Departament for Physical and Regional Geography
Faculty of Geography and History
University of Barcelona

PhD thesis

Holocene alpine environments in Sierra Nevada (Southern Spain)

Marc Oliva i Franganillo
(summary)

Thesis supervisors

Prof. Dr. Antonio Gómez Ortiz

Prof. Dr. Lothar Schulte

Contents

Acronyms

AD	*Annus Domini*
AMS	Accelerator Mass Spectrometry
AV	Aguas Verdes lake
BP	Before Present
C_{org}	Organic carbon
cps	Counts per second
DACP	Dark Ages Cold Period
D-O	Daansgard-Oeschger
ELA	Equilibrium Line Altitude
ETH	*Eidgenössische Technische Hochschule,* University of Zürich (Switzerland)
Fe_d	Dithionite iron
Fe_o	Oxalate iron
H_{ev}	Heinrich events
HWP	Holocene Warm Period
INM	Spanish National Institute of Meteorology
IPCC	Intergovernamental Panel on Climate Change
IRD	Ice-rafted debris
LGM	Last Glacial Maximum
LIA	Little Ice Age
LOI	Loss on Ignition
LRS	Rio Seco lagoon
LSJ	San Juan lagoon
MARUM-UBr	*Marine Umweltwissenschaften*, University of Bremen (Germany)
MM	Minimum Maunder
MS	Mass susceptibility
MWP	Medieval Warm Period
NAO	North Atlantic Oscillation
RS	Rio Seco lake
RWP	Roman Warm Period
UB	University of Barcelona
UBe	University of Bern (Switzerland)
UFr	University of Fribourg (Switzerland)
URV	University Rovira i Virgili
UTL	Universal Temperature Logger
UU	University of Uppsala (Sweden)
WeMO	Western Mediterranean Oscillation
XRF	X-ray fluorescence
YD	Younger Dryas

SHORT NOTES

- The present thesis has an extended version in Catalan language and a summary in English, according to the European thesis model prior to the Bologna process.
- Figures and tables in the English summary correspond to the same numbers in the Catalan version.
- All the figures and tables listed below are mentioned in the English text but do not appear in this version, because they are also written in English in the main text of this thesis.

  List of figures: 2.2, 2.3, 2.8, 2.9, 2.10, 2.14, 4.21, 4.29, 4.30, 5.3, 5.17 and 5.21.

  List of tables: 2.1, 2.2, 5.1, 6.1 and 6.2.

- Study cases of solifluction lobes (chapter 5) and mountain lakes (chapter 6) are presented individually in the Catalan document, with all the figures written in English. In chapter 7 of this version, we discuss and interpret all these results.
- All references are listed in the extended version.

1. Introduction

In the present context of future climate uncertainty, the scientific community is responsible for investigating the precise effect of anthropogenic activities on climate variability and our real capacity to modify the natural system dynamics. One of the main purposes of our research is to encompass the so called climate change onto the natural climate evolution occurred in southern Iberian Peninsula during the Holocene.

Our research is focused in Sierra Nevada, the range which holds the highest summits in southwestern Europe, with peaks exceeding 3000 m at 37ºN latitude. The main interest in studying the palaeonvironmental evolution of this massif lies in its geographical position in an area with crossing influences: between Europe and Africa, between the Atlantic Ocean and the Mediterranean Sea, between the subtropical high-pressure belt and the mid-latitude westerlies.

Changes in the General Circulation of the Atmosphere in the North Atlantic region during the last millennia, with displacements, weakening or deepening of the dominant high-pressure or low-pressure systems could imply different responses of the geomorphological processes that took place in the summits of Sierra Nevada. The reconstruction of the Holocene geomorphic activity in this massif permits to infer natural climate variability in southern Iberian Peninsula.

Sierra Nevada is a low vegetated massif with few locations where to study palaeocological changes during the Holocene due to the lack of places with abundant and continuous supply of water that could preserve the organic matter as a source for potential datable material. Our research is focused in two sedimentary records that can report further environmental information of the Holocene landscape evolution in Sierra Nevada: solifluction lobes and mountain lakes.

Solifluction lobes are typical features of the periglacial belt very sensitive to temperature and moisture changes. Mountain lakes contain continuous sedimentary records, probably covering all the Holocene in Sierra Nevada, and can provide information about palaeoenvironmental changes in the catchments of the highest cirques where they are located.

2. Regional setting

Sierra Nevada is a massif located in the Betic Cordillera with the highest peaks in the Iberian Peninsula (Mulhacén 3478 m a.s.l., Veleta 3398 m). The emplacement of this high semiarid massif at 37ºN latitude and 3ºW longitude couples typical features of arid mountain environments and common characteristics of mid-latitude alpine ranges.

Precisely, its geographical position must have been decisive during the Holocene: little displacements of the General Circulation of the Atmosphere in the North Atlantic area should have implied different climate conditions in southern Iberian Peninsula, which have determined the geomorphologic processes dominating in Sierra Nevada.

This chapter is an introduction to the main geographical features of the study area and a brief review of the previous research related to Quaternary landscape evolution in Sierra Nevada.

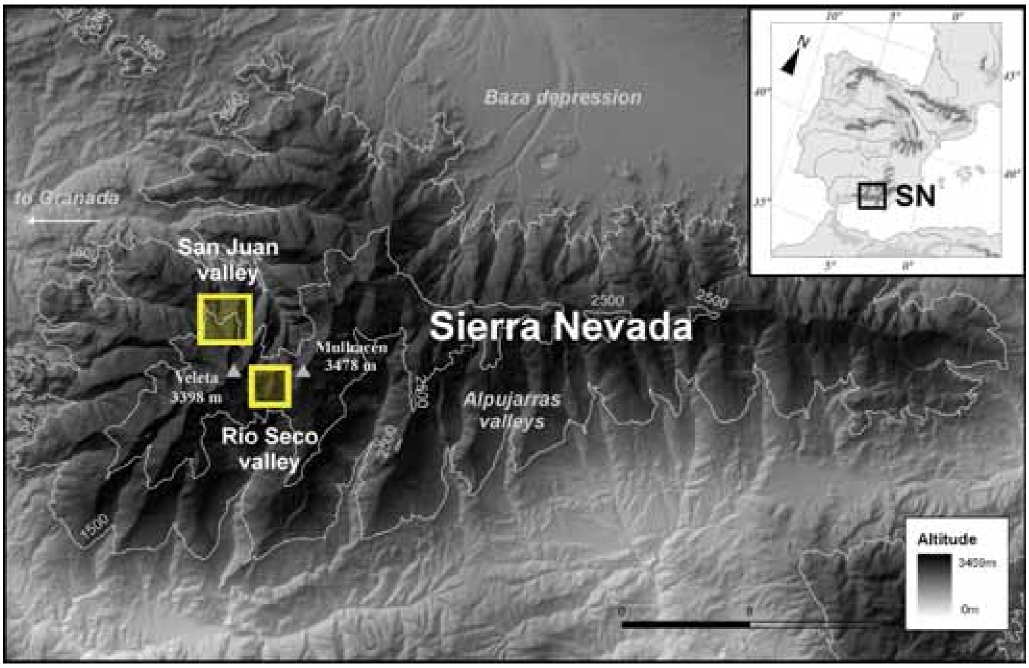

Figure 2.1 Location of Sierra Nevada in the Iberian Peninsula.

2.1 Geographical approach to the study area

The Betic Cordillera is a geologic unit in the southeastern corner of the Iberian Peninsula that connects the Gulf of Cadis with the Guadalquivir valley and the coastal plains. Sierra Nevada is a relative young massif reelevated during the Alpine orogeny with very high emersion rates of about ~ 0.4-0.6 mm year^{-1} (Sanz de Galdeano & López Garrido, 1999). The axial part of Sierra Nevada is mainly composed by schists and micaschists, without carbonate rocks, which only appear in the margins of the massif (figure 2.2). The weak resistance of the dominant bedrock combined with a very low vegetation cover in the alpine belt of this massif enhances weathering and solifluction processes.

Sierra Nevada's landscape combines the glacial morphology due to Pleistocene cold phases and the active periglaciarism that has reworked the cirques and glacial valleys shaped by the LGM glaciation during the Holocene. In the present interglacial, climate conditions have not been cold and/or wet enough to trigger an important glacial development in the highest cirques and periglaciarism has been the dominant geomorphological process in the massif since the Late Glacial cold pulses, with a wide range of characteristic periglacial morphologies over 2500 m: rock glaciers, debris flows, patterned ground, sorted stripes, protalus ramparts, talus deposits and solifluction lobes.

The high altitudes, large extension and compactness of Sierra Nevada, at 37ºN latitude in southern Iberian Peninsula, furnish the massif with typical climate conditions of high semiarid Mediterranean mountains. Sierra Nevada is located in the northern fringe of the subtropical high-pressure belt with winter influence of the mid-latitude westerlies.

The succession of high peaks and deep valleys determines a wide suite of microclimates and a climatic dissymmetry between the west-east and north-south of Sierra Nevada (tables 2.1 and 2.2). At 2500 m mean annual temperature records 4.4ºC and annual precipitation reaches only 702 mm year^{-1} (1965-1992), 80% seasonally concentrated between October and April, mostly as snow (figure 2.3).

Our study area is located in the western side of the massif at altitudes above 2500 m, where vegetation is very sparse due to climate conditions. Nowadays, in the periglacial belt of Sierra Nevada, biophysical characteristics do not allow a dense vegetation cover and edaphic processes are only restricted to valley floors and hygrophyte areas, known as *borreguiles* in local terminology. Despite having a very low vegetation cover, Sierra Nevada holds a huge number of endemic species, concentrating more than 2100 with respect to the 8000 species existing in the Iberian Peninsula.

Solifluction lobes are mainly located in currently vegetated areas which are characterized by an intense use of these fresh meadows by the cattle (*borreguiles)*. These wetlands extend along the valley floors, mostly composed by *Nardus sp.* and *Festuca sp.* and tend to show a peat centre surrounded by a dense grass recover, with scarcer vegetation in the adjacent margins. Slopes and summits are covered by debris with an extremely poor vegetation cover.

In a semiarid region where water resources are limited, Sierra Nevada represents an important spring with the source of the main rivers in Andalusia. The massif acts as a natural reservoir which retains snow during the winter and releases water during the melting season.

During the last few thousand years several cultures have developed in Andalusia (Tartessians, Romans, Visigoths) but none of them has exploited the natural resources of Sierra Nevada. The Muslims ruled southern Spain from 711 to 1492 AD and were the first civilization to penetrate into the massif. Their accurate social system combined with higher demographic pressure led them to take profit of the snow melting waters by constructing a complex hydraulic system.

But it will not be until the 20th century when the biggest changes occurred in this massif: the construction of the highest road in Europe, the railway up to San Juan valley and the southernmost ski resort in Europe threaten its singular geographic wealth. On the other hand, during the last decades there has been an increasing attempt to preserve the natural highlights of Sierra Nevada by protecting the massif with three different categories: Biosphere Reserve (1986), Natural Park (1989) and National Park (1999).

2.2 Palaeoenvironmental evolution of the study area: state of the art

Several authors have tried to reconstruct the geological history of Sierra Nevada. Messerli (1965), Hempel (1960), Lhenaff (1977) i Sánchez Gómez (1990) state the existence of Pleistocene moraine deposits prior to the LGM at altitudes ranging from 1200 to 1600 m (figure 2.8).

The decrease of the mean global temperature during the LGM is around 3.0 ± 0.6ºC (Hoffert & Covey 1992), light in the tropics, ~4-5ºC in the Iberian Peninsula and >10ºC at high latitudes (CLIMAP, 1981). During the LGM, the ELA in the massif remained 1100-1200 m below the present level, which explains the existence of several glacial features above 2500 m. Glaciers in Sierra Nevada flowed down several kilometres from the cirques, longer in southern valleys due to snow redistribution by the wind. Figures 2.9 and 2.10 point out the fact that the ELA in the western valleys was 150-200 m below the ELA in the eastern valleys because of the relative proximity to the warm Mediterranean sea.

Thermal increase since the LGM caused the glacier disappearance in Sierra Nevada, although several advances took place during the Late Glacial period with formation of moraines inside the cirques (Schulte et al., 2002). Most of the rock glaciers located today in the northern and southern cirques must have developed during these cold pulses.

