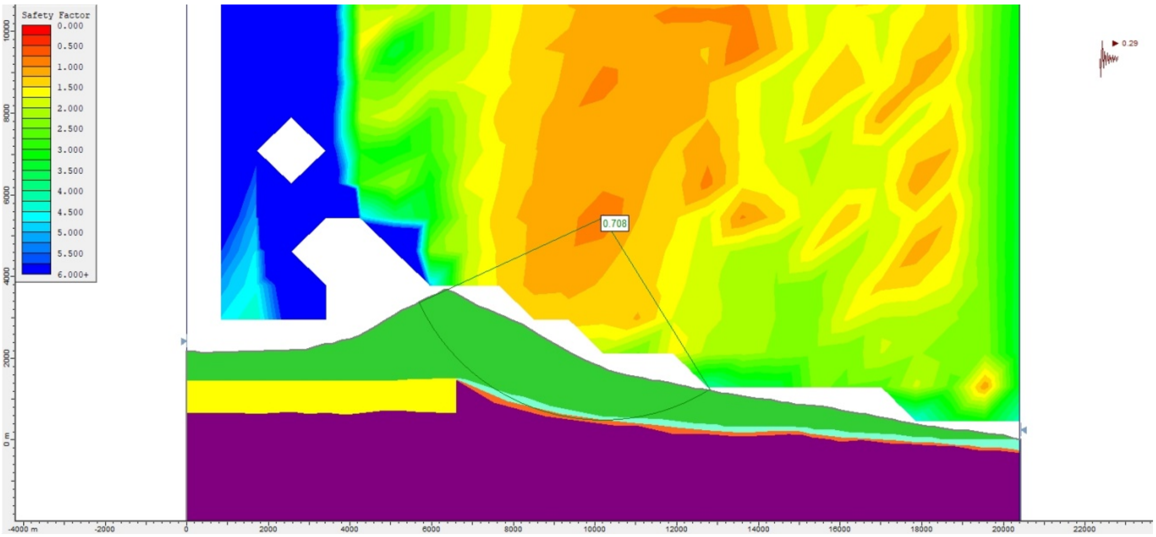

Figure S191. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.29.

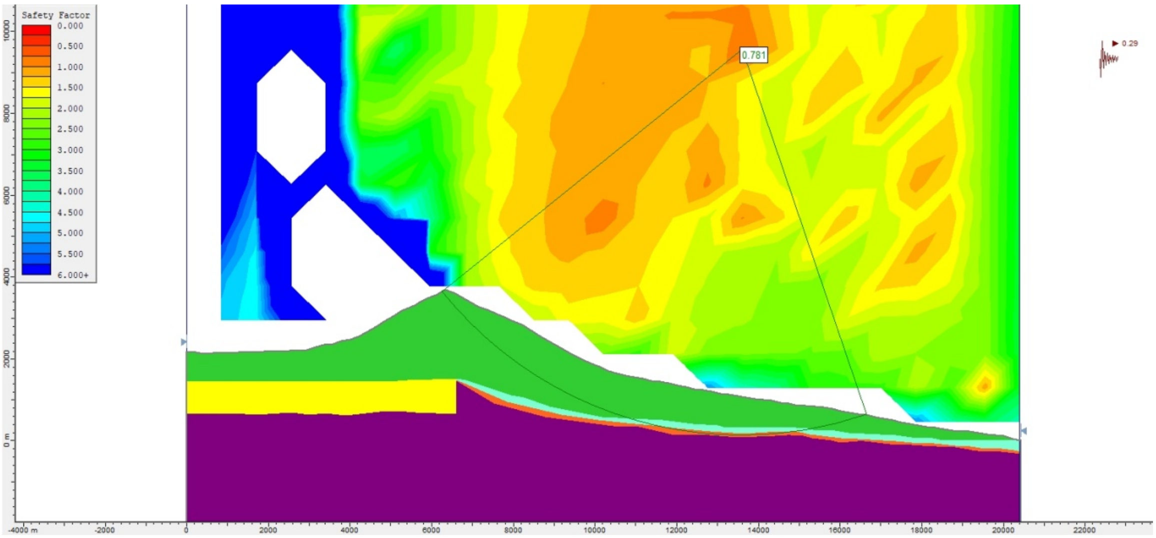

Figure S192. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.29.

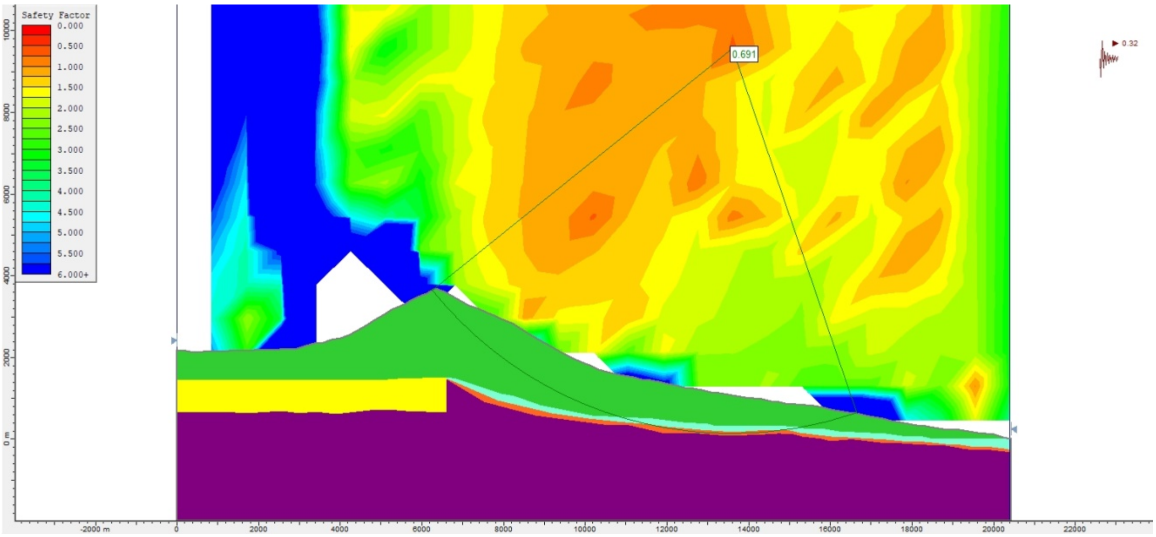

Figure S193. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.32.

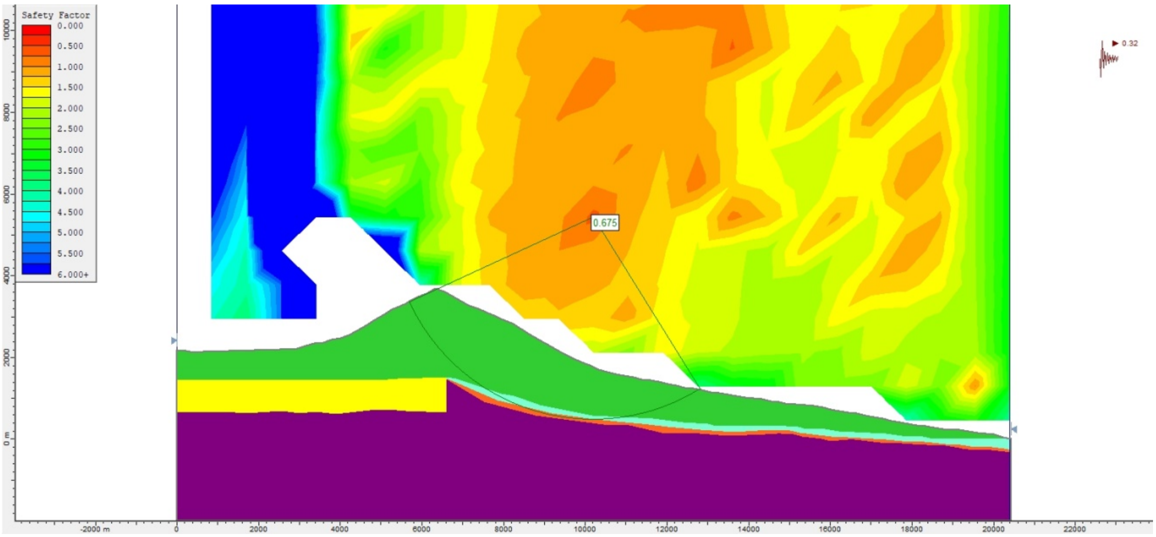

Figure S194. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.32.

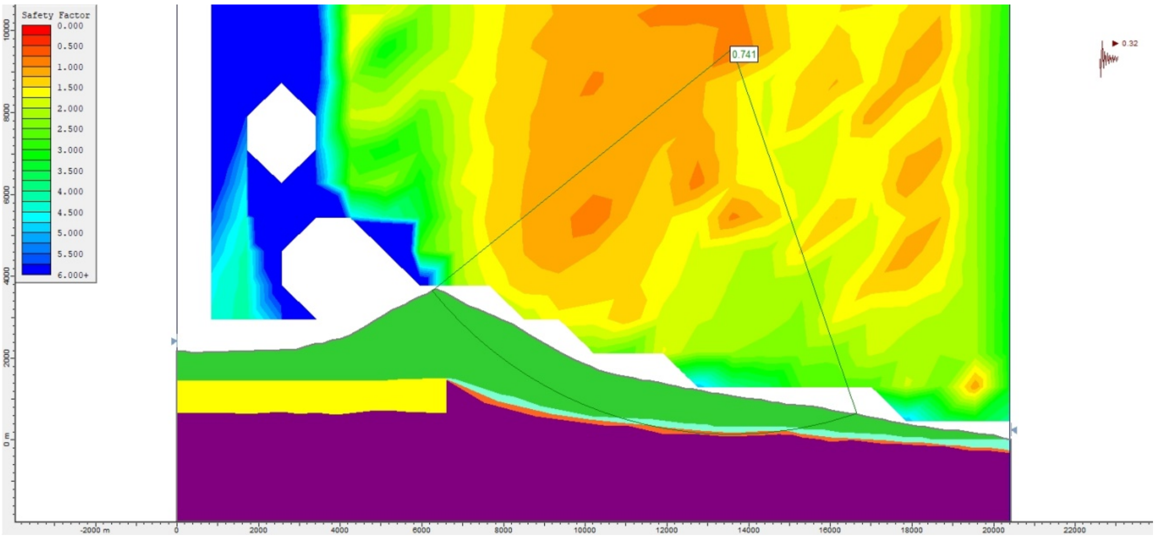

Figure S195. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.32.

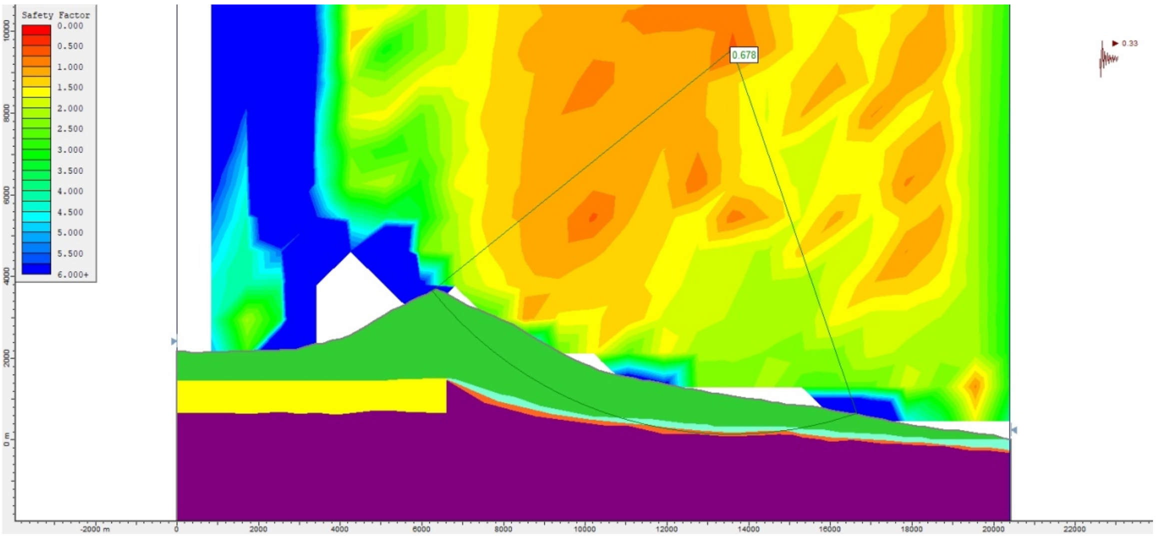

Figure S196. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.33.

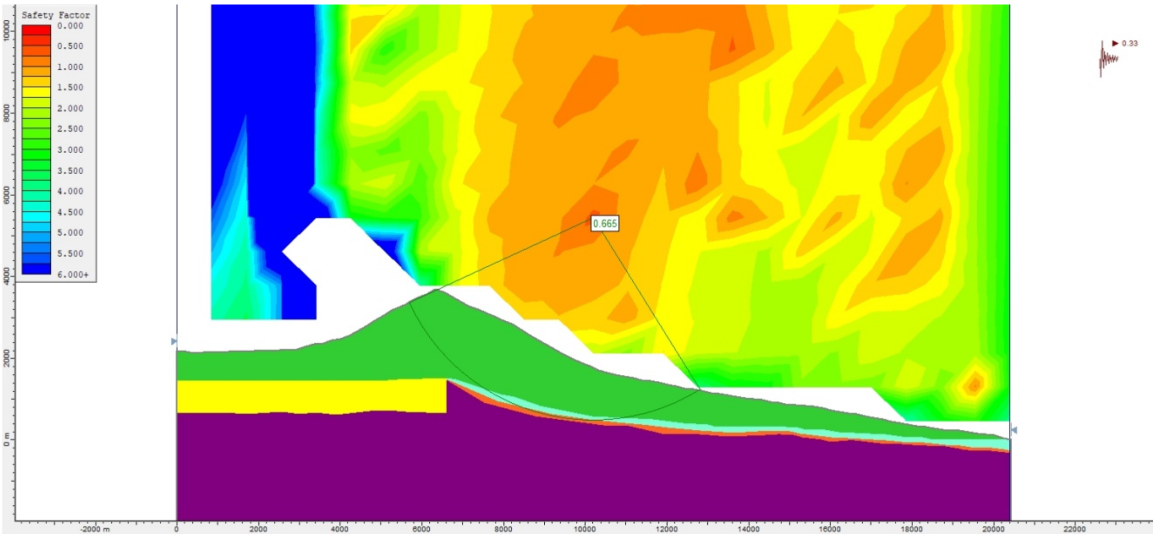

Figure S197. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.33.

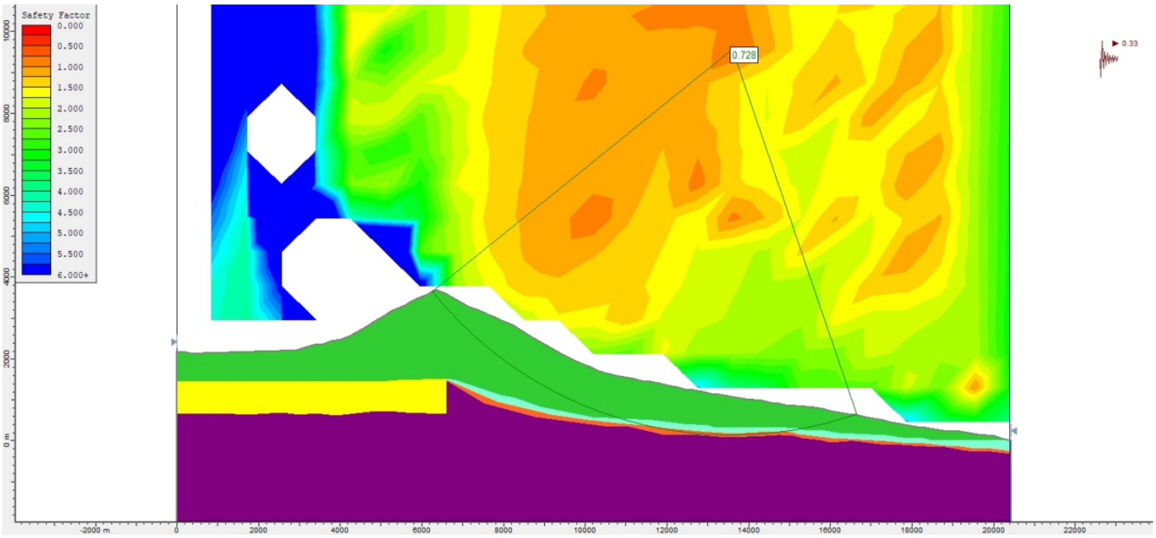

Figure S198. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.33.

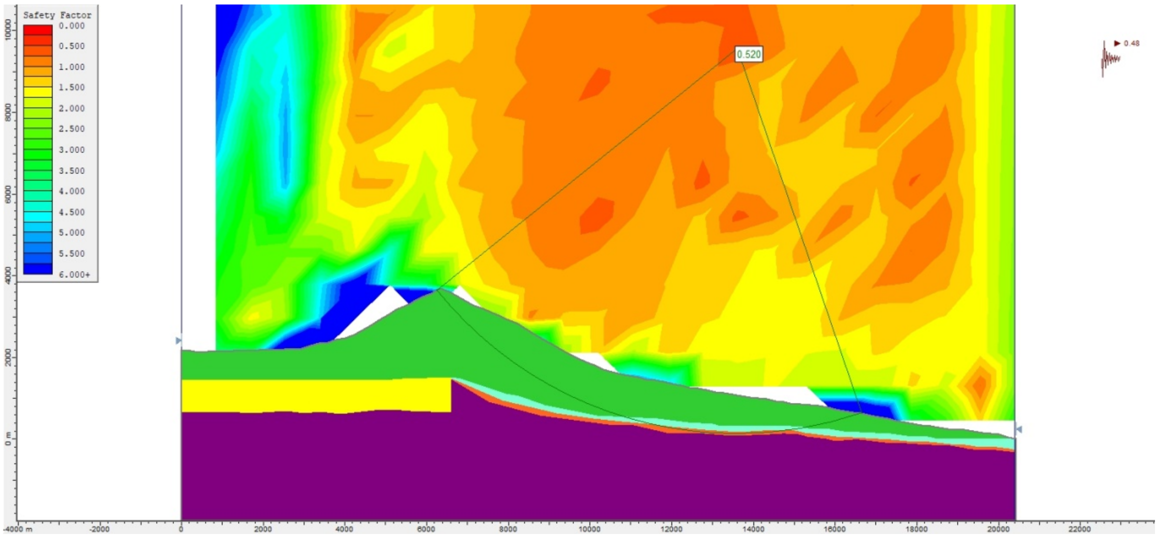

Figure S199. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.48.

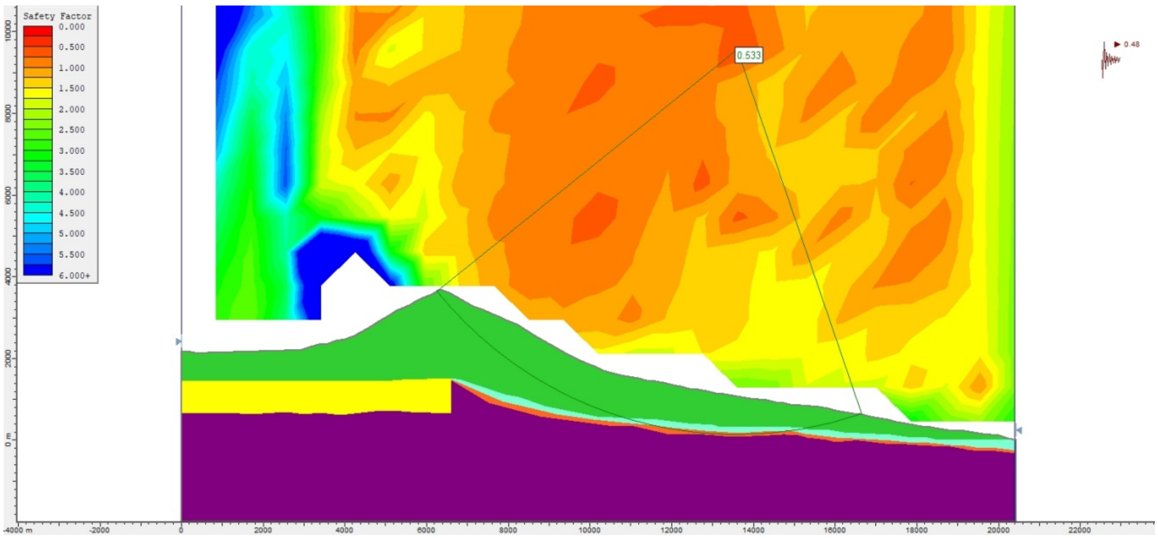

Figure S200. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.48.

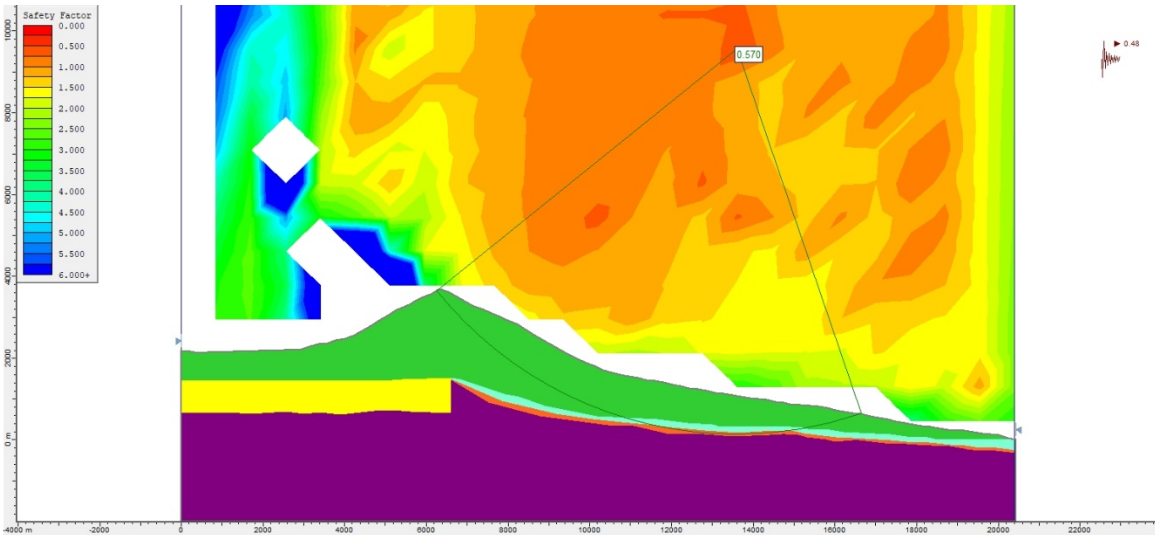

Figure S201. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.48.

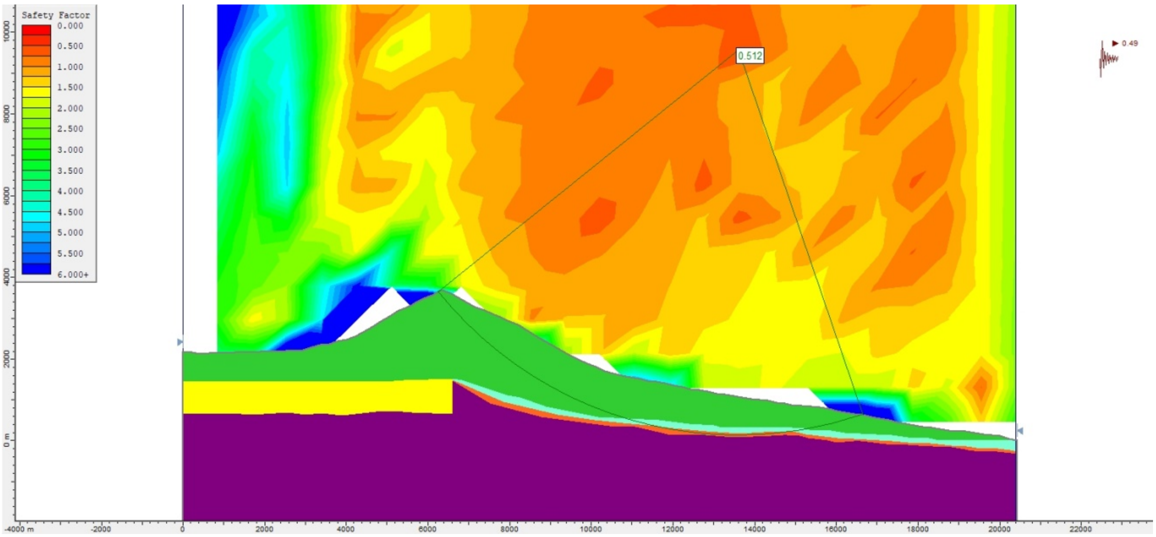

Figure S202. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 0.49.

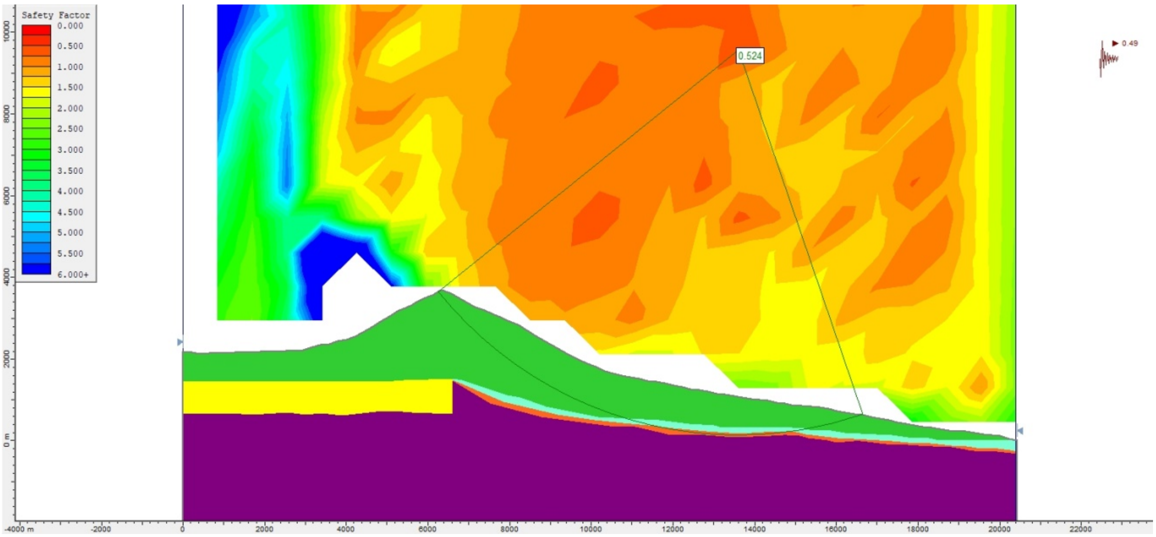

Figure S203. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 0.49.

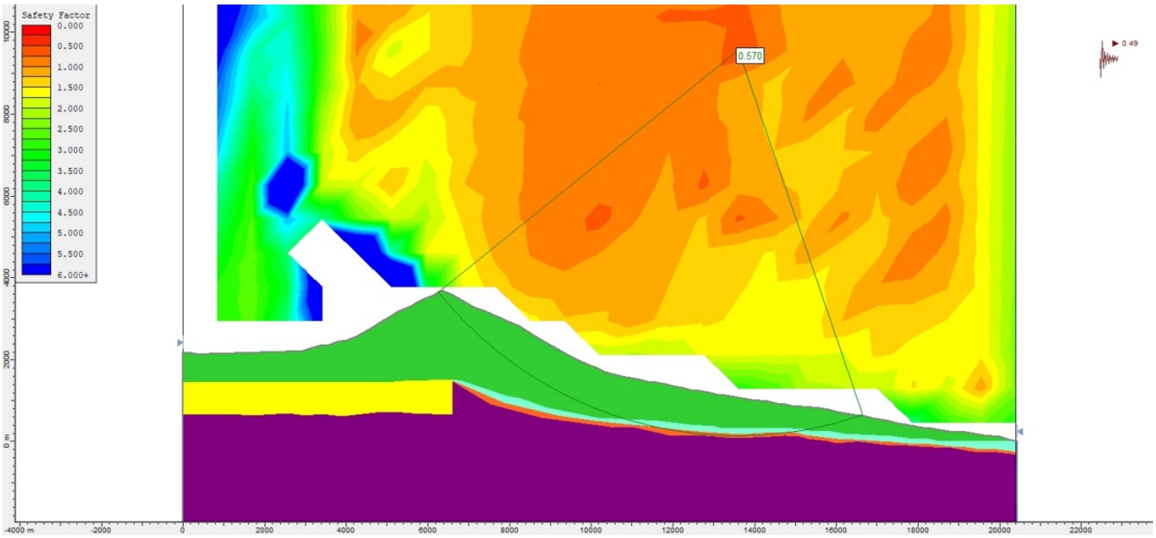

Figure S204. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 0.49.

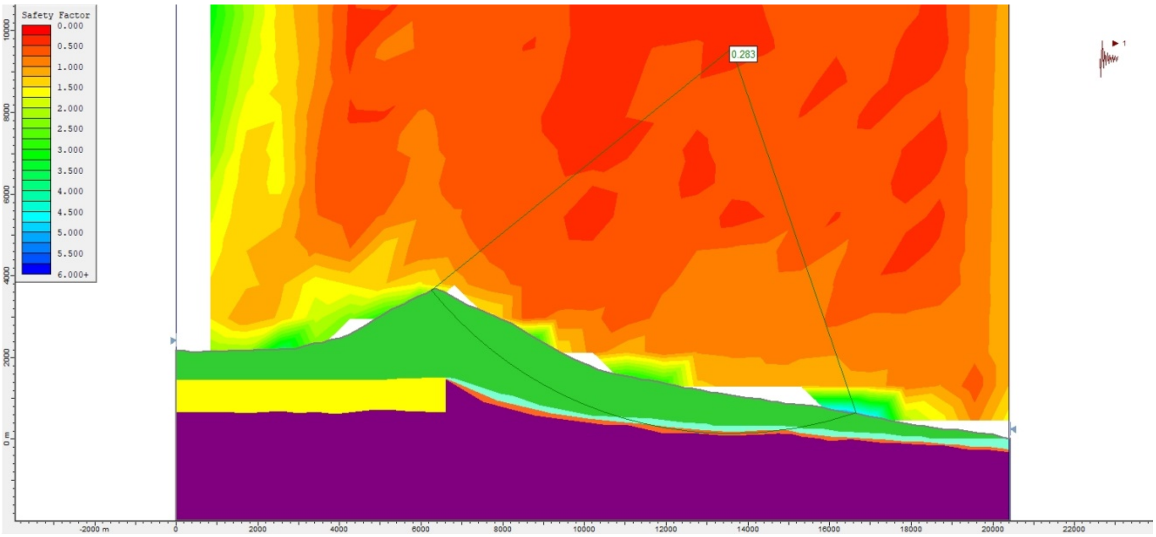

Figure S205. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 1.00.

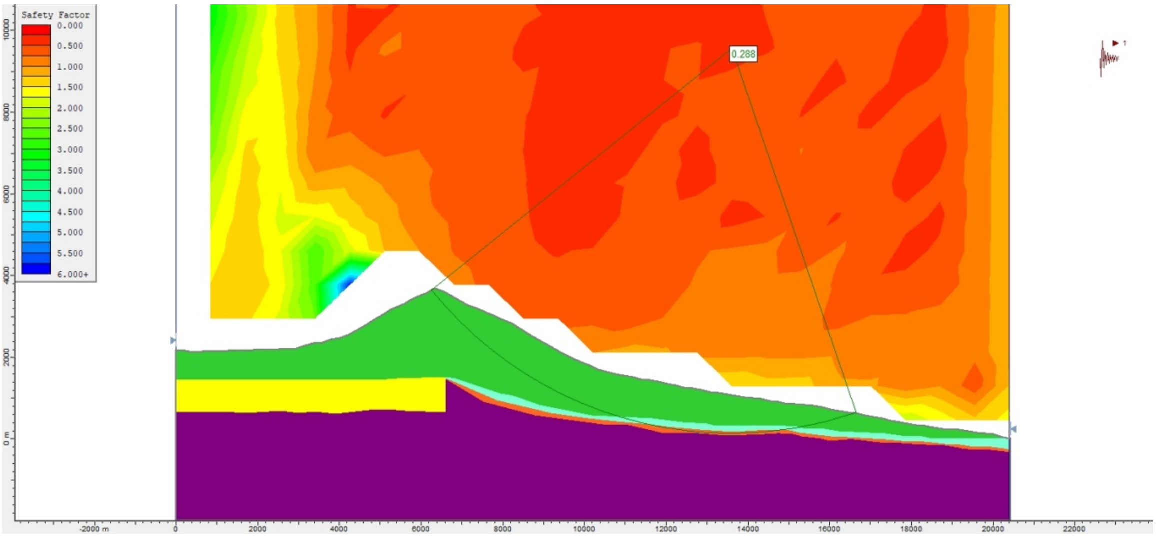

Figure S206. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 1.00.

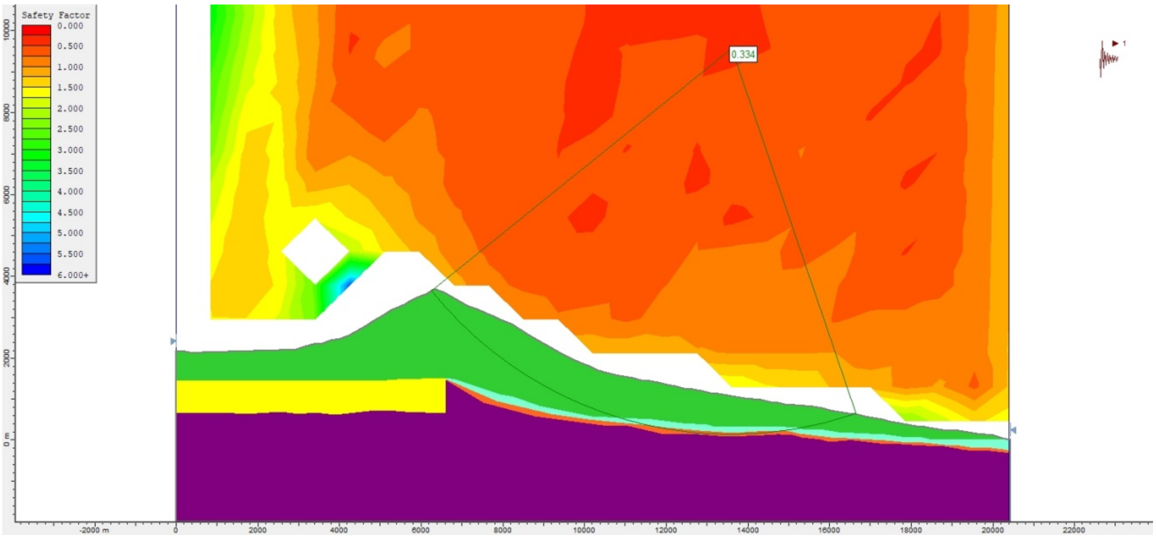

Figure S207. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 1.00.

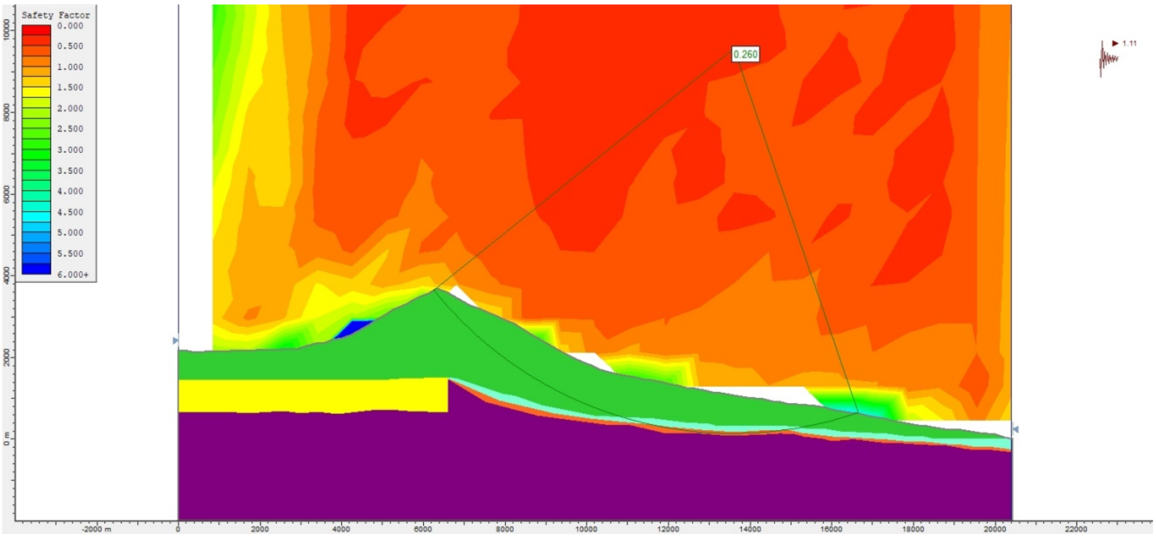

Figure S208. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Bishop simplified method and a k_h = 1.11.

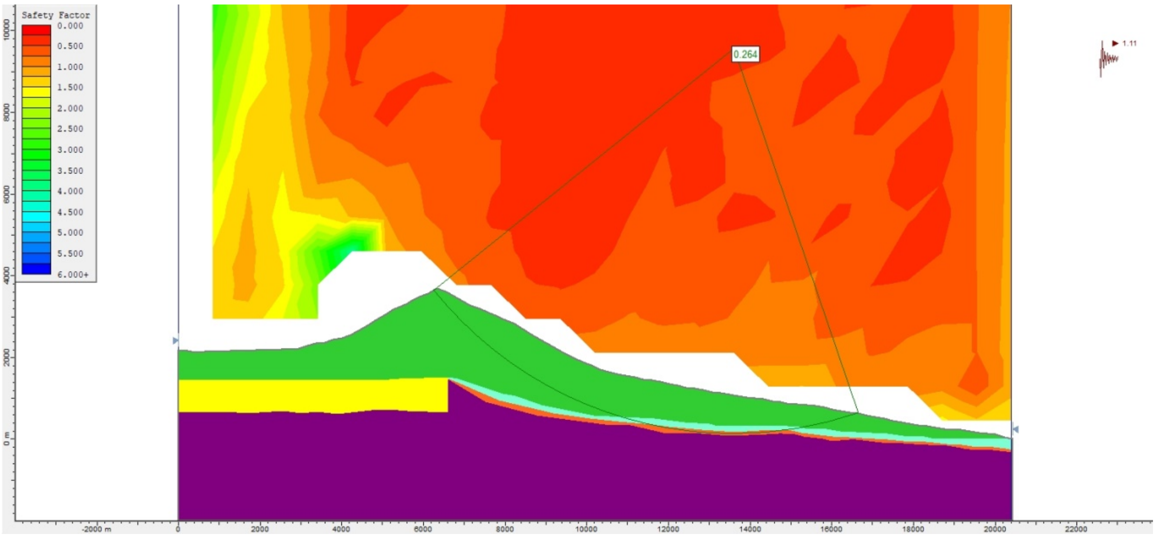

Figure S209. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Janbu Generalised method and a k_h = 1.11.

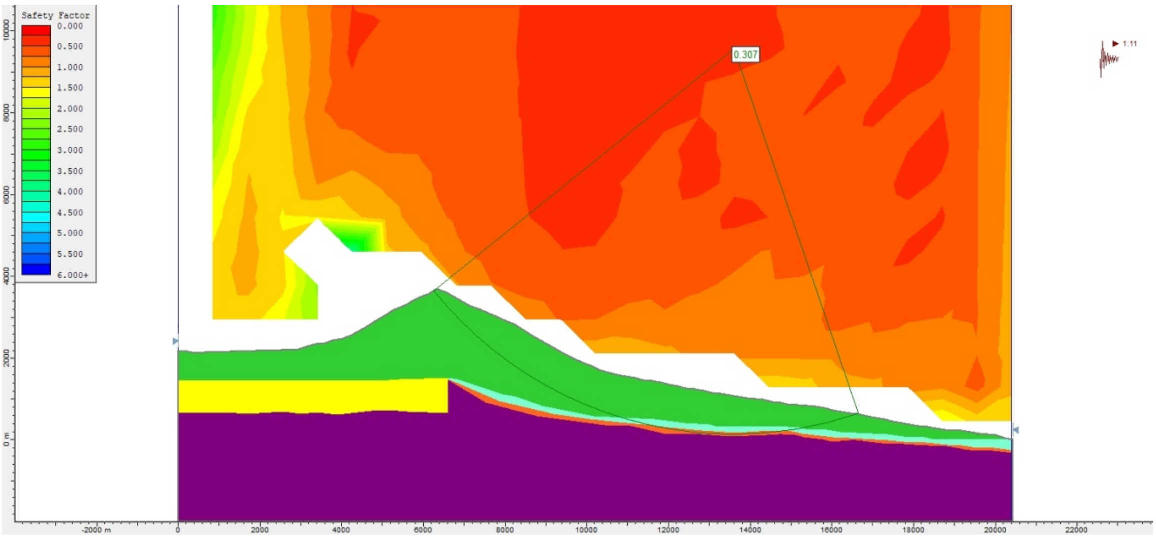

Figure S210. Slope stability pseudo-static analysis for Model 2 (without alteration zones, Figure 4b), using the Morgenstern-Price method and a k_h = 1.11.

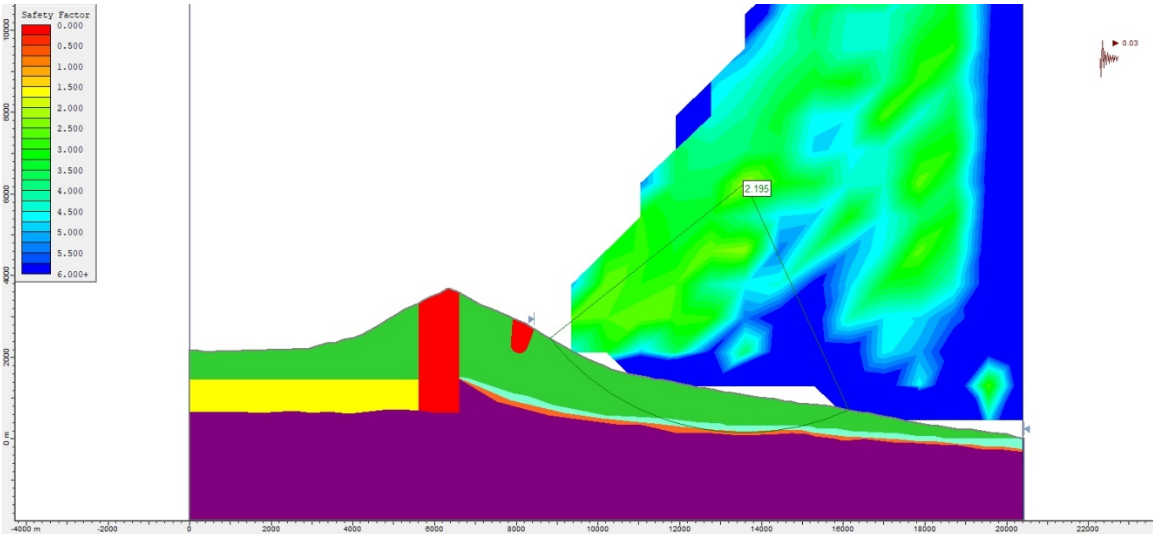

Figure S211. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.03.

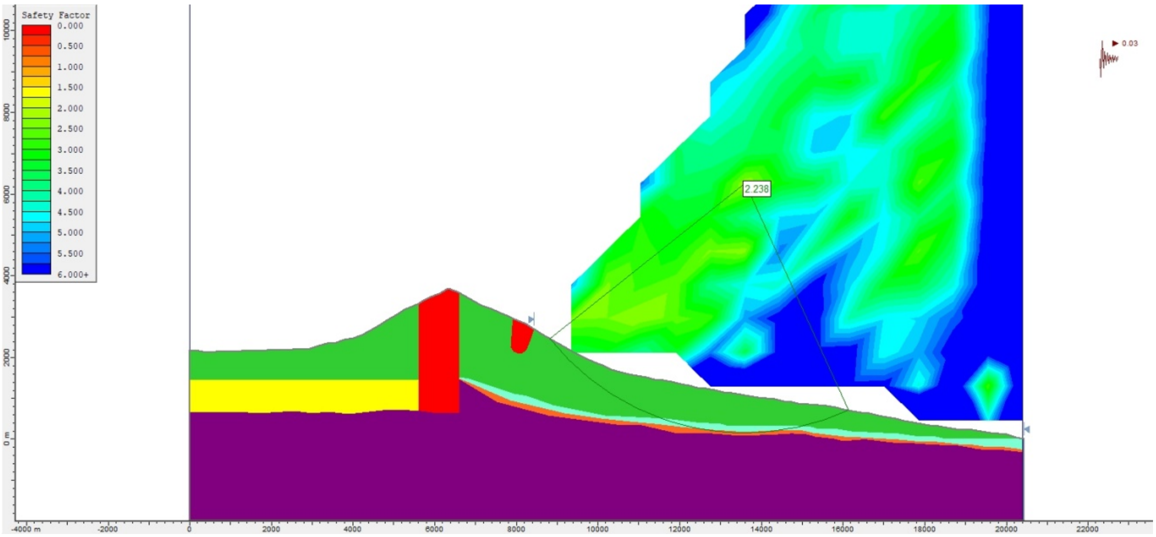

Figure S212. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.03.

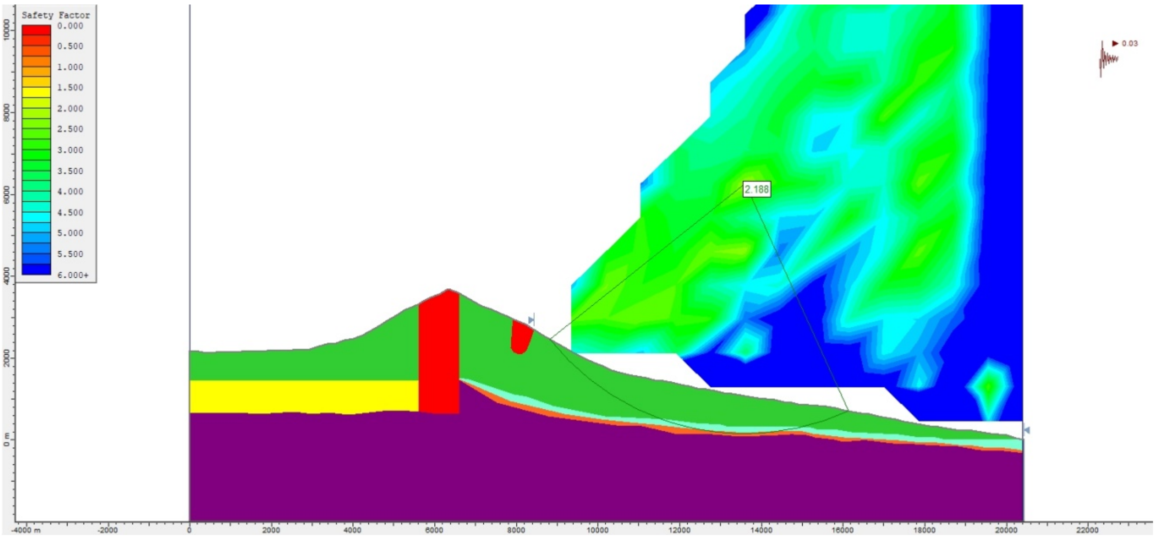

Figure S213. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.03.

