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"Dynamics and structural evolution of collapse calderas: A comparison between field evidence, analogue and mathematical models"

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PART V:

DISCUSSION

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From the individual results obtained in chapters II, III and IV we can derive significant general implications on caldera collapse processes by comparing among them Moreover, we can achieve the final objective of this work, the genetic classification of collapse calderas and the corresponding description of their dynamic and structural evolution.

V.1 COMPARISON BETWEEN FIELD EVIDENCE, ANALOGUE AND MATHEMATICAL MODELS

V.1.1 Introduction and objectives

Throughout this work we have seen that the applicability of analogue and mathematical models, as well as the reliability of field data, are subjected to some limitations already commented in previous sections (see sections II.2.5, III.2.3, III.3.7, IV.4.3 and IV.5.6). During the last chapters, we have separately analysed the results obtained from field data and analogue and mathematical models. The objective of this section is the subsequent comparison of the experimental results with field data and mathematical models.

V.1.2 Comparing analogue models and nature

The experimental results have allowed us to study qualitatively the structural evolution of a collapse process and to suggest which factors play a more relevant role. Analogue models show that caldera collapse is a continuous process that evolves through the appearance of certain sets of fractures and faults. Therefore, we cannot consider the formation of these distinct sets of brittle features as discrete events in a continuous caldera-forming process. Their appearance and development is intimately related to the decompression of the magma chamber that will determine the different phases of a caldera collapse process. Experimental models reveal that the apparent diversity of caldera morphologies and collapse mechanisms that can be deduced from field studies (Lipman 1997, 2000) may result just from the effect of different magma chamber geometries and magma chamber roof aspect ratios, or may simply correspond to different stages of a single collapse process. Therefore, according to the results from experimental modelling the classifications on collapse calderas based on the morphology of the resulting depressions or the inferred collapse mechanism should be revised, as they could just result or correspond to an artefact due to different degree of exposure of natural examples.

As we have seen in previous sections (see section II.3.7.2.2), studies of mining subsidence and scaled experimental models of subsidence provide a useful analogue for caldera. Mining subsidence and scaled experimental models of subsidence obtain results quite similar those acquired with previous or our analogue models, especially those with respect to the geometry of the resulting depressions and the distribution of the bounding faults. However, there is a significant difference between these analogues and natural calderas. During collapse caldera processes, the roof subsides into a magma chamber and in mining subsidence the collapse of the overburden rock occurs into an empty cavity. Of course, this has important implications. For example, contrarily to what happens in mine subsidence, caldera collapses are always related to an initial episode of overpressure in the associated magma chamber, which induces to a deformation pattern that may be latter reused during caldera collapse (see section III.2.1). Some analogue models on collapse calderas are not associated with an empty cavity, e.g. experimental devices that use a water-filled latex balloon as magma chamber analogue (e.g. Martí et al., 1994; Walter and Troll, 2001; Lavallée et al., 2004). Once buried, we can inflate the balloon generating an overpressure in the chamber, i.e. the pressure inside the balloon is higher than in the surrounding host rock analogue (dry quartz sand). During the deflation processes there exist a decrease of pressure inside the balloon and rupture of the analogue host rock may supposedly take place when the underpressure exceeds the tensile strength of dry quartz sand. Apparently, in this respect, analogue models are more faithful to nature that simple scaled experimental models of mining subsidence. Unfortunately, analogue models do not allow to quantify important variables such us stress or pressure and up to now, there is no way to link with fluid mechanics (with the physical properties of magma). Consequently, we have no control on the magma chamber pressure and we do not know if such a magma removal is feasible. Analogue models offer a good approach to the understanding of caldera collapse processes but they only cover part of it.

Results obtained with our analogue models are similar to the main observations of Branney (1995). On the one hand, we observe that the ring faults controlling subsidence do not delimit the area of deformation. A zone of arcuate and ring-fractures surrounds them. Consequently, we can observe in our experiments the "structural boundary" described by Branney (1995) (see section II.3.7.2.2) and calculate the "angle of draw". Moreover, since we can observe a cross-section of some of our experiments we can delimit also the "zone of influence" (Fig. 5.1).