The sudden thermal increase at the beginning of the Holocene melted the YD glaciers and, since then, the periglaciarism turns to be the driving force of the environmental changes occurred in the summits of Sierra Nevada. Little has been written about the Holocene landscape evolution of this massif. Only Esteban Amat (1995) tried to reconstruct environmental changes during the last millennium in the summits with palynological studies from solifluction lobes, although results are quite inconsistent.

More effort has been done to investigate cold processes during the LIA. In most of the mountains in the world, glaciers expanded to their largest volume of the Holocene (Bradley & Jones, 1992). Gómez Ortiz (1997) related examples of several naturalists that during the 18th and 19th centuries described the massif, showing evidences of the existence of a glacier inside the Veleta cirque (figure 2.14).

Reconstructed temperature increase in the Iberian mountains since the MM ranges from 0.8-1.7ºC (Martínez-Cortizas et al., 1999; López Moreno, 2000; González Trueba et al., 2008). Documentary sources point the period between 1590 and 1650 as the coldest and wettest phase of the LIA in Andalusia[1], possibly related to more recurring and persistent negative phases of the NAO-WeMO teleconnection patterns (figure 2.15; Oliva et al., 2006). Oliva et al. (2008) confirm both colder and wetter conditions from sedimentary archives by reporting enhanced solifluction activity during the LIA.

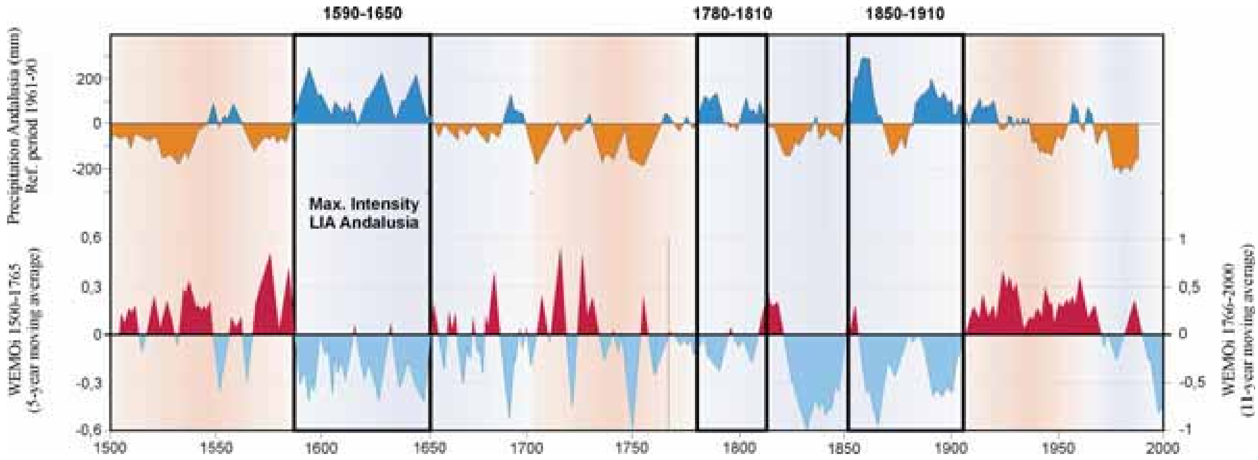

Figure 2.15. Reconstruction of mean precipitation in Andalusia (figure above) and the WeMO teleconnection pattern since 1500 (figure below). Wetter phases in this area correspond to periods with more recurring and persistent low-pressure systems around the Gulf of Cadiz (Oliva et al., 2006).

From the beginning of the 20th century, the warming trend and a significant decrease in precipitation led to the disappearance of the small glaciers installed in the highest northern cirques. Nowadays, the remnants of dead ice bodies left by those glaciers in the highest northern cirques explain the existence of some active glacier-derived rock glaciers, although dynamic control suggests that melting of the buried ice slows horizontal displacements and accelerates sinking, possibly as a consequence of global warming (Gómez Ortiz et al., 2001).

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[1] An intense snow trade activity took place in Sierra Nevada during these decades; several tracks and snow wells were used to carry snow from the massif to Granada during the summer season (Rodrigo, 1994).

3. Methodology

3.1 METHODOLOGY USED WITH SOLIFLUCTION LOBES IN SIERRA NEVADA

	Purpose	Methodology	Information	Equipment	Centre
FIELD WORK	Thermal control	Installation of *dataloggers* inside a lobe and annual maintenance	Ground thermal control every 2 h at depths of 2, 5, 20, 50 and 100 cm.	UTL-1 Datalogger	Field work, Landscape Research Laboratory (UB)
	Dynamic monitoring	Stakes settlement and annual control	Horizontal displacement annual rates. Uplift of the stakes.	Stakes (50 cm long x 3 cm wide)	Field work, Landscape Research Laboratory (UB)
	Mapping and morphometry	Distribution, geometry and typologies of lobes	Location, origin, development, morphology. Why some lobes move and others do not?	Field work tools	Field work, Physical Geography lab (UB)
	Field soil description	FAO (2006)	Lithostratigraphy. Key profiles.	Field work tools, Munsell soil color charts	Field work, Physical Geography lab (UB)
LAB WORK	Grain size	Automatic grain size measurements for clays and silts and wet sieving for sands and gravels	Grain size of solifluction deposits/organic units. Slope activity.	Micromeritics SediGraph 5100 and sieves	*Geographisches Institut* (UBe)
	Organic matter	Ratio C/N	Organic matter content. Edaphic processes.	Elemental Analyzer vario MACRO	*Geographisches Institut* (UBe)
	Iron fractions (Fe$_d$ and Fe$_o$)	Standard procedures (Mehra & Jackson, 1960)	Intensity of soil development and weathering. Relative age indicator.	Lab equipment and spectophotometer HACH D/R 2000	*Geographisches Institut* (UBe)
	Mass susceptibility	Scanning samples	Mineral fraction in the sediments. Detrital input and erosion.	Bartington MS2E- High Resolution Surface scanning Sensor	*Geographisches Institut* (UBe)
	X-ray fluorescence (XRF)	Proportion of the elements	Different behaviour of the elements. Erosion in the catchment.	Spectophotometer (Philips PW 2400)	Institute of Geological Sciences (UBe and UFr)
DATINGS	Datings (AMS)	Concentration of pollen grains from organic layers	Concentration of fossil pollen to avoid contamination by modern roots.	Lab equipment	Prehistory Department lab (URV)
		AMS dating of pollen concentration	Correlate geochronology with depositional environment.	AMS (Accelerator Mass Spectrometry)	Angström Laboratory (UU)

UB - University of Barcelona (Catalonia); **UBe** - University of Bern (Switzerland); **URV** - University Rovira i Virgili (Tarragona, Catalonia); **UU** - University of Uppsala (Sweden); ; **UFr** - University of Fribourg (Switzerland).

3.2 METHODOLOGY USED WITH LAKE SEDIMENTS IN SIERRA NEVADA

	Purpose	Methodology	Information	Equipment	Centre
LAB WORK	Core description	Standard	Sediments composition, structure, lithostratigraphic units.	Lab equipment, Munsell soil color charts	*Geographisches Institut* (UBe)
	Water content	Wet/dry samples	Water content. Texture indirect measurement.	Lab equipment	Physical Geography lab (UB), *Geographisches Institut* (UBe)
	Mass susceptibility	Scanning cores	Mineral fraction in the sediments. Detrital input and erosion in the catchment.	Bartington MS2E- High Resolution Surface scanning Sensor; Kappabridge KLY-2	*Geographisches Institut* (UBe), Scientific-Technical Services (UB)
	Grain size	X-ray diffraction	Texture changes. Depositional palaeoenvironment.	Malvern laser grain sizer	Limnogeology Laboratory (ETH)
	Organic geochemistry	Ratio C/N	Organic matter content. Terrestrial/aquatic inputs. Lake productivity.	Elemental Analyzer vario MACRO	*Geographisches Institut* (UBe)
		LOI determination (550ºC, 4 hours)	Organic matter content.	Naberthern 30-3000ºC, Controller B170	Physical Geography lab (UB), *Geographisches Institut* (UBe)
	X-ray fluorescence (XRF)	Proportion of the elements: K, Ca, Ti , Mn, Fe, Cu and Sr	Different behaviour of the elements. Aeolian input and erosion in the catchment.	XRF scanning core	MARUM Center (UBr)
	Pollen analysis	Pollen diagrams	Plant succession.	Lab equipment	Institute of Plant Sciences (UBe)
DATINGS	Datings (AMS)	Pollen concentration	Concentration of fossil pollen to be dated.	Lab equipment	Prehistory Department lab (URV)
		Datings of plant fragments, *charcoal* and pollen concentration	Correlate geochronology with depositional environment.	AMS (Accelerator Mass Spectrometry)	Angström Laboratory (UU)

ETH - *Eidgenössische Technische Hochschule,* University of Zürich (Switzerland); **MARUM-UBr** - *Marine Umweltwissenschaften*, University of Bremen (Germany); **UB** - University of Barcelona (Catalonia); **UBe** - University of Bern (Switzerland); **URV** - University Rovira i Virgili (Tarragona, Catalonia); **UU** - University of Uppsala (Sweden).

4- Sedimentary records in Sierra Nevada: solifluction lobes. Distribution, morphometry and present dynamism

Despite the existence of several kinds of sedimentary records in Sierra Nevada, only two of them can provide further information about Holocene landscape changes in this massif: solifluction lobes and mountain lakes. Moraines or polygonal soils are widespread in Sierra Nevada but reflect punctual cold phases mostly related to the LGM and can not give a continuous succession of the environmental evolution. More recently, documentary sources and instrumental data help us to encompass the so called climate change onto the natural climate variability of the last centuries in Andalusia (figure 4.1).

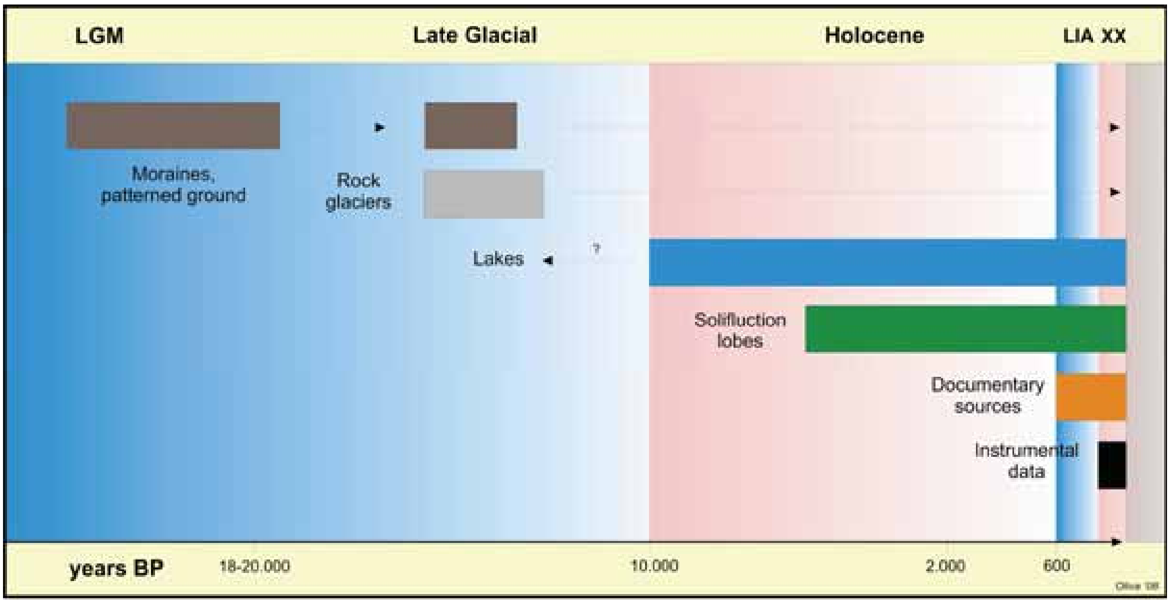


Figure 4.1. Existing sources for environmental information in Sierra Nevada: natural archives, documentary sources and instrumental data. This thesis is focused in solifluction lobes and lake sediments, which can provide information about landscape changes during the last millennia in the massif.