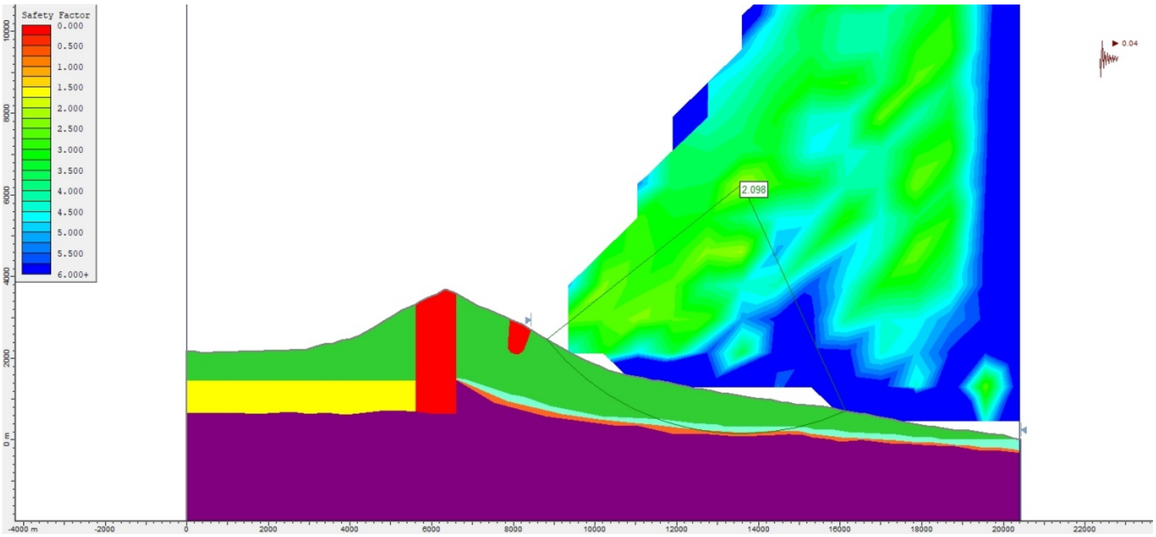

Figure S214. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.04.

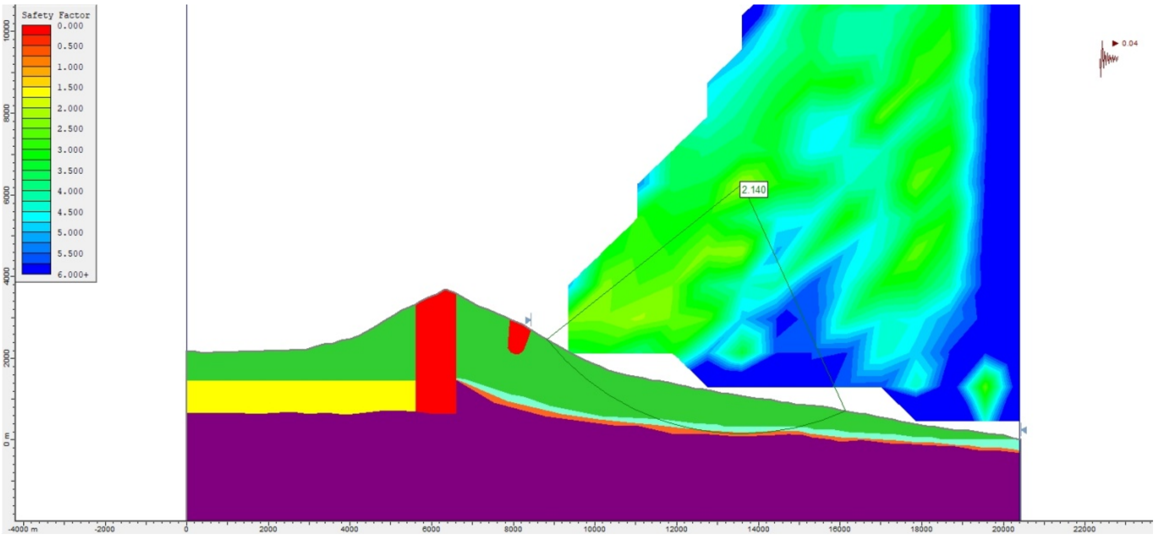

Figure S215. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.04.

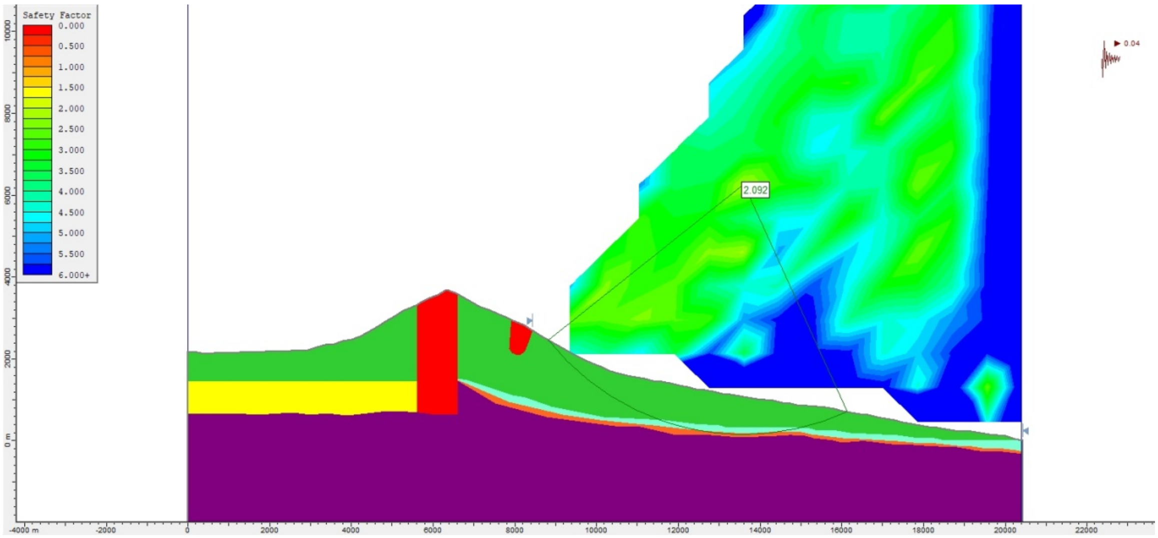

Figure S216. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.04.

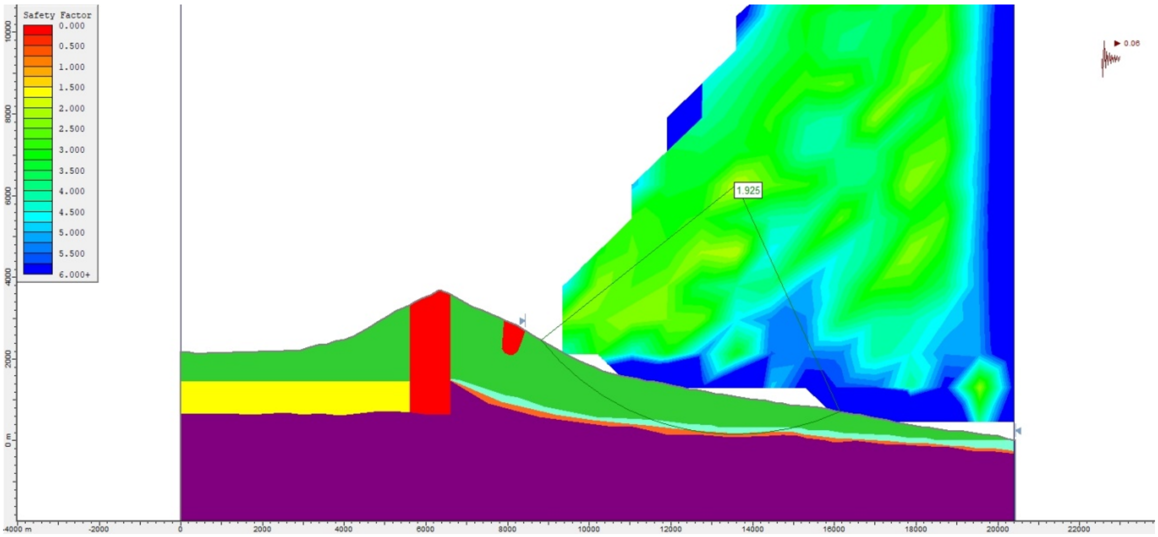

Figure S217. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.06.

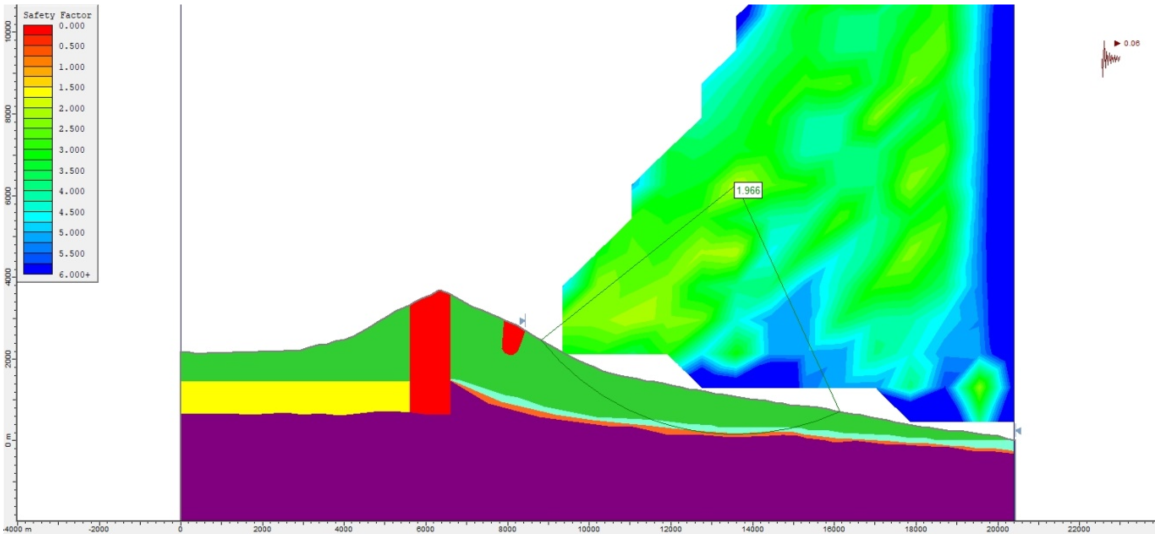

Figure S218. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.06.

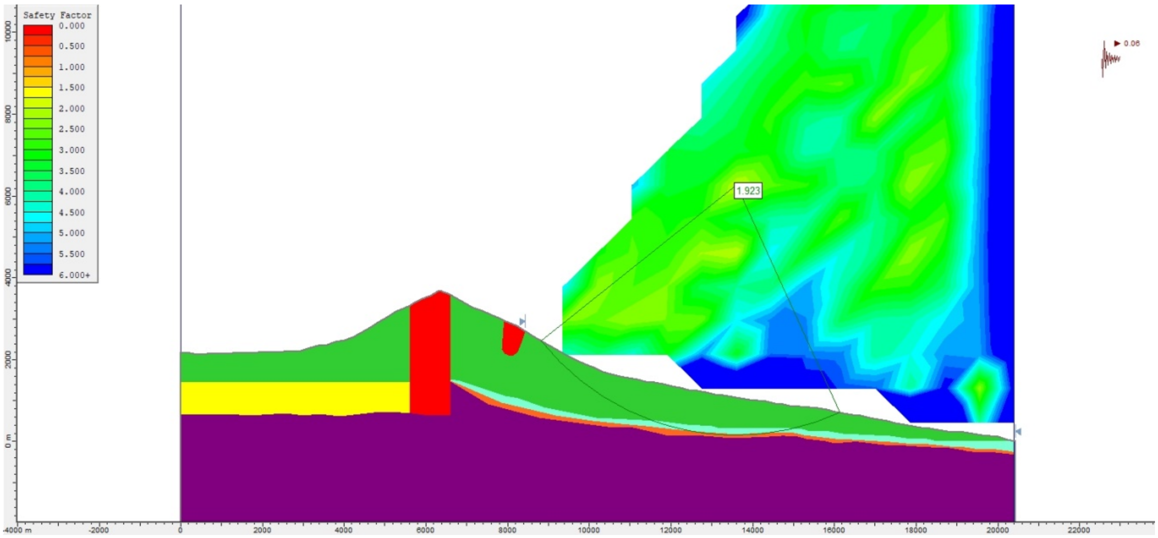

Figure S219. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.06.

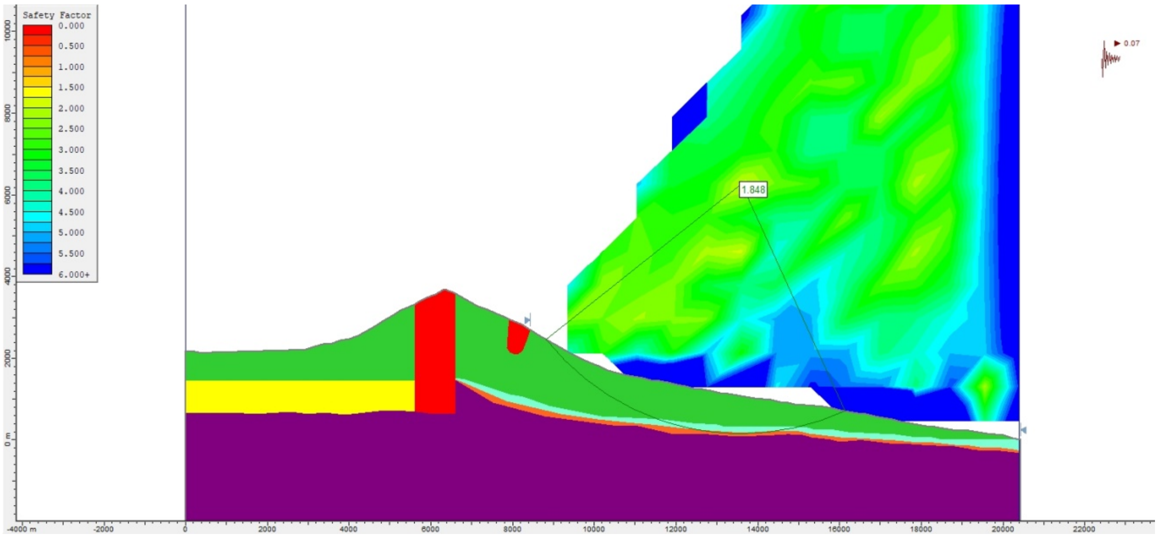

Figure S220. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.07.

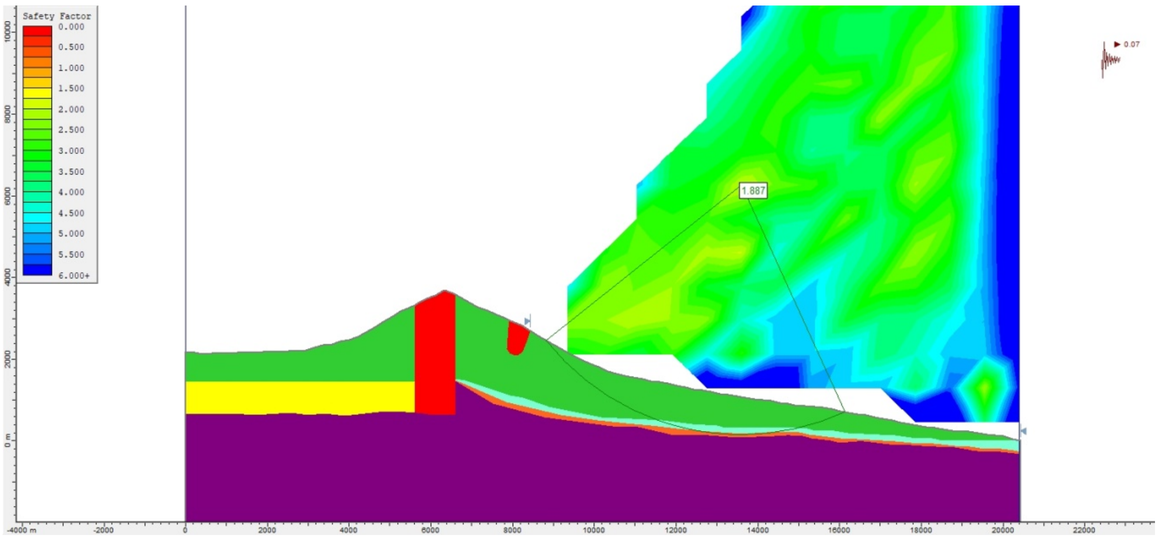

Figure S221. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.07.

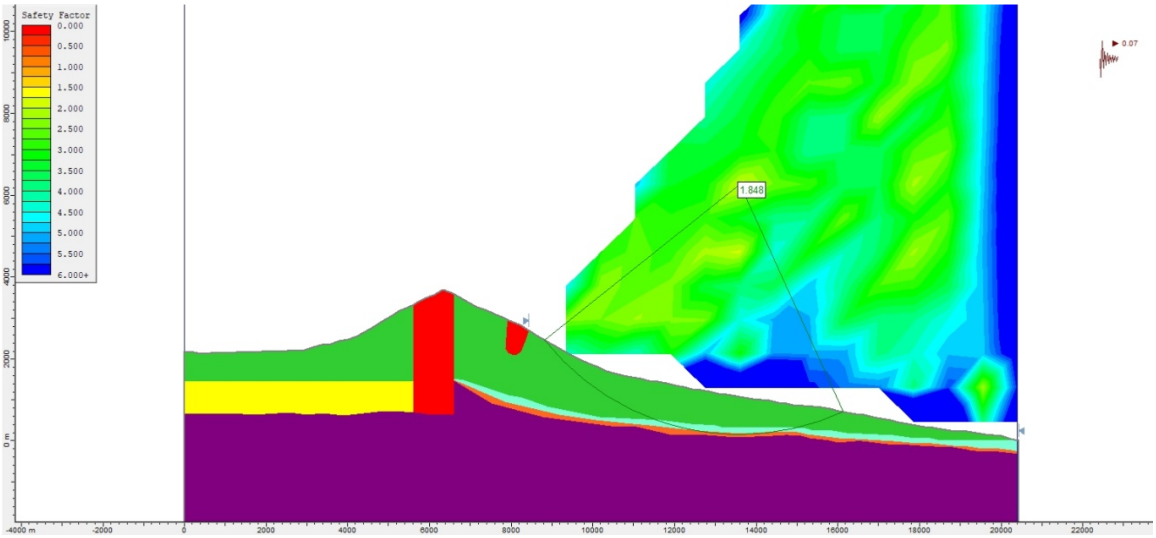

Figure S222. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.07.

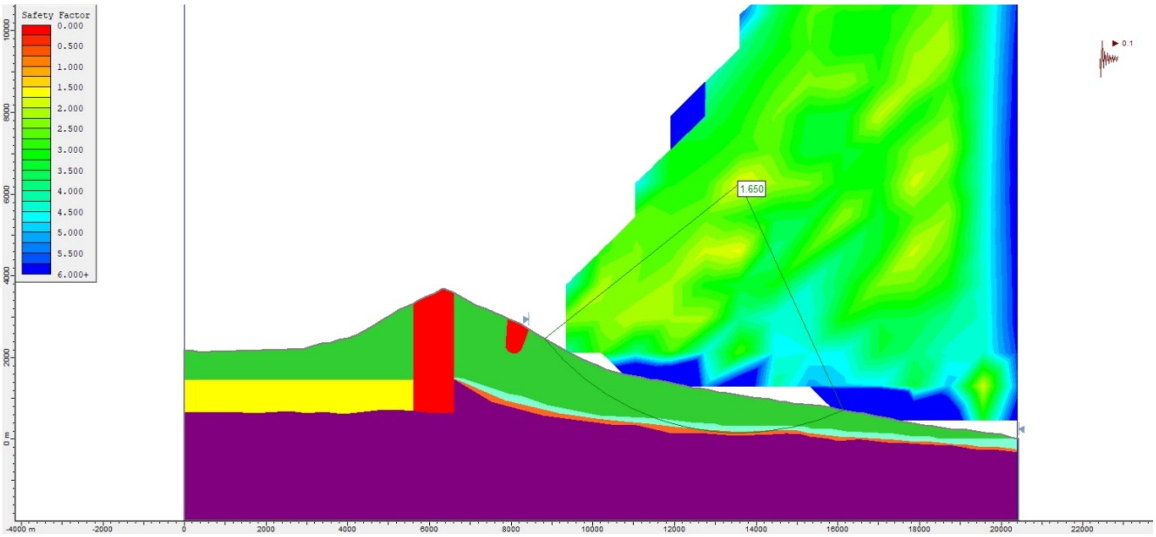

Figure S223. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.10.

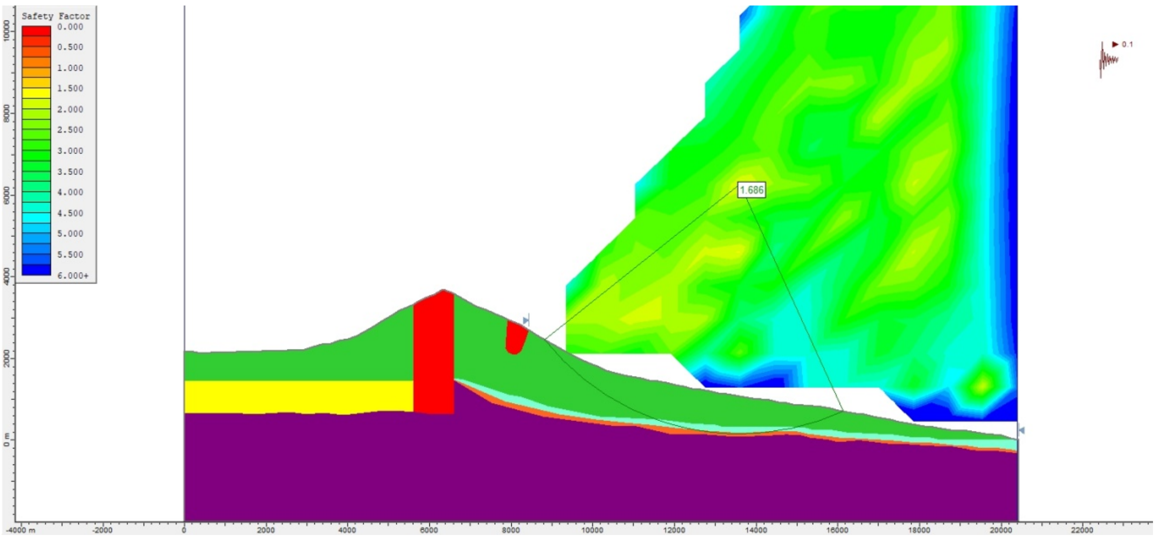

Figure S224. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.10.

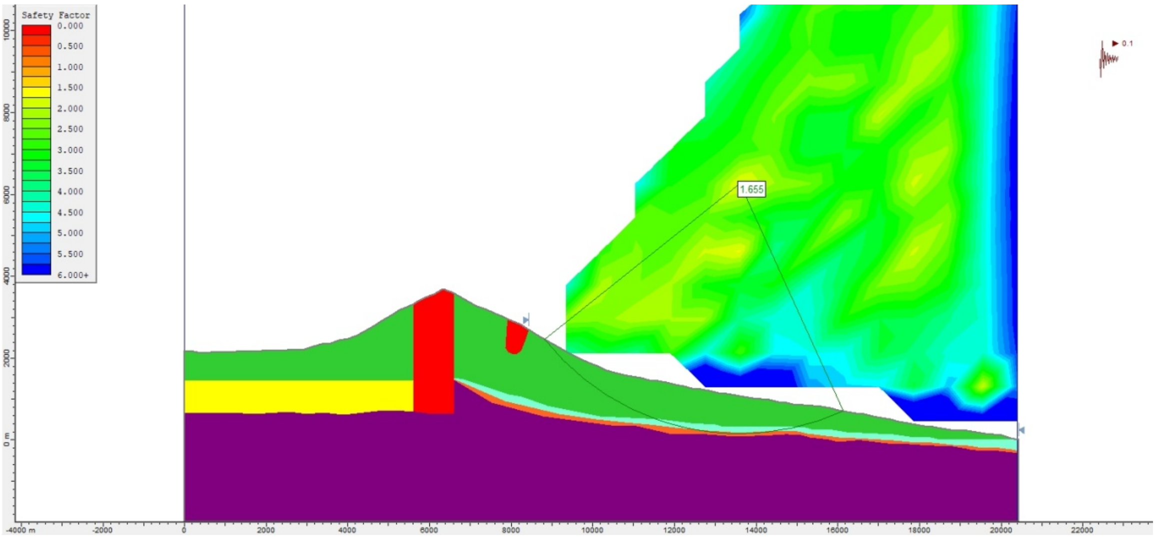

Figure S225. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.10.

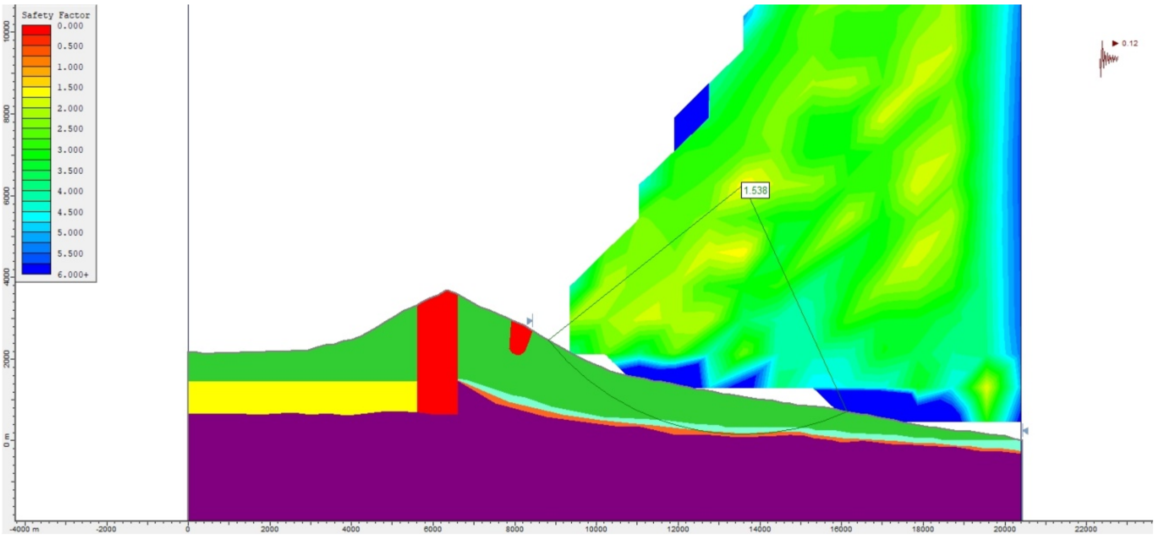

Figure S226. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.12.

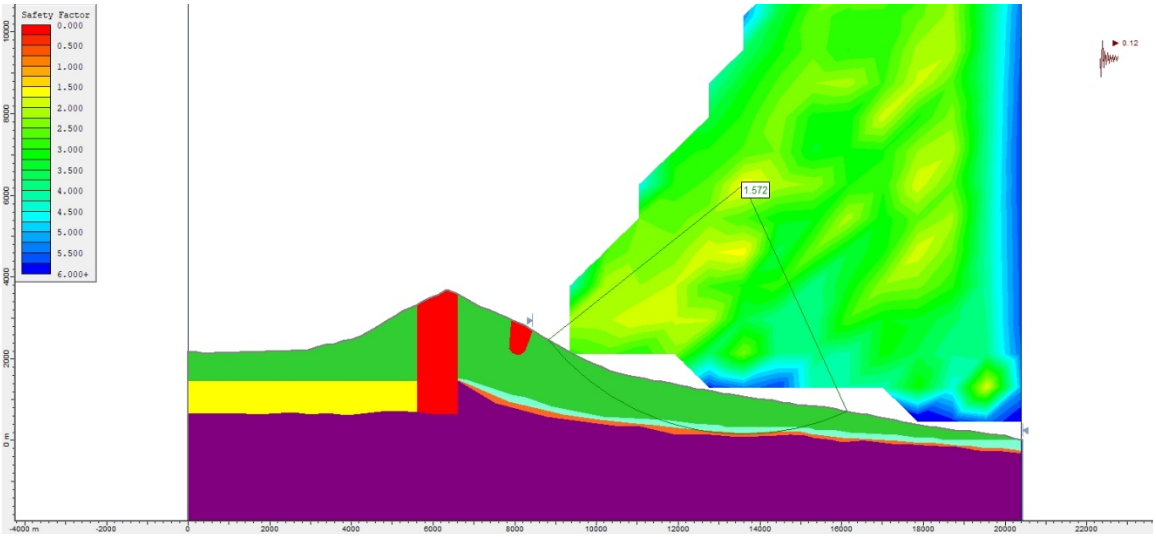

Figure S227. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.12.

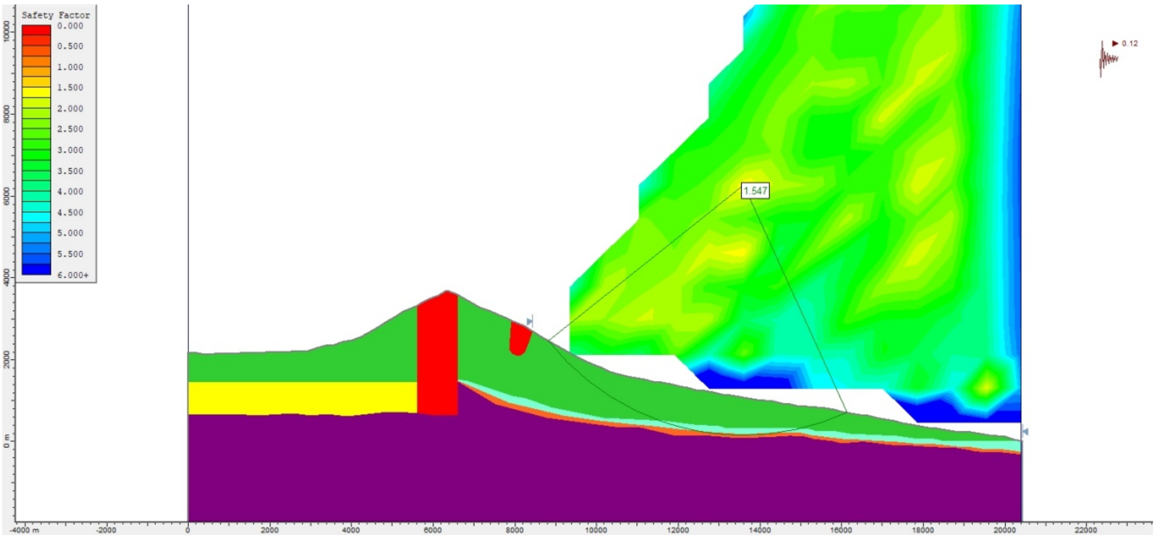

Figure S228. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.12.

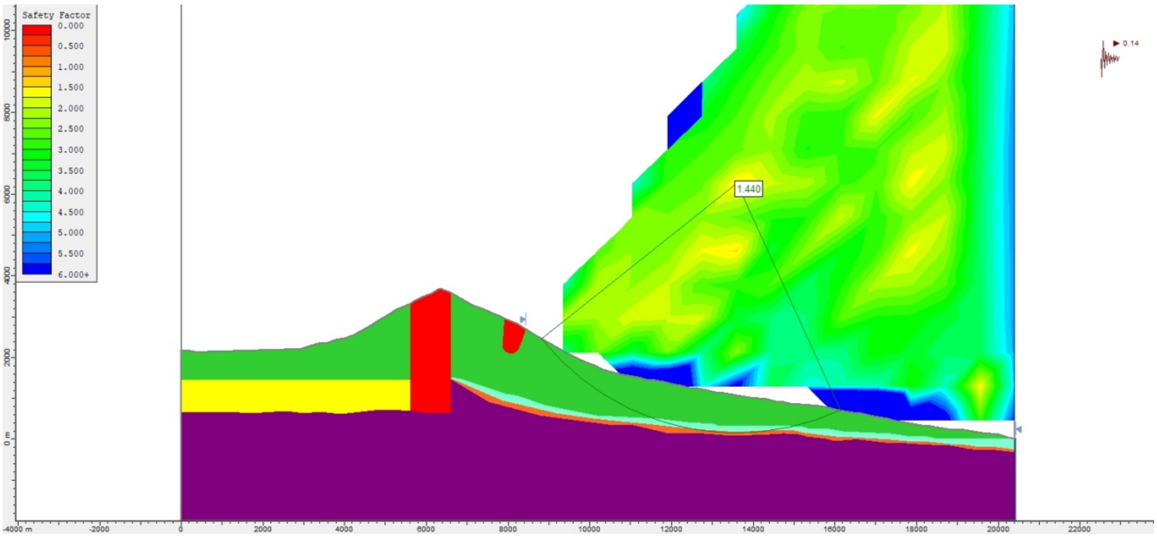

Figure S229. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.14.

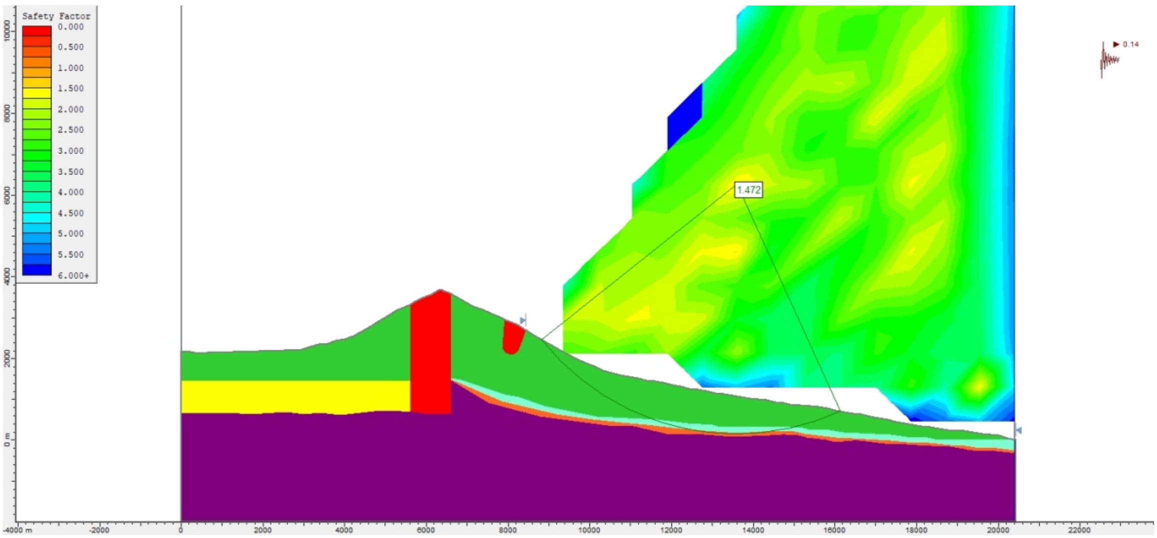

Figure S230. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.14.

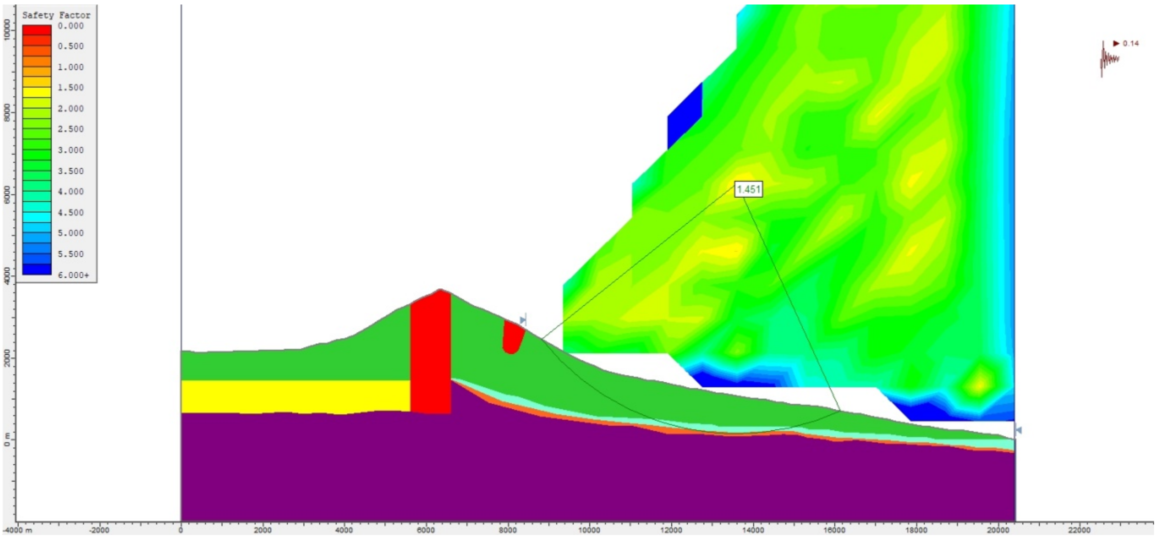

Figure S231. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.14.

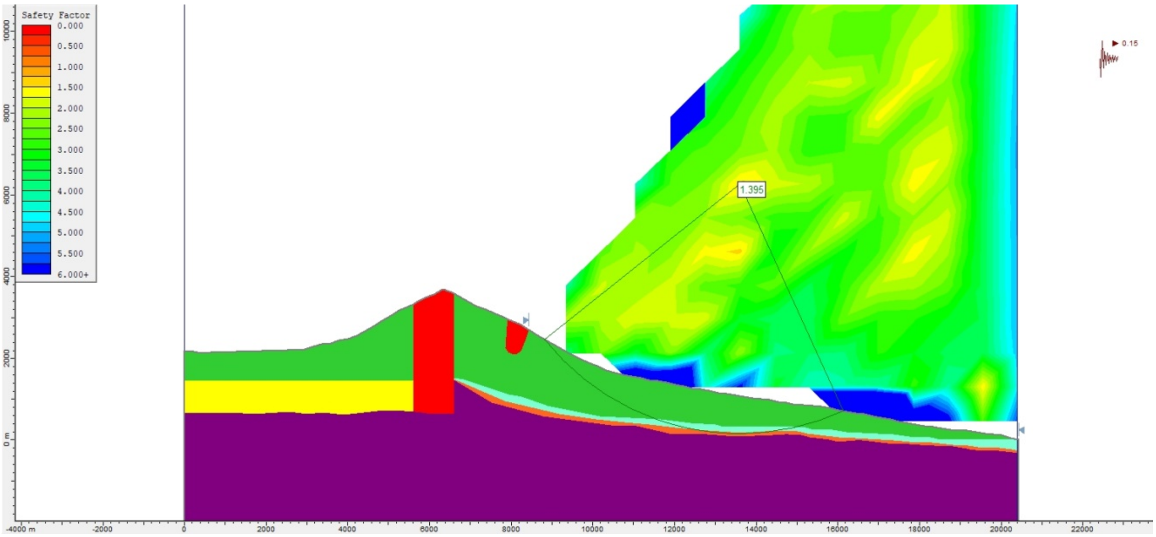

Figure S232. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.15.

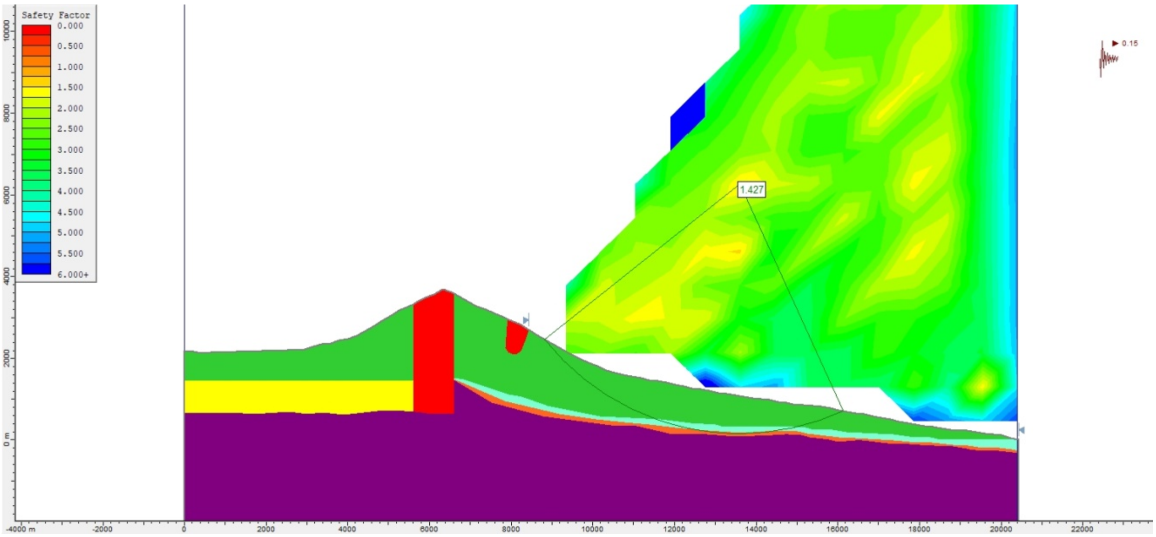

Figure S233. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.15.

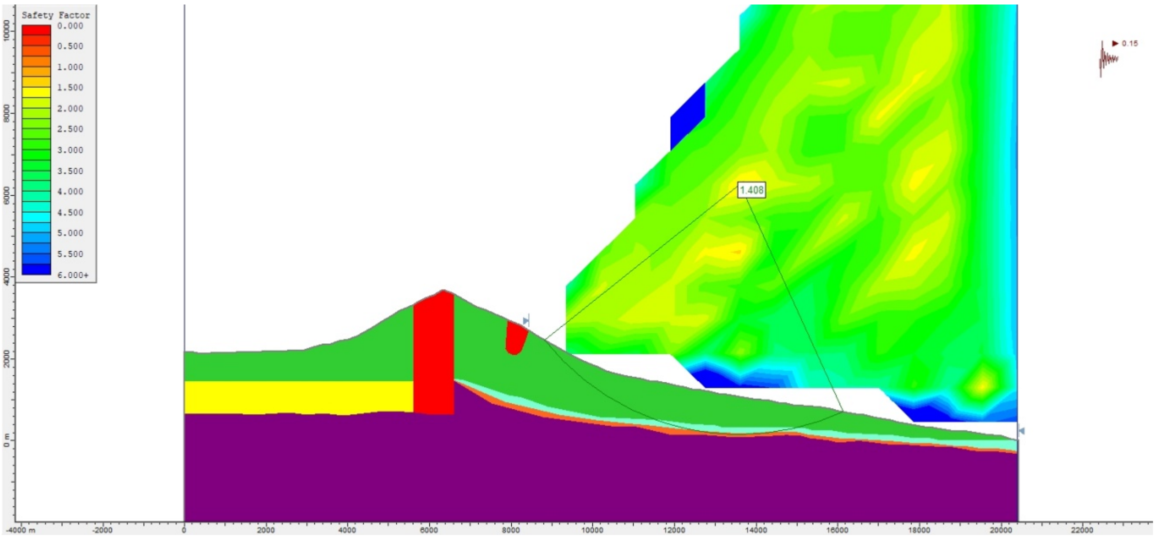

Figure S234. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.15.

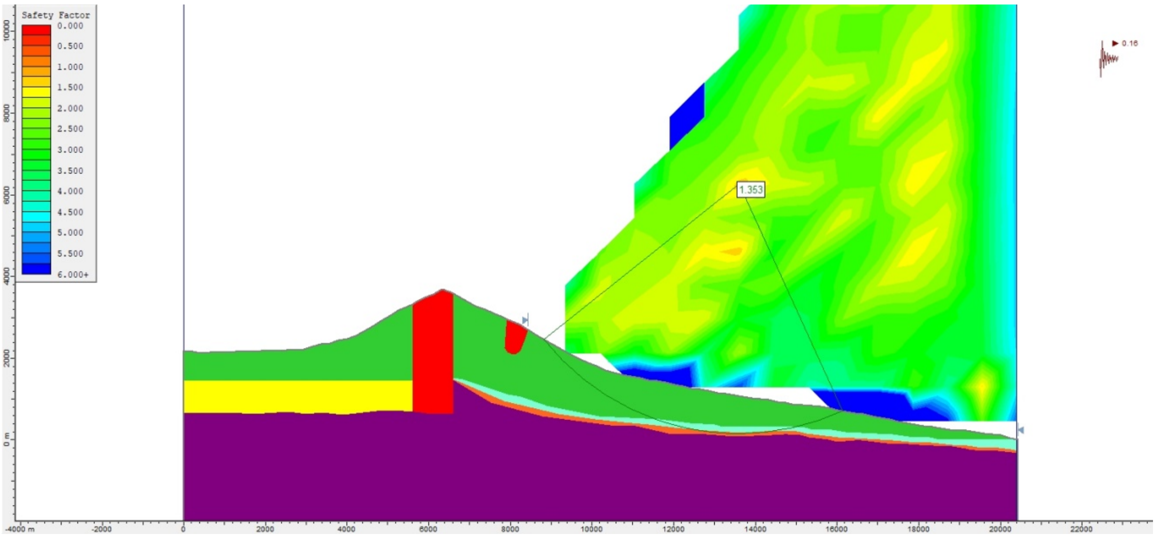

Figure S235. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.16.

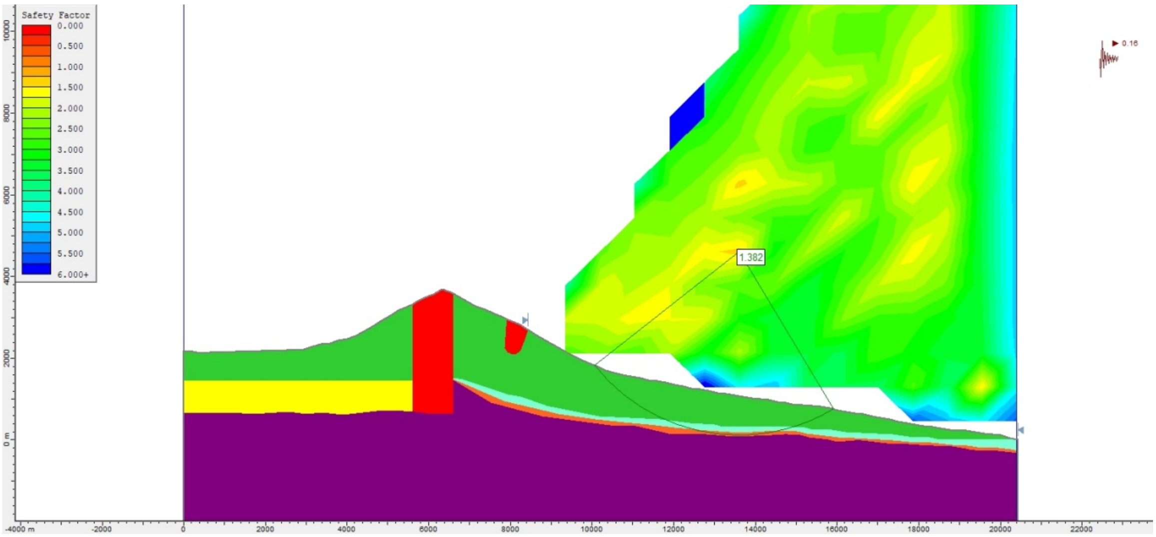

Figure S236. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.16.