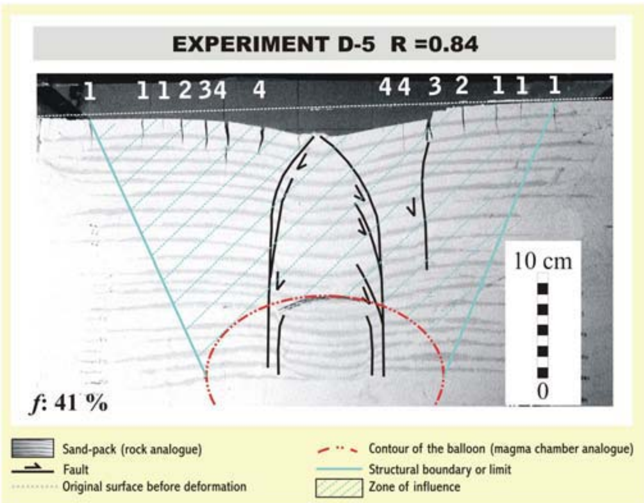

Fig. 5.1: Shot of the caldera collapse process of experiment D-5. The removed volume fraction f is indicated. White numbers, in concordance with those of Figure 3.17, indicate the order of appearance of fractures at surface. Inclined broken blue lines indicate the zone of influence of the collapse.

In order to calculate the angle of draw θ we use the information recorded in tables 3.3 and 3.6 and consider that (Fig. 5.2):

$$\tan\theta = \frac{\mathrm{EXT - W}}{\mathrm{P} + \frac{\mathrm{H}}{2}} \quad [5.1]$$

and

$$\mathrm{E - W} = \frac{\mathrm{OL - D - \ P - D}}{2} \quad [5.2]$$

where **E-W** is the width of the extensional zone, **H** the height of the water-filled latex balloon, **P** the depth of the top of the balloon, **P-D** the piston diameter at surface and **OL-D** the diameter of the outer limit of the collapse (see section III.3.4.3 and Fig. 3.14). As an example we have performed the calculus for experiment D-5 and have obtained an angle of draw θ of 37º. This value is close to the standard value (θ = 37º) considered in mining subsidence studies (Whittaker and Reddish, 1989; Branney, 1995).

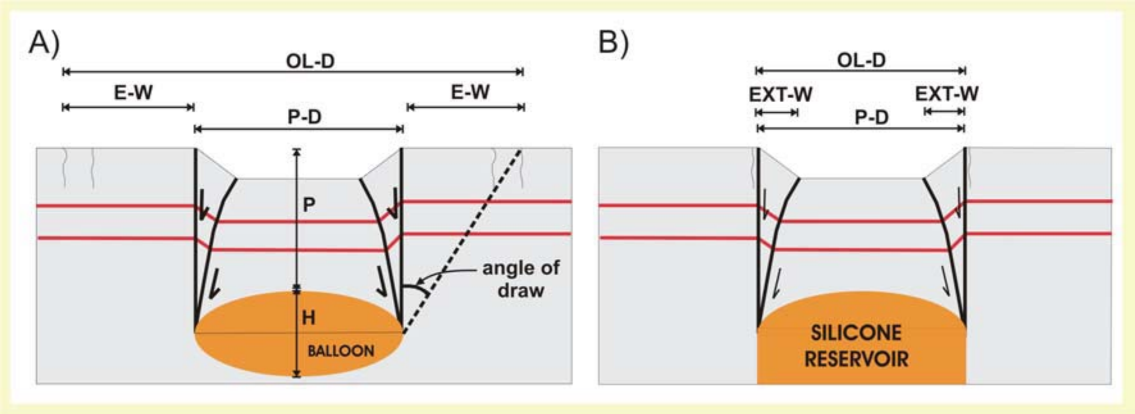

Fig. 5.2: Structural parts of a caldera collapse with a balloon **(A)** or a silicone reservoir **(B)** as magma chamber analogue. **E-W** Width of the extensional zone; **EXT-W** (EXT-W=E-W + T-W) Width of the external area of flexure and extension; **H** Height of the balloon; **OL-D** Structural limit diameter; **P** Depth of the top of the balloon; **P-D** Piston diameter.