Chapter 4 focuses on solifluction lobes. We discuss the emplacement of solifluction lobes, the relationships between topography and lobes geometry and analyze the present solifluction dynamics by comparing monitored displacement rates with ground thermal evolution from 2005 to 2008.

From now onwards, we will use the term solifluction as the generic word to describe the simultaneous activity for frost creep and gelifluction (French, 1996). It was first defined by Andersson (1906) and is considered to be the most widespread mass movement in periglacial areas (Lewkowicz, 1988; French, 1996; Kinnard & Lewkowicz, 2005 and Matthews et al., 2005).

4.1 Geomorphological setting

Our study area is focused in the western part of Sierra Nevada, in the valleys that concentrate the highest summits of the whole range. Solifluction lobes in this area are mainly distributed in two valleys: San Juan and Rio Seco.

San Juan is a smooth U-shaped valley, north exposed, with lobes ranging from 2474 to 2911 m and Rio Seco is a huge glacial amphitheatre in the southern slope of Sierra Nevada with lobes located between 2930 and 3005 m. In both valleys vegetation cover is really scarce: 3.8% above 2500 m in San Juan and 1.6% above 2800 m in Rio Seco (table 4.1).

Table 4.1. Main geographical parameters of the studied valleys.

MAIN CHARACTERISTICS OF THE STUDIED VALLEYS							
Valley	**Study area (m)**	**Orientation**	**Catchment area (km^2)**	**Vegetation cover (%)**	**Slope (%)**	**Lobes elevation (m)**	**Number of lobes**
San Juan	2474-3040	N-NW	3.2	3.8	12.1	2474-2911	156
Rio Seco	2931-3116	S	1.6	1.6	13.8	2931-3005	46

The fact that San Juan holds 77.2% of all the mapped lobes and Rio Seco only 22.8% is due to the different tectonically influenced structure and the singular microclimate conditions of the two studied valleys: the lower insolation exposure of the northern valleys explains higher water availability and is reflected in more common solifluction features. In San Juan, solifluction lobes are mainly distributed in the valley floor in three sectors staggered altitudinally: SJA, SJB and SJC (figure 4.2). SJC is the lowest studied area with 78 lobes (2474-2548 m), SJB concentrates 50 lobes (2787-2843 m) and SJA is the highest one with only 28 solifluction features (2844-2911 m).

In Rio Seco there is a clear correlation between vegetation and solifluction lobes: they only appear in two vegetated areas (RSA and RSB) next to the lakes sampled in this thesis that provide an abundant supply of water especially to RSB (figure 4.9).

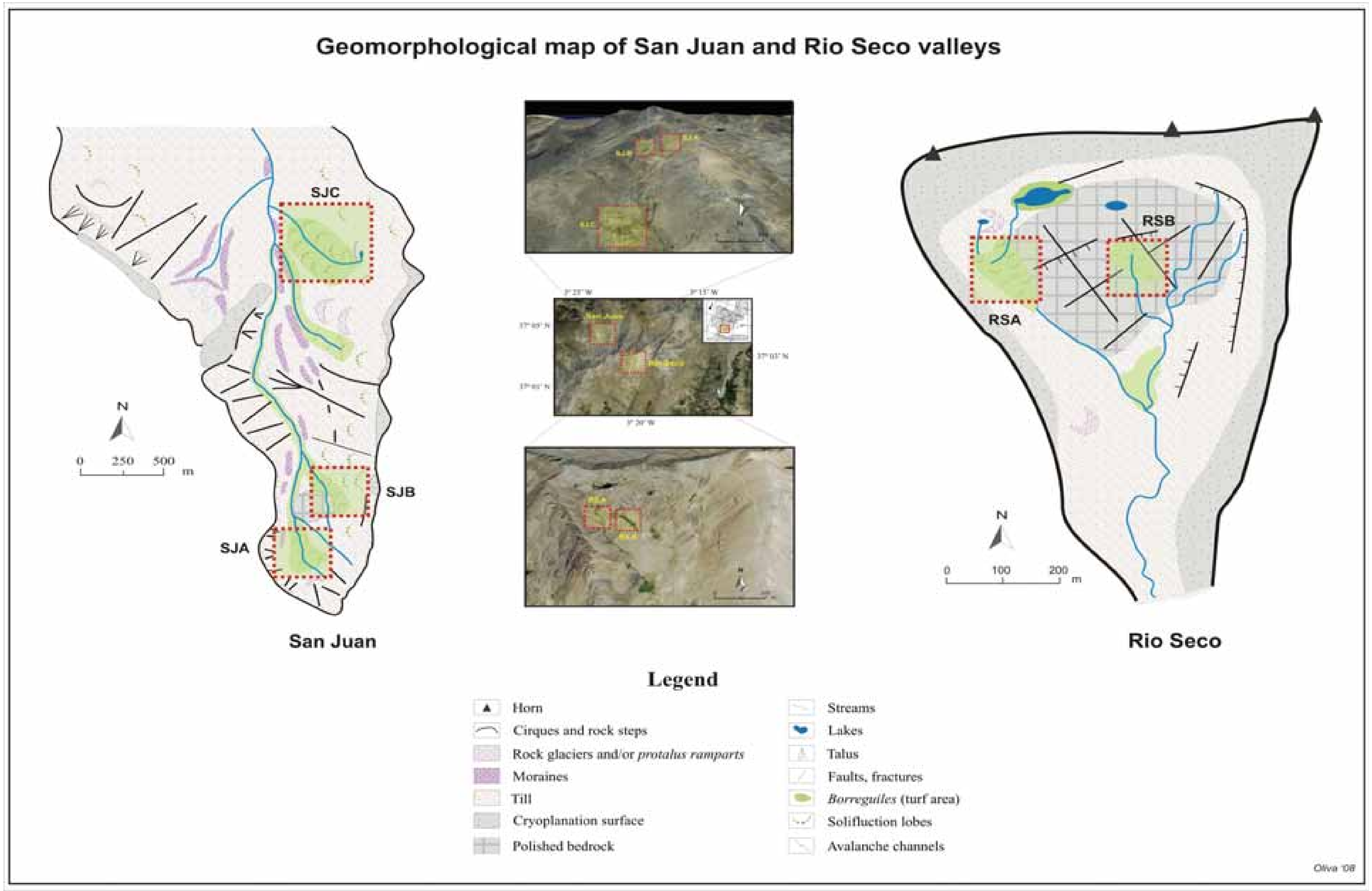


Figure 4.2 and 4.9. Geomorphological maps of San Juan and Rio Seco valleys.

4.2. Morphometrical analysis of solifluction lobes

In order to classify the geometry and different typologies of the two hundred solifluction lobes distributed in these two valleys, we have analyzed their morphometrical and spatial features taking into consideration the previous morphological and geometrical proposal of French (1996), Hugenholtz and Lewkowicz (2002) and Matsuoka et al. (2005): high solifluction lobe (HSL), low solifluction lobe (LSL), stone-banked lobe 1 (STL-1), stone-banked lobe 2 (STL-2), turf-mantled lobes (MST), stone-mantled lobes (MSS), ploughing boulders (STL-Block), solifluction *terrassettes* (ST) and mudflow-affected solifluction lobes (MSL). Table 4.2 resumes the nine different typologies of solifluction features in Sierra Nevada and figure 4.14 shows examples of each of them.

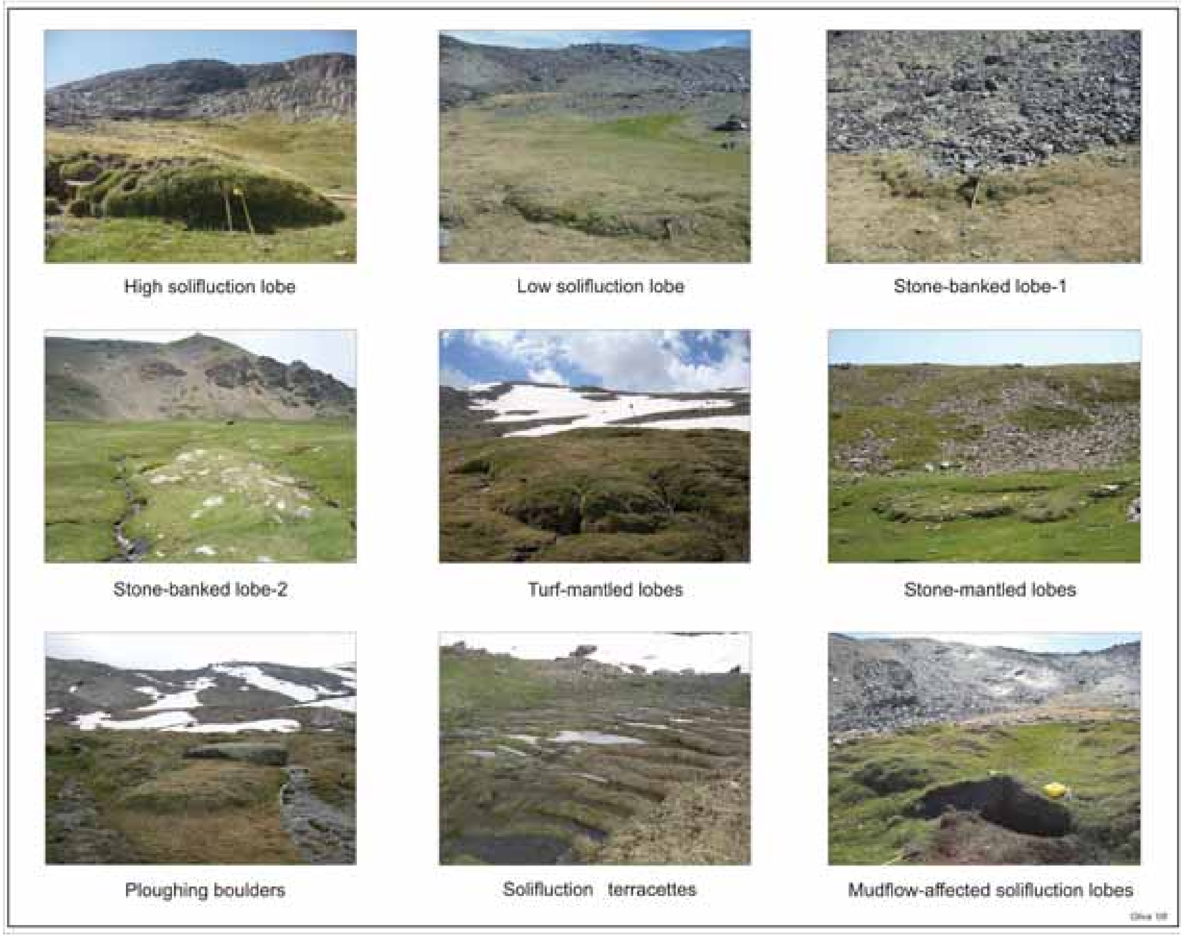
We examined environmental variables (altitude, slope, orientation and vegetation cover) and geometrical parameters of the lobes (length, width, front riser, typology and morphology). Up to 67% of all the lobes correspond to HSL and LSL, 17.4% STL-2 and the other 15.8% group the other six typologies. Lobes tend to show high vegetation recover: 72% are mostly vegetated and 28% of them show a major dominance of gravels and blocks in their surface. Lobes have moderate dimensions: 90% have a length < 8 m, 93% a width < 8 m and 60% a riser height ranging from 20 to 60 cm.

Table 4.3. Correlations between the morphometrical variables of the solifluction lobes.

	H	O	L	W	H	α_1	α_2	T	V	A	V_o	M
H												
O	-0,19											
L	-0,17	0,06										
W	-0,22	0,04	0,59									
H	-0,19	-0,03	0,48	0,38								
α_1	-0,28	-0,02	0,39	0,17	0,47							
α_2	-0,20	0,01	0,46	0,23	0,34	0,91						
T	-0,11	0,11	-0,05	0,01	-0,12	-0,17	-0,15					
V	-0,27	0,09	0,02	0,09	0,13	-0,14	-0,17	0,28				
A	-0,22	0,07	0,81	0,88	0,41	0,24	0,31	0,05	0,02			
V_o	-0,20	0,07	0,58	0,78	0,33	0,13	0,18	0,15	0,04	0,84		
M	-0,19	0,02	-0,15	0,39	0,03	-0,15	-0,14	0,14	0,10	0,15	0,23	

* In red, significant correlations with $p < 0.05$.