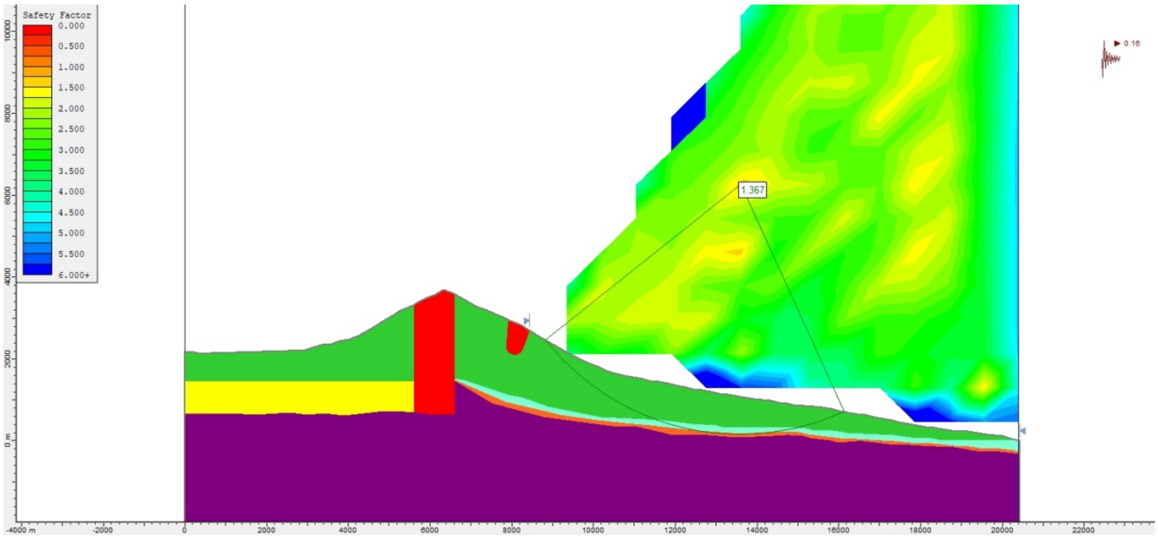

Figure S237. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.16.

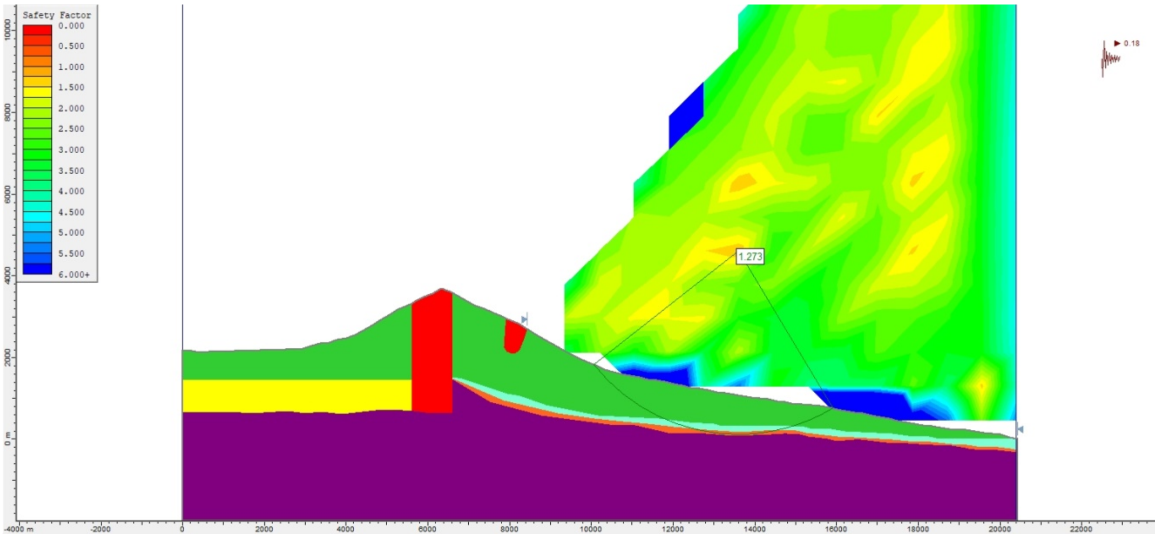

Figure S238. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.18.

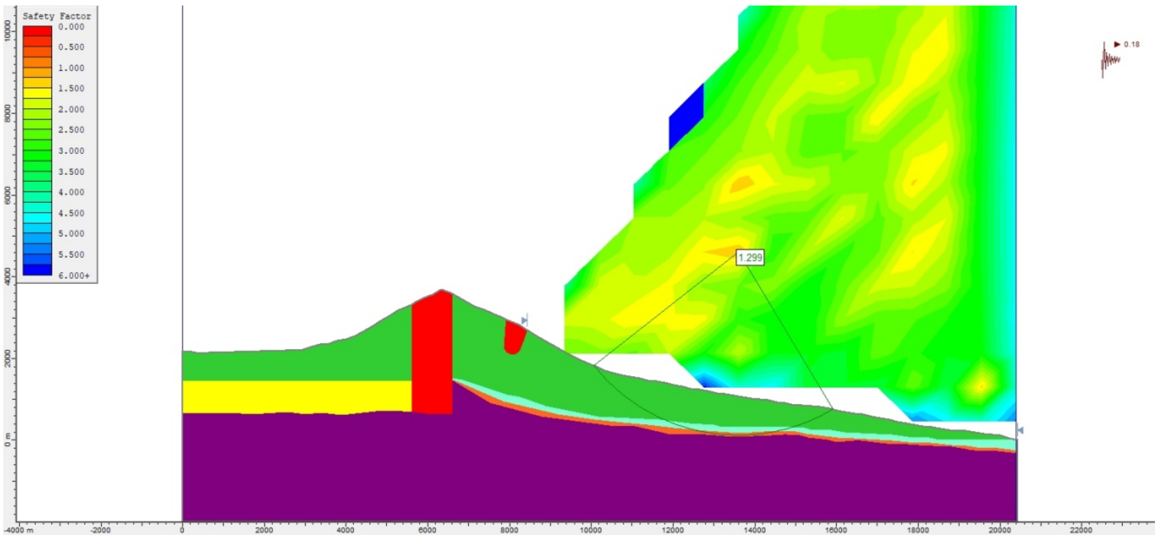

Figure S239. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.18.

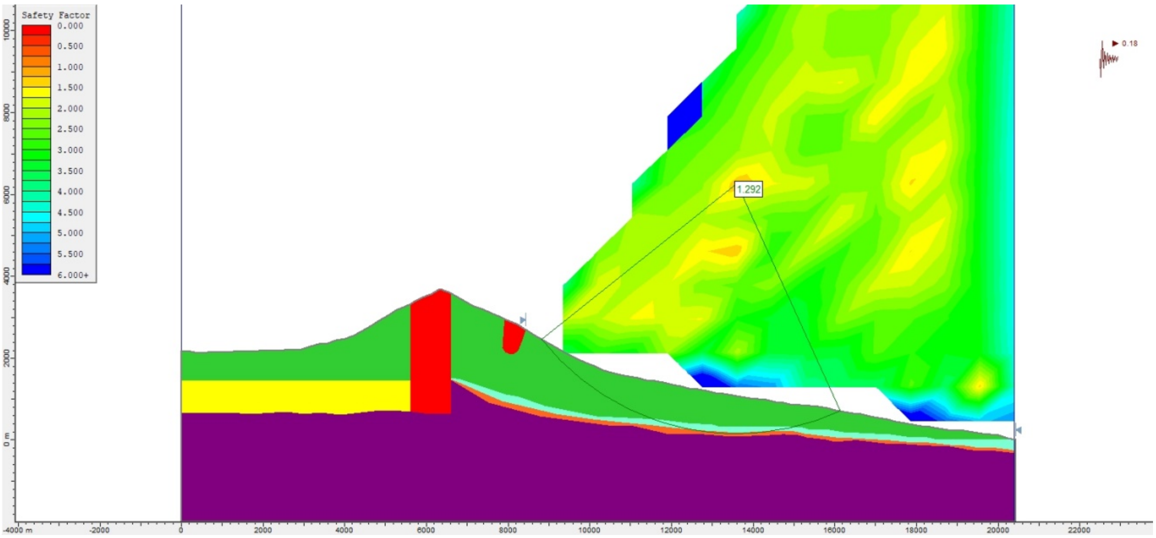

Figure S240. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.18.

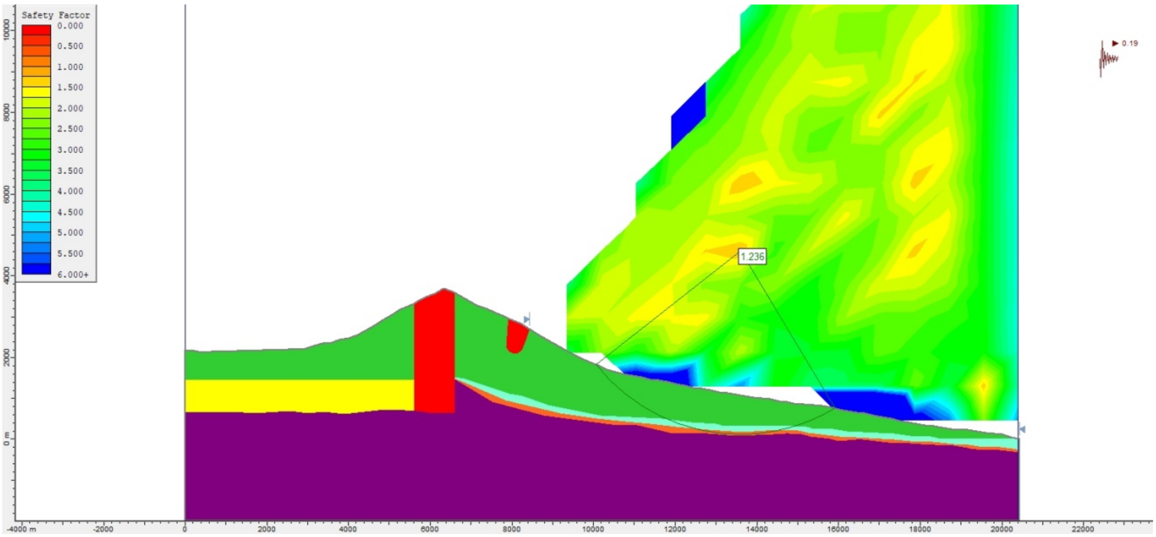

Figure S241. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.19.

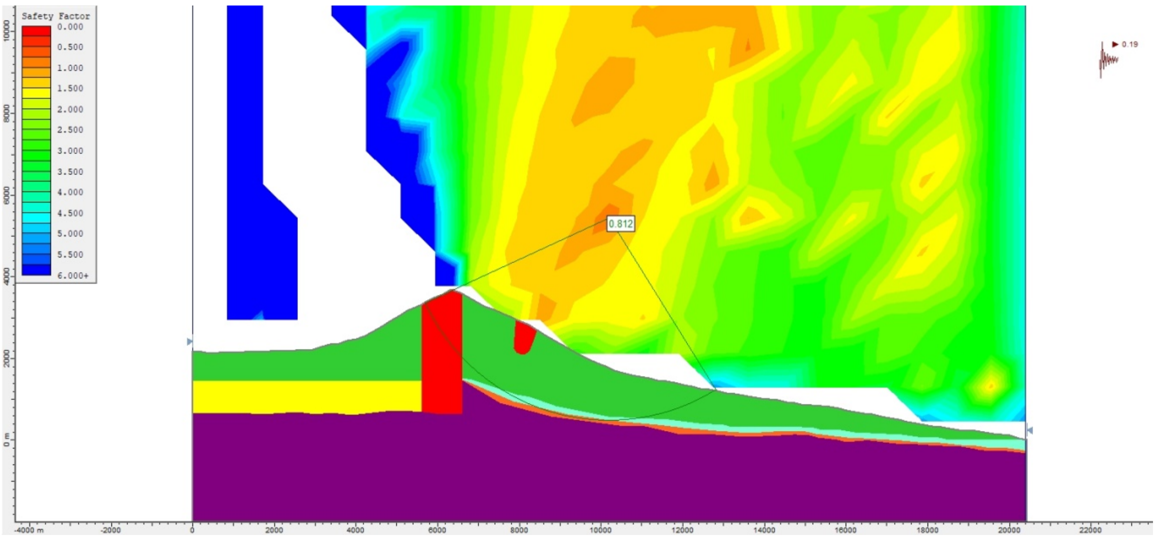

Figure S242. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.19.

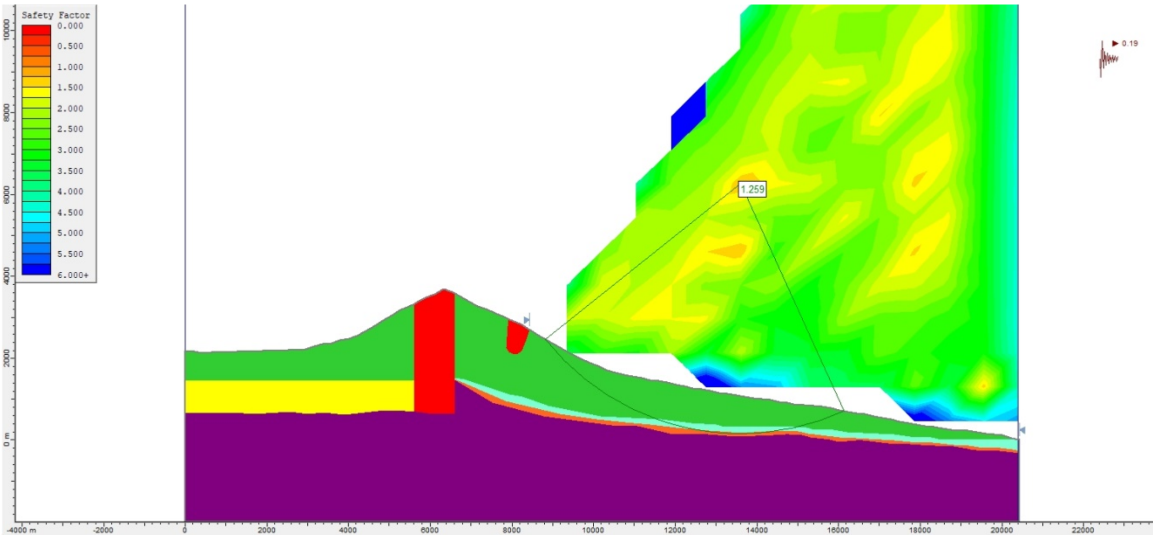

Figure S243. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.19.

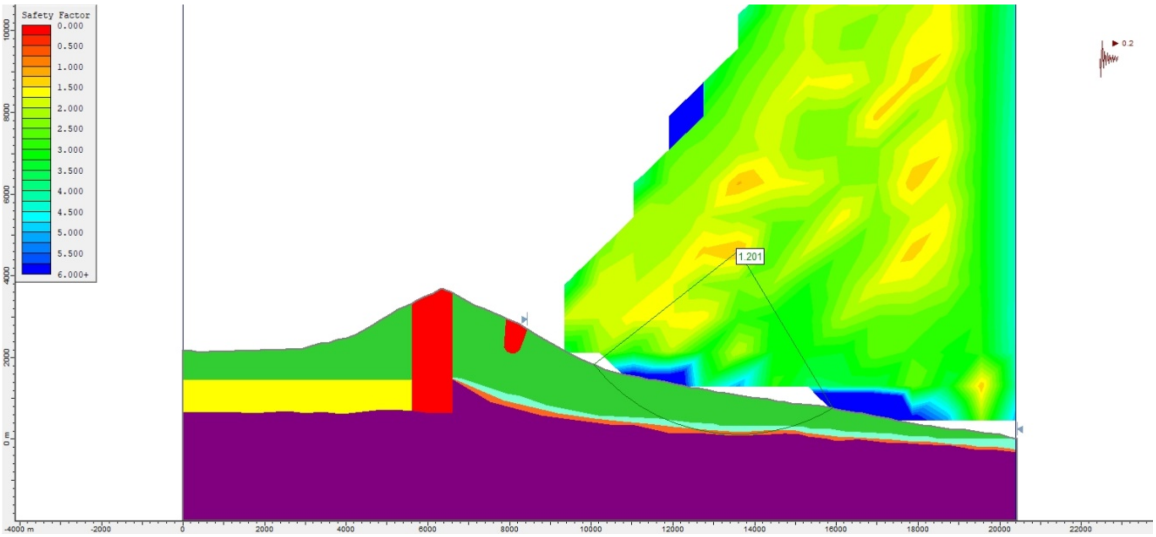

Figure S244. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.20.

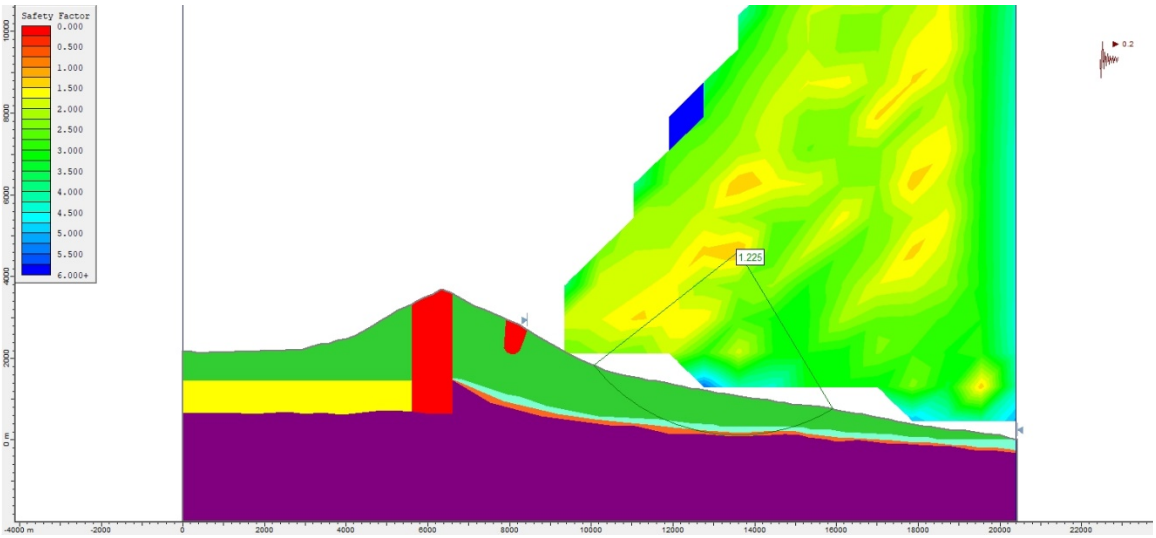

Figure S245. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.20.

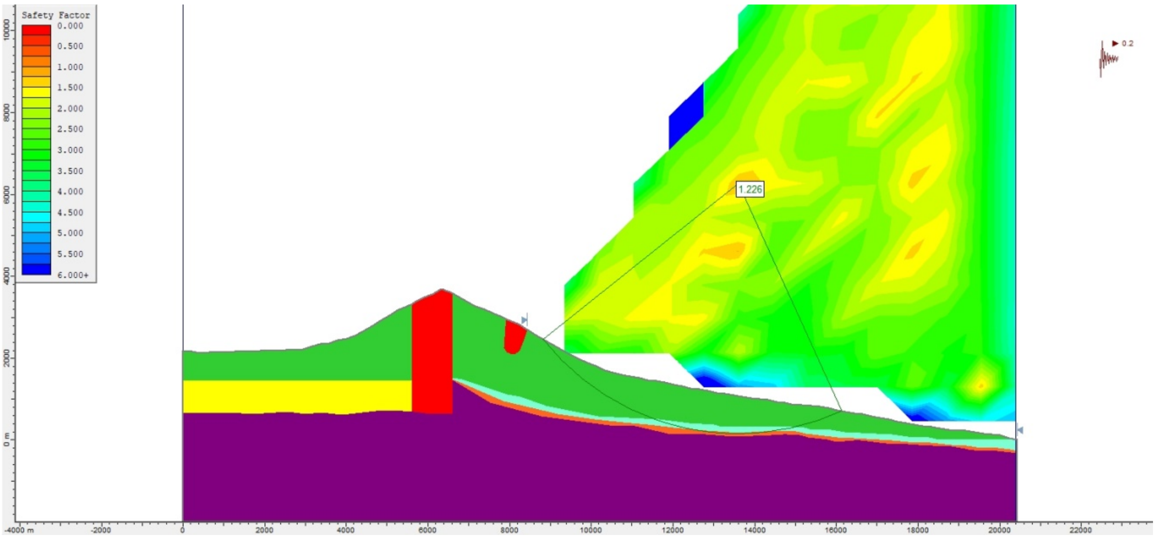

Figure S246. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.20.

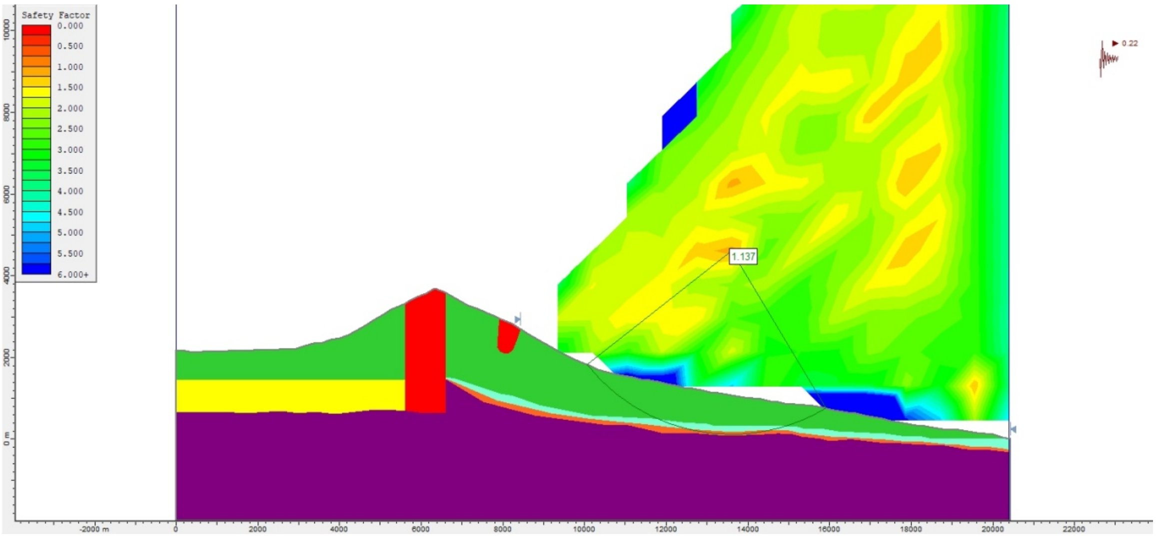

Figure S247. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.22.

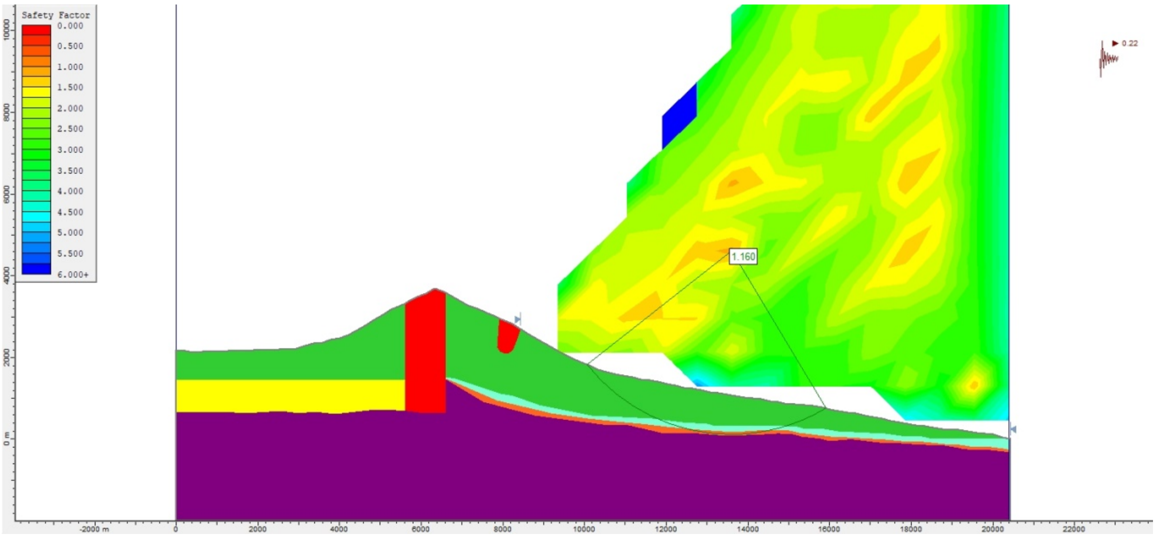

Figure S248. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.22.

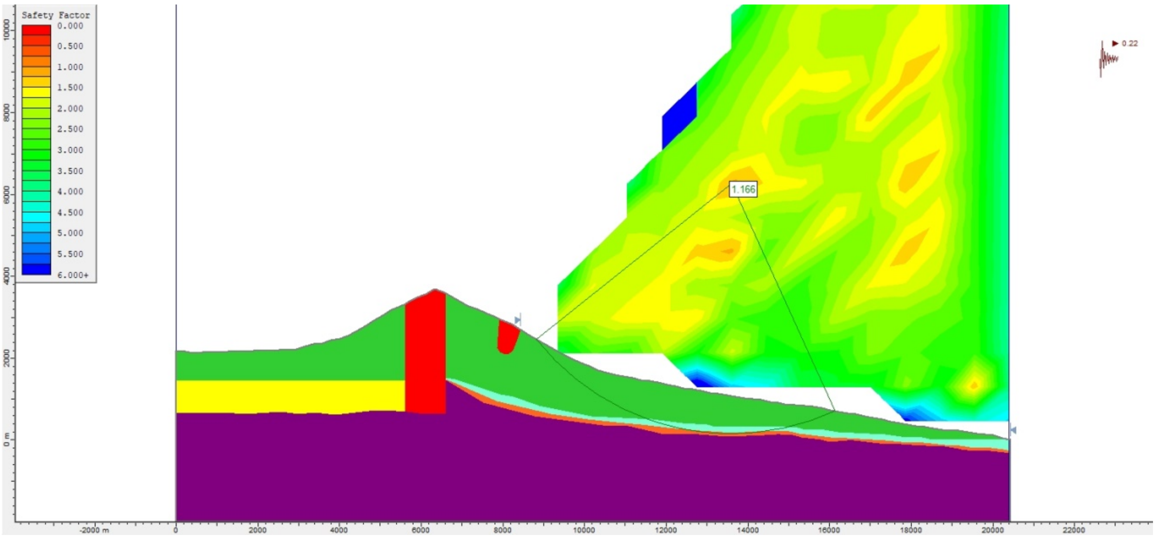

Figure S249. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.22.

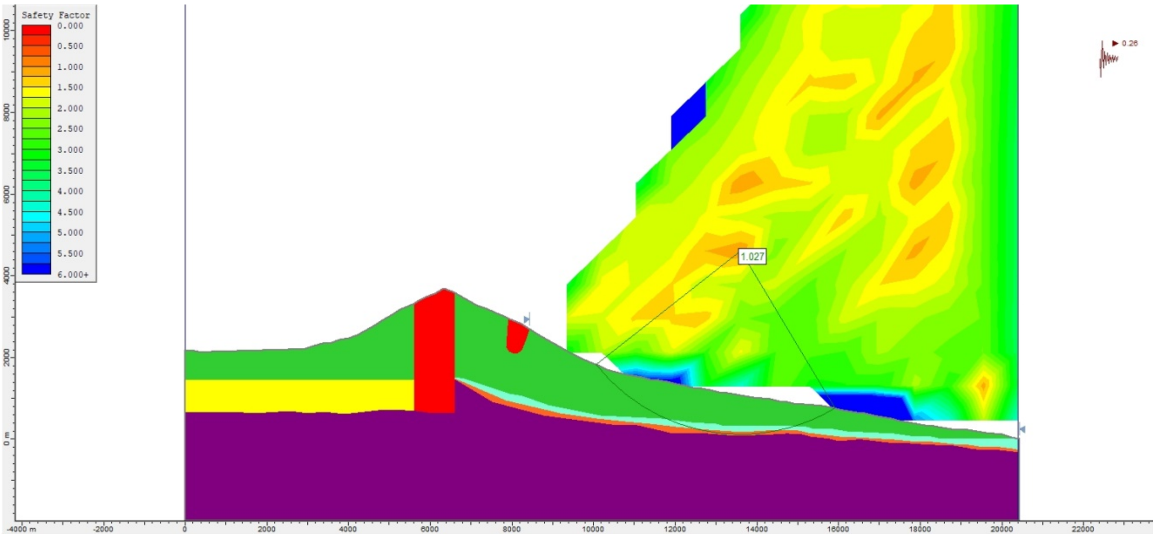

Figure S250. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.26.

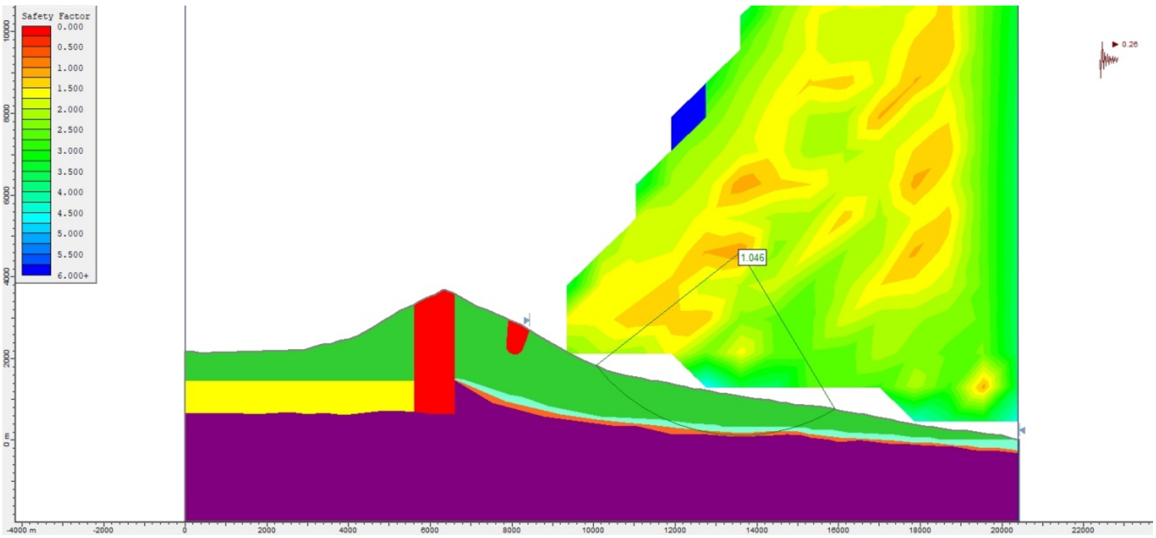

Figure S251. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.26.

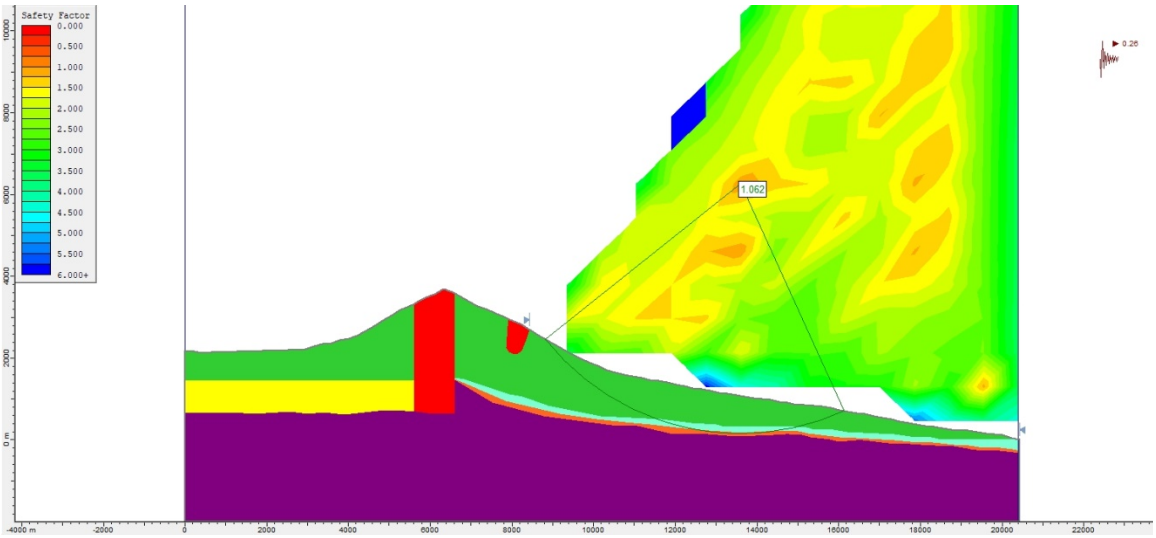

Figure S252. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.26.

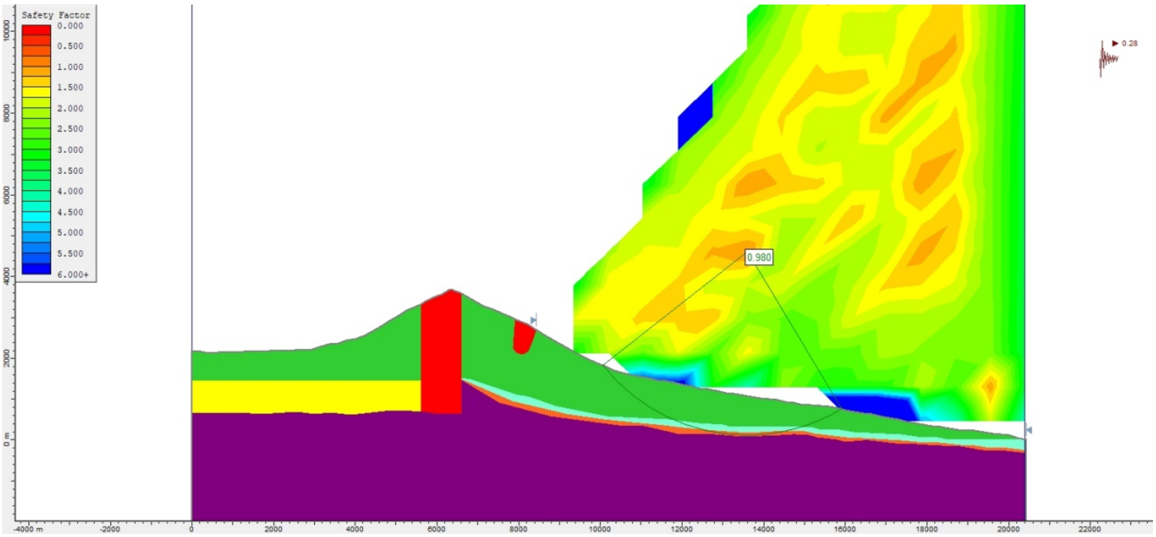

Figure S253. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.28.

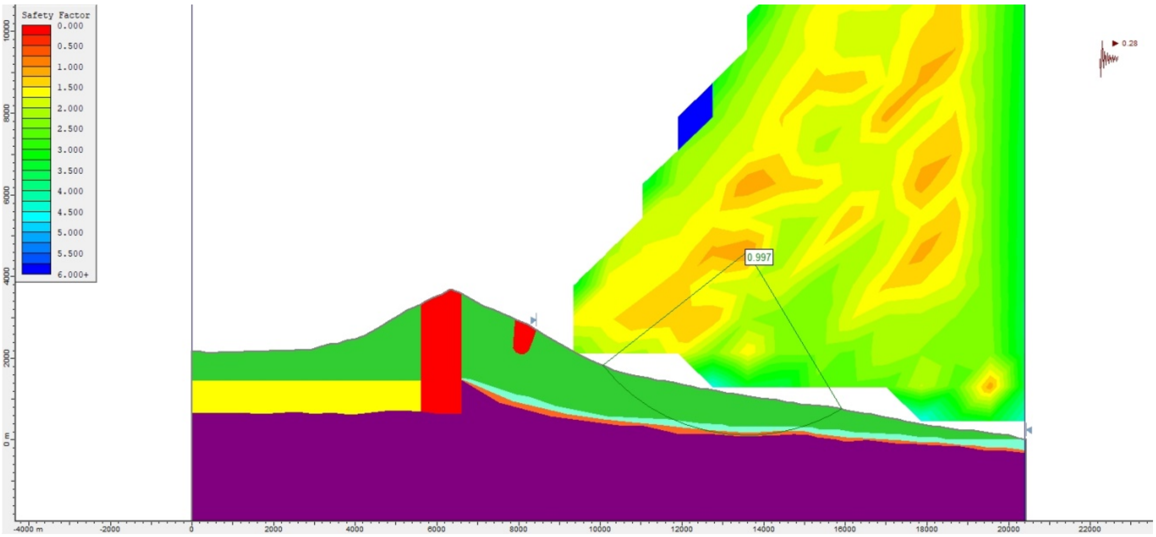

Figure S254. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.28.

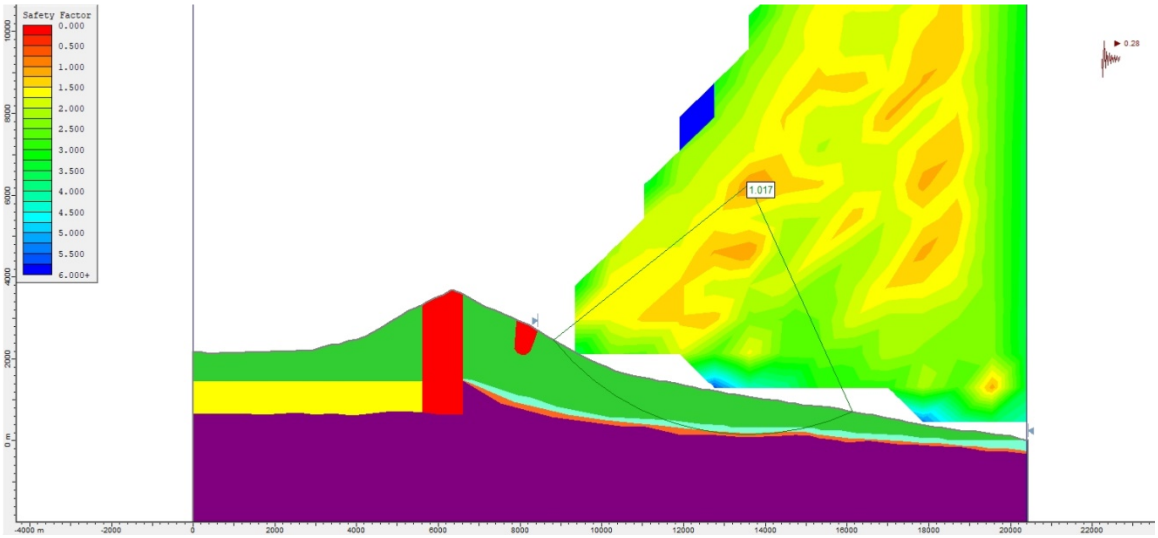

Figure S255. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.28.

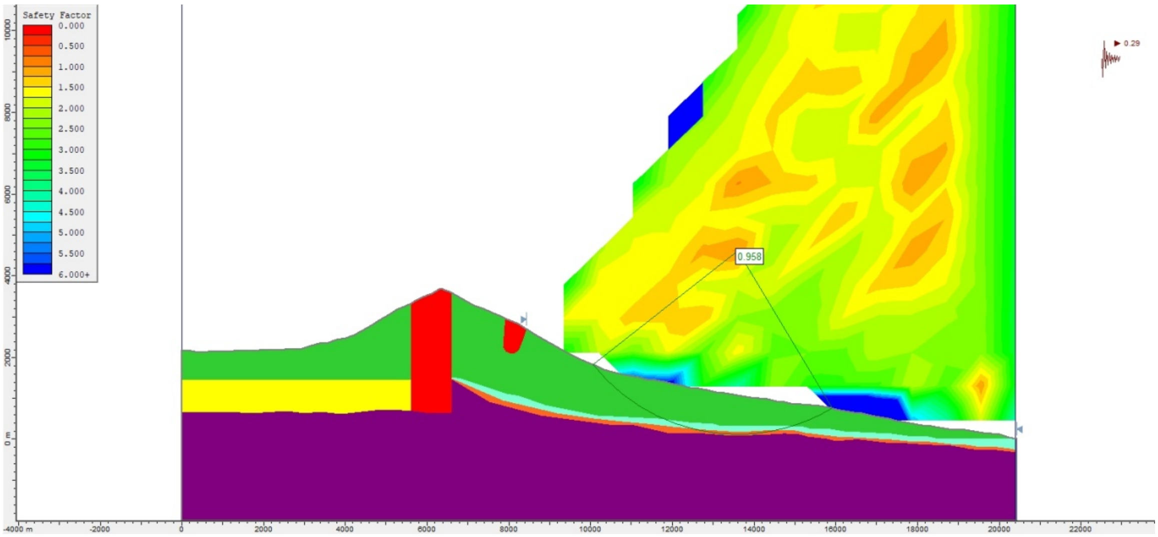

Figure S256. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.29.

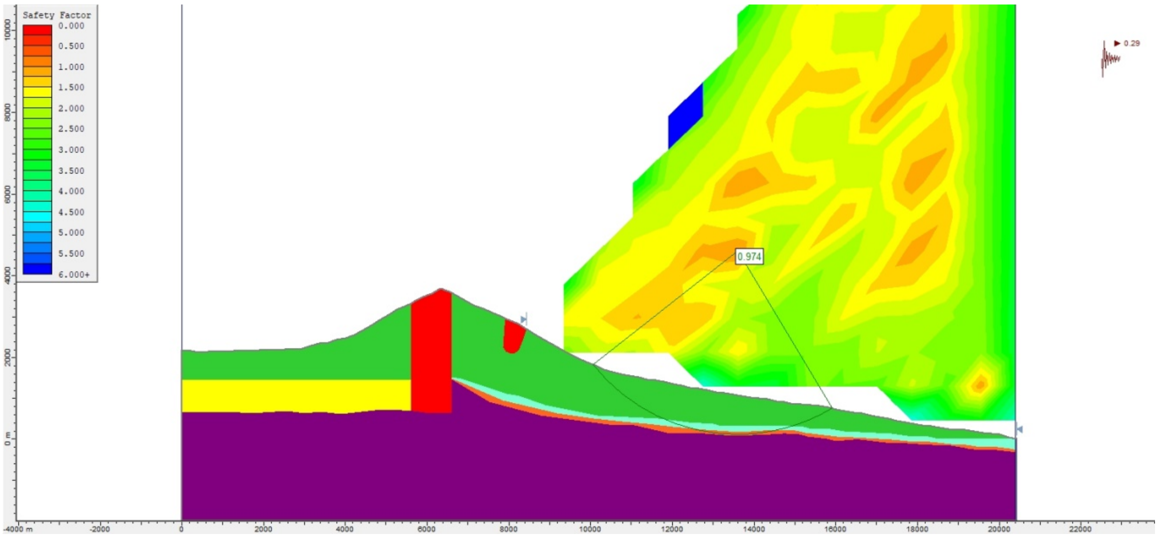

Figure S257. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.29.

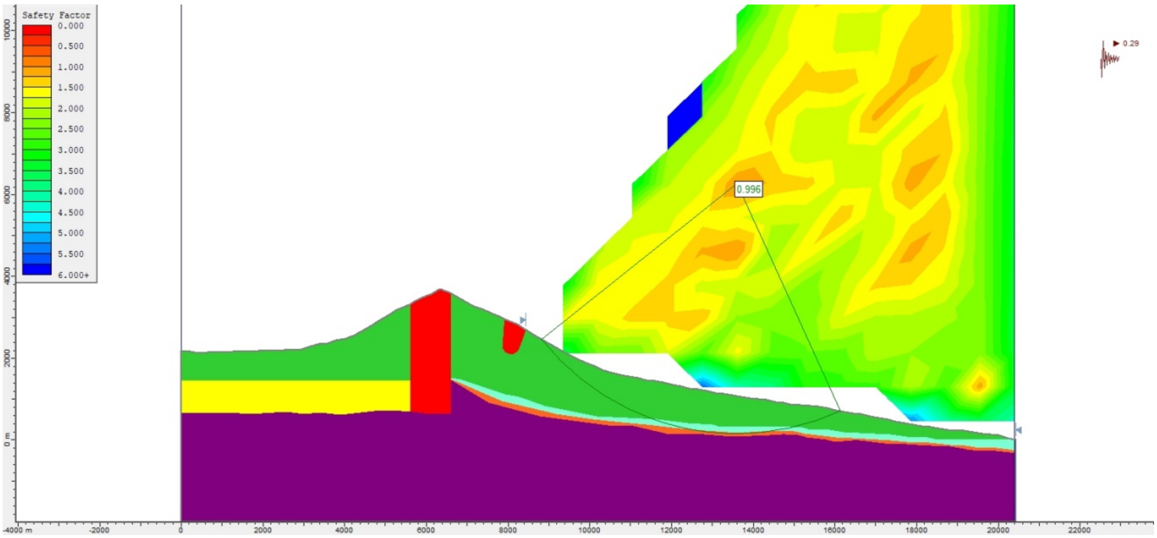

Figure S258. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.29.

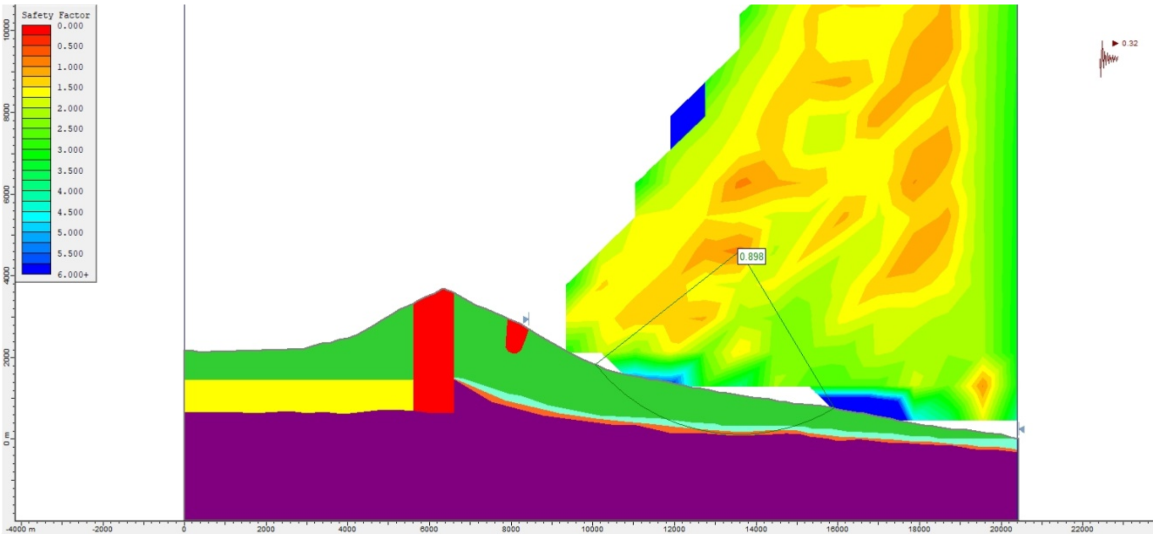

Figure S259. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.32.