The caldera collapse process, similar to ice-melt subsidence processes, begins with the formation of a downsagged zone centred above the analogue magma chamber (see section III.3.4.3 and Fig. 3.18 and 3.19). This deformation process leads to the formation of an extensive fracturing zone around the magma chamber. These observations have important implications. In those analogue models involving the formation of collapse calderas due to doming we do not observe a downsgagged area originated previously to the appearance of arcuate or ring fractures. Doming causes radial fracturing at the summit part of the dome structure and in advanced stages concentric fractures, but at least, in performed analogue models prior to fracturing no downsagging of the roof takes place.

Downsag prior to any fracturing is observed only in those analogue models in which the collapse is caused by the removal of water from the balloon. Consequently, if we extrapolate these observations to nature, we can say that at least for those samples which downsag took place prior to fracturing, the caldera collapse occurred by the removal of magma from a buried reservoir.

V.1.3 Comparing mathematical models and nature

In contrast with experimental models, mathematical models offer the possibility of quantifying the variables considered in each model and to define semi-quantitatively the general conditions for fracture and fault propagation. Although mathematical models are still primitive when simulating fracture and fault propagation, they offer the unique way to understand when and why caldera collapse occurs. This completes the information obtained from experimental models referring to how caldera subsidence takes place. We have seen (see section IV.3) that theoretical models on collapse calderas provide the necessary information to determine the stress conditions that favour caldera collapse and also the ones in which such catastrophic episodes will never occur. In good agreement with the experimental results, mathematical models also show that caldera collapse processes are strongly dependent on the geometry of the subvolcanic system (shape and volume of the magma chamber, chamber depth) and on the physical properties of the host rock and magma. One of the main results from theoretical models is that only very particular stress configuration around the magma chambers will favour caldera collapse, thus implying that this process will only rarely occur along the whole history of a volcanic system. Moreover, theoretical models also indicate that ring faults controlling caldera subsidence will form at the margins of the magma chamber, so that the area of the resulting caldera depression will be of the same order than the plan view of the associated magma chamber. This implies, in coincidence with experimental results, that we should not expect very wide calderas from relatively narrow magma chambers and vice versa.

Furthermore, theoretical models demonstrate that ring faults controlling caldera collapse may originate from magma chambers both at overpressure and underpressure. Examples supporting both types of caldera processes exist in nature. On the one hand, there are examples of large calderas, usually located in continental settings, which show sequences of caldera deposits suggesting that caldera-forming deposits developed immediately into massive proportions without any preceding central vent eruption that could explain previous decompression of the magma chamber (e.g. Sparks et al., 1985). On the other hand, there are numerous examples of caldera episodes preceded by Plinian, central vent eruptions that account for a significant decompression of the magma chamber previous to the initiation of caldera subsidence (Williams, 1941;

Mahood, 1980; Bacon, 1983; Heiken and McKoy, 1984; Heiken et al., 1990; Hildreth and Fiestein, 2000).

However, there are still some aspects that need to be studied in more details in order to confirm the validity of the mathematical models. One of the main uncertainties corresponds to the rheological behaviour of the host rock. Most of the existing theoretical models on collapse calderas assume a pure elastic behaviour for the magma chamber walls. This is clearly an unrealistic situation as the long deformation history of the magma chamber, including episodes of inflation and deflation, and the thermal effects of magma on the host rock do not account for such simplistic rheology. Development of theoretical models using more realistic rheologies is definitively needed in order to better constrain the mechanics of caldera processes.