H: altitude; O: orientation; L: longitude; W: width; H: riser height; α_1: slope/lobe angle; α_2: slope; T: typology; V: vegetation cover; A: area; V_o: volume; M: morphology.



High solifluction lobe
Low solifluction lobe
Stone-banked lobe-1
Stone-banked lobe-2
Turf-mantled lobes
Stone-mantled lobes
Ploughing boulders
Solifluction terracettes
Mudflow-affected solifluction lobes

Figure 4.14. Solifluction lobe typologies in Sierra Nevada.

Table 4.2. Main solifluction lobe typologies and dynamic control (Oliva et al., 2008).

Type	Characteristics	Number of lobes	Monitored lobes	Active / stable
High solifluction lobe HSL	Dominance of turf with a frontal height ≥ 80 cm	32	5	1/ 4
Low solifluction lobe LSL	Dominance of turf with a frontal height < 80 cm.	104	4	2 / 2
Stone-banked lobe-1 STL-1	Abundance of gravels/rocks > 50%	6	1	1 / 0
Stone-banked lobe-2 STL-2	Abundance of gravels/rocks < 50%	34	2	1 / 1
Turf-mantled lobes MSP	Turf-dominance large lobe ≥ 8 m length	6	1	0 / 1
Stone-mantled lobes MSS	Stone-dominance large lobe ≥ 8 m length	11	0	0 / 0
Ploughing boulders STL (block)	Lobe with a rock above	4	1	1 / 0
Solifluction terracettes ST	Low solifluction terraces	3	2	0 / 2
Mudflow-affected solifluction lobes MSL	Irregular-shaped lobes with muddy matrix	2	1	0 / 1
Total	-	202	17	6/11

We present a correlation matrix with the geometrical parameters and topographical variables involved in lobe morphology in Sierra Nevada (table 4.3). Slope is the main factor controlling the geometry of the lobes, showing positive correlations with length (r = 0.46), riser front (r = 0.34) and width (r = 0.23). Vegetation cover is less controlled by altitude (r = -0.27) and slope (r = -0.17): lobes tend to be less vegetated when increasing altitude and inclination. Gently slopes allow a slower drainage and a higher infiltration, what promotes edaphic processes and vegetal cover. By contrast, orientation does not play any role regarding lobe morphology in Sierra Nevada. There is also a moderate correlation between internal variables of the lobes: length/width r = 0.59, length/front riser r = 0.48 and width/front riser r = 0.38.

Human impact in the *borreguiles* has affected these wetlands since the last decades of the 19th century (Martin Civantos, 2007). Historically, people from villages around Sierra Nevada feed the cattle in these fresh meadows in summer. The shepherds tried to redistribute water during the snow melting season by channelizing the runoff in small streams excavated in the *borreguiles*, so that these areas expanded occupying a greater extension: 60% are located between 2400-2800 m, mostly in northern and gentle slopes. These human-induced incisions are modifying the natural morphology of many solifluction lobes, creating also pseudolobes and microalluvial fans (figure 4.21) but we can not state if these modifications affect the natural pattern of solifluction dynamics.

4.3. Present dynamism of solifluction lobes in Sierra Nevada

Several studies on present solifluction dynamics have been carried out in polar and subpolar regions and mid-latitude mountain ranges, mostly the Alps (Veit, 1988; King & Schmitt, 1993; Matsuoka, 2001; Mailänder & Veit, 2001; Jaesche et al., 2003; Mastuoka, 2006).

In mid-low latitudes such as the Mediterranean region, research about solifluction topics has been limited due to the restricted area affected by periglacial processes with only a few attempts in mountain areas of the Iberian Peninsula: Pyrenees (Creus & García Ruiz, 1977; Gómez Ortiz, 1980; Chueca & Julián, 1995 & García Ruiz et al., 2004), Balearic Islands (Grimalt & Rodríguez, 1994), Peñalara massif (Palacios et al., 2003) and Sierra Nevada (Gómez Ortiz et al., 2005).

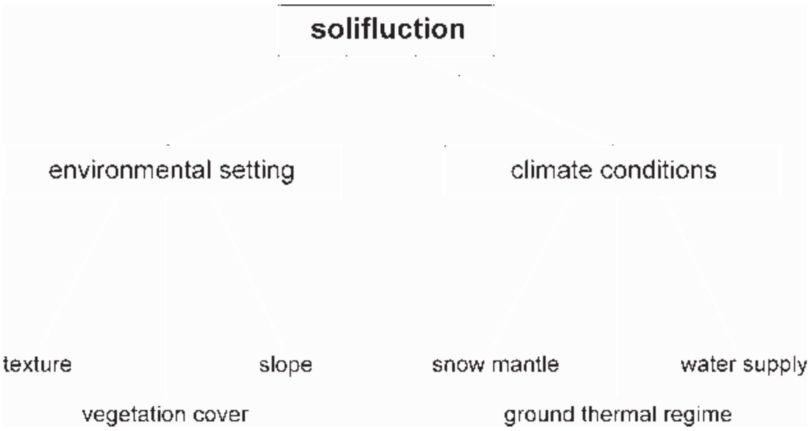


Figure 4.23. Parameters controlling solifluction dynamics in Sierra Nevada.

There are many factors involved in solifluction processes in this high semiarid massif. Figure 4.23 resumes the main parameters that control solifluction activity in Sierra Nevada. Environmental factors (slope, texture and vegetation cover) are decisive to explain the existence of solifluction features in these two valleys. The fact that many of them are relict suggests that climate conditions are determining to understand the present and past activity/inactivity of these periglacial mass movements: snow cover, ground thermal regime and water supply play a crucial role in controlling solifluction dynamics in Sierra Nevada.

There is a clear relationship between ground temperatures and active periglacial processes (Hoelzle et al., 1999; Vieira et al., 2003). Late spring in Sierra Nevada, as reported for other mountain regions, is the most favourable period for solifluction displacements (Jaesche et al., 2003; Mastuoka, 2005; Kinnard & Lewkowicz, 2005). Thermal control from September 2006 to August 2008 in a lobe in Rio Seco cirque, at 3005 m, reveals the persistence of a 70 cm thick frost layer in Rio Seco (figure 4.28 and 4.29) between November and beginning of June. Despite the existence of this deep frozen horizon, no movement was reported in this lobe. Another solifluction lobe, located at 2817 m north exposed in San Juan valley, was monitored from August 2007 to August 2008: we detected a frost layer extending more than 100 cm under the surface at early spring with a freeze-thaw timing similar to that in the Rio Seco unit (figure 4.30); dynamic control reflected a horizontal displacement of only 0.5 cm year^{-1}.

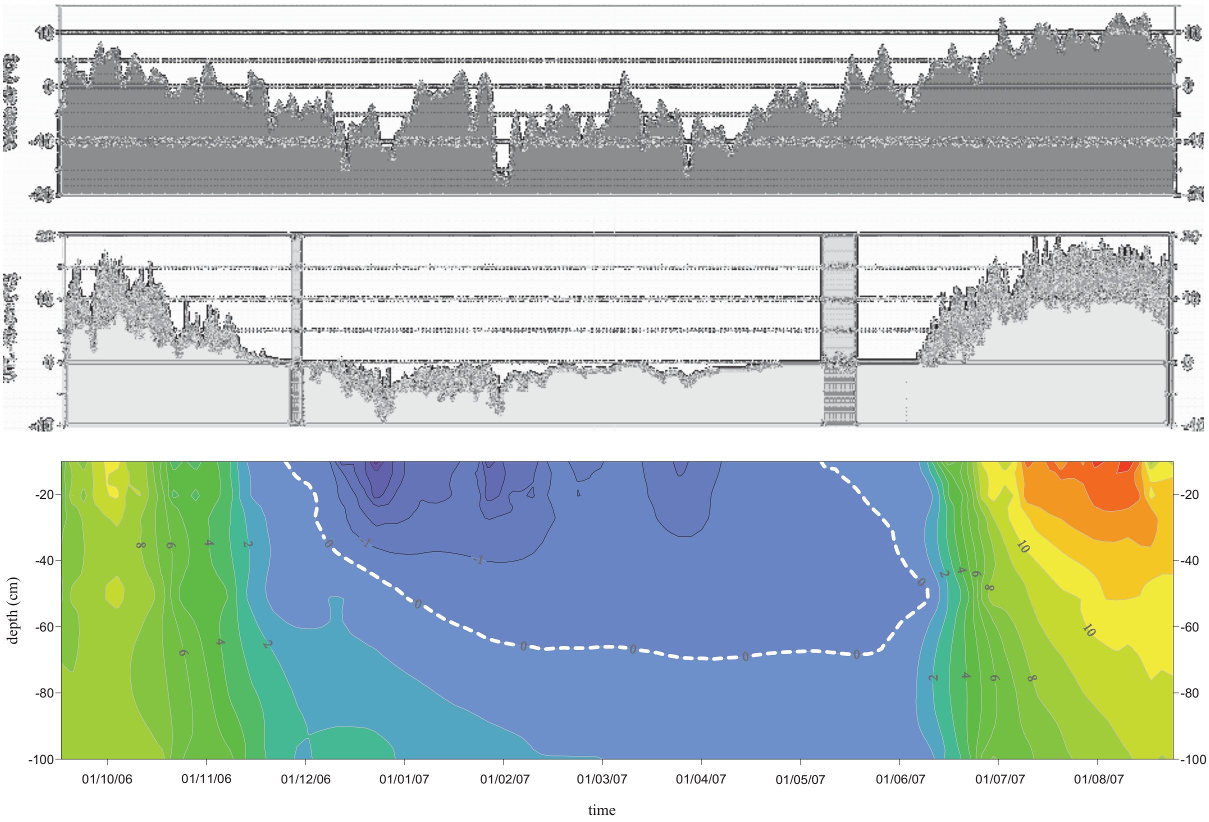


Figure 4.28. Mean daily air temperatures at Veleta peak, 3398 m (figure above), ground temperatures at 10 cm (figure in the middle; the grey bars point the freeze-thaw cycles) and through 100 cm under the surface in a solifluction lobe of the Rio Seco cirque at 3005 m (figure below) from September 2006 to August 2007.

Field observation also remarks the well defined morphologies of the majority of the solifluction lobes in both valleys (steep sloping lobe riser, a dense grass cover, intact root network and formation of thin A horizons), suggesting the inactivity or very weak solifluction activity nowadays in Sierra Nevada (Oliva et al., 2008).

Dynamic control of 17 solifluction lobes in San Juan and Rio Seco valleys from August 2005 to August 2008 confirms the relative stability of these lobes and the weak activity pattern of slow mass movements in the periglacial belt of Sierra Nevada. In both valleys, during the monitored period very small solifluction displacements were reported, in all cases < 1 cm year^{-1} (table 4.5). In San Juan we have detected higher rates in those lobes with more water availability: near streams and late-lying snow patches, especially in SJB, where a larger and longer lasting water supply implies a dense turf cover and a great number of solifluction lobes.

By contrast, the lower runoff in Rio Seco determines very small displacements: only ~20 % of the stakes in RSA and ~50 % in RSB showed relative movements. Solifluction rates are much lower compared to those recorded in subpolar regions and wet alpine environments but similar to rates reported in polar latitudes and dry mid-latitude mountain areas (Matsuoka, 2001).

Table 4.5. Mean annual horizontal rates of the stakes registered during the monitored period 2005-2008.

HORIZONTAL DISPLACEMENTS STAKES 2005-2008									
Study area	**2005-2006**			**2006-2007**			**2007-2008**		
	n	**mobile (%)**	**cm year^{-1}**	**n**	**mobile (%)**	**cm year^{-1}**	**n**	**mobile (%)**	**cm year^{-1}**
SJA	7	42.9	0.5	14	85.7	0.63	14	92.9	0.67
SJB	0	0	0	9	66.7	0.35	9	77.8	0.40
RSA	9	22.2	0.20	9	22.2	0.20	9	11.1	0.20
RSB	8	37.5	0.33	8	37.5	0.33	8	62.5	0.38

The expulsion of the stakes due to the frost heave action reflects similar annual rates to horizontal values (table 4.6). Water content also seems to play a decisive role in the vertical uplift of the stakes, being higher in those places with more water availability (SJB and RSB) and lower in drier areas (SJA and RSA).