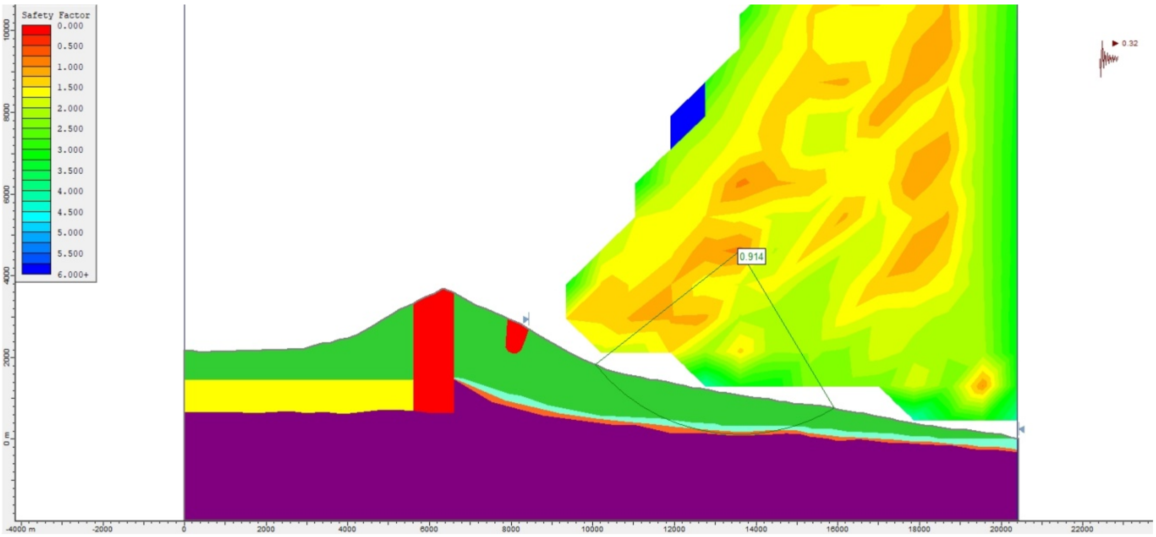

Figure S260. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.32.

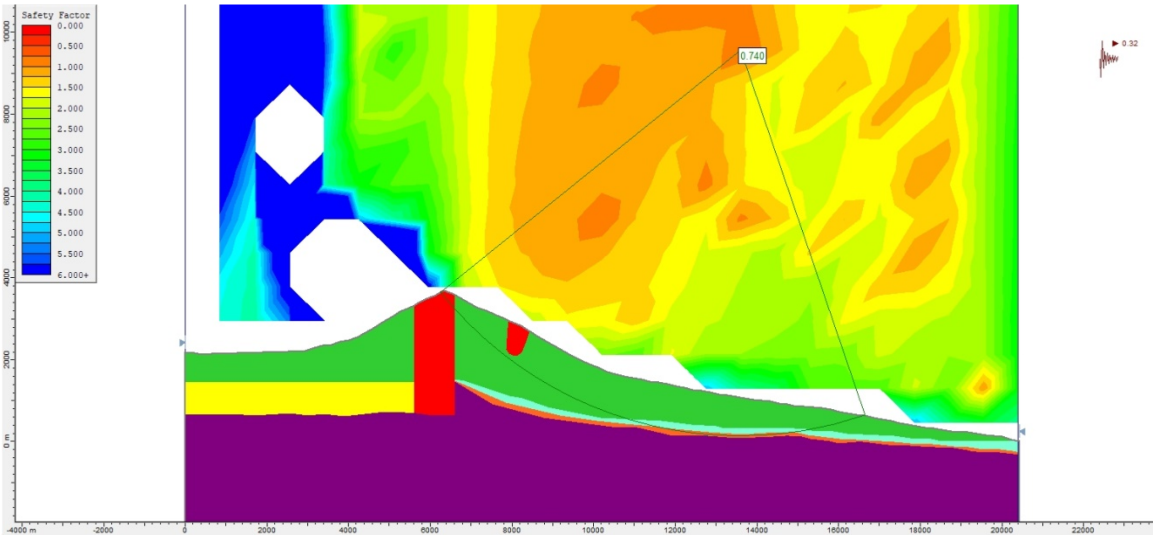

Figure S261. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.32.

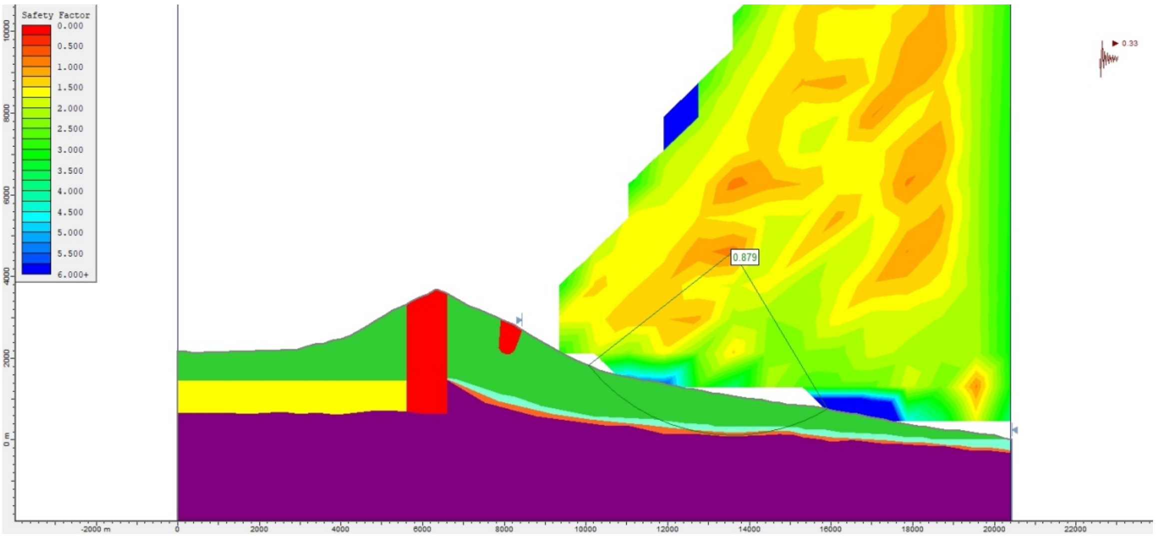

Figure S262. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.33.

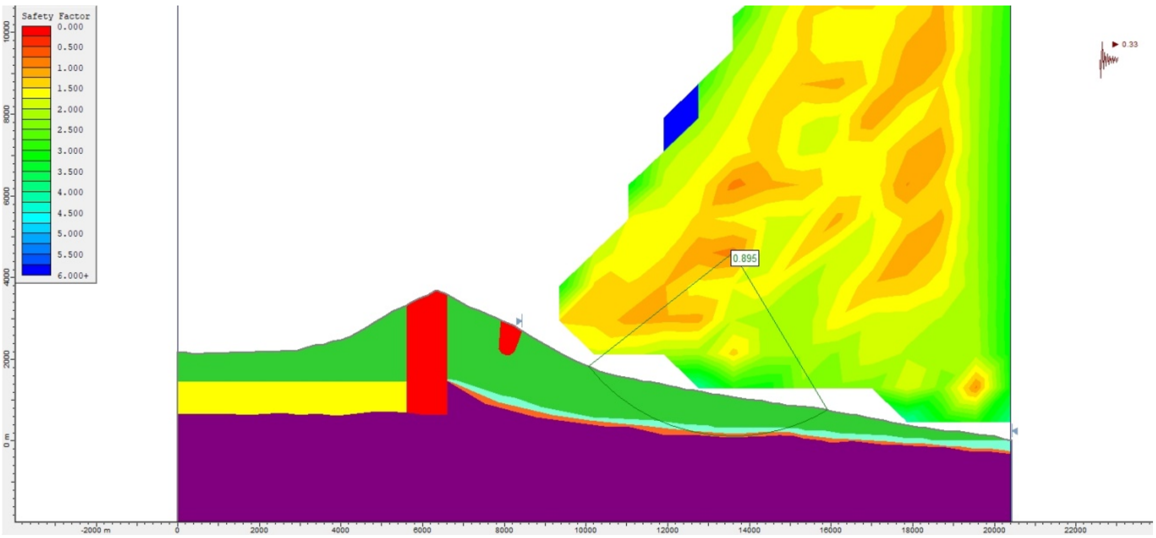

Figure S263. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.33.

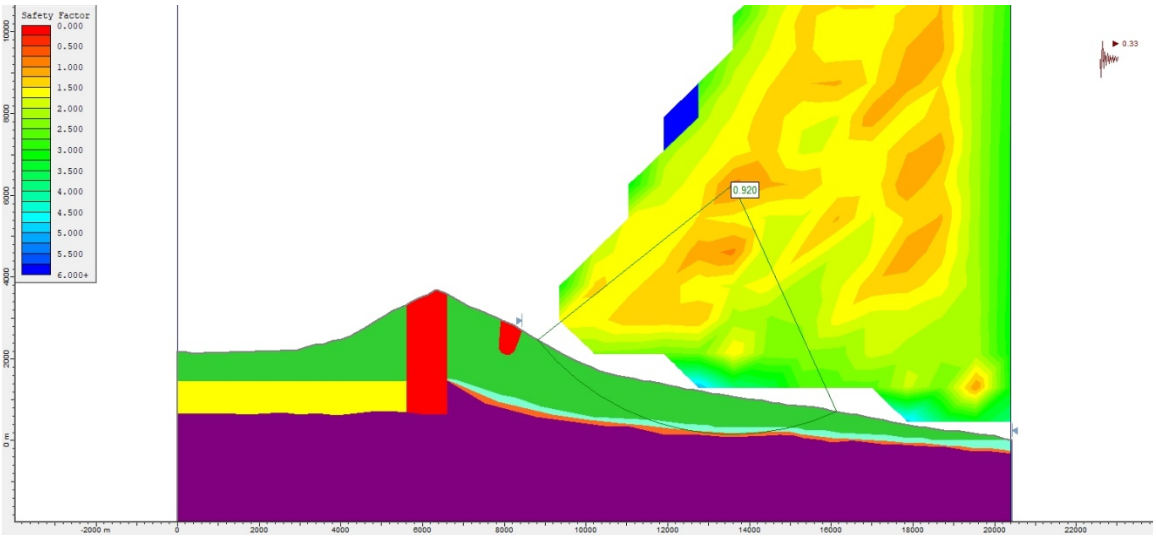

Figure S264. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.33.

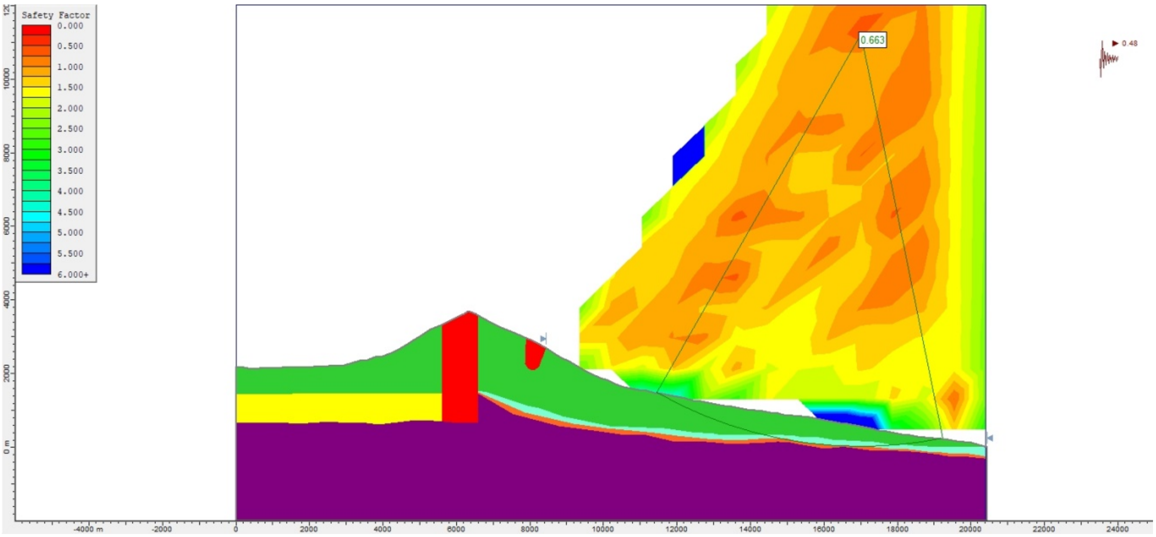

Figure S265. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.48.

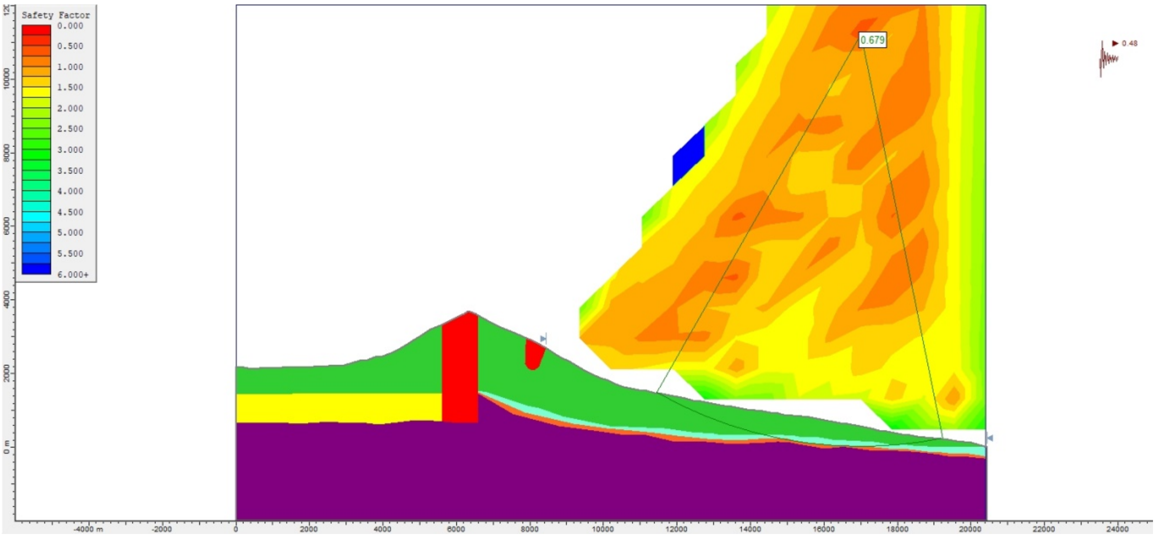

Figure S266. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.48.

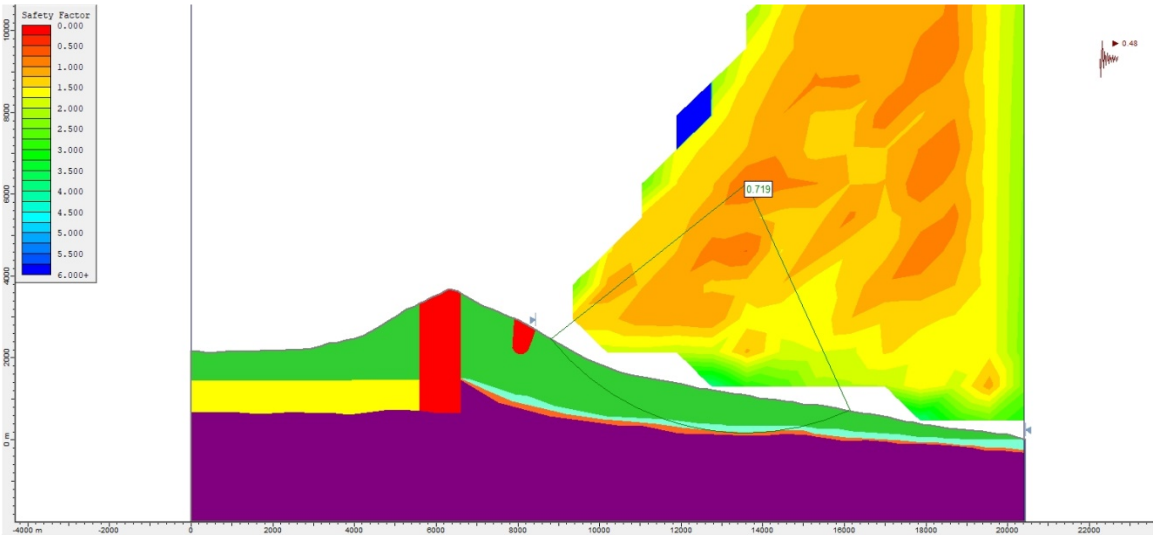

Figure S267. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.48.

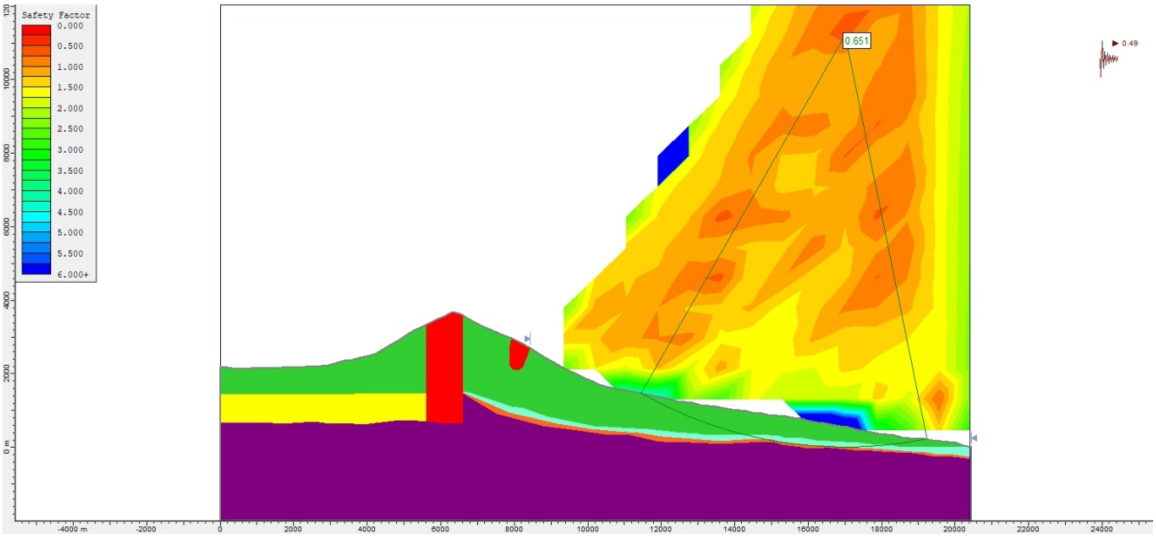

Figure S268. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 0.49.

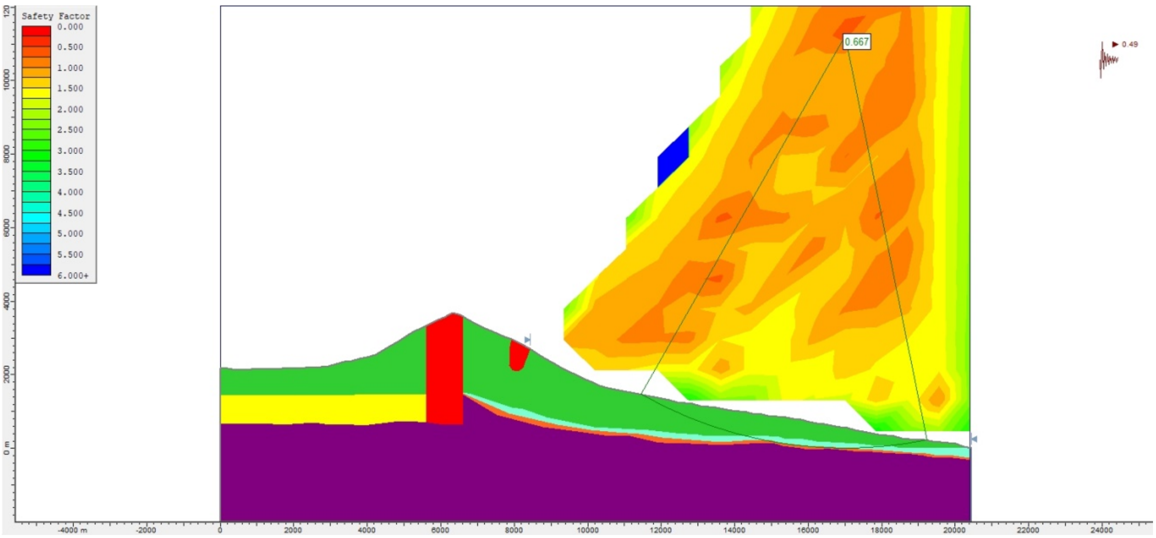

Figure S269. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 0.49.

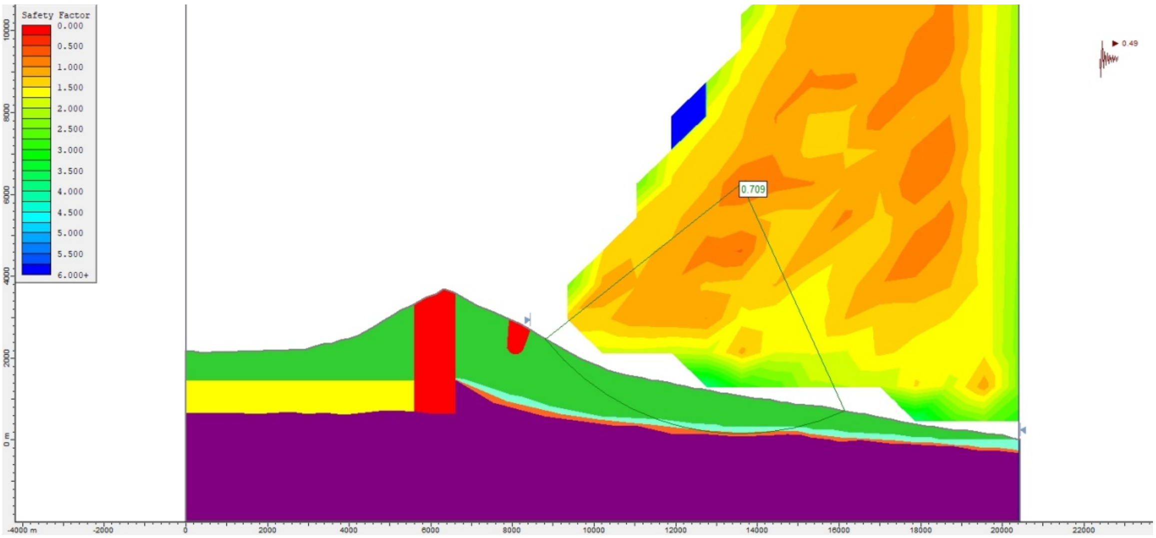

Figure S270. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 0.49.

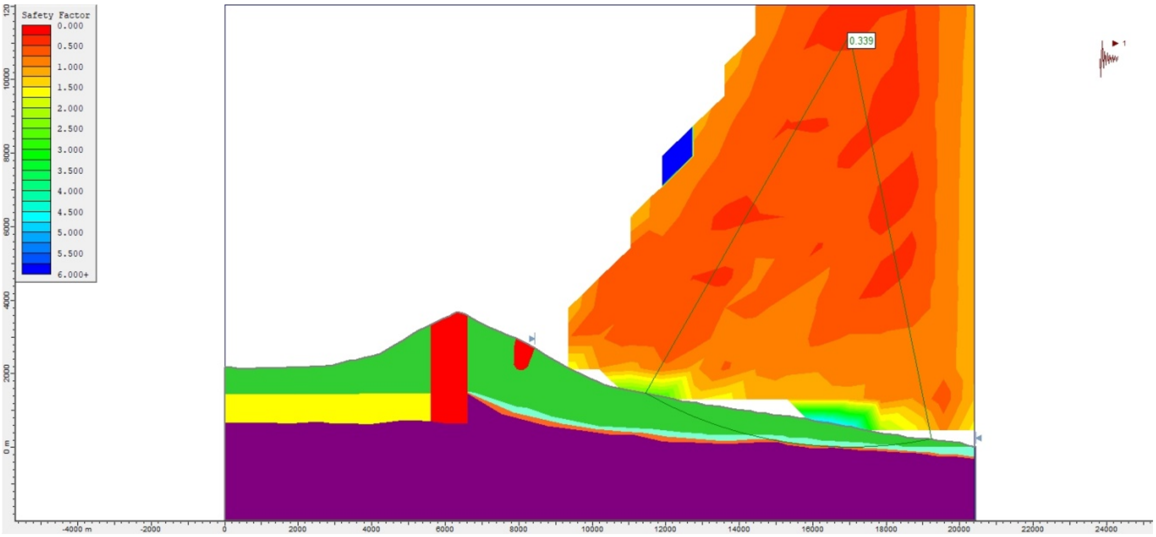

Figure S271. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 1.00.

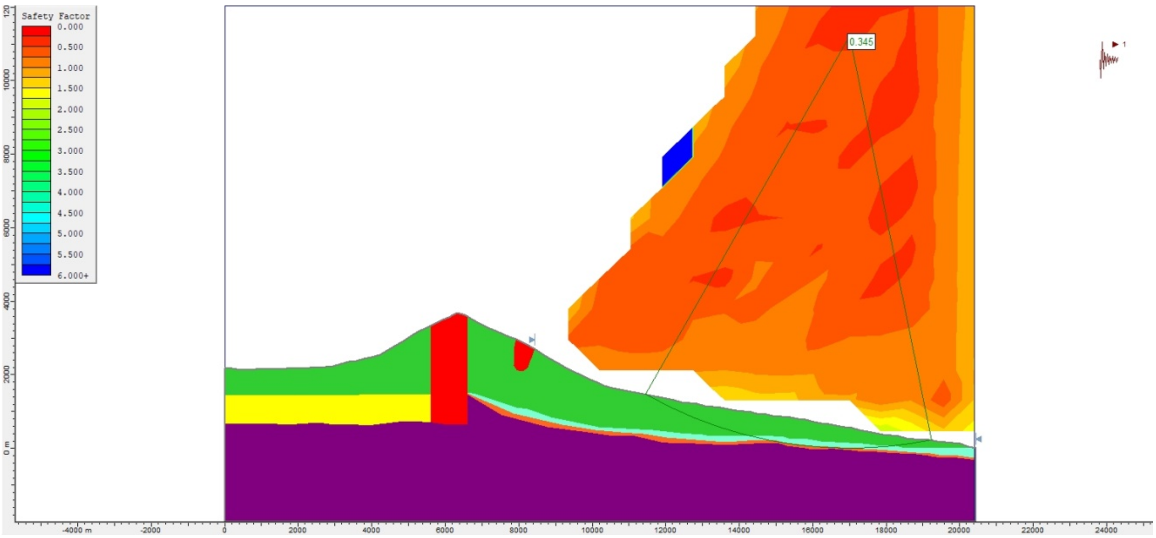

Figure S272. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 1.00.

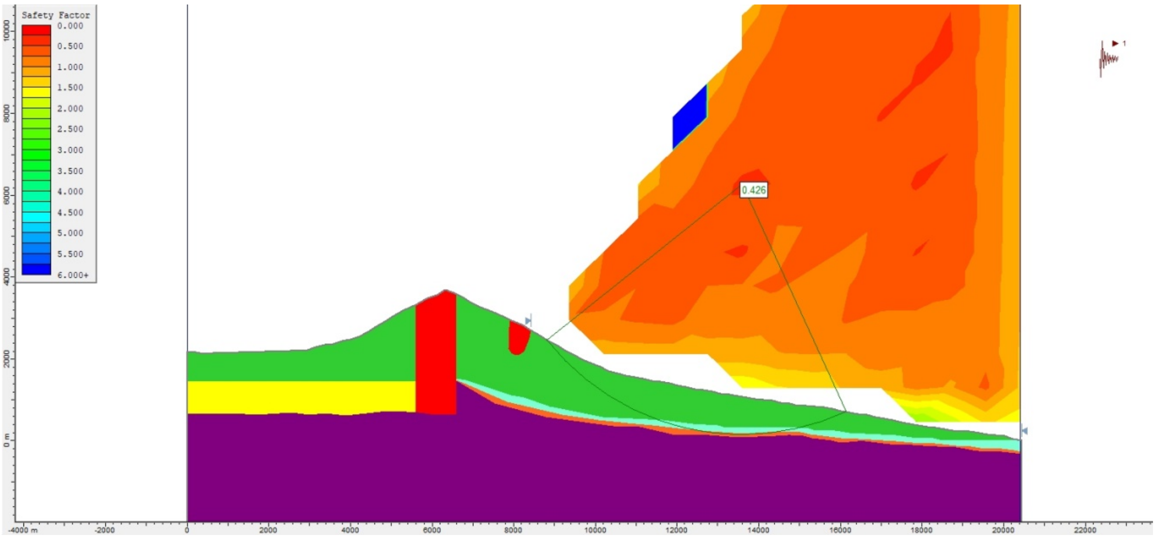

Figure S273. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 1.00.

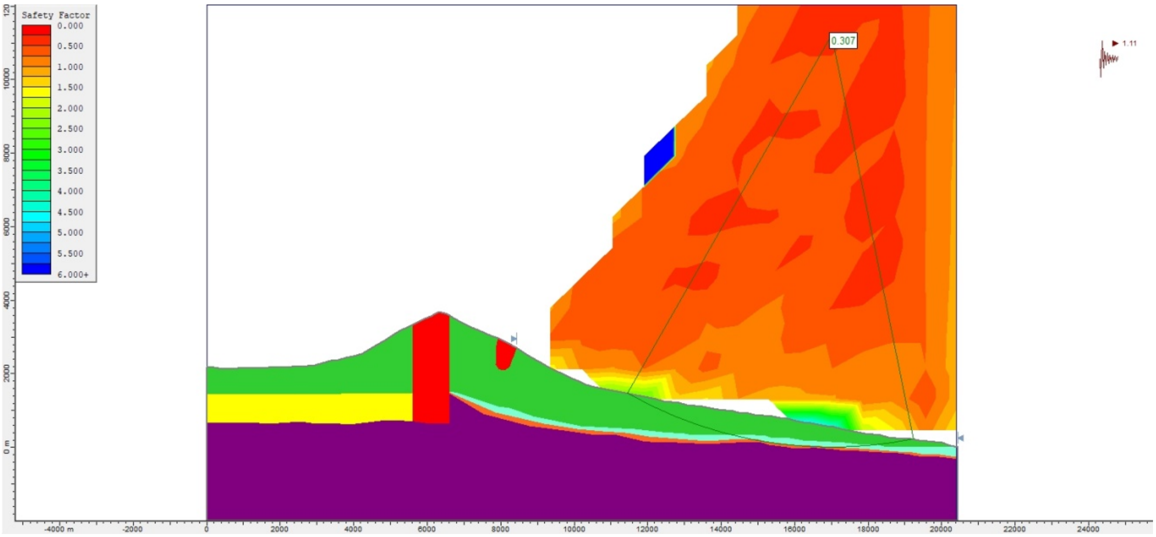

Figure S274. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Bishop simplified method and a k_h = 1.11.

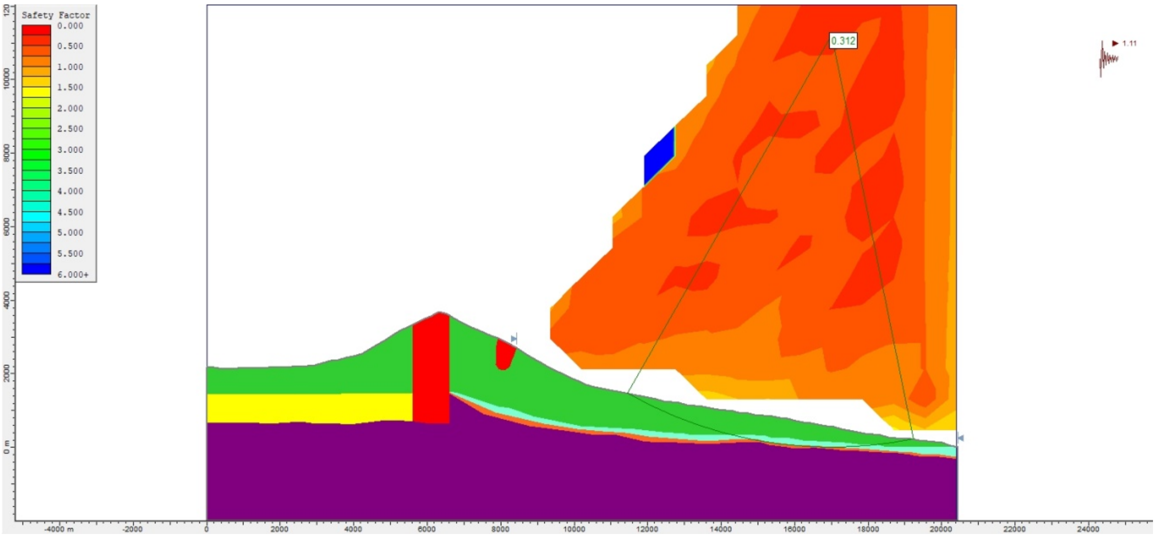

Figure S275. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Janbu Generalised method and a k_h = 1.11.

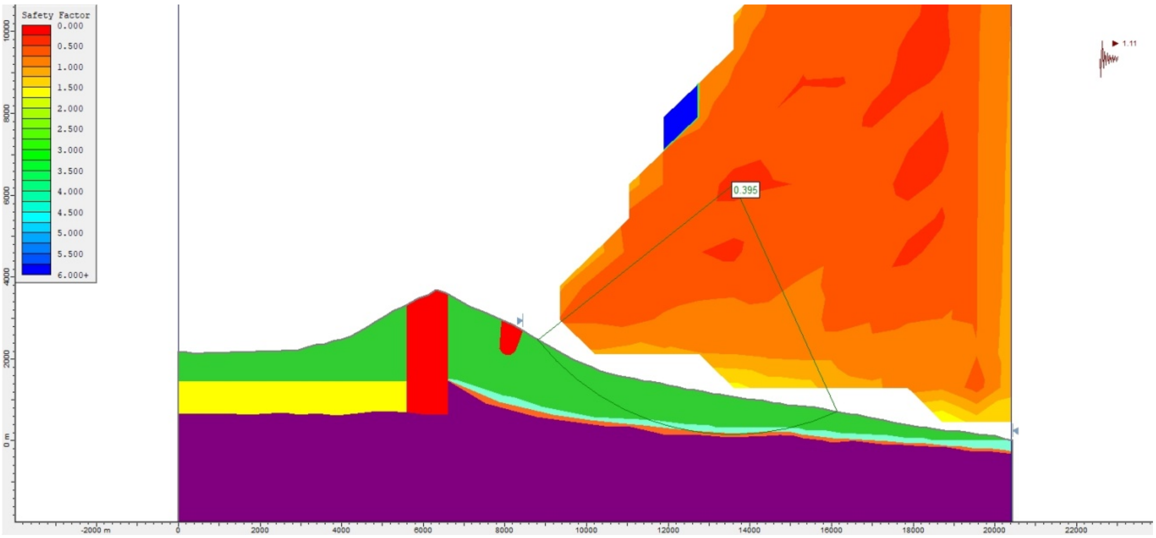

Figure S276. Slope stability pseudo-static analysis for Model 1 Bis (assuming a caldera collapse), using the Morgenstern-Price method and a k_h = 1.11.

Annex 6. Supplementary Material 3: Interviews

Interview to Ásgrímur L. Ásgrímsson (Icelandic Coast Guard)

1. Could you tell me your complete name and position?

I'm Ásgrímur Ásgrímsson, and I'm the Chief of Operations at the Icelandic Coast Guard.

2. When was the Icelandic Coast Guard created?

It was established in 1926.

3. What is the area of your jurisdiction?

Jurisdiction primarily extends to the territorial sea, and to some extent, the exclusive economic zone, within 200 nautical miles. Additionally, through international treaties, Iceland has jurisdiction over the Icelandic SRR (Search and Rescue Region), which stretches south of Greenland, east of the Faroe Islands up to zero degrees, and north of Jan Mayen. Consequently, we bear the responsibility for search and rescue operations in this area.

4. So if something happens, for example, in Greenland, you are in charge of the rescue?

Jurisdiction does not extend to land, but it does encompass the coastal territorial sea. This means that any claims over the seabed or other resources are not included. The jurisdiction solely pertains to search and rescue operations, and does not involve territorial or resource rights.

5. What are the main tasks of the Coast Guard?

Two main tasks of ours are maritime law enforcement, with the largest part dedicated to fishery law enforcement. Additionally, we are responsible for enforcing any activities permitted by Icelandic law in the ocean surrounding Iceland. This includes fisheries, customs regulations, and general law enforcement. Furthermore, we actively participate in search and rescue operations. It is important to note that we are not a military entity; rather, we are law enforcement officers operating in maritime settings.

6. Where do you receive your monetary funds from?

We receive it from the government.

7. What is your organizational chart within the Agency?

The Coast Guard is led by the Director General, who serves as my superior. As the Chief of Operations and Deputy Director General, my role encompasses overseeing the day-to-day functioning of the Coast Guard. This involves monitoring our activities, such as ship operations, helicopter deployments, and aircraft missions. I am responsible for coordinating tasks for our ships, helicopters, and aircraft. This includes determining whether our helicopters are engaged in training exercises or coastal patrols, and whether our aircraft are conducting deep-sea patrols, among other duties. Additionally, I oversee our special operations unit and stay informed about ongoing events in the surrounding waters. Essentially, my job entails staying knowledgeable about these matters and providing guidance on where our operations should be conducted.

8. How many sections or departments is the Agency divided into?

There are four operational divisions within our organization. Let me provide you with a copy of the brochure for more details [a brochure about the organization is provided]. The Director General oversees the overall operations, while I hold the position of Chief of the Operation Division. In addition, we have the Aviation Division, Maritime Division, and Defense Division. It's important to note that the Defense Division does not consist of military personnel like army or armed forces. Instead, we manage the Keflavik NATO base and radar sites situated around Iceland's coastline. These facilities are used for NATO training and missions. As part of the Coast Guard, we maintain and operate the base and radars for NATO purposes. These operational divisions are supported by various departments, including the Human Resource Division, Financial Division, Legal Division, and Technical Division. The Technical Division plays a crucial role as they are responsible for aircraft and ship maintenance. However, the other three divisions, such as Law, Finance, and Human Resources, are relatively small, with around three lawyers, approximately ten finance personnel, and two or three individuals managing human resources. Overall, the entire Coast Guard consists of approximately 250 personnel.

9. Which kind of relation exists between the Police and the Coast Guard?

We have extensive cooperation, particularly with the National Commissioner of Police. As part of the Coast Guard, we provide coverage and support to all nine police districts across the entire island. This close collaboration is facilitated by the fact that we operate under the same Ministry, the Ministry of Justice. However, it's important to note that despite this cooperation, the Coast Guard remains entirely independent of the police.

10. And between the Coast Guard and the ICE-SAR?

ICE-SAR is legally recognized as a volunteer organization, and according to the law, they are obligated to collaborate and work alongside the Coast Guard specifically in search and rescue operations. Their involvement is strictly limited to search and rescue tasks and does not extend to law enforcement or any other activities. In situations where an aircraft crashes at sea or goes missing, it is the responsibility of the Coast Guard to engage ICE-SAR. On the other hand, when incidents occur on land, the police are responsible for coordinating with ICE-SAR. Although ICE-SAR and the police have a similar cooperative arrangement, the legal framework explicitly outlines their role, emphasizing that ICE-SAR always operates on behalf of either the Coast Guard or the respective police districts.

11. Do you work jointly with the University of Iceland, the Met Office or other scientific institutions?

Yes, we collaborate extensively with the Met Office, as they have various instruments positioned around Iceland for monitoring weather, avalanches, and seismic activity. We assist them in installing and maintaining these instruments, utilizing our helicopters to reach remote and challenging locations. Additionally, we provide transport support for repairs or battery replacements. In late winter, we also share information about icebergs in Greenland with mariners, who contact us for such updates. This information is then incorporated into their broadcasts or databases. Regarding research, our cooperation with the University and Marine Research Institute is project-based. While they have their own research vessels, we assist them in deploying or retrieving buoys and other equipment that they may not have the means to handle independently. We collaborate with Icelandic universities, scientific organizations, as well as foreign scientific institutions. On occasion, we are requested to deploy objects in the ocean, either by aerial or maritime means, and we fulfill these tasks regularly.

12. Do you carry out prevention tasks for natural disasters during the year, when there is no emergency?

No, we are a response organization.

13. Do you conduct courses and trainings throughout the year?

Yes, on a daily basis. An organization like ours has to undergo continuous training. Some of it involves attending courses abroad, while some are conducted within the country. We seek training opportunities both locally and internationally, ensuring a well-rounded preparation. Our aviation crews and ship crews engage in daily exercises to enhance their skills and readiness.

14. Do you conduct drills or give courses to the population?

No, we don't provide such services to the general population. However, certain specific groups, such as mariners, fishermen, and sailors on board merchant ships in Iceland, are required to undergo safety courses. These courses are designed to ensure their preparedness and knowledge of safety procedures in their respective maritime roles.

15. Sigrún Karlsdóttir, from the Met Office, explained me that every day, at 2 pm, you have a meeting where different institutions are updated on the situation regarding various phenomena, meteorological, geological, etc., for example, weather forecasting,

seismicity, risk of avalanches, eruptions, etc. Do you participate or have you ever participated in these meetings?

Yes.

16. What is the role of the Coast Guard in these meetings?

The role of the Coast Guard in these meetings is typically to discuss and establish standards for our assets in terms of their capability for personnel evacuation and their suitability for conducting various observations.

17. When there is an anomalous situation, e.g. an increase in the seismicity prior to a possible eruption, or extreme weather forecasting, risk of avalanches, or any kind of risk in this area, does someone inform the Coast Guard to be prepared?

Yes, typically the communication is carried out through the Civil Prevention Division of the National Police. When events like adverse weather conditions or high avalanche risks are anticipated, we take proactive measures to ensure preparedness. For instance, if we are aware of severe weather conditions or heightened seismic activity in a specific area, we make sure to position a ship in that location in advance. This is necessary because sometimes helicopters are unable to reach the area due to unfavorable weather conditions. By strategically placing our ships in key locations based on weather forecasts and seismic data, we aim to enhance our response capabilities.

18. So I guess that the Met Office is the institution that informs you about this weather?

No, it's usually the Civil Protection Division of the Police. The Met Office informs the Civil Protection, and the National Police informs us.

19. Once an emergency has been declared, what are the main tasks of the Coast Guard?

Once an emergency has been declared, the main tasks of the Coast Guard are search and rescue operations. Additionally, they play a crucial role in observation. This involves deploying helicopters, aircraft, or ships to assess the situation and provide reports to the relevant decision-makers. For instance, during volcanic eruptions, the Coast Guard transports scientists in their aircraft or helicopters. In subsequent flights, they may carry reporters, recognizing their role in disseminating information to the public, who have a right to be informed about potential dangers.

20. Do you activate any contingency plan?

For the Coast Guard, our operations encompass search and rescue missions as well as various tasks carried out in the ocean surrounding Iceland. We have developed multiple plans, particularly those related to emergency situations and search and rescue, based on international standards such as IMO (International Maritime Organization), ICAO (International Civil Aviation Organization), and IAMSAR (International Maritime and Aviation Search and Rescue Manual). These standards are crucial as the ocean and airspace are international domains, requiring a unified approach. However, when it comes to operations within Iceland, the contingency plans are formulated by the Civil Protection Division of the National Police. As an example, if there is an aircraft crash near an airport, we align our actions with the designated plan. Moreover, there are specific plans in place for catastrophic events in areas like the Westman Islands, which experienced an earthquake and volcanic eruption several decades ago. In such cases, we coordinate our efforts based on the designated plans that outline our role and responsibilities.

21. Are you in charge of the evacuation process? If so, how is it carried out?

No, the Coast Guard is not directly responsible for the evacuation process on land. In such situations, the police take the lead role. However, the Coast Guard plays a crucial part in the overall process. For instance, in the case of bus accidents that occur around the island, the Coast Guard's involvement becomes significant. Bus accidents in Iceland are considered major incidents, especially due to the limited capacity of hospitals outside of Reykjavik. When there are a significant number of injured individuals, typically around 20 to 25 people, it becomes necessary to transport them to Reykjavik for proper medical care. In these scenarios, helicopters are often utilized to retrieve people from mountainous areas and transport them to an airport. From there, the individuals are further transported to Reykjavik. In this regard, the Coast Guard plays a facilitating role by establishing an "air bridge" for transportation. While the police are in charge of the overall evacuation process, the Coast Guard takes responsibility for this particular aspect since they are the sole providers of helicopters. On the other hand, when it comes to evacuations at sea, the Coast Guard assumes full responsibility. In situations such as evacuating passengers from a ferry, the Coast Guard is in charge of coordinating and executing the evacuation process.

22. What are the biggest difficulties you encounter during natural disasters?

The role of the Coast Guard varies depending on whether the situation is on land or at sea. When it comes to operations at sea, the Coast Guard is primarily responsible for coordination. For example, in the case of a fishing vessel in distress with a foreign crew who may have language barriers, the Coast Guard coordinates the response efforts. They dispatch ICE-SAR units, position helicopters, and address communication challenges. This task involves managing multiple organizations and groups that may not be accustomed to working together, which can present challenges.

Inland, the Coast Guard's role often involves clarifying expectations to cooperative personnel who may have a misconception that helicopters can handle any situation. However, there are limitations due to weather conditions or other factors. Some individuals may overly rely on helicopters to resolve emergencies, without considering their limitations. The Coast Guard's responsibility in such cases is to educate and explain the constraints to ensure a proper understanding of the available resources and capabilities.

23. What happens when circumstances during an emergency exceed your ability to contain or act?

It is facilitated through national rescue coordination centers in neighboring countries. The Icelandic Coast Guard maintains regular communication with these centers on a daily basis. In the event of a significant incident, such as the sinking of a passenger vessel, the Coast Guard would contact a nearby rescue coordination center, such as those located in Stavanger, Tórshavn, Nuuk (operated by the Danish military with extensive maritime resources), or the UK. Similar coordination centers are also utilized for aircraft-related emergencies. It's important to note that for land-based rescue coordination, the responsibility lies with the police, who collaborate with their respective land-based coordination centers.

24. Do you carry out some tasks once the emergency is over?

No, once the emergency is resolved, our tasks typically come to an end. For instance, when we rescue a ship and bring the crew ashore, they are handed over to the police. The same applies to aircraft incidents. If an aircraft loses contact with control towers while flying overseas and arrives in Iceland, we are responsible for searching for the aircraft until it is located. However, once it is found, and if it has crashed, the police take over the investigation. We do not engage in any investigative activities. This applies even to incidents at sea, where the police and dedicated investigation organizations handle the process. In summary, once the crisis is resolved, our responsibilities cease.

25. I would now like to talk about past experiences. Could you tell me how you experienced the 2010 eruption at Eyjafjallajökull?

Yes. The 2010 eruption at Eyjafjallajökull was quite an experience. Prior to that, we had a smaller eruption that was more of a tourist attraction. It created a sense of alertness among everyone, which had an impact when the bigger eruption occurred. During that time, I was on duty for the Coast Guard and stationed at the emergency center. One vivid memory I have is the influx of foreign media contacting us. It was a busy period, and we had to support each other. Despite the eruption being a land-based event, I found myself on the phone with foreign media, asking questions and providing information. Evacuation and ensuring the safety of people was not a concern because the police were well-informed about the locations of individuals and were able to effectively warn and account for everyone.

26. So you didn't take any role during the 2010 eruption in terms of rescue and search?

No, during the 2010 eruption, our role was primarily focused on assisting scientists. Our helicopters and aircraft were deployed on a daily basis, carrying scientists to observe and gather information about the eruption. However, there was no need for us to carry out any evacuation operations as the situation did not require it.

27. And what can you tell me about the recent eruption of 2021? Did you perform any task?

Yes, during the recent eruption in 2021, we were actively involved in various tasks. Our helicopters were busy assisting scientists by transporting them and their equipment to the eruption site for scientific research purposes. We also conducted rescue operations to pick up individuals who had suffered injuries, particularly broken legs, as the terrain was challenging and it was difficult for them to reach medical assistance on their own. Additionally, we conducted search operations to locate and rescue people who had become lost in the area, especially considering the challenging weather conditions and visibility.