V.2 GENETIC CLASSIFICATION OF COLLAPSE CALDERAS

The ultimate objective of this work is to propose a genetic classification for collapse calderas and to describe the dynamic and structural evolution of the defined end-members. For this purpose, we apply the different results exposed throughout this work and try to correlate the diverse observations.

We start from the results obtained in chapter II: Field studies. Field evidences indicate that there exist two types of collapse caldera end-members: type A and B (see section II.5.7.6). Additionally, analogue models indicate that analogue collapse processes may take place due to the decompression of the analogue magma chamber (see sections III.2.1 and III.3) or at the summit part of dome structures due to the ascent or inflation (i.e. pressure increase) of the analogue chamber (see section III.2.1). In section IV.2, we have presented a summary of the pressure evolution inside the magma chamber and the different pressure conditions that lead to collapse caldera processes. In Figure 4.1 we have distinguished between: Apical collapse, overpressure collapse and underpressure collapse. Remember that apical collapses have a mechanical origin and do not have volcanic implications, i.e. no magma is extruded. Combining all the results obtained we conclude that there exist two genetic collapse caldera end-members (Fig. 5.3): Cordilleran calderas and composite volcano type calderas.

❖ CORDILLERAN TYPE CALDERAS

Calderas included in this group correspond to the type-A calderas of section II.5.7.6 and to the "Overpressure calderas" (see section IV.2). These calderas follow the model proposed by Gudmundsson, (1998). These calderas form due to the overpressurization of a sill-like magma chamber in the presence of a regional extensive stress field and a large scale doming or underplating (Gudmundsson et al., 1997). When the tensile strength of the host rock is exceeded, ring fractures nucleate at surface at a radial distance approximately equal to the projection at surface of the magma chamber extension. These fractures propagate downwards and are normally vertical or sub-vertical inward dipping. The caldera-forming eruption starts due to the decompression of the magma chamber throughout the ring faults. In general, there is neither evidence of a possible pre-caldera edifice (e.g. composite volcanoes or shield volcanoes) nor indication of substantial eruptive phases (e.g. energetic Plinian phases) previous to the formation of the ring faults.

These caldera-forming eruptions tend to generate quite large plate/piston or trap-door collapse structures (D_{CIR} > 25 km) and important volumes of erupted magma (>100 km^3). Additionally, the associated magmas are primordially calc-alkaline, mainly rhyolitic or dacitic.

In a more plate and regional scale, these calderas occur in areas of continental thick or thin crust and occasionally, in evolved transitional thick crust. They are uniquely associated with C-type subduction zones and areas of continental rifting and more locally, the most common structures are extensional and shear-extensional.

❖ COMPOSITE VOLCANO TYPE CALDERAS

These calderas correspond to the type-B calderas (see section II.5.7.6) and to the "Underpressure calderas" (see section IV.2). These calderas represent the culmination of long-lived eruptive cycles in composite volcanoes. They take place at the summit of a stratovolcano that has usually been submitted to various periods of magma chamber inflation and deflation.

The caldera-forming eruption begins with an overpressure inside the chamber that triggers, once overcome the tensile strength of the host rock, magma injection into the host rock and finally, an eruption. Consequently, these collapse calderas may present evidences of eruptive phases (e.g. energetic Plinian phases or low energy mafic eruptions) previous to the formation of the ring faults. The magma withdrawal during these eruptive phases leads to a pressure decrease in the magma chamber. The caldera collapse begins once the resistance of the host rock is exceeded so that it breaks and subsides. Notice that the different previous periods of deformation and the diverse eruption cycles may weak the host rock and consequently, the required underpressure to trigger caldera collapse may decrease. Evidently, field evidences regarding these calderas detect the existence of pre-caldera edifices, particularly composite volcanoes: stratovolcanoes or stratocones.