Table 4.6. Mean annual vertical rates of the stakes registered during the monitored period 2005-2008.

UPLIFT STAKES 2005-2008															
Study area	**2005-2006**					**2006-2007**					**2007-2008**				
	n	**U %**	**cm/ year**	**T %**	**cm/ year**	**n**	**U %**	**cm/ year**	**T %**	**cm/ year**	**n**	**U %**	**cm/ year**	**T %**	**cm/ year**
SJA	9	0	0	22.2	0.2	23	43.5	0.36	4.3	0.2	23	47.8	0.36	17.4	0.25
SJB	0	0	0	0	0	22	63.6	0.34	9.1	0.25	20	70.0	0.24	10.0	0.2
RSA	2	0	0	100	0.25	26	19.2	0.30	7.7	0.40	26	26.9	0.43	7.7	0.60
RSB	9	0	0	22.2	0.25	14	35.7	0.32	14.3	0.50	14	50.0	0.50	21.4	0.40

U: uplift; T: thaw settlement.

In conclusion, nowadays solifluction activity is very weak in Sierra Nevada. Despite having frost layers extending 7-8 months in the headwaters of the highest valleys (no permafrost regime), solifluction displacements reported in Sierra Nevada were really small, in all cases less than 1 cm year^{-1}. Water availability is a crucial factor controlling geomorphic instability in Sierra Nevada; in that sense, a higher water supply combined with warm temperatures determines a dense grass recover of the lobe surface which impedes mass wasting. However, more water in the ground also enhances solifluction during cold periods.

5- Chronostratigraphy of solifluction lobes

The existence of numerous solifluction lobes mostly inactive nowadays suggests that their formation must be related to different climate conditions. In general, solifluction chronologies have been carried out in two ways: establishing rates of advancement by dating the same buried organic horizon at different distances from the present front and by dating the different organic layers existing in the lobes, so that we determine the onset/offset timing of solifluction. We consider that the first method could be widely used in areas where solifluction does not reflect high intermittences but in places such as Sierra Nevada, where solifluction could be active one climatic favourable year and inactive for a long while, the second method should be more suitable. Moreover, the main goal of our research is to reconstruct not only solifluction activity but also palaeoenvironmental conditions; in this sense the second method is more useful for our purposes.

Sedimentological profiles of several lobes in both valleys reveal an alternation of soil horizons and solifluction deposits, emphasizing the sensitivity of periglacial processes in Sierra Nevada to climate variability during the Holocene. Table 5.1 resumes all the datings performed on samples extracted from organic units in solifluction lobes.

We could not apply the methodology carried out by Veit (1993) in the Alps, due to the lack of different types of organic horizons in Sierra Nevada. The high concentration of modern roots in most of the samples decide us no to date bulk sediment but to process pollen concentration in order to avoid possible modern contamination by recent plant fragments. Further datings should have been done on different fractions of the sampled units to assess the success of this method, but due to restricted budget limitations it could not be done. We present 16 radiocarbon datings that provide a tentative chronology of the solifluction/edaphic periods in the current periglacial belt of Sierra Nevada during the last millennia, although we admit that the small number of datings carried out in this research is not enough to control the precise timing of the solifluction processes. Sampled lobes were selected according to the internal sedimentary structure and to encompass the different kind of solifluction features described in these two valleys.

In chapter 5 of the Catalan text, we present eleven lobes from San Juan and six from Rio Seco, with the main morphometric characteristics, chronostratigraphy and soil properties of each of them. Results are discussed in chapter 7 of the English version.

6- Mountain lakes in Sierra Nevada

Sierra Nevada, at 37ºN in southern Iberian Peninsula, contains the highest lakes in Europe. In this massif lakes are related to a glacial origin, filling glacial depressions or being dammed by moraines. These lakes are located inside the cirques at altitudes between 2700 and 3100 m in the present periglacial belt, where vegetation cover is very sparse (<5%) and limited to the margins of the lakes. Lakes are highly oligotrophic and tend to be small and shallow (2-4 m depth)[2]. The fact that lakes are placed inside the cirques, in the headwaters of the glacial valleys with very small catchments, determines a homogeneous lithology composed mainly by schists, without carbonate rocks; in chapter 7 we also discuss the possibility that lake sediments contain a signal of aeolian input based on variations of the Ca content.

Figure 6.4 summarizes the main processes involved in lacustrine sedimentation in Sierra Nevada. Snow cover and frozen ground retain mass movements from late autumn to late spring, when snow melting and ice break-up of the lakes accelerate dynamic processes. Nowadays, permafrost is geographically very limited and only restricted to the northern highest cirques, but during cold periods in the Holocene might have played an important role in lake sedimentation. Gelifraction provides detrital material to the talus deposits which may also reach the lake. Streams transport fine-grained material and solifluction could represent a small sediment contribution into the lakes.

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[2] The local name *lagunas* (lagoons) also reflects their small dimensions.

Moreover, we should consider the extension of vegetation cover, soil development and aeolian input coming from surrounding areas during the Holocene. Finally, in the last few centuries human impact may have induced changes in the natural sedimentation pattern of these lakes.

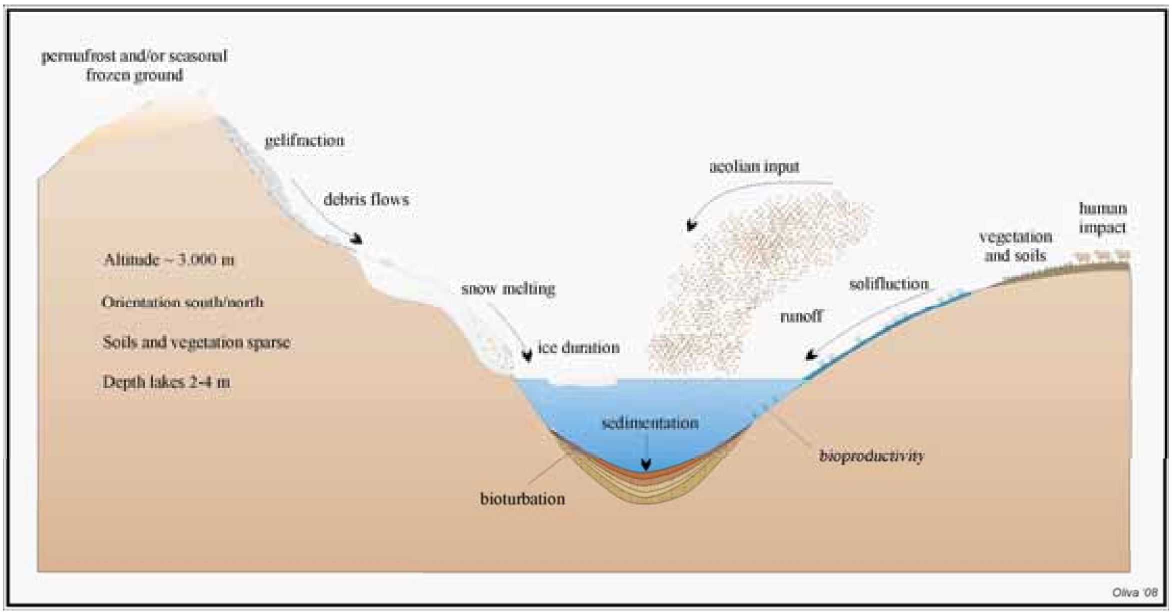

Figure 6.4. Variables involved in lake sedimentation in Sierra Nevada.

Table 6.1 synthesizes the topographic location of the studied lakes in Sierra Nevada and table 6.2 resumes the datings performed on sediments of the extracted cores. We sampled three lakes in the southern slope of the massif (Aguas Verdes, Rio Seco and Rio Seco lagoon) and one northern exposed (San Juan lagoon).

Lake sediments provide a chronology of slope instability in Sierra Nevada for the last 6 ky BP. We distinguish several phases of geomorphic activity characterized by increases in grain-size, low C_{org} contents, peaks in MS driven by maximums of Ti and Fe concentration and minimums of Ca/Ti. On the other hand, we also observe periods with a fine texture parallel to high C_{org} percentages, low MS values, maximums of Ca/Ti and minimums of Ti and Fe.

In chapter 6 we present the results from the seven cores analyzed at high resolution and in chapter 7 we propose an interpretation of the palaeoenvironmental significance deduced from these cores.

7- Reconstruction of Holocene alpine environments in Sierra Nevada

In the previous two chapters of the Catalan version of this thesis we presented individually the results related to solifluction lobes and mountain lakes in Sierra Nevada. The fact that both records are located at similar heights (2500 to 3000 m) at the headwaters of the westernmost valleys suggests that the geomorphic response inferred from lake sediments and solifluction lobes records to Holocene climate variability could be synchronous.

7.1 Environmental changes inferred from solifluction lobes

Solifluction lobes development in Sierra Nevada is a relatively recent geomorphic process, with seven active slope phases reported during the last 7 ky BP. In spite of two dated organic layers inserted in between solifluction deposits that correspond to the Lateglacial and the Early-Holocene, the rest of the lobes developed from the Mid-Holocene onwards. Nowadays, dynamic control of solifluction lobes states a very weak activity in the massif with annual displacement rates < 1 cm yr^{-1}. The existence of hundreds of lobes mostly inactive under the present climate context suggests that their origin must be related to other more favourable climate conditions.

Sedimentological profiles of more than thirty sampled lobes show a succession of edaphic layers alternated with solifluction beds, changes surely driven by climate variability: small climate fluctuations triggered or stopped solifluction activity during the Holocene. Colder and/or wetter phases would extend and postpone the melting period timing, prolong the seasonal frozen layer several weeks and imply more presence of late-lying snow patches, which are decisive to lengthen the runoff water time span and to maintain solifluction processes (Morin and Payette, 1988; Matthews *et al*., 2005). This delay would also shorten the vegetation growing season, reduce grass cover at this altitude and enhance solifluction during late spring and early summer.

On the other hand, warm conditions would favour edaphic processes. Depending on moisture availability, soils are more or less developed; warm and wet periods promote high organic structured soils (histosols) and warm but dry periods induce weak soil formation (regosols).