28. Which natural hazard do you think causes the most damage, injuries or deaths each year in Iceland?

I would say avalanches.

29. Does the massive arrival of tourists make more difficult your work in any way?

Yes, the massive arrival of tourists in Iceland has posed challenges for the Coast Guard in several ways. Firstly, there has been a significant increase in the demand for search and rescue operations and medical transport services. As the Coast Guard is the primary provider of these services, the rise in tourist numbers has put additional strain on their resources, particularly the helicopters. They have experienced a substantial increase in the frequency of calls for medical transportation, as private companies offering such services may be limited in their capabilities to access remote or challenging locations. This increased workload places pressure on the Coast Guard's ability to respond promptly to emergencies and carry out their duties effectively.

30. How do you think that this could be improved in the future?

In order to improve safety in the future, prevention is key. It is essential to effectively inform tourists about the potential risks and hazards they may encounter during their visit. This includes educating them about the unpredictable weather conditions, such as the rapid changes, horizontal rain, and the risk of getting cold. Additionally, it is important to raise awareness about the ease of getting lost, especially when fog suddenly appears in an otherwise pleasant day.

Regarding the road system, which often consists of dirt roads and narrow passages with opposing traffic, it is crucial to provide guidance and caution tourists about the challenges they may face, particularly during slippery winter conditions. Many foreign tourists are not accustomed to such extreme weather, making it difficult for them to fully comprehend and respect the local conditions.

Unfortunately, we have encountered instances where individuals persistently attempt to cross the island despite the risks. While there may not be specific laws to prevent someone from pursuing their intentions, unless they engage in unlawful activities, it remains a concern. It is disheartening to note that we have had incidents where we have had to rescue individuals multiple times or, in unfortunate cases, recover deceased individuals. These incidents have involved people of various nationalities, including Americans, French, and Germans.

To address these challenges, we must continue to emphasize the importance of informed decision-making, responsible behavior, and respect for the natural environment and local conditions. Efforts should focus on comprehensive education and awareness campaigns to ensure tourists have a clear understanding of the potential dangers and risks associated with their activities in Iceland.

31. So, does the person who is rescued have to pay for the rescue services?

The person who is rescued does not directly have to pay for the rescue services provided by the team. In the case of medical evacuations, the team facilitates the process through the National Medical Insurance of Iceland. If a pure medical evacuation is required, the bill is sent to the National Medical Insurance of Iceland, which then contacts the respective medical insurance companies in the visitor's home country, such as Spain or France, to handle the billing.

It should be noted that visitors to Iceland may not be fully aware of the cost associated with emergency services. To address this, the team is exploring the option of sending bills to individuals who knowingly take risks in extreme situations, such as glacier camping in February. This serves as a means to raise awareness and ensure that individuals understand the potential financial implications of their actions.

Furthermore, with the increasing traffic of cruise ships in the North Atlantic, the team has been approached to assist in the transportation of patients from these ships. To cover the expenses of these complex operations, the team is considering sending bills to the ship companies.

While the team is driven by the mission to save lives and provide necessary assistance, it is important to secure funding for the sustainability of these operations in the future.

32. What characteristics does your organization have that you believe make it efficient?

The efficiency of our organization stems from several key characteristics that our members possess. Firstly, our team is driven by a strong sense of mission and purpose. We have individuals who have joined the organization with the specific goal of saving lives and making it their life mission. This deep commitment to our mission fuels our dedication and drives us to perform our tasks efficiently and effectively.

Secondly, our organization is comprised of individuals who thrive on excitement and action. We understand that our work requires us to be in dynamic and often challenging situations. Many of our team members have a natural inclination towards adventure and a desire to be actively involved in their work. This ensures that we have a motivated and engaged workforce that is always ready to respond and adapt to rapidly changing circumstances.

While our members possess a passion for action, it is important to strike a balance and ensure that actions are carried out with careful consideration and adherence to protocols. Sometimes, it is necessary to temper the desire for immediate action with a measured approach to ensure the safety and success of our operations.

Ultimately, our organization is characterized by a strong sense of duty. We understand the importance of our role in saving lives and protecting the well-being of individuals in distress. This sense of duty instills a sense of responsibility and professionalism in our team, which contributes to our overall efficiency and effectiveness in carrying out our tasks.

33. In what areas do you think you should improve?

While our organization excels in many areas, there are always areas for improvement. One aspect that we recognize as needing attention is discipline. As a Coast Guard, we are fortunate to have a team of highly motivated individuals who are passionate about search and rescue and eager to participate in action. However, discipline is an essential component of maintaining order, efficiency, and safety within our operations. I received my training overseas. As a young man, I ventured to the United States and underwent training at a military institution. Additionally, I served as an officer in the U.S. Coast Guard. While the Coast Guard comprises individuals who are highly motivated for search and rescue missions and eager to participate in action, discipline is an area that could benefit from improvement.

34. If you could ask anything of the other institutions involved during a natural disaster that would make your work easier and more effective, what would it be?

If I could ask anything of the other institutions involved during a natural disaster, it would be to prioritize discipline and implement respectful procedures. While we greatly appreciate the willingness and eagerness of all organizations to come to the assistance during emergencies, it would be beneficial to have a more organized and coordinated approach.

Specifically, I would request clear communication and coordination regarding deployment and response procedures. This would involve establishing protocols for alerting and mobilizing resources, as well as guidelines for when to wait and when to take action. It is crucial to have a unified understanding of the situation and a well-coordinated response plan.

For example, in situations where an aircraft needs to divert due to engine failure, it is important to have a systematic approach in deciding which resources to mobilize. In the case of ICE-SAR rescue vessels, their movements are slower compared to aircraft. Therefore, it is essential to evaluate the changing circumstances, such as wind direction or runway changes, before dispatching resources to ensure an effective response.

By fostering discipline and respectful procedures, we can enhance the overall coordination, efficiency, and effectiveness of all institutions involved in emergency response. This would lead to a more streamlined and synchronized approach to handling natural disasters, ultimately benefiting the safety and well-being of those affected.

Interview to Sigrún Karlsdóttir (Icelandic Meteorological Office)

1. Could you tell me your name and position?

My name is Sigrún Karlsdóttir and I am the Director of Natural Hazards Services.

2. When was the IMO created?

It was created in 1920.

3. What are the main tasks of the IMO?

The main tasks of the Icelandic Meteorological Office (IMO) encompass various areas:

- Meteorology: The IMO conducts weather observations and provides weather forecasts, including issuing warnings and alerts related to weather conditions.
- Earth Monitoring: The IMO monitors various aspects of the Earth, including seismic activity, deformation, and other geological phenomena. It provides status updates, assessments, and warnings related to these events.
- Volcanic Monitoring: The IMO monitors volcanic activity, assessing volcanic precursors and hazards, and issuing relevant warnings and advisories.
- Hydrology: The IMO conducts hydrological monitoring, particularly related to floods. It provides monitoring data and issues warnings regarding potential flood events.
- Storm Surge Warnings: The IMO issues storm surge warnings, which are related to coastal flooding caused by severe storms. IMO collaborates with the road authorities regarding storm surge.
- Avalanches: IMO monitors and issues forecast and warnings about avalanches and landslides. In addition, IMO is in charge of issuing evacuation orders in relation to avalanches. This is the only natural hazard that IMO has this responsibility, in other cases it is the responsibility of the Department of Civil Protection and Emergency Management of the National Commissioner of the Icelandic Police (Civil Protection) to issue evacuation orders. The Icelandic Meteorological Office's involvement in avalanche management highlights its importance in ensuring the safety of individuals and communities facing this specific natural hazard.

For other types of natural hazards, the Icelandic Meteorological Office provides information about the event's status and conditions. The decision to order an evacuation in those cases is handled by the Civil Protection, with the Icelandic Meteorological Office playing a supporting role by providing essential data and insights.

Regarding climate and adaptation, IMO has important role regarding research including downscaling of IPCC scenarios for Iceland and surrounding areas. In addition, IMO hosts the office for climate change and adaptation, which has the main role of linking together the research community and stakeholder, enhancing research in relation to climate change and adaptation. The office is the focal point to the international community, including IPCC, as well as communicating and providing information to the public about climate change and adaptation.

IMO conducts research in all these fields mentioned above, i.e. weather and climate, atmospheric processes, glacier and avalanche and landslides, hydrological systems, earthquakes and volcanic processes and geohazards. IMO also focuses on research in multi-parameter geophysical monitoring to develop more accurate forecasts and warnings of hazardous events. In addition, IMO conducts hazard and risk assessments for avalanche, landslide, floods, storm surge, volcanoes and earthquakes.

In summary, the IMO covers a broad range of responsibilities, including weather forecasting, earth and volcanic monitoring, hydrology, storm surge warnings, and climate-related tasks. Its primary focus is on weather and natural hazards, ensuring the safety and well-being of the Icelandic population.

4. **In addition to monitoring and surveillance, do you carry out other different tasks, such as training or outreach, or others that you would like to highlight?**

Yes, the Icelandic Meteorological Office (IMO) also undertakes various other tasks, including outreach and communication to the population. These efforts are considered crucial in effectively conveying important information to the public.

To enhance outreach, the IMO has a dedicated communication officer. IMO utilize different media channels such as radio, television, and social media platforms to disseminate their messages. The IMO also emphasizes the importance of improving their website to ensure that people understand and benefit from the information provided.

The IMO's website serves as a valuable resource for the community, offering a range of maps and relevant information. Their aim is not only to increase public knowledge but also to educate politicians and local planning authorities about various meteorological and natural hazard-related aspects.

Looking ahead, the IMO is committed to further improving their outreach efforts and achieving even better results in the coming years, ensuring effective communication with the public and relevant stakeholders.

5. **Do you elaborate hazard, risk or vulnerability maps of Iceland?**

Yes, the IMO does develop hazard risk and vulnerability maps for Iceland. These maps are an essential tool for assessing and understanding the potential risks associated with natural hazards. As mentioned earlier, the IMO's website contains a variety of maps and information that are publicly accessible and serve as a resource for the community.

Per today most work has been done in relation to avalanches, volcanoes, floods and storm surge. There is still a lot of work that lies ahead, when it comes to hazard, risk and vulnerability mapping for natural hazard in Iceland. The IMO acknowledges the need for continuous improvement in this area. They are actively working on enhancing their mapping capabilities, particularly in relation to natural hazards and their connection to climate change. The IMO utilizes web-based map tools, but they have plans to further develop and enhance these tools to provide even more accurate and comprehensive information.

The IMO's efforts in elaborating hazard risk and vulnerability maps align with their commitment to providing valuable resources and knowledge to the public, contributing to better risk assessment and preparedness in Iceland.

6. Where does the IMO receive its monetary funds from?

The primary source of monetary funds for the IMO is the state. In addition, the international aviation supports the operations and activities of the institute. These fundings ensures the core functioning of the office, including weather observations, forecasting, natural hazard monitoring, and related services.

In some cases, the IMO may receive additional financial support from other institutes or the private sector for specific measurements or projects if they are specifically requested or deemed necessary.

Additionally, the IMO may also obtain funds through national and international research grants. In such cases, if instruments or equipment are acquired through research funding, they sometimes become part of the IMO's network after the end of the research project. This is especially the case if they are seen to be important for monitoring efforts for natural hazards. The office then takes responsibility for the ongoing maintenance and operation of these instruments.

Overall, the state funding forms the primary source of financial support for the IMO's activities, while fundings from the international aviation, research funds and occasional contributions from other organizations supplement their operations and facilitate the expansion and maintenance of their monitoring capabilities.

7. How many sections or departments is the IMO divided into and what is each area responsible for?

Currently (at the time of the interview), the IMO is structured into four divisions: the Observation and Technology Division, IT Division, Research and Development Division, and the Monitoring and Forecast Division. Additionally, there is an Administration department and the Director's Office.

However, there are plans to reorganize the structure, effective from January 1st 2023. The new structure will consist of two main divisions: the Research and Services Division and the Infrastructure Division. These two divisions will be responsible for research, services, monitoring, and IT-related functions within the IMO.

Apart from the divisions, the IMO will continue to have administrative departments such as the Office for Climate Change and Adaptation and the Office for Natural Hazards. These offices primarily handle administrative tasks related to their respective areas.

Overall, the restructuring aims to streamline and enhance the efficiency of the IMO's operations while ensuring effective communication and collaboration between the different divisions and departments.

8. And what improvement do you think you will achieve with this division?

The primary goal of the upcoming division restructuring within the Icelandic Meteorological Office (IMO) is to enhance collaboration and improve services provided to the public. By reducing the number of divisions and creating a more streamlined structure, the IMO aims to foster better focus and collaboration among its staff.

With fewer divisions but a diverse range of tasks within each division, the goal is to create a more cohesive and integrated approach to serving the public. By optimizing communication and cooperation between different areas of expertise within the institute, the IMO seeks to ensure that it effectively fulfills its purpose of delivering valuable services to the public.

The overarching objective is to strengthen the institute's ability to meet the needs of the society and provide high-quality services in the most efficient and effective manner possible. By improving collaboration and focus, the IMO aims to enhance its overall performance and deliver better outcomes for the benefit of the public it serves.

9. Where does IMO stand in relation to other institutions involved in risk management in Iceland (e.g. Civil Protection, the University of Iceland, the SAR, the Government or administrations)?

The IMO plays a crucial role in risk management in Iceland, particularly in relation to natural hazards. By law, the IMO has the mandate to conduct risk assessments for natural hazards at the request of the government. This clearly establishes the institute's role in this domain.

As the monitoring institute for natural hazards, the IMO provides essential information to Civil Protection and other relevant stakeholders responsible for critical infrastructure, such as aviation and energy authorities. The IMO's monitoring activities and information support are vital for effective risk management in the country.

The IMO also collaborates with other institutions, including universities and specialized infrastructure entities like the road authorities and the Icelandic Institute of Natural History. This collaboration allows for the exchange of expertise and resources, enhancing the monitoring and understanding of natural hazards in Iceland.

In terms of comparison, the situation is similar to Spain, where you have the IGN (National Geographic Institute) responsible for monitoring, and collaboration with other research institutes and organizations. In Iceland, the IMO takes on a similar role as the primary monitoring institute, while collaborating with other institutions to enhance their capabilities and knowledge in risk management.

10. How do you differ from those in the institute, or how do you combine your efforts?

When it comes to avalanches, we have a strong collaboration with the Icelandic Institute of Natural History. We work closely together and even have a shared database. That's one of the main tasks we focus on. However, we also recognize the valuable expertise they possess in other areas, and if we see opportunities for collaboration, we make use of that as well. One area where we benefit greatly from their work is in geological mapping. Their expertise in this field provides us with crucial information here at IMO. Additionally, when it comes to landslide, they have extensive knowledge, which is extremely valuable to us.

11. What is the general role of the IMO in risk management in Iceland?

The IMO plays a crucial role in risk management in Iceland, primarily through forecasting and monitoring. As for prevention actions before a natural disaster, we have developed a robust system within our monitoring and forecast division. This system has been in place since 2015, and has proven to be effective in keeping everyone, involved in risk management, informed about the status and precursors of natural hazards in Iceland.

Daily, a meeting is held at 14:00 UTC, where the current status of nature is discussed, i.e. weather conditions, and forecasts for the upcoming days, risk of avalanches and landslides, floods, earthquakes and deformation and other precursors for volcanic activities and other issues related to natural hazards. The Civil Protection, head of police and stakeholders in charge of important infrastructure are invited to join the daily meetings via remote connection. This routine is followed consistently, regardless of whether any significant events are occurring at the time. If we notice any precursors, such as changes in seismic or volcanic activity, or if we receive a weather forecast indicating potentially hazardous conditions, we advise relevant personnel, Civil Protection and stakeholders in charge of important infrastructure to join the meeting. This ensures that those responsible for taking actions are well-informed about the expected conditions and precursors we observe. In addition to these daily meetings, meetings are held more frequently if needed.

A few years ago, we implemented a color-coded impact-based warning system called the Common Alert Protocol, which originated from the World Meteorological Organization (WMO). This system primarily focuses on weather-related events. We have seen its effectiveness in reaching the general public as well as personnel responsible for critical infrastructure and citizen protection. Additionally, we aim to expand this system to incorporate different types of natural hazards, such as landslides and floods, in the near future.

In relation to avalanche risk for large domains, that are known to have a relatively high risk of avalanches in Iceland, a color coded information is issued twice per week through the web-page of IMO. This information is especially crucial for outdoor activities, where people need an overview of the risk in those areas. We provide web-based forecasts for these regions, giving them a comprehensive understanding of the risk for the next few days ahead.

Regarding volcanic activity and aviation, IMO issues color-coded warnings according to the ICAO (International Civil Aviation Organization) guidelines.

12. What does your surveillance network consist of? I imagine it will be different for each type of phenomenon, right?

Our surveillance network consists of more than 600 instruments located throughout the country, each tailored to monitor specific phenomena. We have a variety of equipment, including weather stations and two weather radars—one in the southwest and another in the east. The third weather radar is being installed in North Iceland, which will be operational by the beginning of next year (2023). The ultimate goal is to establish a comprehensive network of weather radars covering the entire country by around 2030 or 2032.

These weather radars play a crucial role in providing essential information for weather-related events and also contribute to aviation safety. They also offer valuable data for public use. In addition to weather monitoring, we have seismic stations, GPS stations, and gas measurement equipment for monitoring volcanoes and earthquakes. In some cases, we may relocate instruments, such as gas measurement devices, to areas where precursors are detected in order to gain more insight into the situation.

We also have flood measurement systems in various rivers, enabling us to issue flood warnings and monitor the flow. As for technical advancements, we recognize the importance of keeping up with the latest developments. The instruments we currently use may be supplemented or replaced by new technologies that further enhance our monitoring capabilities.

An example of implementing new technology can be seen in Seyðisfjörður, in the East, where a significant landslide occurred two years ago in December. Happily, there were no loss of lives, but around 10 or 11 houses were completely destroyed. To monitor the movement of the mountain above, we are now utilizing combination of several types of monitoring system among others InSAR technology, which is an innovative approach. In the Westfjords there is another project to investigate the utility of snow flood radar system, similar to what is used in Spain, as it proves to be essential in certain situations.

It's important to note that in many cases, it's not just a single instrument that provides the answer but rather the combination of various instruments within our network. The synergy of the complete network is crucial. Furthermore, we often find that instruments initially set up for specific purposes can be utilized for broader applications, showcasing the adaptability and versatility of our monitoring systems.

13. How do you detect that there is an anomalous situation in relation to some natural phenomenon?

Detecting anomalous situations involves a combination of factors. We start by gathering data and monitoring the phenomenon over an extended period. This helps us establish the background level or normal conditions. We do have historical data that goes back many years, which allows us to compare current observations with past records.

For example, when monitoring volcanoes, we look at seismic activity and compare it to the average levels. We also analyze data from GPS stations to detect any deformation. These indications help us identify anomalous situations.

In the case of meteorological events, such as storms or extreme weather, we rely on forecasts and observations from our weather stations and radars. By comparing the current conditions to what is expected or typical, we can identify unusual or abnormal patterns. Additionally, we consider the societal context and how it has evolved. For instance, strong winds in the summer can have different impacts compared to the winter. This understanding helps us tailor our warnings and response accordingly, depending on the season and specific circumstances.

14. What is the first thing you do when you detect such an anomaly?

When an anomaly is detected, the IMO relies on its contingency plans. Having well-developed contingency plans is crucial for an institute like the IMO, covering various types of natural hazards. We even prepare contingency plans for less frequent events to ensure preparedness.

The specific actions taken may vary depending on the nature of the hazard. The key aspect is initiating the contingency plan, which involves contacting the relevant entities or authorities. For example, in the case of volcanic activity, we inform the Icelandic Air navigation service provider (ISAVIA) and maintain a close relationship with the London Volcanic Ash Advisory Centre (London VAAC, part of the UK meteorological Office). Our contingency plans outline whom to contact and the necessary steps to follow.

These plans are comprehensive and well-documented, ensuring that everyone involved knows their roles and responsibilities. They provide clear guidelines on how to handle different scenarios, ensuring a coordinated and efficient response. In some cases, where appropriate, there are criteria and protocols to determine the level of alert or emergency that should be declared based on the situation at hand.

15. How does the IMO determine whether an alert should be issued or if it's just an anomalous situation that doesn't require an alert?

The decision to issue an alert or not depends on the specific hazard being monitored. It involves considering various factors and is somewhat of a learning process. Let me provide you with a couple of examples:

In the case of avalanches, we take into account factors such as weather conditions, weather forecast, snow stability, and the history of snow layers. By analyzing this information, we can determine if there is a potential risk and communicate it to our collaborators.

For certain hazards, we may have both long-term and short-term warnings. We continuously monitor the situation and evaluate the likelihood and timing of an event. For instance, if there is a possibility of a flood in a river, we would inform the public and stakeholders, but clarify that it may not happen immediately. We provide updates as the situation evolves.

In the case of volcanoes, we have established a classification system based on precursors observed. Each volcano may have different levels of warning based on their specific characteristics. We have learned from past experiences that volcanic situations can vary, so it's crucial to stay prepared.

The use of a color-coded alters, serves as a visual communication tool to inform the population about the level of alert. Different colors represent different levels of risk, allowing people to understand the severity of the situation at a glance.

Overall, the decision to issue an alert or maintain a heightened monitoring level is based on a combination of scientific analysis, historical data, and ongoing monitoring efforts. It's important to remain adaptable and continuously learn from nature's unpredictable behavior.

16. How does the transition from one alert level to another occur, and who makes the decision to change the color of the alert?

The decision-making process involves collaboration between the IMO, the Civil Protection, stakeholders in charge of important infrastructure and local authorities. It is not solely the responsibility of the IMO. The decision is based on discussions and considerations of various factors, including the forecasted weather conditions, the potential impacts, and the specific region or area affected.

When it comes to the color-coded alerts for weather-related events, the alert levels are based on an impact-based approach. The IMO, in collaboration with the Civil Protection, stakeholders in charge of important infrastructure and local authorities, assesses the severity of the situation and determines the appropriate alert level. This decision is influenced by the level of expected impact and takes into account factors such as the strength of winds, the location, and the season.

The transition between alert levels depends on changes in the forecast or the actual conditions. If the situation is not as severe as initially predicted, the alert level may be lowered. Ultimately, the decision-making process aims to ensure the safety of the population and the appropriate allocation of resources.

It's important to note that the color-coded impact based alert system is currently implemented for weather-related events. However, there are plans to expand it to include other hazards, such as landslides and floods. The system has proven effective in communicating the level of alert during the recent volcanic eruption in the Palma region, and it is well understood by the public.

Additionally, there are separate color-coded systems in place for aviation during volcanic eruptions and for avalanches, which follow international codes and guidelines.

17. Once an emergency has been declared, what is the usual flow of action?

Once an emergency has been declared and a natural disaster occurs, the IMO follows a specific flow of action. Here are the usual steps taken:

- Activation of Contingency Plans: The IMO activates its contingency plans, which include predefined procedures and protocols for managing emergencies. These plans ensure that everyone involved is aware of their roles and responsibilities.
- Manpower Allocation: Sufficient manpower is allocated to cover various tasks and responsibilities during the emergency. This includes personnel who attend meetings, gather information about the event's status and forecasts, and potentially go out for fieldwork.
- Action Manager: An action manager is designated or appointed to oversee and coordinate the response efforts. This individual is responsible for ensuring that the necessary actions are taken, resources are properly utilized, and the response is effectively managed.
- Communication and Information Sharing: Clear and effective communication channels are established to share information among team members, relevant authorities, and stakeholders. This facilitates the dissemination of crucial updates, instructions, and warnings.
- Risk Assessment: Before sending personnel for fieldwork or any on-site activities, a risk assessment is conducted. This assessment ensures the safety of the individuals involved and helps determine whether it is appropriate and safe to deploy personnel to specific areas.
- Prioritization and Resource Management: The IMO manages resources and prioritizes actions based on the severity and urgency of the situation. This includes allocating resources such as equipment, personnel, and support services to address the most critical needs first.
- Adherence to Protocols: Strict adherence to established protocols and procedures is essential throughout the emergency response. This ensures consistency, efficiency, and the proper execution of tasks and decisions.

By following these steps and adhering to contingency plans, the IMO aims to effectively respond to the emergency, mitigate risks, and provide support and assistance as required.

18. How is the transfer of information with the Icelandic Aviation Oceanic Area Control Center (ISAVIA) carried out?

The transmission of information from the IMO to the Icelandic Aviation Oceanic Area Control and the UK Meteorological office is carried out through various channels. Here's how the process typically works:

- Telephone Communication: Direct telephone communication is used to convey important and time-sensitive information to the relevant authorities. This allows for immediate notification and discussion of critical details related to volcanic activity or other natural hazards.
- VONA (Volcano Observatory Notice for Aviation): VONA is an international platform used for sharing volcano-related advisories and graphic information. The IMO uses VONA to issue alerts and notifications to the aviation and government authorities.
- Network Communication: The IMO leverages its network to disseminate information to the appropriate recipients. This network likely includes dedicated communication channels and protocols established with the Icelandic Aviation Oceanic Area Control and the UK Meteorological office. These channels ensure efficient and secure transmission of relevant information.

Through a combination of telephone communication, the VONA, and network communication, the IMO ensures that crucial information reaches the appropriate authorities promptly and accurately. These communication channels facilitate effective coordination, decision-making, and response efforts in managing natural hazards and their potential impact on aviation and public safety.

19. What tasks does the IMO perform after the end of an emergency?

After the end of an emergency or natural disaster, the IMO performs several tasks to ensure a smooth transition and improve their systems. Here's an overview of the typical tasks carried out:

- Monthly Exercises: The IMO engages in regular monthly exercises in collaboration with, ISAVIA (Iceland's air navigation service provider), and the London Volcanic Ash Advisory Centre. These exercises help to practice and evaluate the contingency plans, train staff, and ensure effective coordination between relevant organizations.
- Learning and Improvement: The IMO takes the opportunity to learn from each event or emergency. They conduct a thorough review and analysis of the event, assessing what was done well and identifying areas that could be improved. This evaluation helps to enhance their systems, procedures, and response strategies for future incidents.
- System Evaluation: The IMO evaluates the performance of their systems during exercises, including monitoring and forecasting tools, communication channels, and response protocols. This evaluation helps identify any weaknesses or areas that require refinement to strengthen the overall effectiveness of their operations.
- Knowledge and Experience Sharing: The lessons learned from each event are shared within the organization and with relevant stakeholders. This knowledge sharing

facilitates continuous improvement and ensures that the expertise gained during the event is disseminated for the benefit of future emergency response efforts.

By engaging in exercises, conducting post-event evaluations, and fostering a culture of learning and improvement, the IMO strives to enhance their capabilities, optimize their systems, and be better prepared for future emergencies or natural disasters.

20. Are familiar with the concept of multi-hazard?

Yes.

21. So, there is a separate emergency plan for each natural hazard, isn’t there?

Yes.

22. So, how do you deal with multi-hazard scenarios or possible concatenation of hazards, for example, earthquakes with avalanches, or landslides with tsunamis, or eruptions with major floods?

In our case, we have a monitoring room where our team of meteorological forecasters and natural hazard monitoring specialists work together. We hold regular meetings, the daily 14:00 o’clock meetings, where we review all the available information.

For example, let's say our forecasters notice a weather pattern in the coming days that indicates a potential combination of severe weather and high avalanche risk. The avalanche specialists can take that information and provide their insights based on the snow layers and precipitation forecasts. This collaborative approach within our group is crucial for maintaining a comprehensive multi-hazard overview.

An example can be taken from the volcanic eruptions in the Reykjanes Peninsula (in 2021 over six months period (March to September) and in 2022 over three weeks in August).

Sometimes situations occurred where volcano hazards coincided with severe weather conditions. In such cases, we issued warnings specifically for the area, taking into account both weather-based information and gas threats, which requires close collaboration between the relevant experts.

Ultimately, the success of managing multi-hazard situations relies on our interdisciplinary approach. Our daily meetings play a vital role in gathering different perspectives and expertise. We continuously explore effective ways to convey the combined information, including maps, to the public through various channels such as our media, website, and social media platforms.

This ensures that the public can understand and respond appropriately to the different hazards involved.

Moreover, when dealing with prolonged periods of multiple hazards, maintaining focus can be challenging. Therefore, we remain aware of the potential cascading effects and continuously assess the situation to ensure the appropriate measures are in place.

23. Could you tell me how you experienced the 2010 eruption?

Yes, I was personally involved in the 2010 eruption, and it was definitely a significant learning experience for us. One of the most challenging aspects was the intense media focus we faced. We were inundated with interview requests, to the point where it was affecting our work. However, it was a valuable lesson for us.

Prior to the eruption, we had already established a strong collaboration with the UK Met Office, and ISAVIA. Several years prior the eruption we had pointed out and discussed the possibility of a volcanic eruption in Iceland causing significant disruptions for aviation, and unfortunately, that scenario became a reality in 2010.

Fortunately, our ministry and civil protection agencies quickly recognized the need for assistance with media attention. By the second day, a dedicated media center was established under the Civil Protection authority. This allowed us to focus more on our core responsibilities.

Additionally, the London Volcanic Ash Advisory Centre (London VAAC) also learned a lot from the event, particularly in terms of the information they required from IMO. It was a great opportunity for us to improve the collaboration and information exchange.

Since we had contingency plans in place, we activated them and followed the established protocols. It was crucial to ensure that our manpower was not overstrained, considering the size of our country. We needed to make sure our team had sufficient rest during the six-week period of the eruption. The pressure during such events varies depending on the nature of the eruption. In this case, our forecasters faced the most significant workload. We were seriously considering seeking assistance from our Nordic meteorological colleagues, but happily the eruption ended in time so that was not needed.

Throughout the eruption, we closely collaborated with ISAVIA and the UK Met Office (where London VAAC is located), constantly learning and adapting to the situation. It was a collective learning experience for everyone involved. The changes that occurred in the aviation system following the eruption reflect the lessons learned and have further strengthened our preparedness.

You could say that the eruption served as a valuable training opportunity, helping us achieve an even better state of preparedness. Just a year later, during the Grímsvötn eruption in 2011, the media center was immediately activated, and everything proceeded smoothly based on the lessons we had learned from the previous eruption.

24. Did the COVID pandemic affect your work then (i.e. during the 2021 eruption)?

Yes, the COVID pandemic did have an effect on our work during the eruption, but it also presented us with some advantages. One positive aspect was that everyone was already familiar with using computers and virtual meetings due to COVID restrictions. So, in terms of holding virtual meetings, everything went smoothly.

However, there were challenges when it came to monitoring and fieldwork. We had to ensure that we didn't have a situation where a large number of our monitoring division personnel fell sick simultaneously. It was crucial to maintain the institute's activity. Therefore, we implemented measures such as having individuals who were working closely together or sharing transportation, to work from home for a few days before returning to the office.

Logistics became a significant consideration to minimize the risk of contamination. We made every effort to prevent people from getting infected, including the use of masks and practicing social distancing whenever possible.

Within the institute, we had strict rules in place, and those who could work from home were encouraged to do so. We ensured that all networks were functioning properly to support remote work. Our primary focus was to protect the monitoring room, ensuring that the unit could continue its work without everyone being exposed to the risk of contamination simultaneously.

Overall, it was a logistical challenge, but we managed to navigate through it successfully.

25. Which natural hazard do you think causes the most damage, injuries or deaths each year in Iceland?

The natural hazard that has historically caused the most damages, injuries, and deaths in Iceland is avalanches. However, when it comes to the highest damage on property, it has been caused by earthquakes and volcanic eruptions.

While efforts have been made to implement protection systems against avalanches in towns and villages that are prone to such events, it is crucial to continue building knowledge within Icelandic society. The occurrence of natural hazards can be sporadic, with significant time intervals between events, which can lead to a loss of knowledge over time. Additionally, there are cases where individuals, whether of Icelandic origin or foreign origin, may be unaware or have limited knowledge of the hazards present in certain areas.

Therefore, it is essential to educate both the authorities and the population about these hazards. This includes raising awareness about the risks associated with avalanches, earthquakes, and volcanic eruptions, and promoting preparedness measures to mitigate their impact. By fostering knowledge-building and providing education, it is possible to enhance the overall resilience of Icelandic communities in the face of these natural hazards.

26. Have you noticed that any event has increased its impact in recent years, either by increasing its frequency, area or magnitude (related to climate change)?

Yes, there is a need to be vigilant and cautious regarding the potential impact of climate change on natural hazards in Iceland. One area of concern is the changes occurring in permafrost, which can lead to an increased risk of landslides. There have been instances of severe landslides in recent years, and although there were no casualties, it is important to acknowledge that such events have occurred throughout history.

While it is challenging to directly attribute these events to climate change, the intensity of precipitation preceding the landslides and the overall pattern of increased rainfall over a short period may indicate a potential link. However, it is difficult to definitively pinpoint climate change as the sole cause. Nonetheless, it is essential to remain vigilant and recognize that climate change has the potential to amplify certain patterns and increase the likelihood of such hazards.

Monitoring and studying these changes in conjunction with ongoing climate research can contribute to a better understanding of the relationship between climate change and natural hazards in Iceland. By maintaining awareness and staying proactive, it is possible to mitigate risks and enhance preparedness efforts to minimize the impact of these events on human lives and infrastructure.

27. Has the increase in tourist arrivals led to any disruption in your usual procedure?

The increasing number of tourists visiting Iceland can present challenges in terms of disaster prevention and response. It is true that tourists may lack the local knowledge and experience of the Icelandic population when it comes to dealing with natural events. This can potentially lead to disruptions in normal procedures and an increased risk of injuries or deaths during natural disasters.

The IMO and other relevant authorities have recognized the importance of reaching out to both tourists and new residents in order to provide them with information about natural hazards and weather conditions. Initiatives such as "Safe Travel" aim to inform tourists about potential risks and educate them on how to stay safe during their visit.

However, reaching and effectively communicating with tourists and new residents can be a challenge. The use of technology, such as mobile apps or SMS notifications, can be explored to disseminate important information in a timely manner. The IMO and other organizations are continually working on adapting their communication strategies to ensure that the message regarding natural hazards reaches as many people as possible.

By addressing these challenges and proactively engaging with tourists and new residents, the aim is to enhance awareness and preparedness, ultimately reducing the potential risks and consequences associated with natural disasters in Iceland.

28. Do you have students in training, such as doctoral students, master's students, interns, etc.?

Yes, we do have students in training, including doctoral students and interns. The presence of students and interns at IMO can vary depending on various factors, such as ongoing research projects and collaborations with universities in Iceland or abroad.

In some cases, doctoral students or postdocs may join IMO as part of their research projects or collaborations. Additionally, internships during the summer period are also offered at IMO. The availability of these training opportunities depends on the capacity and resources of IMO at any given time.

Having students and interns at IMO allows for knowledge exchange, research collaboration, and the development of future professionals in the field of meteorology, geophysics and related disciplines.

29. Do you provide training and education to the population on natural hazards?

Yes, we provide training and education to the population on natural hazards. However, improvements can be made. IMO strives to improve its efforts in this regard, e.g. to enhance the outreach and improve the information and material available on IMO web-site. One aspect that hopefully will realize in the coming future is collaboration with the educational authorities. The aim is to provide education on natural hazards and their mitigation from primary school to higher education.

Collaboration with the Civil Protection is also emphasized, as it plays a crucial role in disseminating information and raising awareness about natural hazards among the population.

By strengthening their collaboration and outreach efforts, IMO seeks to ensure that the public is well-informed and educated about the potential risks posed by natural hazards in Iceland.

30. How do you feel the perception of risk in the population?

The perception of natural hazards among the general population in Iceland varies. Some individuals, especially those with long experience or who have lived in areas prone to natural hazards, are highly aware of the risks and collaborate effectively with the measures put in place. They understand the importance of preparedness and take necessary precautions.

However, in some cases, there may be limited awareness or even denial of the potential risks associated with natural hazards. This could be due to various factors such as lack of personal experience, misinformation, or a general sense of complacency. It is crucial to address these gaps in understanding and ensure that all members of the population have a realistic perception of natural hazards and their potential impacts.

31. What do you think are the keys to your way of managing risk in Iceland, compared to other places you know? And where do you think the risk management system should improve?

The key strengths of risk management in Iceland compared to other places are the small and interconnected nature of the country. The close interaction and collaboration between different institutes involved in risk management make communication and information exchange easier. The daily meetings that discuss natural hazards and their status have been instrumental in improving coordination and response efforts. The implementation of color-coded warnings and regular training of contingency plans are also notable achievements.

However, there is always room for improvement. One area of focus is enhancing public education and increasing knowledge and awareness about natural hazards among the population. Improving the web-based information and services provided by the Icelandic Meteorological Office (IMO) can be valuable for both the general public and planning authorities. Strengthening collaboration between civil protection and authorities responsible for critical infrastructure is another important aspect to ensure effective risk management.

Overall, while Iceland has made significant progress in risk management, continuous improvement, education, and enhanced information services remain essential for better preparedness and response to natural hazards.

Interview to Birgir Vilhelm Óskarsson (Icelandic Institute of Natural History)

1. **Could you tell me your name and position?**

My name is Birgir Vilhelm Óskarsson and I am a researcher at the Icelandic Institute of Natural History.

2. **When was the Institute created?**

It's old. I mean, it was in the 1950s, 40s.

3. **What are the main tasks of the Institute?**

Sure, the Institute's main tasks revolve around documenting and mapping the diverse aspects of Icelandic nature, including vegetation, ecology, geology, and biology. We are responsible for publishing maps and conducting various activities such as bird counting and monitoring animal life. Essentially, our role is to oversee and coordinate projects related to Iceland's natural environment.

4. **In addition to conducting basic research on the zoology, botany and geology of Iceland; handling systematic documentation of nature in Iceland; and preserving research findings and specimens in scientific collections, do you carry out other different tasks, such as training or outreach, monitoring or others that you would like to highlight?**

Absolutely. In addition to our core research activities, we actively engage in outreach efforts. We regularly post news and information on our website, including freely accessible interactive maps that provide valuable insights into our work. We also offer environmental assessment services, particularly for major construction projects, where we play a role in evaluating the environmental impact. Furthermore, we collaborate with authorities to provide information on Iceland's nature for parks, geoparks, and natural reserves.

My department, the geology department, has additional responsibilities. We oversee permits for rock sample collection and maintain a comprehensive collection of rock samples, ensuring controlled access for scientists. This helps us monitor what goes in and out, especially concerning fossils and other significant specimens. Currently, we are focused on creating 1:100,000 scale maps and monitoring the protected area of Surtsey. In Surtsey this involves annual expeditions to assess vegetation, geomorphological changes, and geological transformations. I have also been involved in applying photogrammetry to map Surtsey.

Moreover, we collaborate on various smaller projects, often serving as core supervisors. These projects frequently involve mapping and geological surveys. We have also contributed to training students in geological mapping and have collaborated closely with the University in delivering educational programs

5. **Where do you receive your monetary funds from?**

The primary source of our monetary funds is the government. As a government-funded institution, we receive financial support to sustain our operations and carry out our research activities. Additionally, we actively apply for research grants from various sources to secure additional funding for specific projects or initiatives.

6. **How many sections or departments is Institute divided into and what is each area responsible for?**

The Institute is divided into three main sections or departments. We have the Geography department, the Biology department, and the Geology department.

7. **Where does Institute stand in relation to other institutions involved in risk management in Iceland (e.g. the University of Iceland, the Icelandic Met Office, the Government)?**

While the Institute's primary focus is on studying and documenting the natural environment of Iceland, we have started to play a role in risk assessment, particularly in the field of volcanic risk assessment. In this area, we collaborate closely with the Geodetic Institute, the University of Iceland, and the Civil Protection. These institutions work in coordination with the Icelandic Met Office and other relevant organizations. As part of our involvement, our Institute collects raw data, such as aerial images, for risk assessment purposes. I personally collect the data by flying and then generate digital elevation models and 3D models, which I share with my colleagues at the Geodetic Institute. So, our role is primarily in providing data and collaborating with other institutions.

8. **Are there other institutions in Iceland that share your same tasks, i.e. also do research, preservation, dissemination, monitoring? If so, which ones are they? And how do you combine or what is your relationship, i.e. do you work sharing knowledge, sharing resources?**

This institute serves a slightly different role compared to others. The primary responsibility for risk assessment lies with the Met Office, although they collaborate with personnel from various institutes, including universities and our own institute. Our specific role focuses more on data preservation and collection, rather than directly conducting risk assessments. However, it is worth noting that the data we provide plays a crucial role in the risk assessment process. The entire risk assessment system begins with the compilation of data onto a map. It's somewhat intriguing how these institutes are structured currently, and there are plans to consolidate them into a single institute. This proposed unification aims to address the current separation between institutes and improve coordination. We collaborate extensively with the Geodetic institute, and ideally, we should function as a single entity. Consequently, there are plans underway to implement changes and merge some of the key institutes, allowing for better organization, particularly in the realm of risk assessment.

9. Do you work jointly with NGOs? If so, what is this relationship like and what kind of joint work do you do?

Civil protection plays a significant role in overseeing and maintaining close connections with the institutes involved in risk assessment. They are likely to have greater control and coordination in this regard.

10. In terms of natural hazards, what do you do research on?

As a volcanologist and geologist, my primary focus is on studying volcanic activity in Iceland. Given that Iceland is a land filled with volcanic features, my work primarily revolves around mapping old volcanoes and analyzing their geological characteristics. The knowledge and experience I gain from mapping these old volcanoes can be applied to better understand and study new volcanic eruptions.

Since 2010, I have been actively involved in studying volcanic eruptions, particularly the recent eruption in 2021. During this eruption, we employed a new technology called photogrammetry, which allowed us to capture detailed aerial images of the volcanic activity. Although photogrammetry itself is not a new technology, its application in the context of volcanic eruptions was a novel approach for us.

We utilized normal cameras mounted on airplanes to capture images from a safe distance. This method provided several advantages over using drones. By flying at higher altitudes and covering larger areas, we were able to efficiently gather extensive data. It also reduced the risks associated with being in close proximity to an active volcano, as often experienced when operating drones near volcanic plumes. However, we did face challenges in navigating around large plumes and ensuring comprehensive coverage.

The use of airplanes and photogrammetry significantly expedited our data processing time. Instead of working with a multitude of drone images, we could generate a complete model of the entire lava field from a relatively small number of high-resolution aerial images. This approach has proven to be both effective and safer for studying volcanic eruptions.

Overall, my work as a volcanologist combines field mapping, data collection, and the application of innovative technologies like photogrammetry to enhance our understanding of volcanic activity in Iceland.

11. Because this model can be obtained from one single flight, right?

Absolutely. With the photogrammetry technique we utilized, it was possible to obtain the required data from a single flight. The duration of the flight would typically be around ten minutes, during which we would capture a series of aerial photographs. However, certain factors such as cloud cover would sometimes necessitate flying at lower altitudes, resulting in a higher number of images, typically around 300 to 400.

The processing time for generating the model depended on the number of images collected. When flying at higher altitudes and capturing the area of interest with fewer images, we could cover the entire region with as few as ten images. This approach significantly reduced the processing time required to generate the complete model.

12. Are these studies commissioned by any other institution to the Institute or do they come out of the will of the Institute's researchers?

Certainly. The studies using the photogrammetry method were initially driven by the researchers within the Institute. As a volcanologist and geologist specializing in mapping, I recognized the potential of utilizing aerial photography to gather data and create detailed models of volcanic landscapes. It was important for me to demonstrate the effectiveness of this method to other institutions and stakeholders.

When the volcanic eruption occurred, there was already a plan in place to use drones for data collection. However, I proposed using manned aircraft instead, as it offered greater advantages in terms of efficiency and cost-effectiveness. I conducted a flight and successfully covered the area of interest in just three hours. The resulting model was then shared with the relevant stakeholders after a few hours.

The efficiency and cost-effectiveness of using manned aircraft for data collection became evident, as it required minimal resources and could be accomplished in a shorter timeframe. As a governmental institution, our photogrammetry lab operates in collaboration with the Civil Protection, and they requested our services for conducting the surveys during the eruption.

13. So the results of this research were transmitted only to civil protection or to any other institution that also requested it?

The data and findings from our research were shared with multiple institutions and organizations beyond the Civil Protection. While the Civil Protection received the 3D models initially, we also calculated various parameters such as volume, area, and effusion rate, which were shared with both the Civil Protection and other interested parties.

The information was disseminated to different stakeholders, including the media, to ensure broader awareness and understanding of the volcanic activity. Additionally, the digital elevation models were made available to the Icelandic Met Office, which plays a crucial role in monitoring and assessing volcanic events. Furthermore, scientists who expressed interest in utilizing the data were also granted access to the models.

14. Do you carry out hazard assessments for different natural hazards? If so, for which ones?

Yes, I am currently engaged in a study focused on hazard assessments for the Reykjanes Peninsula. The objective of this study is to estimate the eruption capacity of the peninsula by analyzing historical lava flows from the Holocene period. We have access to comprehensive information about the area and the size of past eruptions, which allows us to calculate the mean effusion rate or output rate of these eruptions using relevant equations.

By determining the mean effusion rate, we aim to understand the potential size and scale of eruptions on the Reykjanes Peninsula. This involves identifying the largest and smallest eruptions that have occurred, as well as determining the most common eruption sizes. Through statistical analysis, we can gain insights into the eruption patterns and assess the hazard level associated with volcanic activity in the region.

This assessment will contribute to our understanding of the volcanic hazards on the Reykjanes Peninsula and aid in the development of mitigation strategies and preparedness measures. By evaluating the eruption capacity, we can better anticipate and plan for potential volcanic events, enhancing the overall resilience of the region to volcanic hazards.

15. How do you carry out monitoring? Do you have some kind of surveillance network or is it done through campaigns?

At the Institute, we primarily carry out monitoring through photogrammetry surveys. Our focus has mainly been on monitoring volcanic eruptions in recent years, specifically the eruptions that occurred in 2021 and 2022. During these events, we utilized photogrammetry techniques to capture aerial images of the volcanic activity. This involved flying over the eruption site with airplanes equipped with cameras, enabling us to gather extensive visual data.

In addition to volcanic monitoring, we have a colleague based in North Iceland who specializes in monitoring landslides. We have even conducted drone flights over landslides to gather relevant information. This demonstrates that photogrammetry technology can be applied to various monitoring purposes, including landslide monitoring.

While our current involvement has primarily revolved around volcanic eruptions and landslides, photogrammetry has the potential for broader applications. It can be employed in diverse monitoring scenarios, providing valuable data for different types of natural phenomena. As technology advances and new monitoring needs arise, we remain open to exploring and expanding our monitoring capabilities to contribute to a wider range of research and hazard assessment efforts.

16. What about flooding on avalanches?

Indeed, photogrammetry is a technique that can be employed for assessing hazards, including avalanches. Avalanches typically occur in relatively smaller areas, making them suitable for drone-based assessments. Surveyors or specialized teams, including those within institutes like the Met Office, may be involved in conducting these assessments. Many institutes have their own fleet of drones that can be utilized for such purposes. In the event of an anomalous situation, such as an increase in seismicity or other indicators, the Met Office or relevant authorities can deploy drones to gather data and gain a better understanding of the situation. Drones offer a practical and efficient means of assessing hazards like avalanches in a timely manner.

17. So are you able to detect such an anomalous situation?

We experimented with photogrammetry to detect any surface changes, such as cracks, and the Met Office utilized our photographs and maps to map the cracks before the eruption, which proved to be useful. However, when it came to detecting vertical movement, the resolution of our data was insufficient. We were working with data that had a resolution of around 15 to 20 centimeters. Therefore, if there were uplift or subsidence of 5 to 10 centimeters, it would not be easily visible in our data. Nonetheless, some individuals attempted to utilize our data for such purposes as well.