Apparently, the evolution of the caldera collapse coincides with the observations performed with analogue models of collapse calderas considering decompression of the magma chamber analogue as the magma chamber trigger. The collapse begins with the downflexure of the roof and the generation of extensional ring fractures at surface. Afterwards, outward dipping reverse faults nucleate at the top of the magma chamber and propagate upwards. Notice that although this is an experimental observation, field evidences tend to indicate that faults generated at the top of the chamber would end as injected dikes and would not evolve into faults (Gudmundsson et al., 1997). However, there are still discrepancies concerning these structures. The caldera collapse continues with the downward migration of some of the extensive ring fractures and the arrival of the reverse faults at surface. The extensive ring fractures become vertical or sub-vertical ring faults and control the subsidence of the caldera floor.

Calderas included in this group tend to be smaller than those of the Cordilleran type (D_{CIR} < 25 km). These caldera-forming events can involve important volumes of magma but in general, they are less voluminous that “Cordilleran type” caldera-forming eruptions. Although, the most common associated deposits are primordially felsic calc-alkaline, it is also possible to find mafic calc-alkaline or alkaline samples.

These calderas may occur in any type of crust and tectonic settings and may be associated with any type of local structures (e.g. compressional, extensional, shear, etc.), but the most common are extensional settings.

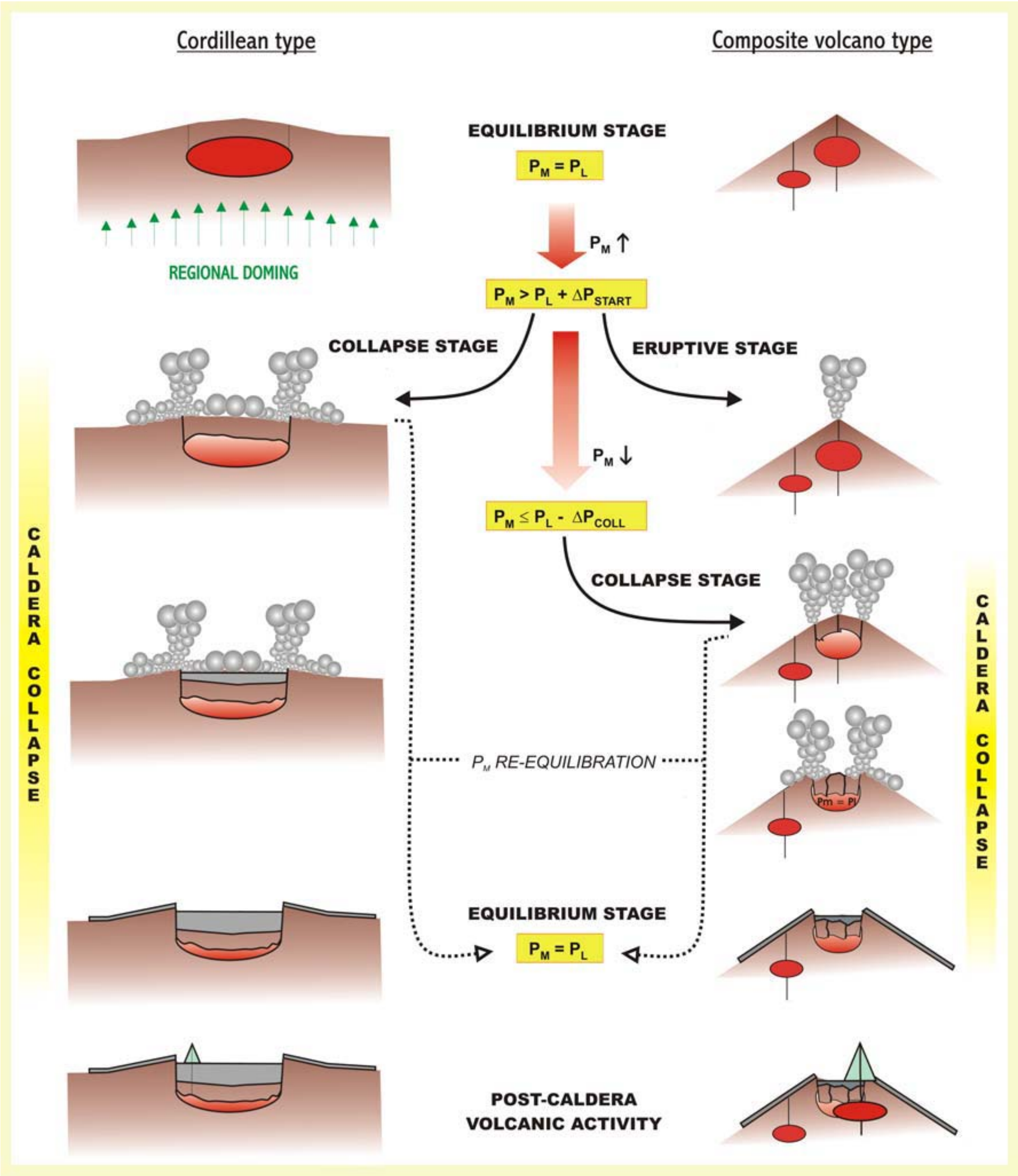

Fig. 5.3: Sketch of the evolution of both a "Cordilleran type" and a "Composite volcano type caldera". **ΔP_{COLL}** Underpressure required to induce caldera collapse; ".**ΔP_{START}** Overpressure required to trigger an eruption; **P_L** Lithostatic pressure; **P_M** Magmatic pressure.