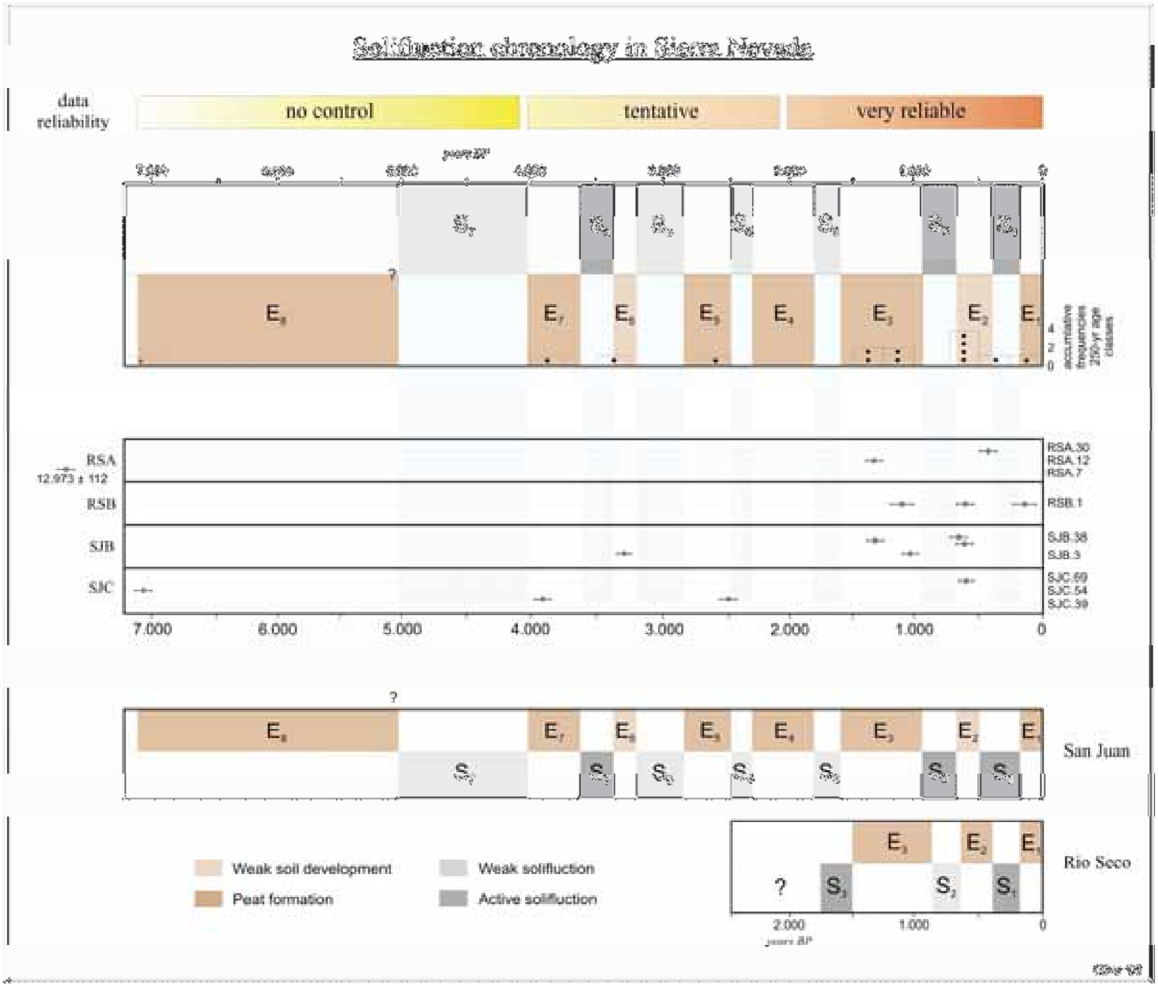

Figure 7.4. Datings of the organic layers in the studied lobes (figure middle), solifluction chronology in the massif (figure above) and in both valleys (figure below).

Figure 7.4 resumes solifluction/soil development chronology for both studied valleys. In the valley floor of the lowest area of San Juan, some solifluction lobes have originated during the Early-Mid Holocene, although most of the lobes of the highest part of this valley report a continuous solifluction chronology for the Mid-Late Holocene. If these periglacial sedimentary records in San Juan valley have developed during the last 7 ky BP, in Rio Seco lobes only extend over the last 2 ky BP. Nevertheless in San Juan, chronology from 7 to 4 ky BP is only orientative, between 4 to 2 ky BP is approximated and for the last 2 ky BP is reliable.

The aggradation of the lobe SJC.54 started during a solifluction phase previous to the buried soil dated 7.098 ± 60 years BP (figure 5.21), edaphic layer that corresponds to E_8. The structure of this lobe suggests another period favourable to soil development before 7,1 ky BP, but we can not precise the timing without more datings.

The existence of two AMS datings in lobe SJC.39 indicates different solifluction phases during the Mid-Late Holocene. In the lowest part of San Juan, according to lobes SJC.54 and SJC.39 (figure 5.17), soil formation was dominant from 7 to 5 ky BP, during the HWM (E_7), and the degradation of these warm conditions from 5 to 4 ky BP promoted solifluction activity (S_7). Between 4 to 3.6 years BP soil development (E_6) prevailed in San Juan prior to a new slope instability from 3.6 to 3.4 ky BP (S_6), which is reflected in a thick gravel deposit in unit SJB.3 (figure 5.3). In this lobe a regosol developed between 3.4 to 3.2 ky BP (E_5), but immediately after another solifluction pulse took place with sands mobilization (S_5).

The last three phases of active solifluction and soil development have a similar timing in San Juan and Rio Seco valleys. During the RWP and the MWP several lobes show evidence of soil formation (E_5-E_3), with thick organic layers in both valleys and peat growth in areas with larger water supply, only interrupted by brief and relative solifluction phases (S_4 and S_3). The LIA determined two solifluction advances in Sierra Nevada occurred between the XII and XIII centuries (S_2) and XVII to the first half of XIX (S_1), with regosol development during XIV to XVI centuries (E_2). Finally, the warming trend initiated since the last pulses of the LIA has extended vegetation cover and induced soil formation in the highest parts of the massif (E_1).

7.2 Environmental changes inferred from lake sediments

High mountain lakes in Sierra Nevada have not been glaciated since the LGM in the southern face and possibly since the Younger Dryas cold pulse in the northern cirques. Lake sediments can provide environmental information of the landscape evolution and palaeoecological changes during the last millennia in this massif.

We sent eight samples to be dated by AMS but only three of them show consistent results; resedimentation processes seem to be responsible for the incongruence of the other five datings in lakes with extremely low sedimentation rates (~1 cm/100 years). Moreover, we considered a continuous sedimentation rate from the datings obtained, which may also induce errors to the chronology. Thus, environmental evolution inferred from lake sediments provides a relative chronology of landscape changes and can not offer a precise timing for slope processes onset/offset in Sierra Nevada.

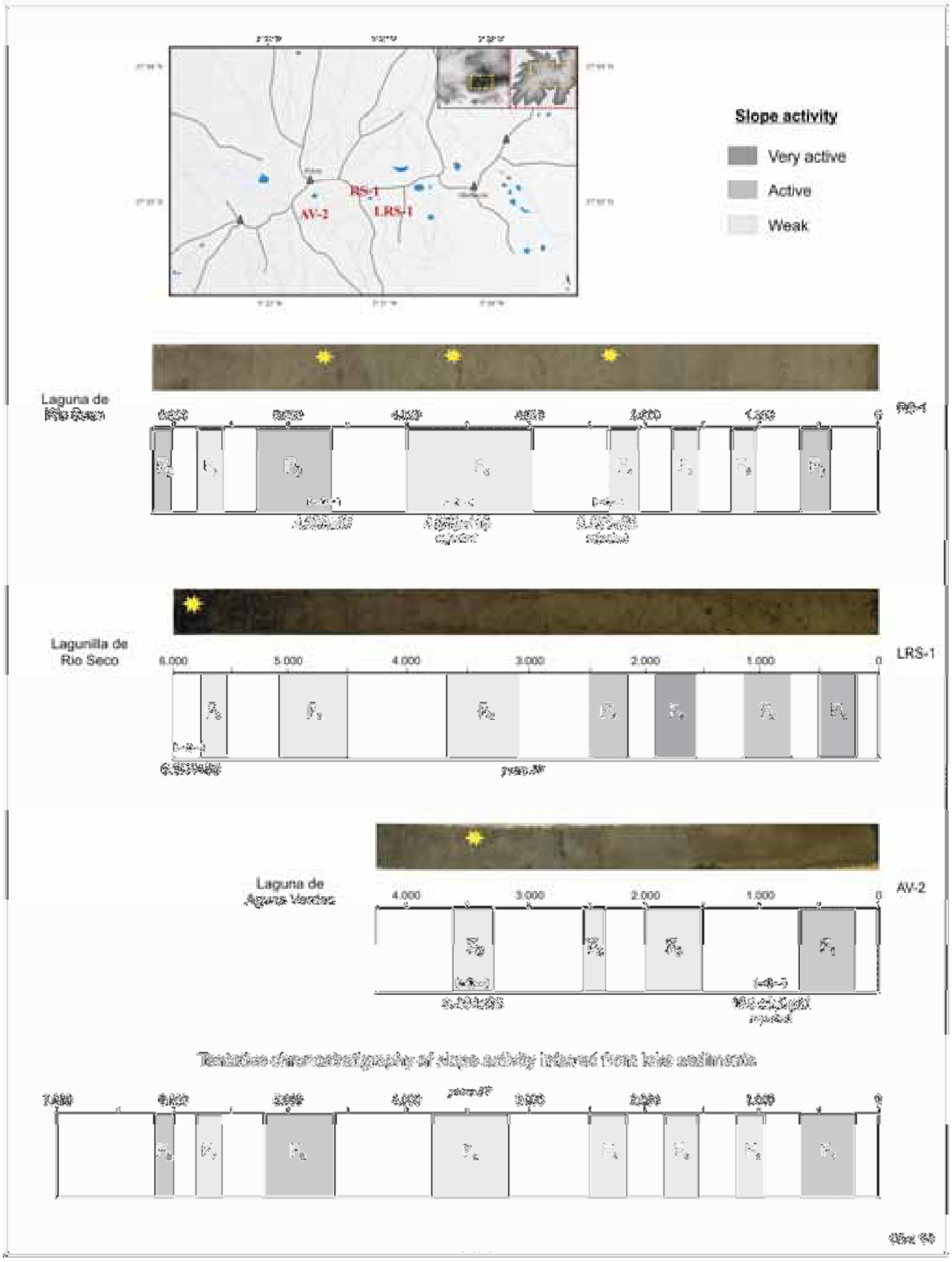

Figure 7.5.Geochronology of slope instability phases inferred from lake sediments.

Four lakes were sampled in this massif, three in the southern slope (Aguas Verdes, Rio Seco, Rio Seco lagoon) and only one northern exposed (San Juan lagoon). Figure 7.5 resumes those phases with dominant geomorphic processes in these valleys during the last 6 ky BP. Instability periods are characterized by a higher proportion of coarse sediments (sands), low organic matter contents and peaks in MS, Fe and Ti concentration with low Ca/Ti values; usually, C_{org} and C/N ratios define similar curves, suggesting the terrestrial origin of the organic matter present in the sediments of these oligotrophic lakes.

By contrast, during those periods in which prevail fine sediments (silt and clay), increase of the organic fraction, diminution of MS, Fe and Ti and higher Ca/Ti ratios, slopes tend to be more stable, with a dense vegetation cover developing around the lakes.

Moist climate conditions combined with lower temperatures were especially effective to trigger active slope periods in Sierra Nevada. A thicker snow mantle implied further snow patches in late spring and early summer providing a longer and larger runoff which mobilized and transported more material into the lakes; otherwise, warm and dry conditions did not promote slope processes, vegetation cover spread in the headwaters of the catchments and less material was deposited into the lakes. Warm temperatures combined with wetter conditions reinforced and expanded a dense grass recover and soil formation developed surrounding the lakes, which also increased their bioproductivity.

The tentative chronology derived from lake sediments suggests 8 active slope phases during the last 6 ky BP with an approximate timing of: 6.2?-6 (F_8), 5.8-5.6 (F_7), 5.3-4.6 (F_6), 3.7-3.1 (F_5), 2.5-2.2 (F_4), 1.8-1.6 (F_3), 1.2-0.9 (F_2) and 0.65-0.2 (F_1) ky BP.

The decrease in C_{org} in the three southern lakes since the Mid-Holocene reflects an increasing aridity trend that diminishes aquatic and terrestrial production in lake catchments. The progressive arid tendency initiated after the relatively moist HWP in southern Iberian Peninsula difficults vegetation cycle in the headwaters of the highest western cirques. The lower water runoff during the snow-free season tends to decrease sediment transfer and slope activity in southern valleys of Sierra Nevada and only permits a very scarce vegetation cover.

7.3 Matching terrestrial and lake records

Solifluction chronology provides a good resolution for the last 2 ky BP, covers roughly the last 4 ky BP and offers an estimated timing between 7 to 4 Ka BP. On the other hand, lake sediments propose a relative chronology for instability phases in the summits of the massif for the last 6 ky BP. The overlapping of both sedimentary archives permits to deduce if solifluction lobes and lake sediments report geomorphic activity during the same periods.