18. Once an emergency has been declared, what is the role of the Institute?

Once an emergency has been declared, the role of the Institute involves two main activities. First, we conduct flights to monitor the situation. In the initial stages of the eruption, we aim to fly frequently, potentially every second day, depending on weather conditions. However, as the eruption progresses, the frequency of flights may decrease to approximately once every two weeks. This allows us to gather aerial data and assess the evolving situation.

Additionally, we establish and maintain a network of control points on the ground. These control points consist of targets, such as plates or flags, strategically positioned around the volcano. With the help of a GNSS (Global Navigation Satellite System) instrument, we accurately measure the precise coordinates of these control points, achieving a high level of accuracy, typically within two or three centimeters per side.

During our flights, we are able to observe these ground targets. By incorporating the coordinates of these control points into our modeling processes, we can accurately georeference and position the generated models in the real world. This allows for precise spatial alignment and enhances the reliability of our analyses.

Throughout the emergency response, we establish and maintain over 100 of these control points to support our operations and ensure accurate geospatial referencing.

19. And how do you process this data?

The data processing is carried out on dedicated workstations. We load the acquired images into specialized software designed for photogrammetry processing. There are various software options available specifically tailored for this purpose.

20. And what about the multi-hazard approach? It is the fact that more than one natural hazard occurs at the same time in one place, or not necessarily at the same time, but in the same place, as for example in Iceland. Here you have volcanic eruptions, avalanches, debris flow, floods, forest fires, earthquakes. And volcanic eruptions themselves are also multi-hazard events, producing lava flows, gas emissions, pyroclastic density currents, etc. How do you integrate this concept into your research, if at all?

In our research and data provision, we strive to integrate the concept of multi-hazard assessment. The data we generate plays a significant role in such assessments. For instance, the maps we produce cover a relatively large area, typically around 25 square kilometers. This extensive coverage allows us to monitor and track various potential changes or events that could occur within that region. Unlike drone surveys, which may focus primarily on the lava or specific areas, our aerial surveys provide a comprehensive overview of the entire area, enabling us to detect changes, landslides, or other significant occurrences.

We also collaborate with the deformation team by sharing ortho images whenever we observe cracks or fissures. This information assists them in monitoring the possibility of new fissure openings or identifying areas prone to such phenomena. Additionally, we remain attentive to other hazards, such as forest fires, that may coincide with the ongoing volcanic activities. By integrating these aspects into our research and data analysis, we contribute to a more comprehensive understanding of the multi-hazard environment and aid in assessing and managing associated risks effectively.

21. Could you tell me how you experienced the 2010 eruption? What was the role of the Institute?

During the 2010 eruption of Eyjafjallajökull, I personally experienced it as a student working on my master's project. Prior to the eruption, I had been researching a ridge on Eyjafjallajökull and had just completed my study on its eruption patterns, glacier melting, and the escape routes of the glacier's floodwaters. The eruption itself was quite complex in nature.

It initially began on the margin of the volcano as a basaltic eruption, triggering a silicic pocket of magma and aiding its ascent. Later on, it also erupted trachytes, which have a more alkaline composition. Interestingly, the eruption involved the simultaneous eruption of both basaltic and silicic magma.

When the Eyjafjallajökull eruption started in 2010, it began with a basaltic eruption on the edge of the volcano just as in my study. This sparked my curiosity as I speculated whether it would activate a silicic magma chamber just as happened in the other eruption. Eventually, the eruption migrated towards the central crater explosively, resembling the type of eruption I had previously described in my thesis.

As news of the eruption spread, many individuals within the field began referring to my thesis for insights and information. It was an interesting and somewhat surreal experience to see the relevance and applicability of my research during the actual eruption. If you're interested, I can show you my thesis to provide more details and context.

22. Did the COVID pandemic affect your work or the work of the Institute?

The COVID-19 pandemic did have some impact on our work at the Institute, although not significantly. One notable effect was related to the use of our main airplane. Typically, there is space for three individuals, but due to the strict protocols in place, the pilot insisted on having only one person aboard. This posed a challenge for training others in the techniques and procedures I was developing during the course of the eruption. I wanted to expand the team and train additional personnel to assist with the work, but the restrictions made it difficult to have another person in the airplane with me.

Additionally, there was an instance where I had to undergo quarantine, and during that time, I had to pass the camera equipment to another person. While this situation presented a minor inconvenience, it was not a major issue that significantly disrupted our operations.

Overall, the pandemic did introduce some limitations and adjustments to our work, particularly in terms of personnel training and adherence to safety protocols. However, we managed to adapt and continue our activities, ensuring the continuation of our research and data collection efforts.

23. Have you noticed that any event has increased its impact in recent years, either by increasing its frequency, area or magnitude?

While I cannot provide precise information regarding volcanic activity, it is evident that landslides, mudflows, and rock slides have increased in recent years. This increase in occurrence is quite apparent and requires proper monitoring to identify potential areas prone to deeper landslides. Although I am not directly involved in landslide monitoring, my role involves mapping mountain ranges and creating 3D models, which are made available for analysis. In the northern region of Iceland, my colleague utilizes these images to assess their accuracy and identify areas of potential landslide hazards.

It is worth noting that the areas of greatest concern for landslide monitoring are the oldest regions of Iceland, including the east fjords, the north, and the west fjords. These areas are characterized by steep mountains and fjords, which are inherently unstable landscapes. However, in terms of volcanic eruptions, Iceland experiences them approximately every three to five years, with a relatively constant pattern.

Regarding landslides, it is essential to conduct comprehensive research and monitoring across various natural hazards to fully understand if there have been any notable increases in frequency, geographical extent, or magnitude in recent years.

24. Has the increase in tourist arrivals led to any disruption in your usual procedure?

The increase in tourist arrivals has not caused significant disruptions to our usual procedures. Since we conduct our flights at higher altitudes, we are above the commercial air traffic, which helps minimize interference. However, the presence of numerous small airplanes and helicopters does pose an additional challenge for our pilots, as they need to maintain awareness of the surrounding air traffic. Although they have radar systems to assist them in monitoring the airspace, it remains a demanding task. As for my role, I am primarily focused on photographing and capturing data during the flights, so I cannot actively keep track of the air traffic in real time. Overall, while the increased tourist activity does introduce some challenges, we have been able to continue our work effectively.

25. What task does the institute or in this case you do after the emergency is over?

After the emergency is over, we typically conduct a few more flights to assess any remaining activity that may not be visible on the surface. We are particularly interested in identifying changes such as contraction due to cooling, subsidence, and collapse. These observations help us understand the post-eruption behavior of the volcano. However, in Iceland, we face challenges related to monitoring during certain times of the year. The darkness in winter months and the presence of snow can make monitoring with cameras difficult, as we rely on visual cues. To overcome this, we have experimented with thermal cameras, but improvements are still needed, especially in terms of lens quality.

There are also other sensors and technologies that could enhance our post-emergency monitoring efforts, such as LiDAR scanners. LiDAR emits light and can scan even in low-light or nighttime conditions, which would be advantageous. However, I am not directly involved in the LiDAR department, and its applicability during live operations may be limited in situations where there is steam or other obscuring factors.

Overall, our focus after the emergency is to gather as much data as possible regarding any lingering activity and changes in the volcanic area. This information contributes to our understanding of the volcano's post-eruption behavior and helps improve our monitoring capabilities for future events.

26. Do you provide training and education courses to the population or to the politicians or to the other authorities?

Yes, we do provide educational talks and seminars to various audiences. My institute organizes a Wednesday seminar series, which is open to the public. These seminars are typically conducted online, allowing for wider accessibility. I often have the opportunity to deliver lectures during these seminars and share insights on our work and research.

In addition to the Wednesday seminars, we also participate in conferences and other events where we can engage with different stakeholders, including politicians, authorities, and the general public.

27. What do you think are the keys to your research and conservation in Iceland, compared to other places you know?

We are using photogrammetry in innovative ways monitoring dynamic environments such as volcanic eruptions, glaciers and landslides.

28. What shortcomings or areas for improvement do you think your organization has?

One area for improvement within our organization is funding. As a governmental institution, we often have limitations on financial resources and need to rely on research grants to support our projects. Additionally, we may need to charge fees for certain services in order to maintain our laboratory and equipment.

In terms of outreach, we have made efforts to engage with different audiences and have received positive feedback. For example, private engineering companies have shown interest in our photographs and 3D models, museums and even people with visual disabilities have contacted us to provide tactile models. These models allow them to experience and understand the volcanic landscape in a unique way. This type of outreach has proven to be effective in providing access to information and experiences that would otherwise be difficult for certain individuals to obtain.

Overall, while there are limitations and areas for improvement, our group is committed to finding creative solutions and enhancing our outreach efforts to serve a wider range of stakeholders and fulfill our mission effectively.

Interview to Árni Guðbrandsson (Isavia)

1. Could you tell me your names and positions within Isavia?

My name is Árni Guðbrandsson, senior ATM expert. My background includes air traffic control and various types of projects.

2. What is Isavia? What are its main tasks?

Isavia limited and its subsidiaries is the aviation company of Iceland and is owned by the Icelandic government. Specifically, I work for Isavia ANS, a subsidiary of Isavia Limited, which specializes in air navigation services. Our primary responsibility is Air Traffic Management in the International Civil Aviation Organization (ICAO)North Atlantic Region as well as the Icelandic domestic area. While we don't directly operate air traffic control or AFIS in the towers, we hold the license and bear the responsibility for these functions excluding Keflavik airport. Our team is dedicated to ensuring smooth and safe air navigation in the region, working alongside other air traffic control authorities to maintain efficient operations. It's an important responsibility that we take seriously.

3. What do its monetary funds come from?

Regarding Isavia ANS, our company, our funding comes from the airspace users through ICAO. The funding structure is based on cost recovery basis. Since our operations fall within the ICAO area, which is an international territory, the funding model is based on cost recovery. This means that we aim to cover our expenses by charging fees for the services we provide. Essentially, our financials are structured in a way that ensures we recover the costs associated with our operations.

4. What is your organizational chart within the institution? How many departments is it divided into?

Within Isavia ANS, we have a well-defined organizational chart. At the top, we have the CEO, and I am part of the Internal Relations and Legal Department under his leadership. The operations department is headed by a Chief Operating Officer (COO), and there's also a Chief Technical Officer (CTO) overseeing the technical aspects. Additionally, we have departments responsible for financial matters, human resources (HR), and safety. The CNS (Communications, Navigation, and Surveillance) department and the ATM (Air Traffic Management) department work closely with the air traffic control center. They collaborate to ensure smooth communication, accurate navigation systems, and effective surveillance. The air traffic control center itself serves as the core operational unit. The crisis center is not confined to a specific department or area. It extends across the entire Isavia conglomerate, including Isavia Limited, Isavia Regional Airports, and Isavia ANS. It is a collaborative effort that spans the entire organization.

5. Do you work jointly with scientists from the University of Iceland, the Met Office or other scientific institutions?

Absolutely. We maintain a close and collaborative relationship with the volcanologists at the Met Office and the London VAAC (Volcanic Ash Advisory Center). Additionally, I actively participate in the Scientific Board of the National Crisis, attending their meetings to address aviation-related matters and provide relevant expertise. So, yes, we do engage in such collaborations.

6. So, do you participate in the daily meetings conducted by the Met Office at 2 p.m.?

Generally, we don't attend those daily meetings. However, if there are specific events or situations unfolding that require our involvement, I may join them on occasion. It's not a regular occurrence, but when it's relevant to aviation matters, they do extend invitations for us to participate, which is great.

7. Do you work jointly with the Department of Civil Protection and/or the Police?

Yes, indeed. We have a close working relationship with both the Departments of Civil Protection and the police. Specifically, we are actively involved in the National Crisis Center, where we hold two positions. Whenever there are incidents or exercises that touch upon aviation, whether it's related to a bus accident or a volcanic eruption, we attend and provide our expertise. This close collaboration allows us to work closely with them and ensure efficient coordination. Additionally, I serve on the board of the National Crisis in the operations department, which is overseen by the National Police. It's a great partnership that enables effective crisis management.

8. And with the Coast Guard?

Yes, we have a strong partnership with the Coast Guard as well. Prior to 2011, we used to be an aeronautical rescue coordination center along with the air traffic control center. However, in 2011, we transferred that responsibility, known as ARCC, to the Coast Guard, which was the Marine MRCC. Now, it's called the JRCC, and they are located in close proximity to us. We have a working agreement and a letter of agreement with them.

Additionally, we conduct annual training sessions for their personnel, specifically focusing on aviation aspects. We also participate in exercises with them, both as part of NATO initiatives and individual collaborations. Moreover, we work closely with the Coast Guard in areas such as the CRC (Control and Reporting Center) on defense-related matters, and NATO projects. This collaboration is particularly important when coordinating visits from foreign military forces. It's a robust working relationship that ensures effective coordination and cooperation.

9. And what about the ICE-SAR?

In terms of the Icelandic Search and Rescue Organization (ICE-SAR), our involvement is primarily through the crisis coordination efforts. While we do not have direct responsibilities in that area, we have individuals within our organization who take care of this part. However, our collaboration with ICE-SAR is more indirect, as it occurs through the crisis coordination activities.

10. Do you conduct courses, trainings or drills throughout the year? And related to natural disasters?

We have a range of training activities and exercises that occur regularly. One notable event is VOLCEX, which takes place every other year and is organized by ICAO. In alternating years, we simulate an eruption in Iceland as part of our exercise. The other years are dedicated to Spain, Italy, and Portugal, where we rotate the exercise location. Last year, for instance, we had Spain as the focus.

Additionally, we have an exercise program called VOLCICE, which aims to conduct smaller exercises on a monthly basis. This involves participation from Isavia, the Met Office, the London VAAC (Volcanic Ash Advisory Center). These exercises simulate the start of an eruption and focus on how to efficiently disseminate initial information and notify relevant parties.

In total, we conduct approximately 10 exercises per year, covering various scenarios. For instance, we also collaborate with the National Crisis Team for exercises related to other natural hazards such as extreme weather forecasts or avalanches. However, one prominent exercise that stands out is the aircraft accident exercise. This multi-person, national exercise occurs regularly, with each airport that has scheduled flights participating every three years.

11. Do you provide training and education to the population?

Our focus primarily lies in conducting exercises and training within our organization and in collaboration with key stakeholders such as air traffic controllers, our staff, and the Coast Guard. As for involving the general population, our involvement is mainly through the exercises that simulate accidents at airports. However, we do participate in exercises organized by the National Crisis Center, which may involve public participation. It's a common practice for various institutions to provide training and education to the population, but the extent of our involvement in such activities depends on the specific institution and context.

12. **When there is an anomalous situation, e.g. extreme weather forecasting, risk of eruption, or any kind of potential risk to the aviation, does someone inform Isavia to be prepared for a possible emergency?**

The primary channel of information for us comes through the airports since our focus is primarily on air navigation above the ground. We stay informed and attend meetings related to these situations. There is a meeting held by the APOC (Airport Operations Center) at Keflavik Airport, as well as other airports affected by the situation. The Met Office has staff members stationed at Keflavik Airport, creating a close connection.

When the weather forecast reaches a certain threshold or trigger, there is a meeting where national or local responses are discussed, and information is shared with all airline operators and relevant stakeholders. The day before the event, there is a checklist to ensure that everyone has done what they need to do and that aircraft are positioned according to the information provided by the Met Office. This structured system ensures effective coordination and preparedness.

So, overall, the information flows through the airports, the APOC meetings, and the involvement of the Met Office to keep us informed and ready to respond to any potential emergencies.

13. **I saw on your website that you also have your own weather stations at airports, what information do you collect?**

Yes, indeed. Our weather station primarily collects data that is crucial for the operations at the airport. This includes wind speed and direction, precipitation, and other relevant weather conditions. This information is particularly important for the air traffic control tower, as they need to make decisions regarding runway usage based on wind conditions.

Additionally, we have a radar system for approach purposes, which detects weather patterns and clusters of rain or snow. This system provides valuable data for our approach radar controllers who monitor weather conditions during aircraft landings.

Regarding data sharing, we have a cooperative agreement with the Met Office. We exchange information with them, sharing both the data they provide and the data we collect from our weather station. This collaborative effort ensures that both organizations have access to comprehensive weather information for effective decision-making.

So, in summary, our weather station and radar systems play a vital role in collecting and monitoring weather data, and we work closely with the Met Office to share and utilize this information.

14. When a volcanic eruption occurs, what is the usual way to proceed?

In the event of a volcanic eruption, Isavia follows a specific flow of action based on the Volcanic Ash Contingency Plan, which is derived from the International Civil Aviation Organization (ICAO) guidelines. The initial steps involve communication and coordination among relevant stakeholders.

The shift manager at the Met Office initiates the process by informing all parties involved, including Isavia. A checklist is followed to ensure that everyone is notified and that the necessary procedures are initiated. Meetings and information sharing take place at the national or local level, involving airline operators, airports, and other relevant organizations.

One of the first actions taken is the establishment of a 120 nautical mile circle around the volcano. This is a precautionary measure to ensure the safety of aircraft and passengers. Initially, all air traffic is stopped within this circle until more information is obtained regarding wind direction and ash dispersion. The closure of the circle can last from 20 minutes to an hour.

Once the Met Office issues a SIGMET (Significant Meteorological Information) with a forecasted ash area, the 120 nautical mile circle is deactivated. The SIGMETs provide information on forecasted areas affected by volcanic ash. The airline operators then make decisions on whether to avoid, traverse, or turn back from the forecasted area based on their own assessments and procedures.

It's important to note that since 2014, there haven't been eruptions with significant volcanic ash impacts. However, the contingency plan and procedures are in place to handle such situations should they occur.

Regarding airline operators, there can be differences in risk tolerance and decision-making processes. Some larger airlines have their own meteorological offices and experts who provide guidance and advice. However, the approach to risk assessment and decision-making can vary between airlines, especially when it comes to ownership of aircraft engines. Airlines that own their engines may adopt a more cautious approach, while those that lease engines may be more inclined to take calculated risks.

Overall, the procedures and coordination among Isavia, the Met Office, airline operators, and other stakeholders aim to ensure the safety of air traffic during volcanic eruptions and mitigate potential risks associated with volcanic ash.

15. What are the main damages of the volcanic products to aircrafts?

The main damages that volcanic products can cause to aircraft are as follows:

- Volcanic Ash: Ash particles ejected during an eruption can pose a significant threat to aircraft. When volcanic ash is ingested into the aircraft's engines, it can melt and solidify, causing engine failure or reduced engine performance. The glassy ash particles can also abrade and erode engine components, leading to further damage.
- Corrosion: Volcanic ash contains corrosive substances, such as sulfur compounds, which can corrode various parts of the aircraft. The exterior surfaces, including windows and windshield, may be affected by the corrosive nature of volcanic ash.
- Reduced Visibility: The presence of volcanic ash in the atmosphere can reduce visibility for pilots. Ash clouds can obstruct the view from the cockpit, making it challenging to navigate and maintain situational awareness.
- Projectile Hazards: Larger volcanic particles, such as rocks and boulders, can be ejected during explosive eruptions. These projectiles can pose a risk to aircraft, causing damage upon impact.
- Lightning: Volcanic eruptions can generate intense electrical activity, resulting in volcanic lightning. This lightning can pose a risk to aircraft in the vicinity of the eruption.

In recent years, attention has also been focused on the potential impact of volcanic gases on aircraft. Gases emitted during volcanic eruptions, such as sulfur dioxide (SO2) and carbon dioxide (CO2), can cause corrosion and affect aircraft systems.

Overall, the primary concern for aviation during volcanic eruptions is the presence of volcanic ash, which can lead to engine failure, reduced visibility, and potential damage to various aircraft components. Efforts are continuously made to monitor and assess volcanic ash hazards to ensure the safety of air travel in affected regions.

16. What other risks exist for aviation during a volcanic eruption, apart from the direct damages to engines?

During a volcanic eruption, there can be various damages and impacts on airports. Some of these include:

- Runway Contamination: Volcanic ash and debris can accumulate on runways, taxiways, and aprons, making them unsafe for aircraft operations. The ash can reduce friction and traction, posing a risk during takeoff, landing, and taxiing.

- Visibility Reduction: Ash clouds can reduce visibility at airports, affecting air traffic control operations and creating unsafe conditions for aircraft movements on the ground.
- Navigational Equipment Damage: Volcanic ash can infiltrate and damage sensitive navigational and communication equipment, including radar systems, radio antennas, and instrument landing systems. This can disrupt air traffic control services and navigation capabilities.
- Terminal and Infrastructure Damage: Volcanic ash can settle on terminal buildings, hangars, and other airport infrastructure, leading to the need for extensive cleaning and potential damage to structures. Ash can also affect ventilation systems and electrical equipment.
- Ground Support Equipment Impact: Ash fall can affect ground support equipment such as fueling vehicles, baggage handling systems, and de-icing equipment. The presence of ash particles can cause damage or clog filters and machinery.
- Environmental and Health Risks: Volcanic eruptions can release gases, including sulfur dioxide and other pollutants, which can have adverse effects on human health and the environment in and around the airport. These gases can also contribute to air pollution and affect the quality of breathing air inside airport facilities.

In summary, volcanic eruptions can lead to airport closures, damage to infrastructure and equipment, reduced visibility, and environmental and health risks. Mitigation measures, such as ash removal, air quality monitoring, and infrastructure inspections, are essential to ensure the safe operation of airports in volcanic eruption-affected areas.

17. What safety measures do you take during a volcanic eruption?

Apart from the temporary area closure, we have several safety measures in place. Firstly, we monitor the quantity of ash being released during the eruption. This helps us determine the severity of the situation. We have also developed strategies for cleaning up the ash because its fine texture makes it difficult to handle. It has a cement-like consistency, so we need to be careful in the cleaning process. There are specific procedures we follow at the airport to ensure safety during volcanic eruptions. While we haven't had significant ash accumulation on the airport grounds, we have studied various methods for cleaning it up. Our runway cleaning staff has explored techniques that involve careful handling, avoiding any hasty actions. One approach is to use a combination of water and clay or cement to effectively remove the ash. In addition to ash-related measures, we also pay attention to gas emissions during volcanic eruptions. Following the eruptions last year and the recent one, we observed the release of gases. Consequently, the Meteorological Office has installed additional equipment in the surrounding villages and the airport to monitor gas levels. If the gas levels exceed certain limits, Isavia has specific procedures in place to respond accordingly. The Meteorological Office has even developed a model to visually track gas emissions, similar to the one used for ash monitoring. When we reach a certain level of volcanic activity, we take precautions to ensure the safety of individuals at the airport. This includes restricting people from going outside and providing them with masks for protection. We have designated equipment and procedures in place to safeguard the well-being of airport personnel during such situations.

18. When there is an extreme weather forecast, what are the main risks for aviation?

When it comes to extreme weather forecasts, there are indeed risks that impact aviation. One of the primary concerns is the landing and disembarkation of passengers. When the wind speed reaches around 50 knots, it becomes unsafe to use the jet bridges for boarding and deboarding as they become too unstable. We have had incidents where aircraft were able to land but had to wait for hours on the taxiway or other designated areas because the wind speed was too high to safely disembark passengers. So, passengers ended up waiting onboard in unfavorable weather conditions.

Another significant risk during extreme weather, particularly when wind speeds are exceptionally high, is the potential for objects to become airborne. This includes roofs and loose items that can pose a danger. To mitigate these risks, we have procedures in place. In preparation for such events, we hold meetings to secure the airport by removing or securing any loose items that could be blown around. Additionally, we ensure that aircraft are properly tied down to prevent them from being affected by the strong winds. This is particularly important at Keflavik, as the winds can become very powerful in this area.

Keflavik holds significance for the aviation industry. Both Airbus and Boeing, the major aircraft manufacturers, often choose Keflavik as a testing location for their new aircraft, especially for crosswind landing trials. This is because Keflavik has a cross runway, making it an ideal site for these tests. It's one of the reasons why we frequently see new aircraft being tested at Keflavik. It's an advantage for the airport and a testament to its capabilities.

19. Are there other natural hazards that can also affect aviation (avalanches, flooding, earthquakes)?

Absolutely, there are other natural hazards that can affect aviation operations. In Iceland, where there are airports located near mountains, avalanches can be a concern. Additionally, earthquakes can pose a risk as they have the potential to damage runways and taxiways. After a significant earthquake, inspection teams thoroughly examine the runways to ensure there are no cracks or structural damage.

Also flooding can impact airports, especially those situated close to sea level. We had a recent incident in Akureyri, where a combination of a high tide and a low-pressure system led to flooding in the vicinity of the airport. The water level came dangerously close to reaching the airport grounds. The weather itself is a significant natural hazard. It can include various factors such as strong winds, heavy rain, or dense fog. These weather conditions can pose challenges to aviation operations and require careful monitoring and decision-making.

20. When air traffic is affected, how do you manage the economic losses?

Managing economic losses during periods of air traffic disruptions is a complex task. In the case of COVID-19, we faced significant revenue declines. However, our operations are structured into three separate entities, each with its own business model.

The first entity is Keflavik Airport, which operates in a competitive environment alongside other airports. The second is the cost recovery system, which is non-competitive but aligns with International Civil Aviation Organization (ICAO) guidelines. Lastly, we have the Isavia Regional Airports, which receive government funding.

During the COVID-19 pandemic, we experienced a drop in revenues. However, our cost recovery system helps to compensate for these losses over time. The system ensures that if we have a good year with higher revenues, we lower charges in the subsequent year. Conversely, if we experience a significant revenue shortfall, such as during COVID-19, we raise charges to offset the losses. The goal is to achieve a balanced financial outcome over the years.

21. Did you implement any specific measures during the pandemic to preserve the workforce and avoid skill loss?

Absolutely. Instead of laying off our air traffic controllers during the pandemic, we opted for a different approach. We reduced their workload from 100% to 80% for a few months. This allowed them to remain at work, maintain their skills, and keep their licenses current. It was a proactive measure to avoid the challenges of retraining and potentially losing skilled personnel. Many other Air Navigation Service Providers (ANSPs) are now adopting similar strategies to mitigate the risk of skill loss when employees transition to other jobs during a downturn.

22. Have you made any changes or learned from past experiences, such as the economic losses following the 2010 volcanic eruption?

The 2010 volcanic eruption didn't have a significant economic impact on us due to our geographical position in Iceland. When the eruption plume blew south, air traffic simply adjusted its routes and flew around the affected area. At one point, when the plume extended as far as Portugal, all North Atlantic traffic was redirected north of Iceland. Unlike the COVID-19 pandemic, air traffic continued albeit with some variations. Therefore, our economic impact was relatively limited during that volcanic eruption.

23. Regarding economic coverage, are there any insurance options or agreements in place to mitigate potential losses?

There is insurance coverage in place, but I'm not an expert on the specifics. We work with multiple insurance companies, and our legal team recently attended a meeting in London to discuss insurance matters. As far as I understand, there are various insurance companies providing coverage for different aspects of our operations. This includes potential accidents, meteor collisions, and other unforeseen events. However, I recommend consulting our legal experts for more detailed information on the coverage and arrangements.

24. Could you tell me how you experienced the 2010 eruption?

Certainly. During the volcanic eruptions, particularly the one in 2010, we activated our regulations and contingency plans in full force. The impact was significant, and I was heavily involved in the crisis coordination center. I participated in numerous teleconferences with Eurocontrol, where hundreds of people were on the line. I had a broad spectrum of experience working as an air traffic controller and a shift manager.

Due to the nature of my role, I didn't have the opportunity to witness the eruption itself as I was always working. My primary responsibility was to be one of the first people to raise the alarm and initiate the necessary actions. We worked closely with various stakeholders, including airline operators, police, the Ministry, the Met Office, Icelandic Transport Authority and others. Together, we formed a coordination meeting where everyone brought their information and expertise to the table. This collaborative approach proved to be very valuable.

We continued to hold these coordination meetings on a daily basis, even after the eruption in 2010. It became a standard practice to bring everyone together to discuss the situation, receive briefings from the Met Office on the eruption's progress, and consult with the air operators about their plans. In 2010, some operators even moved their hub to Scotland, which was a significant undertaking.

I also remember another eruption in 2011 with Grímsvötn. I was working when it started, and I vividly recall making a call to the air traffic control center in the UK. The person on the other end seemed taken aback, likely thinking, "Oh no, not another one." Nevertheless, we managed the situation as best as we could.

These volcanic eruptions triggered various actions and protocols, and it was a dynamic and intense period of work.

25. What did you learn from this event?

Absolutely, we have learned a lot from the cluster eruption and made several changes to our processes. In 2014, we had to revise all the procedures, but even before that, we regularly held meetings to discuss how our operations were functioning and identify areas for improvement. We strive to make the necessary adjustments within the framework of our contingency plan to ensure smoother operations during volcanic eruptions.

Cooperation and coordination are key elements in managing such situations. We maintain constant communication with the air traffic control center, both through our coordination center and our local crisis management facility. This ensures effective coordination and enables us to stay updated on the latest developments and make informed decisions.

Overall, the experiences and lessons learned from past eruptions have contributed to enhancing our processes and improving our ability to handle volcanic events more efficiently.

26. And what can you tell me about the recent eruption of 2021? Did it affect air traffic?

During those years, we encountered volcanic eruptions that were not as significant in terms of ash production. However, we have since learned that seismic activity often precedes volcanic events. As a result, we have implemented a proactive approach by raising color codes to indicate the potential for volcanic activity. Our aim is to always be prepared. Therefore, we consistently follow our established protocols, starting with the 120 nautical mile circle and going through the necessary procedures.

In the specific case where we anticipate a lava eruption without significant ash, there is still a level of uncertainty, especially if it occurs beneath the ocean. Initially, we are unsure of the exact nature of the eruption. Hence, we diligently adhere to the same procedures to ensure comprehensive preparedness.

27. Which natural disasters cause the most expenses or economic losses?

Well, when it comes to air traffic disruptions, the presence of large amounts of volcanic ash poses a significant challenge for air traffic. However, we also have to consider other problems, such as strikes, which can have substantial effects and potentially lead to the closure of airports or specific areas. In some cases, these issues can create bigger problems than natural disasters themselves.

Sometimes, the closure of an airport or a portion of airspace due to various reasons, like adverse weather conditions, can cause significant disruptions to the normal flow of air traffic. In such situations, aircraft may need to divert to alternate locations, such as Scotland or other parts of

Europe. However, it's important to note that airports like Akureyri in Iceland have limited parking spaces, which adds complexity to the decision-making process. Unfortunately, weather forecasts are not always entirely reliable, making it challenging to predict these situations in advance.

To mitigate risks and ensure the safety of flights, we proactively communicate with airlines, such as the recent case where we alerted an airline arriving in the early morning to delay their departure from the United States to Iceland. This way, they could remain in North America, avoiding unnecessary circling and fuel depletion. It's crucial to involve airlines early in the decision-making process to prioritize safety over potential troubles. The aviation industry in Iceland is currently in the process of joining Eurocontrol, which will enhance our participation in the flow management system. This means we will have a greater role and contribute even more to the coordination of air traffic. Delays are a major concern that we aim to address comprehensively in our collaboration with Eurocontrol and other stakeholders.

28. I work on multi-hazard, understood as the fact that more than one event can occur at the same time and/or in the same place. As an organization involved in long-term planning, do you find the multi-hazard approach valuable?

Absolutely. At Isavia, we prioritize proactive planning and considering a multi-hazard perspective aligns with our goals. Understanding the interconnected nature of hazards is crucial. For example, when earthquakes occur, it often indicates an increased possibility of volcanic eruptions. Recently, Sara Barsotti, from the Icelandic Meteorological Office (IMO), raised an interesting point about the potential occurrence of simultaneous eruptions, considering that there are several major eruptions overdue. This raises the question of how we can effectively respond to such multi-hazard scenarios. While earthquakes often initiate the sequence of events, we must also consider the broader chain of events and plan ahead.

Maybe those involved in immediate response and action may prefer individual contingency plans for each hazard. However, for long-term planning purposes, it's beneficial to have a comprehensive approach that encompasses multiple hazards. It allows us to identify potential vulnerabilities, assess the cascading effects of different hazards, and develop strategies that address the complexities of interconnected events.

Finding a balance between individual contingency plans and a multi-hazard perspective could be the way forward. By considering both perspectives, we can create a holistic and adaptive approach to effectively manage various scenarios. This is an area of interest that I will continue to explore and develop.

29. Do you think pilots and aircrew working in Iceland have important skills because of the natural conditions in the country (strong winds, eruptions, storms)?

Absolutely. The pilots and aircrew working in Iceland possess important skills, particularly due to the diverse and rapidly changing weather conditions we experience here. Our pilots gain significant experience and expertise through training in mountainous areas, dealing with mountain winds, and navigating challenging terrains. For instance, at Akureyri Airport, they have to navigate between mountains and land on a runway that requires a specific approach. This demands a high level of skill and familiarity.

Our pilots have extensive experience in handling various weather conditions. They often start their careers with domestic regional airlines, which historically served as a stepping stone. This enables them to gain proficiency in adverse weather conditions. Additionally, we have seen cases where pilots from other countries, who may not be accustomed to such weather challenges, have faced difficulties in decision-making when confronted with adverse weather forecasts that did not necessarily warrant airport closure. Icelandic pilots, on the other hand, are well-versed in handling such situations due to their familiarity with local conditions.

Furthermore, we have a mix of international pilots who have flown extensively worldwide, bringing a wealth of experience to the table. However, the pilots working in Iceland, especially, are accustomed to and more experienced in adverse weather conditions specific to our region. This expertise makes them valuable assets, particularly in training programs and when dealing with the unique challenges posed by Icelandic natural conditions.

30. If you could ask anything to the other institutions involved during a natural disaster that would make your work or communication easier and safer, what would it be?

Well, when it comes to collaborating with other institutions, there are a few aspects that I believe would greatly benefit air traffic operations. Firstly, accurate and reliable forecasts are crucial. While weather forecasts have significantly improved thanks to advanced supercomputers, there are still challenges when it comes to predicting volcanic eruptions and similar events. I think it's a shared goal among all stakeholders to work towards more precise forecasts in these situations.

Looking back at the eruption in 2010, the forecasts provided were quite basic and lacked the necessary details. This caused frustration, especially for airline operators. Therefore, one thing I would request is better communication and coordination with meteorological agencies and volcanic monitoring organizations to receive more timely and comprehensive information. Having more time to prepare and assess the situation would be invaluable.

In terms of precautions, I believe it's important to err on the side of caution. Rather than taking risks and potentially facing the consequences, I advocate for proactive measures that can be adjusted as needed. I understand that predicting volcanic eruptions can be challenging, with some volcanoes exhibiting precursors for months before an eruption, while others give little to no warning. Investing in enhanced monitoring systems and proactive planning can help us mitigate risks and improve response capabilities.

However, it's worth mentioning that funding plays a significant role in the implementation of these initiatives. Ideally, I would like to see more risk assessments conducted on various volcanic areas in Iceland, in collaboration with academic institutions and the Meteorological Office. This would provide a solid foundation for decision-making and resource allocation.

Moreover, exploring alternative funding sources, such as government support through the Met Office or international organizations like ICAO, could be a viable option. ICAO has a vested interest in monitoring volcanic activities for aviation safety, and they provide funding for equipment and research projects. Leveraging these opportunities could help overcome financial constraints and promote more extensive studies on volcanoes like Askja and the Reykjanes Peninsula, which are showing increased activity.

Ultimately, a collaborative approach, improved forecasts, increased risk assessments, and secure funding would significantly contribute to ensuring the safety and efficiency of air traffic in Iceland's volcanic regions.

Interview to Aðalheiður Jónsdóttir (Icelandic Red Cross)

1. **Could you tell me your name and position within the Red Cross?**

My name is Aðalheiður Jónsdóttir, and I am a team coordinator for disaster services in Iceland.

2. **When did the Red Cross arrive to Iceland?**

The Icelandic Red Cross was founded on December 10, 1924, so it will be 100 years next year in 2024.

3. **What are the main tasks of the Red Cross in Iceland?**

The Red Cross in Iceland has various projects and tasks. In addition to disaster services and responding to hazards, we also engage in social services such as harm reduction, visiting and assisting isolated individuals, operating clothing centers, and more.

4. **Where do you receive your monetary funds from?**

The Red Cross in Iceland primarily relies on donations for funding. In the case of a long-term disaster, we may receive reimbursement from the government, but we do not receive regular funding from the government.

5. **What is your organizational chart within the Red Cross?**

Within the Red Cross, we have both an international department and a domestic department. We also have 30 branches located around Iceland, which are supported by the headquarters.

6. **Are all of you volunteers?**

Not all members at the headquarters are volunteers; most of us are staff. However, volunteers play a crucial role in the Red Cross, and without them, we would not be able to carry out our work effectively.

7. **Do you have several bases deployed throughout the territory? If so, does each of them have its own "jurisdiction"?**

The headquarters of the Red Cross are located in Reykjavik. However, we have 30 branches distributed throughout Iceland, with the largest branch in Akureyri. These branches have their own staff and are responsible for their respective districts.

8. **Do you work jointly with the University of Iceland, the Met Office or other scientific institutions?**

No, we do not work jointly with the University of Iceland or other scientific institutions. Our collaboration is primarily with the Department of Civil Protection and other organizations like the police.

9. Do you work together with the Department of Civil Protection or the Police?

I think it was a pretty close relationship because we have an agreement between the Icelandic Red Cross and the Civil Protection. This agreement allows us to provide volunteers in emergencies and in times of need. So, whenever there are natural hazards, incidents like car accidents, and so on, we can respond accordingly. I believe that's great, truly great.

Furthermore, we always have one of our staff members present in the crisis coordination center. In addition, our operations center, which is where I am located, also has a staff member assigned.

10. And with the ICE-SAR?

It's the same with them. They also have a similar agreement with the government, just like us. We work closely together in both the crisis coordination center and the operations center. We have a collaborative approach.

11. Are there other institutions in Iceland that share your same tasks, i.e., that also provide humanitarian assistance? If so, how are you combined or what is your relationship, i.e. do they work cooperatively, joining forces, sharing resources, or separately?

There are other NGOs, but currently, they are not actively responding to the event or the disaster. However, they may join in at a later stage.

12. Do you conduct courses and trainings throughout the year?

Yes, we offer an introductory course to disaster services, which is typically conducted online and takes place around four or five times per year. Additionally, we provide extra courses, such as training for psychosocial support and related topics.

Furthermore, we have training specifically focused on volunteers in mass care. These volunteers are responsible for opening and managing mass care shelters, as well as providing assistance with food and basic needs. In addition, we have a specialized group called the Psychosocial First Aid (PFA) Response Group. This group is lead from our headquarters but they are located around Iceland, and consists of approximately 155 volunteers who are trained to offer psychosocial support to both individuals and groups.

We respond to various situations, including those involving bus accidents. In such cases, we assist the uninjured individuals by providing psychosocial support. It's really nice to be able to help them.

13. Do you provide training and education to the population?

Not really. We may write articles and give presentations upon request, but we are not providing training. .

14. When there is an anomalous situation, e.g. an increase in the seismicity prior to a possible eruption, or extreme weather forecasting, risk of avalanches, or any kind of risk in this area, does someone inform the Red Cross to be prepared for a possible emergency?

The Civil Protection. We are always involved. So if there's something going on, they always invite us to the meeting and we can start preparing for ourselves.

15. At what point during an emergency do you deploy to the area? Is there anyone who requires you to deploy?

We are involved from the beginning. So it's usually required that we open a rescue shelter or whatever. We are not usually working on the scene if it's an accident. It's usually ICE-SAR that's on the scene, but we take care of the people, assist, and provide the necessary support.

16. Once an emergency has been declared, what is the usual flow of action?

It depends on the incident. First of all, we send our Red Cross staff to the crisis coordination center and also to the operation center where the accident is happening. Then we start planning ahead. We think about whether it's necessary to open a shelter or what the next step should be. Sometimes we just have to call our volunteers and ask them to open it whenever there is a need.

17. What are your main tasks during a natural disaster?

Our main tasks are to rescue and assist the affected people. We provide shelter, basic needs, and psychosocial support. It depends on the incident, but we focus on providing the necessary support to those affected.

18. How do you know in which areas to set up reception facilities?

We have established around 100 rescue shelters in various locations around Iceland, but sometimes we may need to find another suitable place. Then the decision is made in the operation center, often in collaboration with the crisis coordination center. They are located in the nearest safest area to the affected zone. We have also a person from the Icelandic Meteorological Office (IMO) who informs us about the conditions and the situation and guides us in those tasks.

19. How do supplies arrive and who provides them?

We have small trailers with essential supplies located in 28 places around Iceland, with blankets, tents, and everything that we could need. We also have a storage room in the capital area where we can store additional resources. We usually provide food from the local area if possible, but sometimes we need to import supplies.

20. Is your work usually the same regardless of the natural hazard that caused the disaster?

Our work is usually the same, but it depends on the specific event and the needs of the affected people. We always have to assess the situation and adapt our response accordingly.

21. What main difficulties do you encounter during a natural disaster?

Usually, one of the main difficulties we face is running out of volunteers. As the disaster progresses, both the staff and the volunteers become tired from working long hours. Sometimes we have to relocate volunteers to the affected area because people tend to work tirelessly when a disaster occurs. It's challenging to ask them to take breaks because they are so willing to help. During some events, we had an influx of people who came forward to offer assistance, and many of them were working long, grueling hours. In such situations, it's important to organize shifts, typically eight hours each, to ensure everyone gets some rest. However, in smaller places, we may not have enough volunteers, as they have their own families to attend to.

22. Is there any written duty that obliges you to give humanitarian assistance for the duration of the disaster or does it come from the will of the Red Cross volunteers?

We have the agreement that I mentioned before with the Civil Protection. This agreement allows us to provide volunteers in emergencies and in times of need.

23. What happens when circumstances exceed your capacity of action or your resources?

The Icelandic Red Cross is part of a very large organization, so we can ask them for assistance.

24. Are you familiar with the concept of multi-hazard?

Yes.

25. Does a concatenation of events during the same disaster affects your way of proceeding, perhaps in the forecast of resources that would be needed?

I'm considering areas like Seyðisfjörður, where mudslide/avalanches occur. In such situations, we may need to have both evacuation plans and shelters, possibly both. Additionally, the challenging weather conditions make it difficult to provide assistance. However, we have a strong cooperation with the search and rescue team, who have reliable snow-capable vehicles. We also coordinate with the Coast Guard, who have ships and helicopters that may be used to transport our resources. Our approach is primarily based on real-time decision making, as we don't have specific hazard analysis or prevention analysis to predict simultaneous hazards. Nonetheless, we make preparations such as having small trailers and volunteers located in specific towns to ensure a quick response. While providing incoming assistance may pose challenges, we have additional equipment stored in a shelter, making it easily accessible and ready to use, as was the case in Seyðisfjörður and Flateyri during the last avalanche incident.

26. Would more prediction of these potential multi-hazard scenarios help you better plan your aid delivery and resources?

We work closely with civil protection and have contingency plans in place for various scenarios. However, in real-time emergency situations, we rely on immediate response rather than extensive analysis or prevention analysis. While we try to prepare and position resources strategically, the unpredictable nature of disasters requires us to adapt quickly. More extended analysis and research on multi-hazard situations would certainly contribute to better organizing our actions and allocating resources effectively.

27. Could you tell me how you experienced the 2010 eruption?

During the 2010 eruption, the Red Cross played a significant role. We set up a shelter not far away from the eruption site, where volunteers provided psychosocial support, warm meals, and a place for people to gather and seek assistance. Since many farmers lost everything, including their homes, we assisted them by clearing ash from their farms. The shelter remained open for several months.

28. And what can you tell me about the recent eruption of 2021? Did you play any role?

For the recent eruptions in 2021 and 2022, the circumstances were different. The eruption sites were accessible to search and rescue teams, but we opened the shelter twice due to inclement weather and lack of proper equipment among people visiting the area. In some instances, we assisted in evacuations and supported those who were separated from their loved ones. Our work varies depending on the specific needs of each situation.

29. Which natural hazard do you think causes the most damage, injuries or deaths each year in Iceland?

It's difficult to pinpoint a specific hazard that causes the most damage, injuries, or deaths in Iceland, as it can vary depending on the conditions. However, I can mention a few examples. Bus accidents have been a significant concern in the past, resulting in injuries and fatalities. Avalanches can also be particularly dangerous. Although it has been many years since a major avalanche disaster occurred, in 1995, more than 20 people died in avalanches in West Iceland. So, while it may not be the most frequent hazard, avalanches have had severe consequences in the past.

30. Does the massive arrival of tourists make more difficult your work in any way?

Not really. But of course there are more accidents. Before the COVID-19 pandemic, there were frequent bus accidents around Iceland, and our volunteers would respond to those incidents. When tourists were evacuated from the buses, they were often not injured but they needed to get a room and there were not available options for accommodation nearby. In such cases, we had to open shelters and provide cots for those who cannot find lodging. So, while it doesn't directly hinder our work, the influx of tourists can create additional challenges and demands on our resources.

31. What characteristics does your organization have that you think are efficient?

One of the key characteristics of our organization is the close and effective cooperation we have with other responders. We can respond quickly and have well-established coordination centers. Our operation centers are spread across nine districts in Iceland, working closely with local police forces. This clear routine and coordination help us effectively organize and respond to emergencies.

As for characteristics I believe our efficiency and preparedness are valuable assets. However, we are always open to collaboration and sharing knowledge and experiences with other organizations and countries to enhance overall effectiveness in disaster response.

32. What shortcomings or areas for improvement do you think your organization has?

One area for improvement that I see for our organization is in preparedness. In recent years, we have mainly focused on responding to events as they happen, but we could invest more in prevention and preparedness efforts. This includes raising awareness and providing training to communities, especially those in isolated areas or towns that may experience temporary road closures due to adverse weather conditions. It is important for people to be prepared and selfreliant for a few days during such situations. So, strengthening preparedness and promoting self-sufficiency among affected communities is an area we can work on.

33. If you could ask anything of the other institutions involved during a natural disaster that would make your work easier and more effective, what would it be?

It's a challenging question since we already have a good level of cooperation with other institutions in Iceland. However, if I were to ask for something, it would be to increase joint training exercises and collaborative efforts. Enhancing training opportunities together would allow us to better understand each other's roles, capabilities, and strategies, leading to more efficient and coordinated disaster response. Although we already maintain close contact throughout the year, further joint training initiatives would strengthen our collective abilities and improve overall effectiveness.

Interview to Guðný Björk Eydal (University of Iceland)

Transcript not available for confidentiality reasons.

Interview to Guðrún Pétursdóttir (University of Iceland)

1. **Could you tell your name and your current position within the University of Iceland?**

My name is Guðrún Pétursdóttir, and I retired just over a year ago from my position as the director of the Institute for Sustainability Studies. Throughout my career, we focused on various areas of study, one of which was natural hazards. We believed that studying natural hazards was a valuable approach to understanding environmental changes, which often occur over extended periods, such as global warming. However, by examining natural disasters or adverse events, we could observe similar hazardous changes in a compressed timeframe. Our primary focus was on assessing the impact of these events on individuals and society, rather than investigating their causes. We left that task to other experts who specialized in studying the reasons behind earthquakes, avalanches, and similar phenomena. Our aim was to examine how people were affected and how we could improve preparedness and response to such disasters. Adequate preparation is crucial in handling these situations effectively.

2. **Which department or section of the University do you belong to?**

The Institute for Sustainability Studies is an interdisciplinary institute that operates within the university. While, for practical purposes, it is affiliated with a specific school, its board members come from all five schools of the university, including health sciences, natural sciences, and social sciences. Our work transcends disciplinary boundaries, and we employ a small core team at the institute. However, we collaborate with experts from various fields on a project-by-project basis. We invite them to join us, and sometimes they even approach us with their ideas, leading to joint grant applications. Essentially, we act as catalysts, expediting progress and bringing together diverse experts for interdisciplinary work.