Additionally, Figure 5.4 illustrates the pressure evolution inside the magma chamber during the whole caldera-forming cycle. In both cases, the eruption takes place due to an excess pressure inside the magma chamber (Fig. 5.4 indication I). For "Cordilleran type calderas" the conditions for ring fault formation are reached in the meantime the magma chamber is overpressurized. During the collapse, the pressure inside the chamber decreases re-equilibrating the system (Fig. 5.4 indication II). Once the caldera collapse has been set on, the magma chamber roof is supported by the magma. Subsidence of the magma chamber roof brings magma pressure at the top of the chamber to lithostatic and keeps it equal to the overburden pressure throughout caldera collapse. Caldera subsidence will continue until pressure of the magma column at the bottom of the ring fault is equal to lithostatic (Fig. 5.4 indication III). If a new injection of magma refills the magma chamber or the remaining magma is able to differentiate and oversaturate in volatiles, the pressure inside the chamber will increase again (Fig. 5.4 indication IV).

In the case of the "Composite volcano type" caldera-forming events, the conditions for ring fault formation are accomplished once magmatic pressure has decreased below lithostatic (Fig. 5.4 indication V). The required underpressure $\mathbf{\Delta P_{COLL}}$ to trigger the caldera collapse depends on the system and its mechanical properties (Fig. 5.4 indication VI_a or VI_b). Again, caldera subsidence will keep on, re-establishing the magmatic pressure (Fig. 5.4 indication VII_a and VII_b), until pressure of the magma column at the bottom of the ring fault is equal to lithostatic (Fig. 5.4 indication $VIII_a$ and $VIII_b$). If a new volcanic cycle begins, the pressure inside the chamber will increase again with time (Fig. 5.4 indication IX_a and IX_b). Notice that depending on the system, the velocity of the system to recover overpressure values capable to trigger volcanic eruption is different.