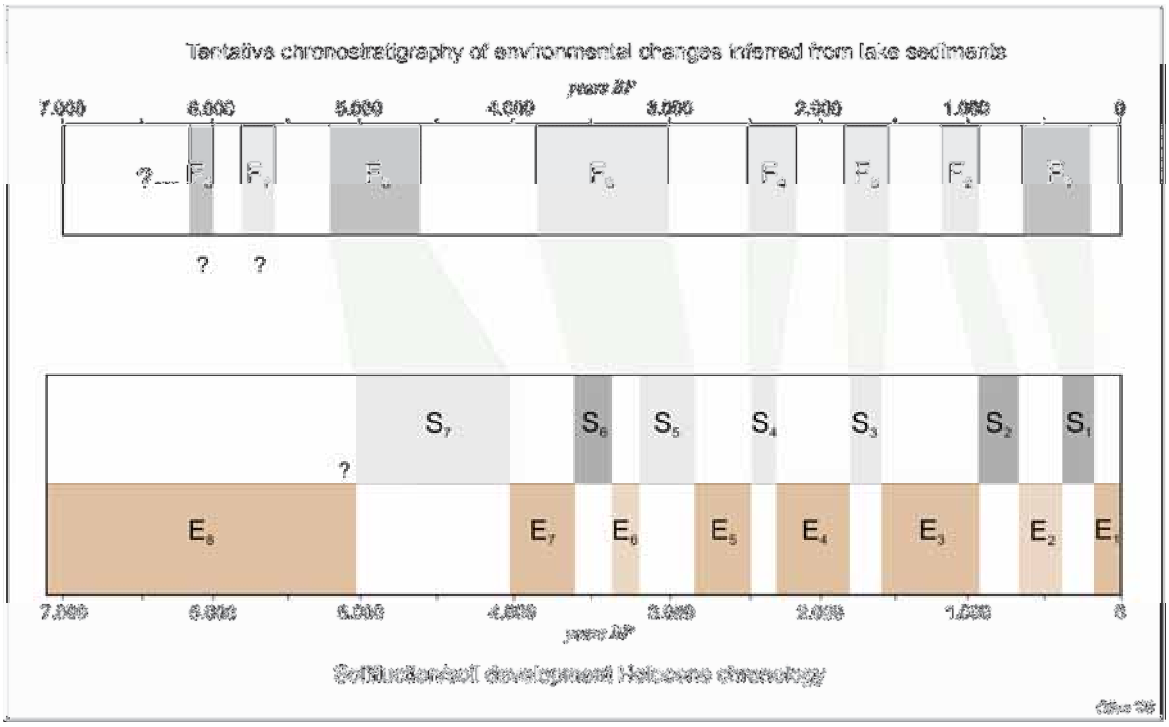

Figure 7.7. Matching solifluction and lake sediments records:
chronology of Holocene slope instability in Sierra Nevada.

Figure 7.7 highlights a clear synchrony between both records: periods with enhanced solifluction correlate with phases of higher coarse-grained input into the lakes. Colder and/or wetter conditions dominated during periods with intense slope instability in Sierra Nevada. Higher precipitations in winter/early spring combined with lower temperatures in late spring/summer postpone the melting season, determine more late-lying snow patches which provide a larger runoff in late spring and early summer and shorten the vegetation growing time, reducing grass cover and potentially enhancing slope mass movements. By contrast, warm periods in general favour soil formation and vegetation cover (more or less dense according to moisture availability), stop solifluction processes and sediment migration to lower areas in the highest western cirques.

7.4 Sensitivity of geomorphological processes in Sierra Nevada in relation to regional, hemispheric and global proxies

Solifluction lobes and lake sediments show evidences of vertical shifts of the periglacial belt in Sierra Nevada during the Holocene in the order of several hundreds of meters. The alpine/subnival ecotone has been defined as a very sensitive environment with rapid response to climate variability (Veit, 2002).

We compared our solifluction chronology in Sierra Nevada with the Holocene solifluction timing reported for the Austrian and Swiss Alps by Steinmann (1978), Gamper (1983) and Veit (1988). We must point out the very different solifluction chronologies among the three study areas in the Alps, with noticeable asynchronies that evidence the local component and the complexity of the diverse factors involved in solifluction dynamics, asserting the difficulties in establishing correlations with our records in Sierra Nevada. The spatial distribution and complexity of the Mediterranean peripheric ranges determines a wide suite of microclimates with different dynamic processes for similar regional climatic trends.

Comparing solifluction chronologies in the Alps with our research in Sierra Nevada, more than 2000 km far away, we observe that only those periods with climate extremes better defined have similar geomorphological responses (figure 7.8). In Sierra Nevada and in the Alps cold periods promote solifluction (e.g. Neoglacial, LIA) and warm periods induce soil formation (e.g. RWM, MWP).

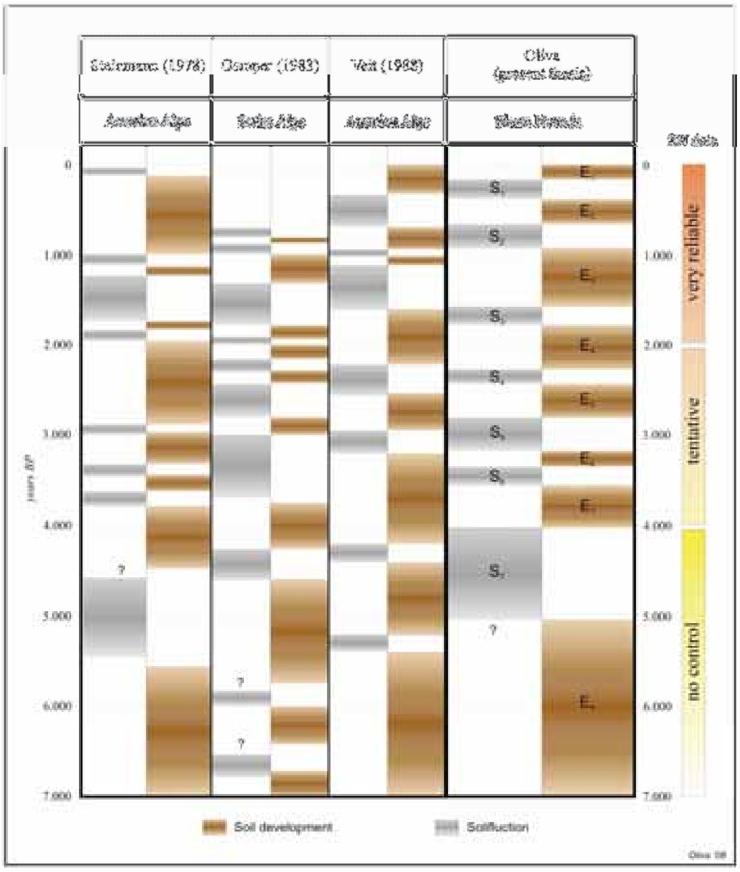

Figure 7.8. Comparison of Holocene chronology of solifluction/ edaphic processes in the Alps and Sierra Nevada.

In order to understand the different scale climate signals influencing the environmental conditions in our study area, we contrast our solifluction chronology with regional, hemispheric and global proxies (figure 7.9). Slope instability is dominant during cold periods and correlates with negative radiocarbon anomalies (Stuiver et al., 1997) and Bond cycles (Bond et al., 2001), whereas soil development is more effective in warm periods with positive radiocarbon anomalies (Stuiver et al., 1997) and arid phases in the western Mediterranean region (Jalut et al., 2000). Some of the society collapses that took place during the last millennia are also reflected in the studied sediments of Sierra Nevada; the Argaric collapse, for example, was caused by a combination of human activities and extreme arid conditions in SE Spain (Carrión et al., 2007) and correlates in the massif with a break of solifluction and an onset of weak soil development around 3.4 ky BP.

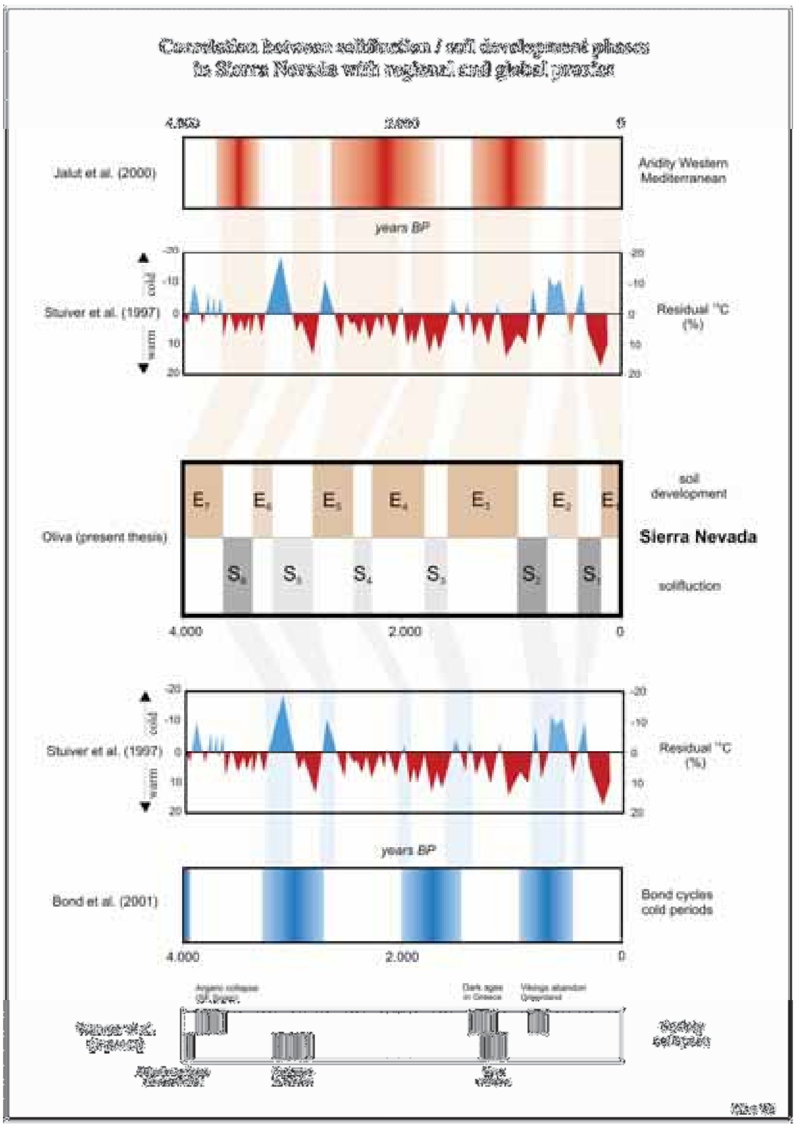

Figure 7.9. Chronology of slope instability in Sierra Nevada and different scale proxies.

8- Conclusions

During the last decades research has demonstrated a complex climate variability during the present interglacial, the Holocene. Our research in Sierra Nevada has proved a succession of environmental changes during the last millennia in this massif surely related to Holocene climate dynamics. Geomorphologic processes in Sierra Nevada react sensitively to small changes in temperature or moisture regimes, showing the proximity of these processes to their climate boundaries.

The marginal position of Sierra Nevada in southern Iberian Peninsula explains major landscape changes during the Holocene; the massif has been as a climate border in southernmost Europe. Small displacements of the General Circulation of the Atmosphere southwards determine the track of the westerlies towards lower latitudes than today, with higher precipitations and colder temperatures in Sierra Nevada; periglaciarism extended downvalleys, solifluction activated at altitudes of 2500 m and enhanced slope dynamics transferred more sediment onto the lakes. By contrast, the major persistence of the subtropical high-pressure belt determined warmer temperatures and lower moisture indexes: cold processes had to move upwards the valleys, grass recover became denser and slowed mass movements, reducing solifluction and sediment inputs into the lakes.

8.1 Distribution of solifluction lobes in Sierra Nevada

We have studied the distribution of solifluction lobes in the headwaters of two valleys in the western part of Sierra Nevada, next to the highest peaks in the Iberian Peninsula. We have mapped and classified according to morphometrical and pedological characteristics 156 lobes in San Juan valley and only 46 units in Rio Seco cirque. The difference in numbers results from the different amount of water supply and tectonically influenced valley topography; gently slopes between 5 and 15º (concentrate 90% of the lobes), northern orientations and altitudes ranging 2500 to 3000 m are the most favourable topography for solifluction lobes development (Oliva et al., *accepted*).

In general, a wide range of solifluction landforms can be observed in Sierra Nevada. All these solifluction features can be integrated into two main groups: peat-topped lobes and uncovered stone block-rich lobes (Oliva et al., 2008).

A topographical and geometrical analysis of all these landforms was carried out considering environmental variables (altitude, slope, orientation and vegetation cover) and morphological parameters of the solifluction features (length, width, front riser, typology and morphology). Lobes mostly show moderate dimensions: > 90% of them have a length and width < 8 m and 60% a riser height between 20 and 60 cm.