3. **What are your background and your area(s) of expertise?**

My background lies in neurobiology, and I also have a foundation in psychology. However, my experience has been shaped through my work, particularly in the realm of interdisciplinary project management. While I am not an expert specifically in natural hazards, studying them has been one facet of my work. So, I bring a project management perspective to our endeavors. In terms of teaching, yes, I have taught at the university.

4. **Do you teach at the University? Could you provide some details about the courses or subjects you taught at the university?**

Certainly. As a neurobiologist, my primary teaching focus was on physiology within the health sciences. However, I also had the opportunity to contribute to an interdisciplinary study program in environment and natural resources. In that context, I taught courses primarily centered around dissemination, aiming to communicate key concepts effectively.

5. **You told me that you were mainly dedicated to the recovery part after a natural disaster, could you explain to me what kind of research you carry out in this area?**

Certainly. One significant study we conducted around 2006 to 2008 revolved around how municipalities can effectively prepare for adverse natural events. To gather insights, we interviewed several hundred individuals who had been involved in the response to severe earthquakes and fatal snow avalanches. We interviewed small groups, typically consisting of four to five people, and engaged in discussions to explore their recollections of the events. For instance, in the case of an avalanche, we spoke with representatives from various sectors such as healthcare, education, religious institutions, rescue teams, and social service providers. By reflecting on events that occurred a decade ago, they shared their memories, including the actions taken and challenges faced. Our interest was in what they remembered from the disaster and its aftermath. We aimed to identify areas of strain and uncover crucial preparations needed. This process allowed us to determine which tasks require attention, who should be responsible for specific roles, and the importance of establishing preparedness measures beforehand. Without defined responsibilities, people tend to react spontaneously, which can lead to an uneven distribution of efforts, with some areas being overrepresented while others are neglected. Therefore, it is crucial to clearly outline the tasks, assign accountable individuals or groups, and ensure that this preparation occurs in every municipality. People need to be aware of their roles, and in the event they are unable to fulfill them, there should be others capable of stepping in. For example, checking on the well-being of elderly care facilities, monitoring the water supply, or inspecting the sewage system all require designated individuals or groups to take charge. These responsibilities must be clearly defined, and there should be an up-to-date system in place, such as mobile phone contacts, to ensure smooth coordination even if personnel changes occur. Keeping such information updated is vital.

6. **Is your work focused on Iceland, or have you conducted studies related to disaster recovery in other countries?**

Our research primarily focused on Iceland and specific municipalities within the country that had experienced natural disasters. However, we believe that the approach we developed is applicable to other regions as well. The principles and methodologies we employed can be adapted and implemented elsewhere. In Iceland, this approach has been successfully embraced by several municipalities, particularly in the southern part of the country, which has faced repeated severe events such as volcanic eruptions, earthquakes, and flooding. Municipalities in the western region, where the risk of snow avalanches exists, have also adopted this approach.

However, it can be challenging to convince municipalities that have not yet encountered adverse events to invest in disaster preparedness. Often, they do not perceive the likelihood of such events affecting them. It would require mandatory measures to ensure their preparedness. Many municipalities are already occupied with day-to-day operations, making it difficult for them to prioritize preparation for potential risks.

7. What main differences have you observed compared to Iceland?

The application of our approach in different countries depends on how their systems are organized, and significant cultural differences exist. When considering other countries, we often look to our neighboring Scandinavian countries, as they share some similarities with Iceland. However, there are variations in terms of which institutions hold responsibilities. In Iceland, due to its small size, we have the advantage of centralizing responsibilities in the hands of a few key entities. For example, the Icelandic Meteorological Office (IMO) oversees natural hazards throughout the entire country, providing comprehensive oversight. Additionally, we have a civil defense or protection system that covers the entire nation. This centralized structure is an asset when it comes to planning and coordination, as we don't need to engage with different actors in various regions of the country.

8. Do you work with any specific types of natural disasters?

Certainly. We specifically selected areas that had encountered natural disasters and engaged with the individuals who had personal experiences related to those events. It was crucial to interact with people who had firsthand knowledge and were motivated to discuss their experiences. Engaging with individuals who had never experienced such events was quite different, as it remained purely theoretical for them. In our research, we primarily looked into the effects of snow avalanches, earthquakes and volcanic eruptions. However, the approach we developed is adaptable to various types of natural disasters.

9. So, regardless of the specific type of disaster, the recovery procedure remains relatively similar?

Yes, that's correct. When it comes to rebuilding society and recovering from a disaster, the tasks and challenges faced are similar. People's lives have been disrupted, and they have experienced significant losses, such as the loss of loved ones, health, or homes. Whether these losses are caused by a flood, avalanche, or any other type of disaster becomes less significant. The critical issue is addressing the fact that individuals are left without a place to live and finding ways to tackle this situation. Questions arise, such as what needs to be secured, who should be responsible for it, and how long the support should last. These are aspects that should be prepared in advance rather than inventing solutions when a disaster occurs. It's important to avoid reinventing the wheel, as you rightly mentioned.

10. The most important question, what happens after a disaster?

After a disaster, the immediate response and actions taken depend on the severity of the event. Various things happen simultaneously since different individuals are affected differently. Some may be trapped in collapsed buildings, while others may be outside or away from the area worrying about their loved ones. The aftermath of a disaster is multifaceted and dynamic, with different situations unfolding concurrently.

One crucial aspect during this phase is the localization and identification of people, as well as establishing a reliable source of information. Creating a central provider of accurate information becomes vital, especially with the prevalence of social media, where unreliable sources can cause confusion and harm. It is essential to provide regular updates, even if there is no new information, to maintain transparency and keep people informed.

Rescue work and addressing dysfunctional infrastructure, such as electricity, water supply, and road closures, are immediate priorities. Assessing the extent of the damage and determining what needs to be done is the first step. However, it's important to note that disaster response should extend beyond the initial search and rescue phase. The focus should be on the long-term recovery and rebuilding process.

Communities often experience an influx of assistance during the acute phase, but sustaining the recovery efforts becomes a challenge once external experts leave. Securing the necessary manpower and finances to rebuild and repair the infrastructure is crucial. Additionally, attention should be given to the psychological well-being of individuals and the functioning of the social system. Re-establishing schools, social activities, and fostering connections among people are important for community resilience and long-term recovery.

Planning for the aftermath of a disaster requires endurance and a long-term perspective, spanning months rather than just a few days or weeks. It's necessary to anticipate the challenges and be prepared to support communities throughout the entire recovery process.

11. Are there national or local plans that indicate how an area should be recovered?

Not exactly. While there are comprehensive risk assessments conducted for many areas, particularly those considered high-risk, there isn't a specific plan in place for how the recovery should be executed. The recovery process itself is not planned in a detailed manner.

12. Who is responsible for determining the recovery process for an area? How is the planning carried out?

There isn't a specific central institution responsible for such decisions. Typically, it is the municipality itself, with support from the relevant ministry associated with that particular area, that takes charge of the recovery efforts. While organizations like the Red Cross may offer assistance, the primary responsibility falls on the municipality and the specific tasks at hand, rather than being based solely on geographical areas.

13. Does the recovery process begin during the emergency phase or immediately after the emergency ends?

The recovery process starts immediately after the disaster itself. It is not a separate phase that begins once the emergency is over. The initial actions, such as search and rescue operations, play a crucial role in setting the tone for the recovery process. Different individuals and communities may be at different stages of recovery, depending on the severity of their situation and their specific needs. It is important to recognize that people affected by the disaster have varying levels of physical and psychological impact, and their recovery experiences differ. Addressing anxiety, post-traumatic disorders, and providing appropriate social services are essential aspects of the recovery process. Conducting studies and gathering feedback from those affected can help identify areas for improvement and better understand people's needs and experiences during and after the event.

14. What are the social and natural factors that you think help the most in a quick recovery of the area?

When it comes to natural factors, the likelihood of the event recurring and how effectively the damages are addressed and repaired play significant roles. These factors have a direct impact on the recovery process. Regarding social factors, the severity of the impact on the community, including fatalities and extensive destruction, is crucial. However, overall, I believe that good preparation, consistent and trustworthy information sources, guidance for individuals on available assistance such as financial and housing support, and the restoration of community infrastructure are key social factors. It's important for people to regain employment, have a sense of normalcy, and find happiness in activities and surroundings. For example, after an avalanche that damages a village or town, efforts should be made to repair and rejuvenate the environment, creating a secure and beautiful space that uplifts people's spirits. This approach aims to foster optimism and a better sense of well-being. Of course, the feasibility of such actions depends on the severity of the event.

15. Have you ever act as an advisor during an emergency?

No, I haven't.

16. Do you deal with politicians or government people on risk management issues?

Yes, we have engaged with politicians and government officials on disaster management issues. For instance, we have had discussions with the Ministry of Justice, which is responsible for the legal framework surrounding these matters. We emphasized the importance of incorporating recovery efforts into the legal framework, something that had not been adequately addressed before. It is crucial to recognize that the process cannot end once everyone is found and provided with temporary shelter. Follow-up and long-term planning are necessary aspects of the recovery process. People are becoming more aware of this, and there is a growing understanding that recovery should be treated with the same level of planning and importance as other aspects of disaster management.

17. Do you work together with the Department of Civil Protection, the ICE-SAR, the IMO, the Red Cross?

Yes, we do.

18. Are you familiar with concept of multi-hazard?

Yes.

19. Do you integrate in some way this concept into your research?

While we haven't explicitly focused on the concept of multi-hazard in our research, we have indirectly encountered it through our studies. When we interview people who have experienced a specific hazard, such as an earthquake, we often find that it triggers other uncertainties and brings their awareness to the fact that they are living in a hazardous area. This realization may lead them to consider moving or reevaluate the larger effects of the hazard on their lives. So, in a way, the research uncovers the complex interplay between different hazards and their impacts on individuals. However, we haven't conducted specific analyses or studies that directly address multi-hazard situations.

20. In what ways do you think you could better introduce this multi-hazard perspective into your work?

I don't know. In certain cases, we do need to consider multiple hazards and their interactions. For example, if an avalanche triggers flooding by overflowing a dam, it would be essential to take into account both the avalanche and the subsequent flooding as interconnected hazards. In such cases, the multi-hazard approach naturally emerges as we analyze the specific situation or event and understand the different hazards and their impacts. It's important to assess the cascading effects and interdependencies between hazards to fully comprehend the overall risk and plan appropriate recovery measures.

21. Do you think people react differently when there is only one hazard with security in an area compared to when there is a combination or accumulation of hazards and their associated effects?

Yes, people's reactions can indeed differ when facing a single hazard compared to a combination of hazards or consecutive events. Experiencing multiple hazards or their cumulative effects can intensify the sense of shock and stress. If someone has already experienced an earthquake and then faces a volcanic eruption, they might feel more apprehensive or alarmed because they understand that the situation could potentially escalate further. The uncertainty surrounding volcanic eruptions, such as not knowing where they will occur, adds an additional layer of anxiety. For example, during the recent eruption in Reykjanes, people in nearby villages experienced continuous shaking and lived with the fear that a crater could open up in their midst. This uncertainty and proximity to multiple hazards can significantly impact their reactions and decision-making, and some individuals may choose to leave the area for their safety.

22. Could you tell me how you experienced the 2010 eruption? What was your role?

Certainly. In 2010, I had a dual role as a citizen and a scientist. I saw the eruption as a unique opportunity to study its impact. As a scientist, I believed it was important to intervene as soon as possible and conduct interviews with the affected people to understand their experiences. We set up a study where individuals self-reported their emotions and thoughts about the eruption. It was a fascinating endeavor to gather valuable insights from them at the earliest possible time.

23. Did you continue with activities or tasks following the eruption? If so, for how long?

Yes, indeed. Some of the studies we initiated are still ongoing even after the eruption. It has been an extended process.

24. How did your approach to research change as a result of this eruption? What were some key lessons you learned?

From the results of our studies, I learned a great deal about the effects of such disasters and what is crucial for the well-being of people affected. Aside from the obvious focus on life-saving search and rescue efforts, we discovered the importance of consistent information dissemination. We also realized the significance of bringing people together in a community setting where they could connect with others, share experiences, have a meal, and find comfort through interaction. Furthermore, we learned the value of centralizing services in one location, eliminating the need for individuals to visit multiple places for insurance, healthcare, or unemployment benefits. It became evident that creating a reliable and easily accessible framework was paramount.

25. Did the COVID-19 pandemic impact the recovery work after some events?

Yes, the COVID-19 pandemic did have an impact on the recovery efforts following some events, such as a landslide and an avalanche at West, which were affected due to the restrictions imposed during the pandemic.

26. Have you noticed that any event has increased its impact in recent years, either by increasing its frequency, area or magnitude?

It is challenging to draw definitive conclusions based on anecdotal observations. While there have been relatively frequent volcanic eruptions in Iceland over the past decade, it would require careful study to determine the long-term effects and any potential trends. However, I haven't noticed a prominent sense of increased nervousness or concern among the general population regarding these events. Partly, this could be attributed to the fortunate locations where these eruptions have occurred, minimizing their impact.

27. Has the increase in tourist arrivals led to any disruption in the recovery process?

The arrival of tourists to the island does pose challenges to the recovery process during emergencies. While residents who have frequently experienced eruptions over the past decades may have a lower risk perception threshold and be more prepared, visitors from other places may lack that firsthand experience and awareness. It becomes crucial to ensure that we can effectively reach and communicate with these tourists, emphasizing the importance of taking the situation seriously, keeping their phones charged and accessible, and respecting any given instructions. The increased tourism undoubtedly puts strain on the system, although it also brings economic benefits in terms of job creation and income. However, it requires the risk management system to account for a completely new sector with diverse cultural backgrounds, adding complexity to the overall process.

28. How do you feel the perception of risk in the population?

The awareness among the population has evolved over time. The frequency of volcanic eruptions and the participation of individuals in exercises or drills, such as simulated evacuations in the south, have contributed to increased awareness. People are more engaged and understand the importance of being prepared for such events.

29. In your opinion, does this increased awareness and sense of community contribute to the recovery of the population after such events?

As a scientist, I would need to conduct further research and analysis to provide a conclusive answer. However, I believe that the feeling of being part of a society that works together towards a solution can be beneficial for individuals affected by such events. It creates a sense of collective support rather than feeling isolated and solely responsible for recovery efforts.

Interview to Úlfar Lúðvíksson and Gunnar Ó. Schram (Police in Suðurnes)

1. Could you tell me your complete name and position?

My name is Úlfar Lúðvíksson, and I hold the position of the Chief of Police. Here we refer to it as the District Commissioner. And I am Gunnar Ó. Schram, a Chief Superintendent here in Suðurnes district.

2. What is the area of your jurisdiction?

It's the Reykjanes Peninsula, including the International Airport.

3. Where do you receive your monetary funds from?

From the government.

4. How many sections or departments is the Department divided into?

The office is divided into three main departments: the Law Enforcement Department, the Department of Law, and the Office. There are four lawyers in the Department of Law, in addition, the Chief of Police is a lawyer.

5. In the event of a natural disaster, how does the office coordinate its response? Do all departments come together, or is there a specific department primarily responsible for handling such situations?

The response to a natural disaster depends on the nature of the crisis. While all departments have their respective roles, the coordination varies. However, one department primarily takes the lead in such situations. The legal office is not directly involved, and the department office of the chief police is also not directly engaged.

The uniformed police play a crucial role in handling and coordinating responses to natural disasters within our jurisdiction.

6. How is the police in Iceland structured, for example, is there a national police force and then a local police force?

In Iceland, we have a national police office located in Reykjavik, the capital city. In addition to the national police, we also have regional police departments. There are a total of nine regional police departments across the country, and the office I represent is one of those nine. We have the national police office responsible for overarching law enforcement at a national level, and we also have the regional police departments that handle local or regional matters.

7. What other state security forces exist in Iceland? Because you don't have army, right?

In addition to the police force, another important state security force in Iceland is the Icelandic Coast Guard. They play a significant role in maritime security and safeguarding the coastal areas. It is important to note that Iceland does not have its own army.

8. What is the position of the Civil Protection Department with respect to you?

The Civil Protection Department is indeed a part of the police organization. It functions as a department within the police and is also under the control of the police. It is affiliated with the Department of the National Commissioner's Office. The Civil Protection Department is an integral part of the police structure and operates under the supervision and control of the police.

9. Under what circumstances do you act instead of the Department of Civil Defense? Or the other way around?

Typically, we work together from the start of any operation. We collaborate closely, especially in the initial stages. While we have different roles and responsibilities, our coordination and cooperation in the field are crucial. So, in most cases, we act together, ensuring effective joint efforts.

10. Where does the Police Office stand in relation to other institutions involved in risk prevention in Iceland (e.g. the Met Office, the SAR, the Government or administrations)?

When it comes to ongoing crises or disaster situations, close cooperation and communication are crucial. We maintain a strong working relationship, especially with the Met Office. The Civil Crisis Unit at the National Commissioner's Office works closely with the Met Office on a daily basis, as their expertise is essential for monitoring and addressing potential threats across the country.

11. What prevention actions do you carry out during the year against natural disasters?

We have comprehensive emergency plans in place for various types of crises. For instance, we have plans for flight-related emergencies at both national and international airports, as well as plans for earthquakes, volcanic eruptions, and so on. We actively practice response plans with voluntary response teams, national healthcare organizations, and the Red Cross, among others.

We conduct large-scale exercises every four years where all stakeholders participate on-site. In addition, we also engage in smaller-scale exercises, such as table exercises, in between the major ones. In certain cases we organize evacuation exercises that may involve the general population.

12. Do you work jointly with the University of Iceland, the Met Office or other institutions?

We collaborate with the University of Iceland, as well as the Met Office and other institutions, to enhance our preparedness. We also engage with the scientific council, including meetings held during the 2021 eruptions and this year's activities. During these meetings, we had the opportunity to participate, whether by listening or asking questions, to benefit from their expertise.

13. What is the role of the Police in these meetings?

During the crisis, we had daily meetings where scientists would join us to provide information and assessments. Additionally, the scientific community held separate meetings where they discussed various aspects of the eruptions, including lava flow predictions and gas pollution.

We met regularly, typically every morning at half past eight, for several months, and it was our responsibility to lead these meetings. Often, it would be either myself (Úlfar) or Gunnar taking charge.

As for the information exchange, the Met Office, although not physically present on-site, relied on us to provide updates on the situation at the eruption site. We had cameras set up with internet connections to capture visuals, but the ground-level information came from our reports to them.

It was a unique opportunity for us to adapt to online meetings, much like during the COVID-19 pandemic. It forced us to embrace technology and learn how to conduct such meetings remotely. While it presented challenges, it also highlighted the importance and benefits of leveraging digital platforms for communication and collaboration.

14. When there is an anomalous situation, e.g. an increase in the seismicity prior to a possible eruption, or extreme weather forecasting, risk of avalanches, or any kind of risk in this area, who informs the Police Office and what do you do?

The regional police office serves as our initial source of information. However, when there are precursors or anomalies like heightened seismic activity, we receive notifications from the National Commissioner's Office. They maintain daily communication with the Met Office and are responsible for disseminating relevant information to us.

If the situation pertains to our region or falls under our jurisdiction, they ensure that the information is shared with us accordingly. This collaborative approach allows us to stay informed and take appropriate actions when necessary.

15. What decisions does the Police Office make that other institutions, for example, the Met Office, cannot make?

During moments of crisis, regardless of the nature of the crisis, the chief of police within a specific region has control over operations. It is not the responsibility of the national commissioner's office but rather the regional chief of police within their jurisdiction. They hold the authority to make all the necessary decisions during these critical situations.

For instance, in the recent eruptions we experienced, the word of the regional chief of police carries significant weight. They serve as the commander of the crisis command and have the power to make key decisions instead of the national commissioner.

However, if we require assistance from other regions, we coordinate through the national commissioner's office. While the national commissioner still has a role to play, the regional chief of police takes the lead when it comes to decision-making during the crisis.

16. Once an emergency has been declared, how is the chain of command in the Police Office?

Once an emergency is declared, the regional command within the police office operates under the control of the chief of police. They assume the responsibility of daily control and decision-making during the crisis. However, the chief of police can delegate this authority to other officers if necessary.

For example, in the case of volcanic eruptions, the chief of police appointed me as the commanding officer for the crisis response. In this role, I take charge of coordinating the operations, while the chief of police supports and works alongside me.

17. Do you have contingency plans?

Absolutely. We have a range of response plans in place to address various types of emergencies. These plans are documented and serve as a reference for our actions. We have three categories of response plans: national plans, regional plans, and special plans that are specific to certain situations.

For instance, we have response plans for volcanic eruptions in the region, other natural disasters, flight-related incidents at international airports, and even plans for road-related contingencies. These plans cover different aspects of the response, including evacuation plans for towns in the affected areas.

Prior to the eruptions in 2021 and this year, we had specific plans prepared and ready for implementation. Additionally, we conducted exercises and drills, such as the one a few days before the 2021 eruption, to ensure that we were well-prepared to the best of our abilities.

18. What are the main tasks of the Police during an emergency?

During an emergency, the police undertake several important tasks. Firstly, we are in command of the crisis response, taking control and making critical decisions. This involves close cooperation with various institutions and stakeholders, including the local community, scientists, the national police, the national commissioner's office, the Ministry of Environment, and other relevant organizations.

We also work closely with landowners, especially in cases where the emergency occurs on private land. This involves negotiating agreements and making necessary infrastructure arrangements, such as creating paths and designated parking areas.

The most vital aspect of our role is ensuring the safety of people, their properties and important community infrastructure. We strive to keep individuals out of harm's way and protect their assets. This requires effective coordination with other agencies, including the aviation system, to ensure accurate reporting and monitoring of the situation.

Ultimately, our main goal is to facilitate smooth operations, foster collaboration among all involved parties, and direct everyone towards a unified and effective response.

19. Are you in charge of the evacuation process?

Yes.

20. What are the main evacuation routes in this area?

One of the main evacuation routes in the area is the road connecting Reykjanes town to the Reykjavik capital area, including the international airport. This route serves as a crucial pathway for evacuation during emergencies.

In the vicinity of the eruption site, which is located in Geldingadalir or Meradalir, there is another evacuation route originating from Grindavík. Grindavík is the nearest town to the eruption site, situated approximately 10 kilometers away. From Grindavík, there are three evacuation directions available, providing multiple options for people to safely leave the area.

Additionally, Grindavík also has a harbor that can be utilized for evacuation purposes. During the 2021 eruption, the Icelandic Coast Guard deployed their largest ship to this harbor in response to our request for assistance. This allowed for an alternative means of evacuation, particularly when road conditions were challenging due to snowstorms and other adverse weather conditions.

The collaboration between the national police and the coast guard was crucial in facilitating this response. With a simple phone call, the coast guard could be mobilized to support evacuation efforts, even in challenging circumstances such as power outages and adverse weather conditions.

21. What happens when circumstances during an emergency exceed your ability to contain or act?

When faced with a situation where our regional resources are inadequate or overwhelmed, our first course of action is to contact the national commissioner's office and their crisis unit. We request assistance through them to augment our capabilities.

Through the national commissioner's office, we can access support from other regions across the country. This includes mobilizing additional search and rescue teams from various parts of Iceland. In exceptional cases, we can also request resources from abroad, if necessary. This could involve assistance from other countries in situations such as a plane crash or a large-scale fire.

There are instances where the capacity of our national health system is limited, particularly when it comes to treating individuals with severe burns. In such cases, we may need to evacuate these individuals to other countries where specialized medical facilities can provide the required care.

It is important to note that during the initial stages of an emergency, we often need time to assess the situation comprehensively. As part of our response, we may temporarily block roads to facilitate effective decision-making and strategizing.

22. How is it decided that a state of emergency has ended?

The decision to end a state of emergency is made by the chief of police in the respective region, in collaboration with the national commissioner's office. While the police have a central role in this process, it is not a decision made in isolation.

Throughout the evaluation and decision-making process, the advice and input of various stakeholders are taken into consideration. This includes consulting with scientists who have expertise in the relevant fields related to the emergency situation at hand. Their insights and recommendations play a crucial role in determining when it is appropriate to lift the state of emergency.

The decision-making process involves a coordinated effort between the police, the national commissioner's office, and relevant scientific experts to ensure that the state of emergency is concluded based on a comprehensive assessment of the situation.

23. Could you tell me how you experienced the 2010 eruption?

Yes, the 2010 eruption of Eyjafjallajökull did have an impact on this region, specifically on Keflavik airport, which is the international airport serving Iceland. The eruption resulted in the closure of the airport for a brief period of time due to the presence of fine ash in the air, which was deemed hazardous for flights.

To manage the situation, a command center was established at the Reykjavik flight tower. From there, authorities monitored incoming flights to Iceland and directed them to alternative airports such as Akureyri in the northern part of the country or Egilsstaðir in the east, where conditions were safer for landing.

24. And what can you tell me about the recent eruption of 2021? What was your role of that of this Police Office?

During the eruption of 2021, we encountered several difficulties and challenges. Firstly, it was noteworthy that the region hadn't experienced an eruption for over 700 years, so it was an uncommon occurrence. However, considering the presence of lava fields and eruption sites in the area and the extensive knowledge of scientists regarding eruptions on the Reykjanes Peninsula, the eruption itself was not entirely surprising.

Prior to the eruption, there were numerous seismic activities, including earthquakes, indicating magma intrusion from the eruption site. The scientific community closely monitored these signs, along with the land rising above the intrusion, which indicated a high likelihood of lava erupting. Although we were expecting an eruption, we didn't specifically anticipate it occurring in this particular area.

In terms of preparation, we conducted an evacuation exercise in Grindavík and established communication channels within the response community. We set up a coordination center to determine the best course of action and whether it was necessary to completely close the area or not. While we were prepared for an eruption, we didn't fully believe it would happen in this area.

One of the main difficulties we faced during the eruption was dealing with people. We had to control the flow of individuals in a safe manner, especially since we didn't want tourists wearing inappropriate clothing, such as sneakers, shorts, and T-shirts in winter conditions in Iceland.

25. How did the COVID pandemic affect your work during the eruption?

The COVID-19 pandemic also played a role in the response to the eruption. The pandemic provided some advantages, such as fewer tourists due to travel restrictions and the ability to coordinate internet teams effectively. It presented an opportunity to improve our systems and learn from the eruption.

26. Are you still carrying out activities or tasks related to the 2021 eruption?

Following the eruption of 2021, we made various improvements to our system. We focused on enhancing the infrastructure in the area, including setting up hiking paths, to ensure the safety of people visiting the eruption site. We implemented age limits due to gas pollution and danger assessments, restricting access for children under a certain age. We also had to close the area multiple times due to weather conditions, wind direction, and gas pollution from the eruption.

27. What did you learn from the 2021 and 2022 eruptions?

Compared to the earlier eruption, the walking distance to the second eruption site was longer, ranging from seven to nine kilometers one way. This posed additional challenges, especially considering the winter conditions during the eruption period. Despite these difficulties, the experience gained from the 2021 eruption made it easier to handle the situation. The response community was well-prepared, and the close-knit nature of the community, including the voluntary search and rescue teams, facilitated effective coordination.

Before the eruption in 2022, we started planning and preparing based on the knowledge and experience gained from the previous eruption. We had a general idea of the area where the intrusion was located, although we couldn't predict the exact eruption site. The rescue team in Grindavík was well-equipped, trained, and experienced, making them specialized in responding to eruptions.

Overall, the eruption of 2021 provided valuable training and lessons for us, allowing us to improve our response system and strengthen our capabilities in dealing with such events. The scientific terminology used during the interview reflects the collaborative efforts between the scientific community and the response community in understanding and responding to volcanic eruptions effectively.

28. You talk about the eruptive process with scientific terms and great knowledge of the phenomenon. Why do you have such a deep knowledge base?

The knowledge about volcanic eruptions in Iceland is widespread among the general population due to various factors. Firstly, living in Iceland means being exposed to information about eruptions through media channels and general awareness. Iceland experiences eruptions every four to five years, with notable examples like Hekla and others. Therefore, it has become common knowledge for the population.

Additionally, the close collaboration between the response community, including the Met office, university, and other scientists, and the scientific community during eruptions is crucial. This collaboration ensures that the response community is well-informed and equipped with the necessary knowledge to handle volcanic events effectively. The close relationship between the response community and the scientific community allows for the transfer of knowledge and expertise. It’s also a learning process for us.

Furthermore, Icelanders have a unique relationship with geological phenomena due to their frequent exposure to earthquakes. Every year, Iceland experiences several earthquakes, which contribute to the population's understanding and interest in geology. It is often said that every Icelander is an amateur geologist because geological activity is an integral part of their environment.

In summary, the knowledge about volcanic eruptions in Iceland is acquired through a combination of general awareness, media coverage, the collaborative efforts between the response community and the scientific community, and the frequent exposure to earthquakes and geological phenomena in the country.

29. Do you carry out training on natural hazards for your own employees in the Office?

Yes, in the police office, various trainings and courses are conducted to enhance knowledge and preparedness for natural hazards, including volcanic eruptions. Exercises are carried out regularly to test and refine response plans. For instance, there are exercises focused on response plans at the International Airport, involving a significant number of participants every four years, as well as smaller exercises held annually in between. Police officers undergo specific courses for on-scene commanders and receive training to develop their skills in managing crisis situations.

The National Commissioner's Office, which oversees the police force, takes the lead in planning these exercises and courses. They organize training opportunities and send officers to participate. Additionally, the National Commissioner's Office has a department dedicated to handling crises and employs scientists, including specialists in eruptions and related matters. Their expertise contributes to the overall knowledge and preparedness of the police office in dealing with volcanic eruptions and other hazards.

30. How do you feel the perception of risk in the population?

The perception of risk among the population in the region can vary depending on where people live. In areas closest to the eruption site, such as Grindavík town, there was a mix of reactions. The general public, who were familiar with earthquakes and eruptions due to their experience living in the region, remained relatively calm and at ease. They understood that while the situation was not normal, it was not uncommon either.

However, there was a significant portion of the community in Grindavík who were of Polish origin and had no prior experience with earthquakes and volcanic eruptions. Despite efforts to provide information and reassurance through media alerts in Polish, some individuals relied on Polish media sources that provided incorrect information, leading to fear and concern.

To address these concerns, meetings were organized in Grindavík with geophysicists and interpreters to provide accurate information and alleviate fears. Over time, as the eruption progressed and remained at a safe distance of 10 kilometers from the town, people in Grindavík began to feel relieved and more relaxed.

Overall, Icelanders, in general, have a better understanding of the natural hazards they face, such as earthquakes, and have learned to adapt and live with these events. Earthquakes with magnitudes up to 3 or 4 are relatively common in the region, and the population has become accustomed to them.

31. How did you manage the media and handle the pressure during the eruption?

From the onset of the eruption, I entrusted Gunnar with the responsibility of being the main point of contact for the media. However, I want to emphasize that our approach involved a collective effort, with the involvement of the entire police team. We engaged in extensive written communication, publishing updates and statements. Nevertheless, Gunnar played a pivotal role as the primary liaison with the media.

As the eruption unfolded in 2021, it became evident that the demands placed on a single individual were overwhelming. Consequently, a decision was made to assign two police officers to handle media interactions. In addition, we had three response units comprised of dedicated volunteers stationed the area.

To distribute the media interviews effectively, I took on a significant number myself, while also delegating some to others. This approach allowed us to present a united front and ensure comprehensive coverage. It was crucial for us to avoid relying solely on one person for media engagement. Naturally, the chief of police also made regular appearances in the media. Overall, we can say that four staff members, including Gunnar and I (Úlfar) in the head office, played prominent roles in handling media affairs.

I believe our strategy worked quite well. Although it was undoubtedly exhausting, the team made round-the-clock phone calls to maintain constant communication. Controlling the information we conveyed to the media was of utmost importance. We maintained close coordination among the two officers in the area, the three volunteers, and ourselves. We constantly discussed what to say and ensured consistency in our messaging to control the narrative as best we could.

By fostering this approach, we could carefully manage the type of information shared with the media. It was essential for everyone involved to convey the same message consistently. I should note that Gunnar, along with the two officers, spent considerable time in Grindavík, overseeing the on-scene command when necessary.

In summary, we made sure to have a strong presence and coordination within the media landscape. We strived to control the information flow, maintained a united front, and established close communication between all parties involved.

32. What features does your system have that you think are efficient?

There are a few key factors that contribute to our system's efficiency. Firstly, being part of a small community has its advantages. It allows for close-knit cooperation and effective communication channels.

However, there are certain difficulties we encounter when it comes to the question of "who" rather than "how." It can be challenging to determine the responsible parties or individuals to address specific issues.

Another essential aspect of our operations is the collaboration with voluntary response teams, particularly search and rescue teams. These teams play a crucial role in Iceland and are made up of volunteers. In 2021, we had approximately 1800 voluntary response individuals participating in the operation, which is a substantial number for Iceland.

One of the limitations we face is the lack of manpower within the local police force to handle all aspects of crisis management. Therefore, we heavily rely on the support of voluntary response teams. However, it's important to note that these volunteers have other jobs and obligations, as the duration of the crisis during the 2021 eruption lasted for six months.

Given the challenges we faced, both the local police and voluntary response teams agree that having a professional response team would be beneficial in the future. We envision a professional rescue team that could consist of around 80, 90, or even 100 members. This would provide additional resources and manpower to better manage crises.

From the perspective of the police force, our operations extend beyond the context of an eruption. Crimes and other ongoing responsibilities cannot be neglected during such events. This dual workload can be quite demanding and challenging to handle.

While being a small community and a small team has its advantages, there are instances where we require additional manpower. It can be challenging to address complex situations with limited personnel. Therefore, we recognize the need to strike a balance between the benefits of a small team and the necessity for additional resources in certain circumstances.

Looking ahead, we may consider the establishment of professional response units, similar to what exists in other regions like the Alps. This would allow us to enhance our capabilities and better align with established practices in crisis management.

33. What shortcomings or areas for improvement do you think your organization has?

I believe introducing a professional rescue team is an important improvement that we are considering. In the coming years, we may see the implementation of such a team.

34. Could you provide more details about the professional rescue team? Is it related to ICE-SAR?

Yes, I'm referring to ICE-SAR (International Search and Rescue). Part of ICE-SAR would consist of professional rescuers. While ICE-SAR itself is primarily composed of volunteers, we have an agreement with ICE-SAR and the Red Cross. ICE-SAR operates on a voluntary basis. However, after the initial 72 hours in a life-threatening situation, the units involved in the rescue operations are compensated. It's important to note that the compensation is provided to the units rather than individual members.

35. After the initial 72 hours, does the compensation apply to both ICE-SAR and the Red Cross?

Yes, the 72-hour period pertains to life-threatening situations. After that, the units involved, which include both ICE-SAR and the Red Cross, receive compensation for their work. The government is responsible for funding these institutions. We have a special agreement with ICE-SAR and the Red Cross regarding this matter. We have an agreement in place since 25 October 2021 (the older agreement since 2011). While it does involve a significant amount of money, the teams have the responsibility to remain in the field for the entire duration.

36. Is there a possibility for the members to leave or discontinue their service during the operation?

The agreement is designed to prevent such situations, and we have not encountered this issue in recent times. However, it's important to acknowledge that it could potentially be a problem in the future, although it's not anticipated in the near term. The volunteers who make up ICE-SAR are valuable assets during crisis situations, and their dedication is commendable. However, considering the duration and the fact that they also have their regular employment, it becomes a sensitive matter. It would be difficult to expect volunteers to carry the responsibility for that length of time. It's a sensitive matter that needs careful consideration.

Interview to Guðbrandur Arnarson (ICE-SAR)

1. Could you tell me your complete name and position within the ICE-SAR?

My name is Guðbrandur Arnarson and I am the project manager for search and rescue in Iceland. The association I work with is called ICE-SAR. My main responsibility is to provide overall oversight for the 93 rescue teams within the organization. Additionally, I am a member of the National Command, which is comprised of one central command and 16 regional commands. These regional commands coordinate the activities of the 93 teams, with some regions having three teams and others having around ten to twelve teams. I will provide more detailed information later.

2. When was the ICE-SAR created?

The ICE-SAR was founded in 1928, although the first team in the organization was established in 1918.

3. What is its legal framework?

The legal framework of the ICE-SAR consists of three main layers. Firstly, there is the law on volunteer search and rescue, which allows us to carry out our activities. Secondly, there are regulations that further explain how the organization operates, including operating under the auspices of entities such as the police, fire chiefs, and the coast guard. Lastly, there is the framework for public safety in Iceland, which lays out the foundations for the association and its consolidation from three competing rescue teams into one.

4. What are the main tasks of the ICE-SAR?

Search and rescue and accident prevention programs.

5. Where do you receive your monetary funds from?

The financing of the organization primarily comes from fundraising efforts directed at the general public. While we do receive some government grants, they do not make up a significant portion of our fundraising. However, we have an agreement with the government that in situations where there are life-threatening events affecting the local community, the government will compensate us for our response efforts once the life-threatening phase is over. This agreement was particularly relevant during events like the volcanic eruption in 2021 and 2020, where we deployed a large number of our members to ensure the safety of people and assist in stabilizing and rebuilding society. For life-saving measures, such as search and rescue operations, we do not charge, as it is our principle not to do so. However, for accident prevention initiatives and patrolling activities, we can seek funding and, in some cases, receive substantial compensation for our services.

The most important fundraising activity is selling fireworks, which accounts for a significant portion of each team's annual budget, ranging from 60% to 80%.

6. Do you charge for life-saving measures?

We believe that life-saving measures should not come with a price tag. Charging for saving lives goes against our principles but if a person is specifically insured for extreme activities we might seek compensation for our costs from the insurance company. However, for accident prevention activities and patrolling, where the focus is on prevention rather than immediate life-saving, we can seek funding and charge for our services. We have also made it clear to the government that our work should not be viewed as a simple hourly rate organization since we dedicate our free time and volunteering efforts, which should be valued differently. Hiring contractors or individuals on a basic salary to perform the same tasks should be appealing for the authorities to encourage them to find permanent solutions to the problem. Should permanent solutions not be available volunteers will consider taking on the task.

7. What is your organizational chart within the ICE-SAR?

Currently, we have 93 teams within the organization, although this number has decreased over time due to mergers. Previously, in the early days, there were more teams, often multiple teams in the same town. However, through consolidations, we now typically have one to three teams in larger cities and towns, with Reykjavik having around eight teams or teams in the surrounding areas. It's important to note that each team operates independently, which is crucial for the organization's preservation. In our organizational structure, the teams actually own the organization, rather than the other way around. This inverted pyramid structure sets us apart from international organizations like the Red Cross, where directives flow from the top down. Here, the teams have significant autonomy but adhere to a common philosophy. We can describe our decision-making process as a blend of representative democracy and direct democracy, with teams holding considerable power. Constant diplomacy and discussions are necessary, and decisions can take time. However, when it comes to response efforts, we act within a rigid and strong chain of command, with no disagreements or bickering. Afterward, though, we may spend days or months debating and reflecting on the actions taken.

8. Could you provide an example of the differences or specializations among the teams?

In the early days, teams had distinct specializations. For instance, the first organization was focused primarily on maritime operations, with a strong majority of their activities being related to maritime accidents. However, over time, teams diversified their capabilities. Another organization organization was formed in the 1930s had limited maritime experience, focusing more on land-based operations. We also had air-to-ground or ground-to-air teams founded in the 1950s that showed great interest in locating missing aircrafts. As time went on, the differences among the teams became less pronounced, and many teams developed a broad range of capabilities. It's important to note that not all teams possess the same capabilities. For example, my team doesn't have maritime expertise or boats, but we excel in mountain rescues. Overall, our teams cover a wide spectrum of operations, including diving, boat rescues, swift water rescues, search capabilities, first aid, and even road assistance during winter storms. Occasionally, some teams may charge for their services, particularly when tourists find themselves in need of road-side assistance after disregarding warnings. However, we exercise discretion, and there are cases where we provide assistance without charge, such as a person crossing a highland pass for medical purposes to name an example. Our approach leans more towards being a reserve force, considering the circumstances and individual needs.

9. Are all of you volunteers?

Yes, we are all volunteers. Within our organization, we have approximately 7,500 volunteers. Out of this number, around 800 are teenagers who participate in our activities. We also have dedicated accident prevention units, which primarily consist of women. When it comes to the search and rescue aspect, we have approximately 4,200 volunteers on roster. We have in addition about 1,000 members not on the roster that are typically older individuals who still contribute to fundraising efforts and the administrative tasks. These older members often provide support by serving warm cups of coffee to tired team members after a call-out, creating a social atmosphere within the organization.

However, while the majority of the individuals involved with ICE-SAR are volunteers, there are paid positions within the organization. Those working in the head office, such as administrative or management roles, receive payment for their work. These paid positions serve as their daytime jobs. It's worth noting that volunteers in ICE-SAR come from various professional backgrounds, and some may have had different careers before joining the organization. For example, the person mentioned in the conversation had a degree in business and previously worked in corporate Iceland in financial management. However, due to their passion for the mountains and involvement with ICE-SAR, they transitioned into a role within the organization.

10. Do you have several bases deployed throughout the territory? Has each of them its own jurisdiction?

Yes, we have deployed our operations across the territory in 16 regions. These regions align almost with the nine police regions, which sometimes leads to complexities in coordination with the police. In the southern part of Iceland, we have three regions, while in Reykjavik and its surrounding areas, we have a single region aligned with the police region. In the north east, we have two regions within the same police precinct with headquarters in Akureyri. Furthermore, in the west fjords, we have three regions within the same police region. Although the police may find this arrangement complicated, we assure them that we will handle it efficiently. Each team within the organization has its own home base, and most teams own their clubhouses. These facilities serve as a central hub where teams store their equipment and hold meetings and training sessions. While there is healthy competition among the teams, such as when a team acquires a new vehicle, there is also collaboration and cooperation between them.

11. Are there other institutions in Iceland that share your same tasks, i.e., that also perform search and rescue services?

Yes, there are other institutions in Iceland that share similar tasks to ICE SAR in terms of search and rescue services. However, ICE SAR defines its scope as being a first responder organization that assists when other responders, such as the police, EMS, and fire services, are overwhelmed or lack the necessary technical expertise. ICE SAR aims to fill in the gaps and provide assistance in such situations. However, ICE SAR does not want to take on the role of daily EMS (Emergency Medical Services) providers. This is because if rescue teams were to handle EMS duties every day, the government would be obligated to pay for those services. ICE SAR prefers to focus on occasional search and rescue missions, typically occurring around five to six times a year or every other month, allowing volunteers to participate while avoiding the need for daily provision of EMS services.

12. What kind of relation you have with the Department of Civil Protection?

ICE-SAR is a key member of the Civil Protection consortium. Stipulated by law ICE-SAR is a permanent member of the public safety regional commands with the police, public safety municipal committee, Red Cross, and participating first responder authorities based on the type of incidents. ICE-SAR also collaborates with various stakeholders in the public safety consortium. The relationship between ICE-SAR and scientific institutions like the Met Office and the University of Iceland is indirect and primarily facilitated through the Public Safety Office. ICE-SAR, as an association, is part of the Public Safety Consortium, which is under the umbrella of the police, and includes various EMS, fire departments, ambulance services, critical infrastructure agencies, and airport authorities. These organizations collectively handle daily accident response.

In the context of natural disasters, scientific institutions, including the Met Office, play a role in monitoring and assessing risks such as seismic activity and avalanche conditions. While ICE-SAR focuses on response and rescue operations, the scientific community provides valuable monitoring and advisory services. In the case of avalanches, ICE-SAR may collaborate with the Met Office for evaluating avalanche risk or seeking advisory support during an emergency.

During large-scale events or emergencies like avalanches impacting towns, ICE-SAR may request assistance or advice from the Met Office. The MET office, through their expertise and monitoring capabilities, can provide valuable insights and guidance to aid ICE-SAR's response efforts. Overall, while the direct interaction between ICE-SAR and scientific institutions may be limited, they both contribute to ensuring public safety and have a seat at the table when addressing emergency situations.

13. Do you conduct courses and trainings throughout the year?

Yes, ICE-SAR conducts courses and training for its members. We have a school that operates from autumn to spring, allowing members to focus on mountaineering and other activities during the summer. The school services approximately 4,000 students per year.

The training program caters to different groups within ICE-SAR. Approximately 60% of the students are new recruits or individuals who have recently joined the organization. The remaining participants consist of existing members who undergo refresher courses to maintain their skills and knowledge.

Even experienced members like the individual being interviewed need to attend refresher courses periodically. In the given example, the interviewee mentions that they have to undergo a refresher course after a gap of four years since their last training on average.

Training and refresher courses are crucial for ensuring that ICE-SAR members are equipped with the necessary skills and knowledge to perform their search and rescue duties effectively.

14. Do you provide training and education to the population?

Yes, ICE-SAR does provide training and education to the general public. They have a school that not only trains their own members but also serves as a source of teachers for the teams. Members of ICE-SAR teams may act as instructors and teach courses to their respective teams.

Additionally, ICE-SAR extends its training and education services to the tourism industry and the general public. This appears to be a sideline business for the organization. The interviewee mentions that they personally teach about four to five courses a year for their team, which suggests that other team members may also be involved in teaching.

While the team members act as instructors, there is a fee for the learning materials, which is paid by the team. This arrangement allows the team members to contribute their teaching skills without imposing a financial burden on their respective teams.

These courses focus on areas such as first aid, mountaineering, and snowmobile usage. These courses are not limited to individuals but also extend to employees of various companies, particularly those involved in industries like electricity transmission and utilities.

For employees in industries like critical infrastructure, ICE SAR provides training on first aid, how to evaluate avalanche risk, operate snowmobiles and handle challenging weather conditions in mountainous areas to name a few examples. This training ensures that employees, even if they are skilled in their respective fields, are well-prepared for the specific challenges and risks they may encounter in mountainous terrain, such as avalanche awareness and risk identification.

15. When there is an anomalous situation, regarding a hazard, does someone inform the ICE-SAR to be prepared for an emergency?

The responsibility for providing alerts or warnings lies with entities such as the Icelandic Met Office, which monitors weather patterns and issues notifications. They hold daily briefing meetings and are in contact with the Public Safety Office. During these meetings, specific warnings or information regarding large-scale events are shared.

ICE-SAR has access to these notifications and often joins the daily meetings at the Public Safety Office to stay informed. They also collaborate with a joint venture fostered by ICE-SAR called "Safetravel," (www.safetravel.is) which is a partnership between ICE-SAR, government entities, and tourism organizations. Safetravel focuses on accident prevention for the tourism industry, providing warnings and notifications to both foreign tourists and Icelandic travelers. They have a mailing list with approximately 3,800 tourist operators and send out emails advising them about potential hazards or weather conditions.

During natural disasters, ICE-SAR plays a role in communication and coordination. They work closely with the Public Safety Office and are involved in discussions and decision-making processes related to emergency response. Additionally, ICE-SAR is responsible for participating in educating responders and other public safety stakeholders, providing training for individuals operating in the National Crisis Center.

Overall, the communication and coordination between various organizations and agencies ensure that ICE-SAR is prepared and informed about potential emergencies or hazards, allowing them to respond effectively when needed.

16. Once an emergency has been declared, what is the usual flow of action and your main tasks?

Once an emergency has been declared, the flow of action within ICE-SAR depends on the type and scale of the incident. The overall responsibility for emergency management lies with the police, who operate in nine regions for emergencies on land, and the Coast Guard, which operates in a single national region for emergencies on sea.

ICE-SAR's response is coordinated based on the incident's magnitude and nature. They mirror the command structure of the regional commands, consisting of three layers: coordination, strategy, and tactics.

The coordination level is the National Command, which is typically the National Crisis Center. ICE-SAR plugs into this command structure to receive information and directions. The strategic level involves defining the objectives, strategies, and resources needed to address the incident. The tactical level, also known as the on-site command, handles specific decision-making on the ground and individual group tasking.