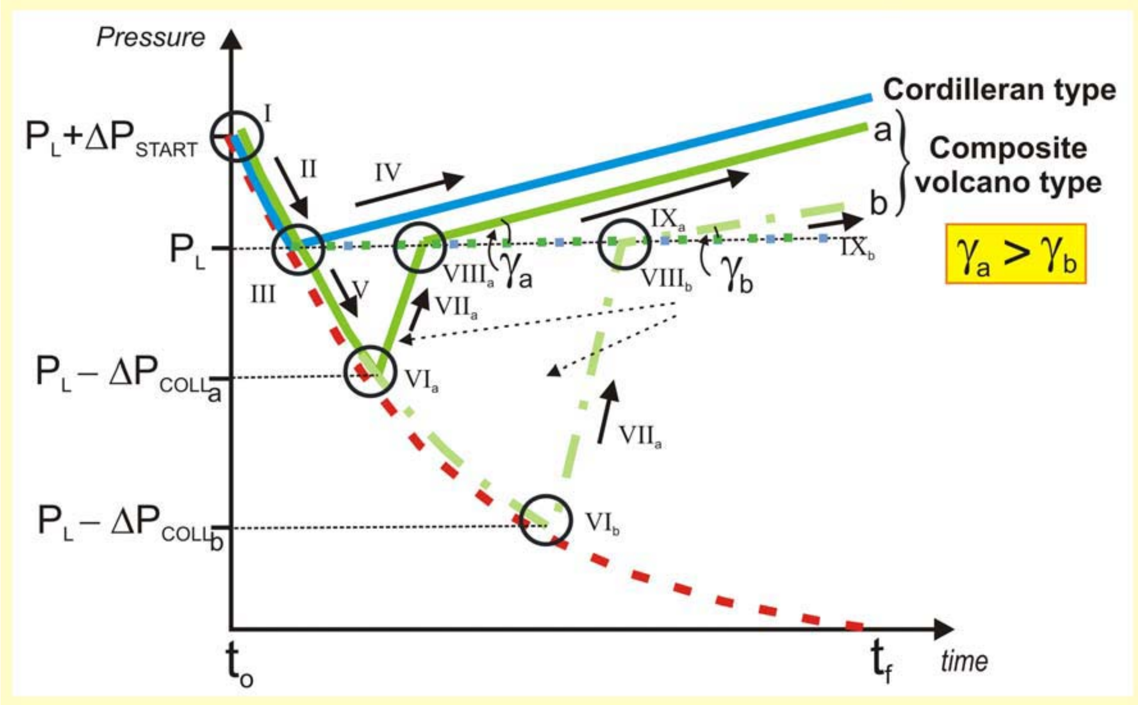

Fig. 5.4: pressure evolution inside the magma chamber during the whole caldera-forming cycle. Δ**P**$_{\mathbf{COLL}}$ Underpressure required to induce caldera collapse; ”.Δ**P**$_{\mathbf{START}}$ Overpressure required to trigger an eruption; **P**$_{\mathbf{L}}$ Lithostatic pressure; **P**$_{\mathbf{M}}$ Magmatic pressure.

Finally, if we compare our genetic classification with previous studies, we observe that “Cordilleran type” calderas could be associated with the model of resurgent calderas proposed by Smith and Bailey (1968) (see section II.3.5)(Fig. 2.14). Thus, these calderas may be characterized by a period of regional tumescence and ring fault generation, caldera-forming eruption and associated collapse, pre-resurgence volcanism and sedimentation, resurgent doming and major ring fracture volcanism. By contrast, “Composite volcano type” calderas were already recognized by Williams (1941) and van Bemmelen (1929). Figure 2.11 shows the different steps characterizing a caldera collapse evolution according to Williams (1941) and van Bemmelen (1929). In general trends, this is similar to our description for the “Composite volcano type” calderas. The collapse caldera forms due to the removal of magmatic support. The authors described that in composite volcanoes, magma evisceration is usually by violent and rapid explosions.

Finally, we can integrate this genetic classification into Figure 1.1. Thus we can visualize at once, the spatial scale and relationship between those geological processes that influence and determine the nature of a caldera-forming eruption (Fig 5.5).

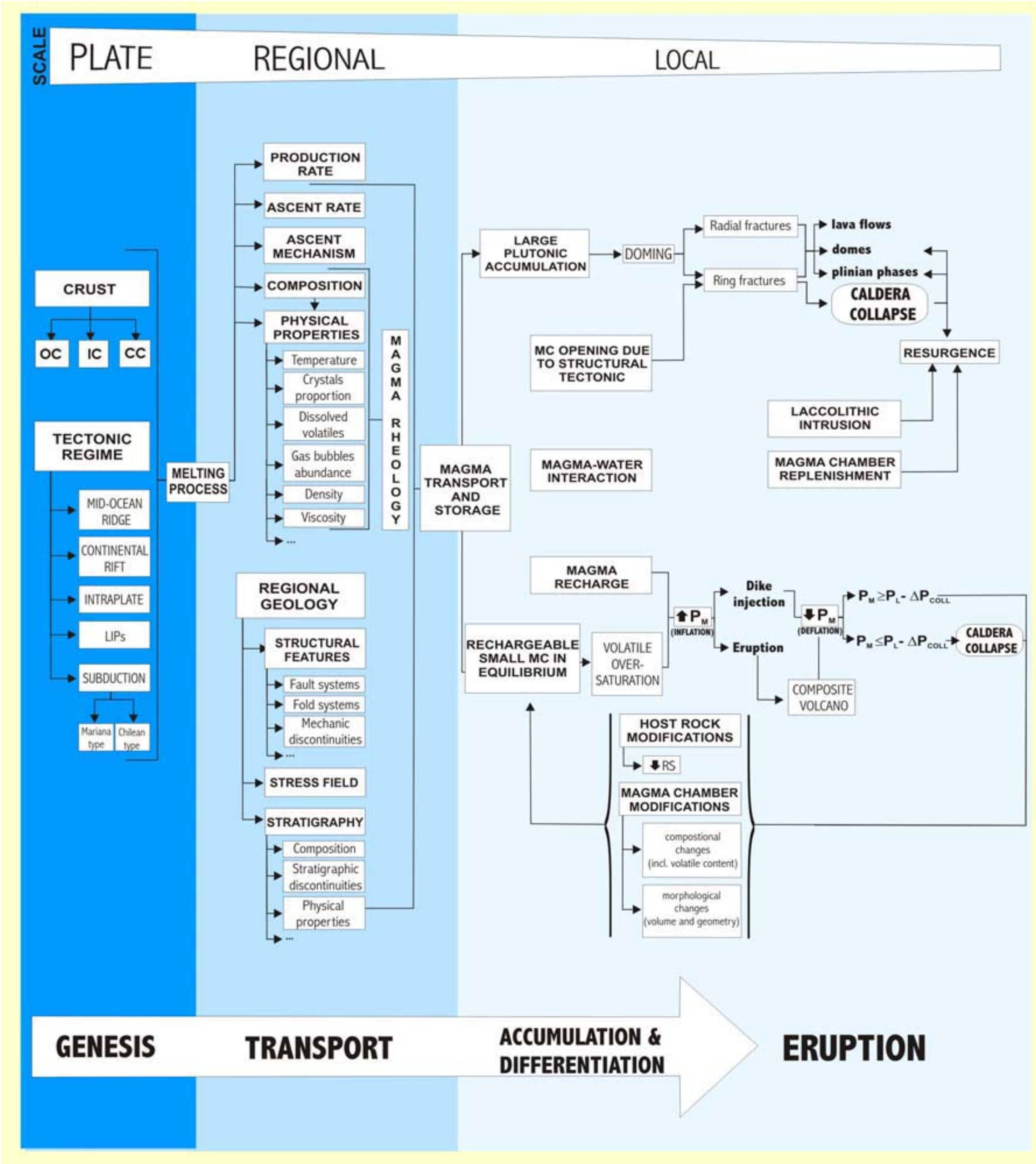

Fig. 5.5: Spatial scale and relationship between those geological processes that influence and determine the nature of an eruption at surface. These processes are controlled by specific factors also represented in the sketch. **OC** Oceanic crust; **IC** Intermediate/transitional crust; **CC** Continental crust; **LIPs** Large igneous provinces; **MC** Magma chamber; $\mathbf{P_L}$ Lithostatic pressure; $\mathbf{P_M}$ Magmatic pressure; **RS** Rock resistance; $\Delta\mathbf{P_{COLL}}$ Underpressure required to induce caldera collapse.