During a national calamity, a significant number of people, such as around 50, may be activated at the coordination level. At the operational level the regional command ensures that the on-site command requests for support are met. The regional command assesses need for resource allocation and may request additional support to the national command.

For natural disasters, such as volcanic eruptions, there is usually some warning period. During this time, regular meetings are held to assess the situation, evaluate the potential eruption, and make preparations. The response is location-based, with pre-planned strategies based on field visits and evaluations. The eruption's location and characteristics determine the specific actions taken.

ICE-SAR follows a unified command structure called SÁBF, which is derived from the American Incident Command System (ICS) and National Incident Management System (NIMS). This system enables effective communication and coordination among different agencies and organizations involved in emergency response.

The main difficulties encountered during natural disasters include ensuring the safety of responders and managing the risks associated with hazards such as gas, flying debris, flowing lava, and unstable terrain. Crowd control may also be a concern in certain situations. However, the primary focus and responsibility of ICE-SAR lie in keeping their personnel safe while carrying out their duties.

Overall, ICE-SAR's actions during an emergency are guided by established command structures, protocols, and contingency plans to ensure effective response and the safety of responders.

17. If the catastrophe exceeds your containment capacity, do you ask other organizations for help?

We may need to request assistance from other organizations. However, their first line of defense is the police, fire departments, and emergency medical services (EMS). ICE-SAR collaborates with the Red Cross, but their roles have minimal overlap.

ICE-SAR is the reserve force for other first responders. With approximately 4,200 people on their roster, the largest pool ICE-SAR has drawn from in a serious incident was 25% of their capacity. In the unlikely event that they faced a severe shortage, they could call upon capable former members who are still knowledgeable and equipped to assist.

If ICE-SAR were to exceed their capabilities, foreign aid would be the next step. The specific aid needed would depend on the nature of the calamity. For example, if there were widespread building collapses, they might require assistance from USAR teams from various countries, such as Germany, France, Spain, Italy, the UK, the US, Sweden, Norway, and others.

The procedures for search and rescue generally follow a generic framework. However, there are specific standard operating procedures (SOPs) for different types of hazards and rescue scenarios. For maritime rescue, ICE-SAR adheres to the IMSAR (International Aeronautical and Maritime Search and Rescue) agreement, which provides a standardized approach worldwide. Mountain rescue procedures may vary slightly depending on whether they align with the Alpine Mountain Rescue or the American Alpine Rescue guidelines, but efforts are being made to achieve a unified approach in the field.

18. And how do you deal with the possible concatenation of events during the same emergency, e.g. landslides or avalanches following earthquakes, or floods following eruptions, or even tsunamis, etc.? Is it a possibility that you know about or you have experienced?

When it comes to dealing with a concatenation of events during the same emergency, such as landslides or avalanches following earthquakes or floods following eruptions, ICE-SAR has a flexible approach. They do not have specific response plans for every possible scenario because the nature of such events can vary widely.

ICE SAR follows the SÁBF framework (S=Incident Management, Á=Planning, B=Resources, F=Operations), which is adapted from the American Incident Command System (ICS). This framework provides a structure and standard operating procedures (SOPs) that can be applied to different types of emergencies. Whether it's a landslide, avalanche, missing person search, or earthquake, the framework guides their response.

The framework includes several key layers: incident management, operations, planning, logistics, public relations, and safety and security. These layers help coordinate and manage the response effectively. It allows ICE-SAR to handle various scenarios, from planning conferences to responding to small incidents or major disasters.

Within the framework, contingency plans are developed to address specific challenges that may arise during different types of emergencies. For example, an airline crash would have its own set of SOPs focused on triage, sheltering, staging areas, communication, and more. If a hazardous material leak or a chemical event occurs, additional SOPs specific to that situation would come into play. Each team within ICE-SAR knows their roles and responsibilities based on the overall framework, but they can adapt and activate specific SOPs as needed.

ICE SAR aims to have individual processes for various scenarios. If something unprecedented occurs, they take a dynamic approach. They learn from similar incidents or situations and adapt existing SOPs to create new ones. This ensures that their response remains dynamic and agile, acknowledging that emergencies are constantly changing, and rigid plans may not always apply.

Rather than relying on extensive manuals or predefined steps, ICE SAR focuses on having SOPs that can be adjusted and combined as needed. They understand that emergencies are fluid, and a flexible approach allows them to respond effectively to the evolving circumstances they encounter.

19. Do you think that if there were more prevention measures implemented in scenarios where multiple hazards occur simultaneously, your job would become much easier?

Absolutely. Increased prevention in such situations with multiple hazards would definitely make my job easier. It's safe to say that the conclusion is embedded in the question itself. Pre-planning is always a good practice, but as General Patton once said, "No plan survives contact with the enemy." So, while you can create a plan, the real value lies in the process of planning itself. Through planning, you gain a deep understanding of the surroundings and how things work.

For instance, I have extensive experience working in the energy sector, providing training in incident management. I've also trained individuals in the aviation industry, despite having little prior knowledge of it. This cross-industry exposure has allowed me to grasp how different sectors operate and think. Participating in several search and rescue missions for missing planes has further enhanced my understanding of the airline industry. So, when faced with a specific scenario, I can quickly identify the necessary processes and adapt accordingly. However, it's crucial to emphasize that it's not just about understanding the structure of the ecosystem; the human factor is equally significant.

You can't simply hand over a checklist to someone who has no knowledge or experience in a particular field. They may be able to go through the motions, but they won't grasp the importance or relevance of each item on the list. That's why it's essential to have individuals who not only understand the people involved but also comprehend the environment and can make dynamic decisions based on that knowledge. Efficiency is important, but effectiveness matters more. You can have someone who efficiently follows a checklist, but if the list itself is irrelevant or inadequate, it won't lead to the desired outcome.

20. Did you experience the 2010 eruption?

Although I was living in Sweden at the time, I frequently traveled to Iceland, almost twice a month. I had the opportunity to witness the Eyjafjallajökull eruption firsthand as I accompanied my rescue team to the site. It was a powerful volcano that demanded the utmost respect.

From my observation, the Public Safety Authority had the situation well under control. They implemented extensive closures, effectively sealing off a large area. While there were some alternative routes accessible by snowmobiles and back roads, it prevented casual tourists from venturing into dangerous areas. The media coverage was substantial, but for the rescue teams, it was a manageable task. We conducted organized patrols in the area, and the operation ran smoothly.

Initially, during the small eruption, there were hikers who ventured into restricted zones, but as soon as the larger eruption occurred, the authorities promptly closed off the entire area. However, I'm not sure how successful such measures would be today, as we might encounter more significant challenges. In terms of casualties, there were only two fatalities during that operation. Three young individuals drove on a road, got stuck in the harsh weather conditions with temperatures around -20 degrees Celsius, and made the unfortunate decision to walk for help separately. Tragically, the two who left the car were found deceased, while the woman who remained in the vehicle survived. This serves as a stark reminder never to abandon your vehicle in such circumstances.

21. And what can you tell me about the recent eruption of 2021? How was it experienced?

The recent eruptions in 2021 and 2022 were indeed very different from the Eyjafjallajökull eruption in 2010. The timing of the eruptions coincided with the COVID-19 pandemic, which had an impact on tourism and travel. While there were still some tourists in the country when the eruption started in March, the number of visitors decreased as people canceled their flights and the tourism industry slowed down significantly.

During the eruption, especially before the second phase, there were still around 350,000 to 400,000 people in the country. Prior to the second eruption, there were approximately 2,500,000 tourists, visiting Iceland every year. Covid caused a massive reduction in number of tourists visiting but that changed with the appeal of the eruption. First we had quarantine mandates limiting the influx of tourists but we still had tourists that came in before the quarantine requirements and came to the volcano site. All in all we saw around 300.000 visitors coming to the volcano site in the first few months of the eruption. It's worth noting that this occurred during winter, which meant challenging weather and harsh conditions. Some individuals, like me, equipped themselves with glacier gear, including crampons, ice axes, and safety lines, to navigate the mountains until the spring thaw made conditions safer but far from easy.

In terms of hazards and difficulties faced by Icelandic volunteers, one significant aspect was the identification that the response to volcanic gases was not as well-prepared as it could have been. Although Iceland experiences eruptions approximately every three years, they usually don't require close proximity to the volcanic activity. However, with the current system and the recognition that these eruptions attract tourists, it has become necessary to have individuals trained in operating gas sensors and using filters to respond effectively to such situations.

The evolving nature of volcanic eruptions and the increased attention they receive as tourist attractions have prompted the need for better preparation and response capabilities in Iceland's volunteer and emergency response teams.

22. So, has the increase in tourists altered your work, hasn't it?

Yes. In regards to eruptions it has.

23. What characteristics does the ICE-SAR have that make it efficient compared to other organizations you know?

The ICE-SAR organization has several characteristics that make it efficient and distinguish it from other organizations:

- Expertise: ICE-AR has a large pool of volunteers, with approximately 4,200 individuals on roster. Within this group, there are experts in various fields, such as geophysics, geology, poisonous gases, communication, explosives, and more. This diverse range of expertise allows ICE-SAR to access specialized knowledge and skills when needed.

- Adaptability: ICE-SAR volunteers are known for their adaptability. They are eager to learn and can quickly adjust to different situations and challenges. Many of the volunteers have other professions, such as police officers, EMS personnel, firefighters, carpenters, electricians, priests, teachers, doctors and are truly a mirror of society. This broad spectrum of backgrounds brings different perspectives and problem-solving abilities to the organization.
- Outdoor skills: Most ICE-SAR volunteers are outdoor enthusiasts who love the rugged nature and are comfortable in the tough outdoor environments. This affinity for the outdoors gives them a practical understanding of navigating challenging terrains and adverse weather conditions, which is crucial during search and rescue operations.
- "Bras" mindset: The Icelandic word "Bras" describes a concept of willingly engaging in physically and mentally strenuous tasks, finding enjoyment and fulfillment in overcoming challenges. ICE-SAR volunteers embody this spirit of "Bras" and are willing to take on difficult and demanding tasks to accomplish their mission. Whether it's fixing a broken engine, rescuing a stuck vehicle, or tackling other challenging situations, ICE-SAR volunteers have the determination and perseverance to get the job done.
- Energy and motivation: ICE-SAR volunteers are driven by a strong sense of purpose and a desire to make a difference. They possess a remarkable energy and dedication, capable of moving mountains metaphorically, in terms of their commitment and the impact they can have during search and rescue operations.

24. What shortcomings or areas for improvement do you think your organization has?

One aspect that we have identified for improvement is our approach towards risk-taking. There are instances where we feel that we may be too inclined to take unnecessary risks, which sometimes leads to an imbalance between risk and reward. For example, there have been situations when we encounter challenging weather conditions that make it difficult to recover bodies, and it would be more prudent to wait for more suitable conditions. However, there is a tendency within our organization to push forward and proceed immediately. This eagerness reflects a lack of patience and situational awareness, as we should be able to evaluate the risks versus the potential rewards more effectively.

25. If you could ask anything of the other institutions involved during a natural disaster that would make your work easier and more effective, what would it be?

The primary thing we seek from other institutions is empowerment. It's crucial for us to have the freedom to operate in our own way. While we are not typically compensated for our work, there are instances where rescuers may receive some benefits. For example, if our team conducts fundraising activities or patrols in the eruption area, a rescuer might receive a new jacket or a GPS device from the team. However, in most cases, the rescuer would have to contribute a portion, usually around 20% to 50%, towards the cost of personal gear. The level of dependency on the team varies, so some individuals bear the expenses while others do not. Nonetheless, it is essential to acknowledge and support the volunteers, allowing them to perform their duties effectively.

Unfortunately, there are instances where certain teams face challenges or even collapse temporarily because they are not given sufficient opportunities to contribute or utilize their skills. Some people may hesitate to approach the rescue team, assuming they shouldn't bother them. However, it is crucial for us to be engaged and utilized effectively. It's comparable to playing golf – you don't simply go out to play golf; you train and exercise to compete. Similarly, we train diligently to be prepared for our role. Nevertheless, there exists a delicate balance, with some teams struggling to maintain sustainability, while others are more secure. Most teams hover around the line of adequacy. When we have a high volume of call-outs, our training may be slightly reduced to accommodate the workload.

Interview to Thor Thordarson (University of Iceland)

1. Could you tell me what is your current position within the University of Iceland?

I am currently serving as a professor in Volcanology and Petrology at the Faculty of Earth Sciences.

2. What are your background and your areas of expertise?

My background is primarily in Volcanology, encompassing both academic and practical experience. It's a field that can be somewhat challenging to define, as I have also had the opportunity to work in the mining industry. It's fascinating to note that many precious metals are found within volcanic formations, and I have utilized my expertise in Volcanology in that context as well. My primary focus, however, lies in studying volcanism at hot spots such as Iceland, Hawaii, and also in New Zealand. In fact, I was present during the Ruapehu eruptions in 1995 and 1996. Additionally, I have conducted research on Archaea and volcanic deposits. So, I have been involved in a wide range of topics within the field.

3. What are you currently working on?

Currently, my primary focus revolves around two main areas. Firstly, I am delving into the eruption history of Iceland during the post-glacial period. This involves examining the dynamics of explosive basaltic to rhyolitic eruptions across a range of intensities, from low to high. The aim is to understand why some eruptions exhibit weak fountaining while others are incredibly powerful and explosive. We have discovered that simply attributing it to interaction with external water is an overly simplistic explanation that fails to account for all the unknown variables at play.

4. Where do the monetary funds for your projects come from?

Typically, the monetary research funds for my projects come from a variety of sources. Firstly, there is an internal university fund that has consistently provided me with support over the years. Although the funding amount is not substantial, it remains reliable and steady.

Additionally, I have been fortunate to receive grants from the Iceland Science Foundation, which has been instrumental in supporting my research endeavors. Collaboration has also enabled me to secure funding from the National Science Foundation in the United States. This support encompasses a range of areas, including regular climate studies and physical volcanology in Hawaii.

Furthermore, the Norwegian Science Foundation has been another valuable funding source for my research. In addition, the Nordic Innovation or the Nordic Council of Ministers has extended their support to a portion of my research projects.

In the past, I have also received funding from the New Zealand Science Foundation, the Australian Science Foundation, and even mining companies. These diverse funding avenues have contributed to the progression of my work.

5. Do you work on hazard assessment and/or risk management issues? If so, in which way?

Yes and no. While hazard assessment and risk management are integral aspects of our work, our primary focus lies in monitoring ongoing volcanic activity and evaluating the associated risks. We contemplate the risks associated with an ongoing eruption and continuously assess the potential hazards.

However, the work we do in this area extends beyond monitoring to impact other domains of risk assessment and risk management. We engage in extensive communication with town councils situated in volcanic active areas in Iceland. Through the utilization of long-term and short-term eruption hazard assessments, we employ tools such as VETOOLS to provide municipalities with valuable information regarding potential volcanic hazards and associated risks in their respective regions.

Although hazard assessment and risk management have not been the primary component of my research, they have gained prominence and have become increasingly significant over the years.

6. Does your research group develop hazard or risk maps?

Yes, we do engage in the creation of hazard maps. Our work encompasses various aspects, including event trees, hazard maps, ash dispersal modeling, and term maps. While I may not personally produce them, I actively contribute to their development and interpretation as part of our research efforts. Hazard mapping is an integral component of our work and plays a significant role in understanding and communicating potential risks associated with volcanic activity.

7. Are the results of your research requested by any other institution?

It varies. At times, these results are indeed requested by municipalities, indicating their recognition of the importance of hazard assessment. Additionally, we take the initiative to offer these hazard assessment results ourselves. In fact, both myself and another colleague have been actively involved in the development and implementation of tools such as VE-TOOLS and EVE.

To showcase the value and effectiveness of these tools, we initially took the initiative to create and present hazard assessment results independently. As a result, these efforts gained attention, and people began to take notice of the usefulness they offered.

So, in summary, we both respond to requests from municipalities and proactively offer hazard assessment results to demonstrate their importance and effectiveness.

8. Do you normally work jointly with the Department of Civil Protection?

We don't have extensive collaboration with the Department of Civil Protection. However, in times of crisis, I serve on their advisory board and provide relevant expertise and advice when needed.

Interestingly, the Department of Civil Protection has shown less interest in our hazard maps compared to the municipalities and other stakeholders in Iceland. This disparity can be attributed to political factors.

9. And with the Met Office?

In terms of collaboration with the Meteorological Office, we face a similar situation. The Meteorological Office and the Civil Protection Department find themselves in a similar position, while we operate independently. We coexist and work parallel to each other in our respective areas of expertise.

10. And with ONGs, such as Red Cross?

Regarding non-governmental organizations (NGOs) like the Red Cross, our collaboration has been limited. They are more closely associated with civil protection efforts. Instead, our focus within volcanic hazards lies in monitoring the eruption and providing reliable and quantitative information about potential hazards based on the evolving eruption dynamics.

We believe that our role in this equation is to offer the greatest good by providing accurate and valuable information on the future hazards associated with volcanic activity.

11. What are the main difficulties you encounter when explaining your research, sharing your results, or providing advice during emergencies, considering you come from the scientific world?

The main difficulties can be summarized quite swiftly. One of the challenges lies in explaining the difference between intensity and magnitude to individuals who may not have a background in volcanology. It's crucial to distinguish between power and size, as large eruptions are not necessarily powerful, and vice versa. This concept can be challenging to convey, as many people assume that bigger eruptions automatically mean greater power. However, understanding this distinction is crucial for determining appropriate responses to different volcanic events.

For instance, an effusive eruption may have significant power, but it will never reach the same level of power as a large explosive eruption. Therefore, the response and necessary precautions vary depending on the intensity of the eruption.

Having candid discussions with stakeholders, including those in the Department of Civil Protection, helps bridge this understanding gap. It's encouraging to see that they often grasp these concepts and comprehend the nuances involved.

Another difficulty in dealing with volcanic eruptions is the significant jumps in time scales. During an eruption, everything can be extremely dynamic and unpredictable, but then there can be decades-long intervals of relative calm before the next eruption. It can be challenging to convey the significance of these time gaps and help people comprehend the potential risks that may arise after an extended period of quiescence.

Moreover, the recurrence intervals of volcanic events, which can range from 30 to 60 years, pose challenges due to social memory. People tend to forget and become complacent after several decades of inactivity. This is exemplified by the residents living on Mauna Loa volcano in Hawaii, who, since the last eruption in 1974, may mistakenly believe that the volcano will never erupt again. Educating and raising awareness about the inevitability of future volcanic activity is crucial to prevent complacency and ensure appropriate precautions are taken.

In summary, the difficulties lie in explaining the nuances between intensity and magnitude, grappling with the dynamics of volcanic eruptions, and addressing the challenge of social memory and complacency over long periods of volcanic inactivity.

12. **When there is an anomalous situation, regarding a hazard, do you receive information about that? If so, who and how informs the researchers in the University?**

We do receive information in such cases. We are kept updated through the civil defense advisory board meetings, where we are informed about the current situation and any significant developments. However, the official monitoring institution in Iceland, the Icelandic Meteorological Office (IMO), does not provide us directly with a steady stream of data or information regarding precursors or ongoing volcanic activity. As researchers, we proactively seek information by accessing various databases that are available to us, which are maintained by IMO. These databases enable us to gather and analyze the necessary data independently.

13. Could you explain me a bit more about those meetings?

Yes, there are advisory board meetings held when there is a potential hazardous event. However, these meetings are more like information meetings rather than true advisory board sessions. The meetings are typically announced in advance, and a large number of people, around 120 individuals, are invited to attend.

While it is good to receive information during these meetings, I believe there is a gap in our system when it comes to true advisory board functions. In a typical advisory board, a small group of experts would assess the data and provide advice based on their analysis. They would have access to the data before the meeting and come prepared to discuss and provide recommendations.

In our case, the meetings are more focused on providing information to different aspects of the scientific community, such as environmental monitoring agencies. These meetings are not specifically designed to offer advice to civil defense or other authorities on how to respond to the situation.

It seems that the current structure lacks a dedicated scientific advisory board that can independently advise the authorities. Such a board should consist of scientists who are not directly involved in research or monitoring related to the event, ensuring their independence as consultants.

So, while there are meetings and information sharing, there is a need for a more formalized and independent scientific advisory board in the system.

14. Do you work mainly with volcanic eruptions or also with other types of hazards?

Yes, my main focus is on volcanic hazards. I believe that is where my expertise can be most effectively applied. Therefore, I dedicate my research and work entirely to studying and understanding volcanic hazards.

15. Once an emergency has been declared, what is the usual flow of action here in the Institute?

The usual flow of action within the institute during an emergency declaration can vary and may lack coordination. Different groups within the institute tend to operate independently based on their own interests and objectives. There may be redundancies in the actions taken, and a lack of collaboration and coordination among the groups. Personal grievances, internal politics, and the desire for individual recognition or competition can also influence the response.

Historical factors and the perception that research scientists can operate independently contribute to this fragmented approach. The focus is often on monitoring precursors leading up to an eruption rather than actively monitoring the eruption itself. However, some researchers, including myself and my colleagues, recognize the importance of monitoring the eruption and have taken the initiative to observe and document its behavior independently.

Efforts have been made in the past to establish a more coordinated and inclusive response within the institute, but achieving this has been challenging. There is a recognition that collaboration and a systematic approach to monitoring both precursors and the eruption itself are crucial for understanding and responding to volcanic hazards effectively.

16. What kind of tasks do you do in the field during an emergency?

During an eruption, your team performs various tasks in the field to document and study the event. Some of the tasks you mentioned include:

- Mapping the extent of the lava flow: This involves mapping and recording the boundaries of the lava flow to understand its size and direction.
- Using drones for visual documentation: Drones are utilized to capture high-resolution videos and images of the eruption from different angles, providing detailed visual documentation of the event.
- Systematic sampling: Your team collects samples of both tephra (volcanic ash and fragments) and lava. The sampling strategy is designed to obtain specimens for scientific research, enabling the investigation of specific questions related to the eruption.
- Thermal imaging: Thermal cameras are used to detect and record the heat signatures and temperature distribution of the lava and surrounding areas.
- Documenting eruption behavior: You observe and document the behavior of the eruption, including changes in eruption style, intensity, and other dynamics. This helps in understanding the evolution of the eruption and identifying any significant variations or patterns.
- Assessing physical properties of lava: Measurements and analysis of the physical properties of the lava, such as its temperature, viscosity, and composition, provide valuable insights into the eruptive process and behavior.
- Monitoring gas emissions, including sulfur dioxide and other gases, is also an important aspect of studying volcanic eruptions.

Overall, your team focuses on capturing and analyzing various aspects of the eruption to enhance understanding and contribute to scientific research.

17. Is there any control for sampling?

Anyone can come here to sample. It's an open policy, and no one is going to tell you that you can't sample something. Each institution is free to sample it however they want.

18. Is it common for other countries to allow everyone to take samples and measurements during an eruption?

That's a good question. The answer is yes and no. For example, in New Zealand, no one would stop you from sampling a part of a recent eruption as long as you were outside of the declared danger zone. But if you want to enter the danger zone, you would have to make an arrangement with an institute like the one I work for, GNS, and go in with their guidance. It's more for safety reasons. In the United States, there's no one stopping you from sampling, but if you're in a national park, you have to get permission from the national park.

19. How do you work with the Department of Civil Protection and/or the Coast Guard during an emergency?

Personally, I don't work with civil protection. None of us do. However, occasionally we interact with the Coast Guard for logistical support. They sometimes drop us off at specific locations. While in the field, I do meet civil defense personnel, and we have informal conversations, exchanging information. There's no formal arrangement, but if we require quick access or face difficulties, the Coast Guard assists us by providing transportation.

20. Do you work with the ICE-SAR?

Not really directly. However, we maintain an open communication channel with them. We always inform them about our intended locations and activities. There have been instances where they have provided assistance in accessing certain areas or facilitated the arrival of additional personnel when necessary. Additionally, we have also collaborated with them in terms of providing assistance in cases of tourist injuries. Since we are often closer to the scene, we help in bringing the injured individuals to safety. This collaboration between us and ICE-SAR is a regular occurrence, and personally.

21. And with the Icelandic Met Office?

No really. But if we meet in the field, then we can collaborate up to a certain extent.

22. What tasks do you usually perform once the emergency is over?

After the eruption, there are several tasks that we undertake. Firstly, there are loose ends that need to be tied up from the eruption period itself. These are tasks that couldn't be addressed during the eruption but are essential for a comprehensive understanding of the event. This often involves some additional fieldwork, although in the most recent eruption, the need for post-eruption fieldwork was relatively less compared to previous eruptions. In those cases, we would go on field expeditions for three or four consecutive times during summer to gather any remaining field-related data.

Additionally, a significant portion of our work takes place in the lab. We analyze the collected data, including samples and digital data such as videos. The analysis process involves processing and interpreting the data, which can sometimes take years to complete. The ultimate goal is to conduct research projects based on this data and eventually publish our findings.

23. Are you familiar with the concept of multi-hazard?

Absolutely, I used to teach natural hazards.

24. Do you consider the possibility of multi-hazard scenarios or the potential concatenation and cascading effects of events in your research?

Absolutely, especially when it comes to volcanic eruptions. Throughout my research career, I have examined various potential hazards associated with volcanic eruptions. This includes hazards related to lava flows, volcanic ash fall, volcanic gases, and their atmospheric impacts. I have been involved in studying these factors comprehensively.

I also take into account the approach of considering the chain of events or the amplification of hazards due to simultaneous occurrences. For example, I have investigated the effects of fluorine in volcanic gases adhering to ash grains, which had severe consequences for livestock in Iceland, leading to significant mortality. Additionally, I have researched sulfuric aerosols and their pollution impacts on regions far away from the eruption site, as well as their implications for European communities.

Furthermore, my research explores how volcanic eruptions can affect the thermal structure of the atmosphere, leading to alterations in atmospheric currents and changes in weather patterns. For instance, the Laki eruption in Iceland in 1783 had a profound impact on atmospheric circulation, resulting in a stationary low-pressure system east of Japan throughout the summer. This caused cold and rainy conditions, leading to a failed rice harvest and a devastating famine in which approximately one million people lost their lives. Similar indirect impacts were observed in other historical eruptions such as Tambora, which shifted monsoons and caused drought in India and North Africa, affecting the local populations significantly.

In summary, I do consider multi-hazard scenarios, the potential chain of events, and the cascading effects in my research, recognizing their crucial role in understanding the wide-ranging impacts of volcanic eruptions.

25. Could you tell me how you experienced the 2010 eruption? What was your role?

During the 2010 eruption, I was initially involved in monitoring and studying the Fimmvörðuháls flank eruption. I spent about three weeks there, working closely with my colleague and developing principles of eruption monitoring. At the time, I was based at the University of Edinburgh in Scotland.

In mid-April, while I was in Scotland, I received news that a summit eruption had started in Iceland. I immediately wanted to return to Iceland, but all flights were already closed. So, in the first few days of the eruption, I didn't play a direct role. However, I did serve on the advisory council in the UK as their specialist on Icelandic volcanoes. We engaged in discussions about the situation, including the closure of airspace due to concerns about ash.

There were questions raised regarding the extent of the ash cloud, and my postdoctoral colleague, John Stevenson, initiated a project to collect ash samples in the UK and other parts of Europe to characterize the distal part of the ash fall. We wanted to gain a better understanding of the actual ash distribution and its potential impact.

The advisory board in the UK is constructed based on the specific hazard at hand. In the case of volcanic hazards, they call in volcanologists, environmental experts knowledgeable about volcanic pollution, and physicians specialized in dealing with health issues related to volcanic pollution. The advisory board consists of selected specialists, and it operates effectively for addressing various hazards.

Interestingly, volcanic eruptions were not initially listed as a hazard by the advisory board in 2010. However, that has changed since then, and it is a positive improvement in their preparedness and response.

26. Did the massive arrival of tourists disrupt your work in the field?

Not really.

27. And the media pressure?

Yes, there was a lot of media pressure during the previous eruption in 2009. It was almost daily, with multiple media requests per day. It added extra stress and workload, especially when combined with the other tasks and responsibilities. It could be exhausting, but I understand the importance of media communication in disseminating information. It's crucial to deliver the information in a way that is easily understood by the public without compromising the quality of the scientific content. It's not an easy task, as talking down to people can hinder effective communication.

28. Could you tell me which areas have a higher potential volcanic risk in Iceland? And in terms of earthquakes?

Well, based on my experience and recent events, I believe the Reykjanes Peninsula will likely experience volcanic activity in the next decade. Additionally, I have a strong suspicion that volcanoes like Askja and Katla will also erupt. The southern part of the eastern volcanic zone, specifically Katla and Hekla, are highly likely to erupt. Askja, located in the northern volcanic zone, also shows signs of significant activity. On the other hand, Grímsvötn frequently erupts, although its eruptions typically have minimal impact, especially when they occur within the glacier's boundaries.

29. Considering that two-thirds of the population resides in Reykjavik, which volcanic areas pose a greater risk to the city?

The Reykjanes Peninsula, where Reykjavik is located, is not likely to experience a life-threatening eruption. However, it could cause some inconvenience. There might be a small amount of ash fall in the greater Reykjavik area, and there's a possibility of lava flows approaching important infrastructure, potentially leading to its destruction. If there's a sustained eruption with a reasonable intensity, around 200 to 400 cubic meters per second, there could be significant sulfur pollution. This pollution could have a noticeable impact in populated areas, potentially causing health issues, especially for those with respiratory problems. I don't anticipate a life-threatening eruption, but there will definitely be eruptions in the Reykjavik Peninsula that will impact society, primarily through the destruction of infrastructure. Reykjavik itself is relatively safe in that regard. However, many people might be bothered by the smell of sulfur or other inconveniences.

The larger concern lies in eruptions affecting the operation of Keflavik Airport. It could disrupt the airport routes, potentially rendering both of them inoperable. This would have significant economic consequences as Keflavik Airport, excluding tourism, contributes to 10 to 15% of Iceland's GDP. Keflavik Airport plays a crucial role in our economy, and if it's affected, it could result in an economic recession. When you factor in the importance of tourism on top of that, the potential damage goes beyond the physical impact of lava flows.

30. What do you think are the keys of the research that you conduct in the University of Iceland related to natural hazards, compared to other places you know?

There are several factors that make Iceland an excellent location for conducting volcanological research, particularly in terms of hazard assessment and risk management. One of the primary advantages is the easy accessibility to numerous eruptions and eruption sites. This accessibility is a result of two factors: the abundance of volcanoes in Iceland and their widespread distribution across the country.

Furthermore, many of our eruptions are often of low intensity, allowing researchers to get close to them without significant obstacles. While Hawaii also offers similar opportunities at times, there are instances where eruptions occur on remote slopes, requiring arduous hikes or even days of travel. In contrast, in Iceland, we can easily reach eruption sites by land or helicopters.

This accessibility enables us to take a holistic approach to the problems we seek to solve. With smaller eruptions, we can observe and analyze various aspects, including the volcanic vent and its distal parts. It's beneficial to have a confined system that offers good control, which is not always the case in many other locations. Often, the front of the lava might be accessible while the vent remains inaccessible.

Another advantage of conducting research in Iceland is the frequency of eruptions. We experience eruptions every three to five years, which provides researchers with ample opportunities for observation and study. Moreover, Iceland boasts an impressive diversity of volcanoes, unlike some other regions where eruptions tend to be of the same type.

While access to eruptions and the ability to sample them is undoubtedly valuable, the efficiency of research also relies on the fortunate proximity to these events. Living in a location that offers access to eruptions allows us to observe and record them, contributing to our understanding of volcanic activity.

However, it is essential to appreciate these opportunities, which can sometimes be a challenge from a social perspective. Nonetheless, the key advantage lies in the ability to capitalize on the accessibility and frequency of eruptions, which enhances the efficiency and effectiveness of our research efforts.

31. What shortcomings or areas for improvement do you think the Institute or researchers have?

When it comes to the structure of monitoring, risk assessment, and related activities, I think there is a need for a comprehensive re-evaluation and restructuring. The current approach should be discarded, and we should start afresh. For instance, while civil defense functions adequately, I'm not convinced that its placement within the government structure is ideal. It should be established as a separate entity rather than being part of the police department.

Moreover, there should be a clearer separation between management and mitigation activities and crisis research. Those involved in management and mitigation should not be leading the research, although their participation is valuable. Similarly, the responsibility of monitoring should not overlap with risk assessment. The Icelandic Meteorological Office (IMO), for instance, should focus solely on monitoring and providing accurate information to relevant stakeholders, while independent parties should handle risk assessment.

The creation of a new organization or the transformation of an existing entity into an independent body needs careful consideration. Whether it should be a private company or a separate government identity requires thorough examination. The importance of risk assessment extends to various aspects of our society, including infrastructure reinsurance and conveying accurate perceptions of events to the public.

Additionally, I have concerns about potential conflicts of interest and institutional biases. When a single entity handles both monitoring and risk assessment, there is a risk of prioritizing personal or institutional benefits over impartial evaluation. Independent scrutiny of monitoring data may be lacking in such cases, as individuals or organizations tend to focus on maintaining payment and avoiding critical assessments.

In summary, addressing these shortcomings and ensuring a more transparent and independent approach to monitoring and risk assessment would be crucial for enhancing the effectiveness of research related to hazards.

32. If you could ask anything of the other actors involved in risk management that would make your job easier and more efficient, what would you ask for?

I would ask them why we can't gather all the leaders and operators of the main organizations involved and have them sit down, talk, and coordinate their efforts. Currently, such coordination is lacking. Establishing a more coordinated structure would not only make my job easier but also benefit everyone else involved.

In my vision, each volcanic eruption should be treated as an experiment set up by nature. To maximize the knowledge and understanding we gain from each eruption, we need to be well-organized and well-coordinated. This coordination should extend beyond individual teams to encompass the entire response effort. Ideally, there should be a well-trained and coordinated international response team, not limited to Icelanders alone. When an eruption occurs, everyone would know their roles and responsibilities, collect necessary data efficiently, and provide timely information to relevant parties.

Furthermore, I envision a comprehensive volcano eruption response team that documents every aspect of the eruption, addressing specific research questions and enhancing our knowledge of how volcanoes work. This coordinated approach would ensure that all essential measurements and observations are conducted at the right time, providing a complete understanding of the eruption process.

In summary, my wish is to establish a fully coordinated and well-equipped volcano eruption response team that can comprehensively document eruptions, contributing to our overall understanding of volcanic phenomena.

Interview to Hulda Ragnheiður Árnadóttir and Jón Örvar Bjarnason (Natural Catastrophe Insurance)

1. Could you tell me your name and position within the NTI?

My name is Hulda Árnadóttir and I am the CEO of NTI.

My name is Jón Örvar Bjarnason and I am responsible for the insurance part at NTI. My background is in civil engineering, and I specialize in modeling and natural hazard risk analysis for the institution.

2. When was the NTI created?

It was created in 1975. The main reason for its establishment dates back to the 70s, following the volcanic eruption in the Westman Islands. In response to that event, the government decided to implement a specialized insurance program. Every property in Iceland, including houses, is insured against named natural perils, including volcanic eruptions. After the eruption, the government provided support to the affected residents, helping them rebuild their homes and even relocating them to other parts of Iceland. This led the government to conclude that it was not feasible to rely solely on the national fund for dealing with all natural catastrophes. Instead, they wanted to establish a system that would continuously protect the entire Icelandic community. Thus, the NTI was created.

3. What are the main tasks of the NTI?

The NTI handles claims in accordance with the law. We also manage the fund ourselves, despite being a government institution. Additionally, we are responsible for securing reinsurance abroad, which needs to be renewed on an annual basis.

4. What is its legal framework?

The NTI was established under law number 55 from 1992. We also adhere to a specific regulation that governs our operations. I can provide you with a booklet that contains the relevant information and references to these laws and regulations if you'd like to have a closer look.

5. What is the organizational chart within the institution?

Within the NTI, we have two main departments. The first is the service department, which handles various administrative and support functions. The second is the insurance department, which is headed by Jón and focuses on insurance-related matters. In terms of staffing, we have a small team of six individuals who work here on a daily basis. However, to carry out specific tasks such as assessments and research, we engage contractors and specialists. Additionally, we outsource our IT services, allowing us to focus primarily on our core business operations.

6. Does the NTI work together with other institutions in the country? (the Police, The Department of Civil Protections, ONGs, Met Office…).

Yes, we do collaborate with the Met Office and the Civil Defense Office, which are our main partners in Iceland. In addition to these institutions, we also work with scientists like Dr. Ármann Höskuldsson and other researchers in Iceland on various research projects. We seek their expertise and gather information on specific topics as needed. Furthermore, there is the earthquake research center in Selfoss, which is part of the University of Iceland. They specialize in recording ground motion during earthquakes and conduct studies on property strength and vulnerability. It's worth mentioning that we maintain close relationships with the municipalities as well. In the event of an incident or loss, we directly communicate with the mayors, keeping them informed about our processes and operations. After an event, we often visit the affected sites. While we don't conduct loss assessments ourselves, we meet with the people involved, gaining an understanding of the situation and determining the necessary resources for the subsequent processes. It's important to note that, being a government-owned institution, we adhere to strict administrative regulations. This ensures that we treat everyone equally and follow the required procedures when settling claims or providing compensations.

7. Is there any specialist in natural disasters, such as a geologist or similar, working in the NTI?

We have Jón Bjarnason, he is an Earthquake and structural engineer. We are fortunate to have his expertise here at NTI.

8. What other ways are there in Iceland to cover economic losses due to disasters? Are there other organizations, companies or funds with the same function? In what do they differ and how do you combine with each other?

NTI (Natural Catastrophe Insurance of Iceland) is responsible for covering certain losses, and there is also a fund specifically set up to address agricultural losses. However, the availability of funds for agricultural purposes varies each year based on the amount allocated. Therefore, it is not guaranteed that individuals have a right to receive compensation. Additionally, the government sometimes provides support to municipalities and those who suffer significant losses that are not covered by the NTI. It's important to note that no public fund covers losses that are insurable. The compensation provided by the NTI and other organizations is specifically for losses that are uninsurable. It is mandatory to have insurance for all houses, and if individuals choose to purchase fire insurance for their contents, they are also obliged to buy the natural catastrophe insurance.

However, it's worth mentioning that the NTI does not cover business interruption. We only cover the direct loss of property and contents. And as far as we know, there is no organization or company that covers business interruption in Iceland. This means that in the event of a major volcanic event causing extensive property damage, there will likely be a significant disruption throughout Iceland. There will be a chain reaction of various consequences, such as power outages, which can result in substantial costs that are not compensated by us or anyone else. We estimate that we would cover around 50% of the direct loss, and the indirect losses could amount to a similar value. However, the exact extent of the indirect losses is uncertain.

This highlights a significant gap in protecting the entire community or Iceland as a whole, mainly due to the lack of compensation for business interruption. The current system focuses solely on direct property damage and does not account for the broader economic impacts caused by disruptions.

9. Where does the NTI receive its monetary funds from?

The private insurance companies collect the premium from policyholders for both fire insurance, which is mandatory in Iceland, and catastrophic insurance. They then forward the portion of the premium that belongs to the NTI to us.

10. How do citizens make payments for this national insurance? When they purchase a property, do they have to pay a monthly or yearly amount?

The payment is made on an annual basis, as per the arrangement with the insurance companies. However, many individuals choose to divide the annual payment into 12 monthly installments, so they pay on a monthly basis. The amount paid is typically a proportion of the fire insurance value of the property, which represents the replacement value.

11. How much money would someone need to rebuild their property if it were completely destroyed in a fire or collapsed during an earthquake?

The amount of money needed to rebuild a property is based on its estimated replacement value. As a general guideline, individuals pay 0.025% of the fire insurance value of their property. The specific amount can be found in the booklet that I will provide you with.

12. Are there different categories or options for additional coverage, depending on various factors?

It's important to note that you cannot insure for more than the estimated fire insurance value determined by your insurance company. If you believe that the fire insurance value is too low, you have the option to purchase additional protection. However, the final assessment of whether the fire insurance value adequately reflects the value of the house before it was damaged will be made. If you feel that the insurance value is too low, you should request a reassessment of the replacement value. Ultimately, it is the homeowner's responsibility to ensure they are sufficiently insured.

13. Are there any cases that are exempt from the payment of this fee?

No, there are no exemptions. The payment of the mandatory fee applies to everyone.

14. What losses does the NTI cover?

The NTI covers losses that are related to five named perils: earthquakes, volcanic eruptions, snow avalanches, mudflows and rock falls, and sea floods, including coastal and river floods. These named perils are the basis for the coverage provided by the NTI. It is important to note that the coverage is only for these perils.

15. Does the NTI also provide coverage for common infrastructure such as bridges, roads, and public buildings?

Yes, the NTI does cover common infrastructure, but the handling of such cases is slightly different from residential properties. For common infrastructure, we directly communicate with the owners, which are typically the government and municipalities. They pay the premium directly to us for the coverage. In the booklet that I will provide, you can find more detailed information in Article 2 regarding the types of structures that are compulsory to be insured by us. It's important to note that it is not all types of roads that are insured by us, but bridges longer than 50 meters and certain infrastructure such as sewer systems may be covered. Private roads, on the other hand, are not typically covered by the NTI.

16. Does NTI cover damage to persons or fatalities?

No.

17. When a disaster occurs, what is the usual way to proceed of the NTI? Is it the same independently of the type of disaster?

In most cases, our approach is similar regardless of the type of disaster. Initially, we gather information about the event to understand its magnitude, the potential number of claims, and the estimated total loss. We use our earthquake model to assess the expected number of claims based on factors such as the location, type of property, and the nature of the event, whether it's a flood, earthquake, or volcanic eruption.

Once we start receiving claims, people report them electronically through our website. We have an in-house claim handling system that helps us organize and manage the claims. We assign specific adjusters to handle different claims based on their expertise and workload. The adjusters also have access to the system, allowing them to review and process the assigned claims.

The adjusters then visit the sites of the losses to assess the damages based on the circumstances. The timing of the site visits may vary depending on the specific event. For instance, in the case of a mudflow in the East Fjords, access to the affected area may be restricted for a certain period of time. Similarly, in the event of a volcanic eruption, we wait until the volcanic activity has subsided before conducting assessments. It's important to note that we do not consider ourselves as first responders but rather work on the sidelines, focusing on the assessment and handling of claims.

18. How is the economic cost during a disaster quantified?

To assess the cost of recovery and calculate the damage that occurred in the area, we use a sophisticated model, particularly for earthquakes, as they are the most significant events in terms of compensation. For earthquakes, we input information about the event into our model, which utilizes vulnerability functions based on past experiences from significant earthquakes in 2000 and 2008.

Using this model, we can estimate the affected area and the potential total loss. We can also apply similar estimation techniques for other events such as volcanic eruptions, lava flows, or asphalt damages. By identifying the properties in the area, knowing their replacement costs, and understanding their vulnerability, we can make preliminary estimates of the potential losses.

However, it's important to note that these estimates are based on models and serve as indications rather than precise figures. The actual assessment of the damage is done by trained engineers and contractors who visit each property in the affected area. They inspect and document the damages, and then estimate the cost of repairing the damage to restore the property to its pre-event condition.

We are responsible for compensating the amount of money required to restore the property to its previous state. As we receive reports from the engineers and contractors, we can review and adjust our initial estimations based on the actual assessment of the damages. The goal is always to ensure that the property is rebuilt or repaired to its original condition, so that the policyholder does not suffer any loss or gain from the event.

19. What difficulties do you normally encounter when quantifying this cost?

One of the difficulties we commonly encounter when quantifying the costs is distinguishing between the condition of the property before and after the event, especially in the case of earthquakes. This is because properties may already have pre-existing cracks or damages unrelated to the earthquake. Therefore, our assessors need to be highly trained to accurately determine which part of the property's condition is directly attributable to the earthquake and what is part of the property's normal wear and tear or pre-existing damage.

In contrast, when it comes to events like lava flow, the distinction is usually clearer. The damage caused by a lava flow is typically more evident and easier to identify. It is a matter of assessing whether the property has been affected by the lava flow or not.

If you have specific questions you'd like to focus on, please let me know, and I'll be happy to address them.

20. What happens when circumstances, for example during an emergency, exceed the capacity of payment of the NTI?

If the circumstances during an emergency exceed the capacity of payment of the NTI, there are established measures in place to address this situation. The NTI has a predetermined maximum loss limit, which is set at 1% of the total sum insured for all insured items. This limit is defined by law.

In the event that the total amount of compensation exceeds the 1% threshold, the NTI utilizes different strategies. Firstly, the NTI has its own fund where collected premiums are kept until they need to be paid out. This fund is used to cover the compensation payments.

Additionally, the NTI purchases reinsurance from foreign entities. Reinsurance acts as an extra layer of coverage for the NTI. If the compensation amount exceeds the NTI's own fund, reinsurance funds can be utilized to cover the remaining costs.

Furthermore, if necessary, the NTI is allowed to borrow money. In such cases, the government takes responsibility for the loan. This ensures that the NTI can fulfill its obligations even if the compensation costs go beyond its immediate financial capacity.

However, it's important to note that the NTI's aim is to distribute the full amount of compensation available. If the compensation exceeds the 1% limit, the NTI will distribute the funds available among all eligible claimants.

21. Could you walk me through how you personally experienced one of the past eruptions and the procedures you followed?

Sure, let's take the Westman Islands eruption as an example, which we consider to be a worst-case scenario. In terms of past events, we also had the eruptions in 2010 and 2011, which were relatively minor for the NTI, with just a thin layer of asphalt being affected. This gives you an overview of the events we've dealt with. There's also a significant historical event in 1987 related to earthquakes, which I can elaborate on. It's worth noting that earthquakes pose the greatest risk in terms of damage and financial impact. However, volcanic eruptions are also a concern for us.

22. What features does your system have that you think are efficient?

One feature that I find highly efficient is the fact that we have insurance coverage for every single building, and individuals are unable to opt out of this coverage. This is of utmost importance for a country as active as Iceland when it comes to natural catastrophes. I believe this is the most crucial aspect, and I wouldn't want to see it changed. It is vital for Iceland that everyone is insured and pays the same percentage of their property's value. The amount is set at a low, flat rate, which doesn't pose a significant burden on individuals as it is a small proportion of the property's financial value. People don't really feel the impact of paying it individually, but when everyone contributes, it feels more like a collective responsibility, similar to a tax. This notion is widely accepted in Iceland, and it's important for everyone to contribute to the fund, as it allows us to support each other in times of need. So overall, there is a general acceptance of this system in our country.

23. What shortcomings or areas for improvement do you think your organization has?

While we strive to do our best, there are certain areas where we recognize the need for improvement. One challenge we face is the size of our team, as we currently consist of only six people. In the event of a major catastrophe, we would have to completely restructure our office setup and rely on contractors to support us. The involvement of contractors can be complicated, as it's difficult to predict how smoothly the transition will go. However, we do have a response plan in place, which provides initial guidance during such events.

Another aspect we are actively working on is implementing more automated procedures. Currently, many tasks require manual intervention at each step, which can be time-consuming and prone to errors. We are currently in the process of tendering for a new system that will introduce more automated flows, streamlining our operations.

To conclude, the major gap we see within our society, and for Iceland as a whole, lies not necessarily in compensation for our organization, but in the overall interruption caused by a disaster. For instance, if a hospital loses power, such situations are not adequately covered by any entity. In my opinion, this poses the most significant challenge in the case of a large-scale disaster.

Annex 7. Supplementary Material 4: Movies

**The movies corresponding to the tsunami simulations can be found at the following link:*

https://drive.google.com/drive/folders/1y5w0drCTsd98ZUxz93_3TVZ9hwKAxmaW?usp=sharing

***The movie ms01 corresponds to a simulation made with a yield strength of the sliding block of 50,000 Pa, while the movie ms02 corresponds to a simulation made with a yield strength of the sliding block of 100,000 Pa.*

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