Crossing the different analyzed parameters we deduce that slope is the main factor controlling lobe geometry in Sierra Nevada, showing positive correlations with length ($r = 0.46$), riser front ($r = 0.34$) and width ($r = 0.23$). Orientation has no relationship with lobe morphology and vegetation cover is mostly determined by altitude ($r = -0.27$) and slope ($r = -0.17$): lobes tend to be larger and less vegetated when increasing altitude and steepness. By contrast, moderate inclinations allow a slower drainage, higher infiltration and permit developing of edaphic processes and vegetal cover.

Evidences of human traces are widely found in the *borreguiles* areas (human induced-channels, microalluvial fans, new pseudo-lobes formation), but spatial and topographical analysis of these wetlands show a natural trend in their distribution: they are mainly developed on northern valleys, gentle slopes and altitudes between 2400 and 2800 m.

8.2 Thermal and dynamic control of solifluction lobes

Solifluction dynamics in Sierra Nevada is determined by a complex interaction between environmental factors (slope, vegetation cover, texture) and other parameters highly variable at annual scale (ground thermal regime, length and thickness of the snow cover, water supply). Interdependant feed-back mechanisms among all these variables make difficult to understand the key factors involved in present and past solifluction processes, although monitoring control performed on lobes with different emplacements suggest today’s favourable environmental conditions for solifluction displacements (figure 8.3).

Nowadays, climate conditions are not appropriate to active solifluction in Sierra Nevada. Dynamic monitoring carried out in lobes of San Juan and Rio Seco valleys from August 2005 to August 2008 evidences very small solifluction displacements. Only 30% of the stakes installed in lobes of Rio Seco registered movements of ~0.3 cm yr^{-1} and 80% of the stakes in San Juan showed annual rates of ~0.5 cm yr^{-1}. The northern orientation of San

Juan valley explains relatively higher solifluction rates: solifluction is enhanced because of more late-lying snow-patches and a deeper seasonal frost layer.

These small displacements are similar to the vertical expulsion rates observed in both valleys due to frost heave, in all cases < 0.5 cm yr^{-1}. We should also point out that 4-21% of the stakes reported vertical measurements lower than previous years, which could be caused by thaw settlement and/or vegetation growth during a period favourable for soil formation.

Thermal control was performed in two lobes, south and north exposed, from September 2006 to August 2008. In Rio Seco, a lobe located at 3005 m showed a seasonal frost layer extending from November to beginning of June reaching 70 cm thickness. In San Juan the lobe was placed at 2817 m and monitoring control took place only between August 2007 to August 2008, detecting a deeper frozen layer down to 100 cm, with a freeze-thaw timing similar to the one in Rio Seco. No movement was detected in the Rio Seco lobe and a mean rate of 0.5 cm yr^{-1} was measured in San Juan unit.

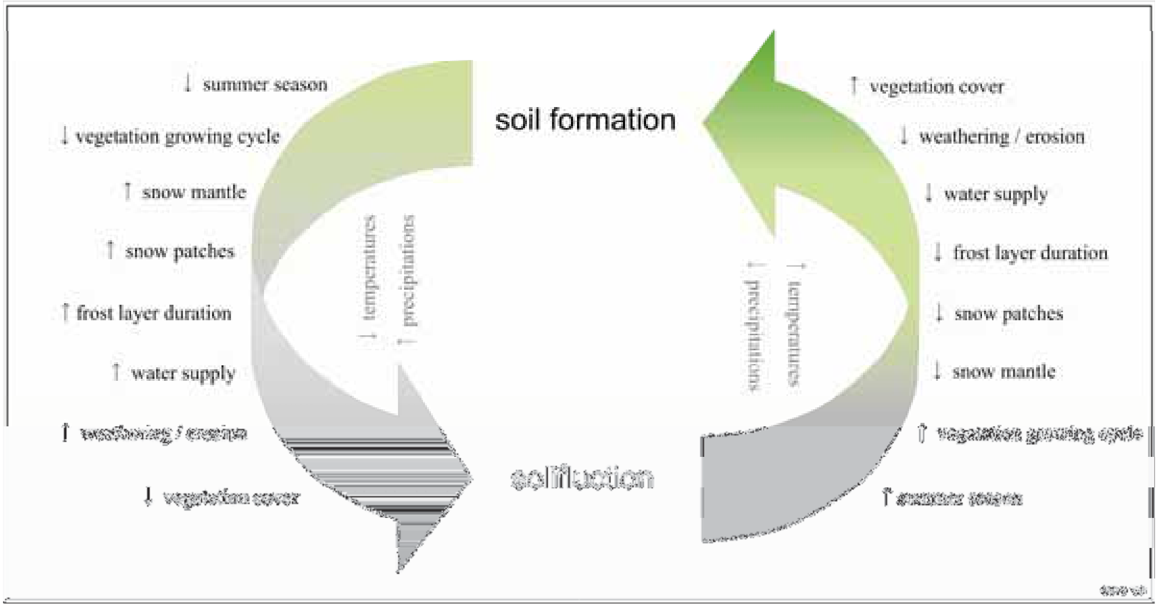

Figure 8.3. Sketch of the processes controlling solifluction-soil formation.

Late spring is the only period along the year when solifluction can take place in Sierra Nevada. Snow melting provides high water availability and thawing of the first decimetres of the surface, but there still exists a deep frozen layer which may facilitate small slips. Moreover, as the thaw front progresses freeze-thaw cycles can translocate individual particles; this process is more effective in spring than in autumn[3], when ground water availability is restricted and permits a deeper frost penetration into the ground. Colder and/or wetter phases would extend and postpone the melting period, prolong the seasonal frozen layer several weeks and imply more presence of late-lying snow patches, which are decisive to lengthen the runoff water period and to maintain solifluction processes (Morin and Payette, 1988; Matthews *et al*., 2005). This delay would also shorten the vegetation growing season, reducing grass cover at this altitude and enhancing solifluction processes during late spring and early summer (Oliva et al, *accepted*).

8.3 Holocene solifluction activity in Sierra Nevada

The very weak activity pattern of hundreds of solifluction lobes in the two studied valleys suggests that they must have developed in other more favourable climate conditions. Water availability controls both vegetation cover and slope processes. In fact, currently water supply determines the grass cover in gentle valley floors, but it is also decisive to provide water for the small solifluction displacements detected during the monitored period. Thermal regime plays a decisive role to activate solifluction or soil formation with similar moisture regimes: lower temperatures than today promote solifluction and similar or higher temperatures soil development.

Lobes developed in places with favourable topography and high water supply. Although nowadays lobes are mostly covered by vegetation, which is also a physical impediment for mass wasting, during active geomorphic periods lobes had a sparse vegetation cover on their surface that enhanced solifluction. Gradually, as temperatures rose, grass recover became denser and inhibit solifluction displacements. Vegetation cover of the lobes is also affected by other feed-back mechanisms: less late-lying snow patches, thinner and shorter frost layers, lower water supply during the melting season, lower albedo effect for snow-free surfaces, etc), contributing to slow down periglacial processes in the massif.

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[3] For example, during the period 2006-2007, we detected eight consecutive days at 10 cm depth with freeze-thaw cycles in spring (5-12th May) in contrast to only two cycles at the same depth in autumn (23-24th November).

More than 30 analyzed sedimentological profiles from solifluction lobes in San Juan and Rio Seco valleys reveal an alternation of solifluction/edaphic cycles during the Holocene, with nine different geomorphic phases in the highest western cirques of Sierra Nevada. In San Juan valley there are several generations of solifluction lobes covering the last 7 ky BP, while in Rio Seco lobes developed more recently, during the last 2 ky BP.

Figure 8.4 shows that the oldest lobes are distributed in the lowest areas of San Juan, with solifluction deposits corresponding to the Early-Mid Holocene. According to the oldest soil layers dated, lobes placed at higher elevations developed more recently, between the Mid-Late Holocene. This pattern can reflect the arid trend dominating in Sierra Nevada since the Mid Holocene with solifluction only active at higher elevations where there were more late-lying snow patches, but it can also indicate that the inactivity of the solifluction in the lower areas preserve the oldest deposits while those located at higher altitudes could have been eroded.

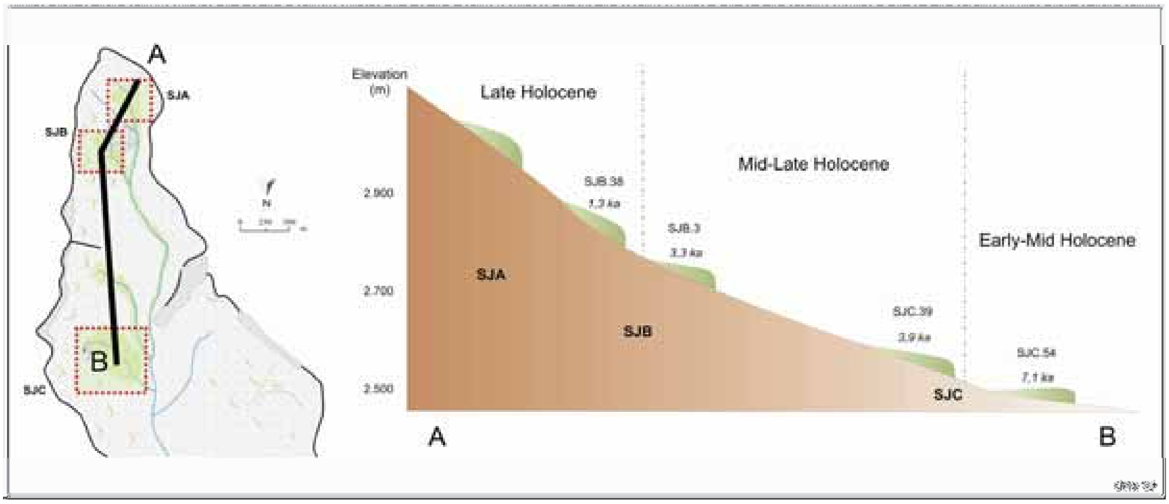

Figure 8.4. Oldest soil layers developed over solifluction deposits in San Juan valley.

The existence of thick slope deposits corresponding to the LIA at altitudes below 2500 m, when solifluction is currently very weak between 2900-3000 m, suggests colder and wetter conditions dominating during this period. Several researchers reconstructed the thermal increase in Iberian mountains since the coldest pulses of the LIA in a range between 0.8-1.7ºC (Martínez-Cortizas et al., 1999; López Moreno, 2000; González Trueba et al., 2008). Considering the mean temperature gradient of 0.65ºC/100 m, temperature by itself can not explain the altitudinal difference ~500 m between geomorphological processes dominating during the LIA and today (figure 8.5), precipitation must have played a determining role to activate solifluction at altitudes of 2470 m during the phase S_1 (Oliva, 2008). The historical reconstruction of precipitation in Andalusia since 1500 by Rodrigo et al. (1999) indicates that the wettest and coldest phase of the LIA corresponds to the period between 1590 and 1650, possibly related to more recurring and persistent negative phases of the NAO-WeMO teleconnection patterns (Oliva et al., 2006), which are very favourable conditions for solifluction activity.

The observed geomorphological pattern from solifluction records in relation to climate variability suggests that colder and/or wetter periods are favourable for solifluction movements, whereas warm phases induce extension of grass cover and soil formation in valley floors above 2500 m in Sierra Nevada. Cold and/or wet periods postpone snow melting, prolong the existence of the seasonal frost layer for several weeks, increase late-lying snow patches and lengthen the water runoff period. These conditions also shorten the vegetation growing period, implying slopes with scarcer vegetation cover and enhanced geomorphic processes. The combination of larger water supply with a frozen layer underneath would be favourable in late spring and early summer to trigger active solifluction processes in this massif. On the other hand, warmer periods with similar moisture conditions would induce soil formation.

The seasonality of the climate variability is certainly decisive to understand the geomorphologic processes dominating in the summits of Sierra Nevada. Solifluction is enhanced during periods with increased precipitation in winter and early spring that imply more snow and a longer water runoff in late spring and early summer. Otherwise, edaphic processes are more effective when significant precipitations (either in winter or summer) are combined with warm temperatures in late spring and summer. Higher temperatures than present do not seem to promote solifluction unless being accompanied by very increased precipitations in winter and early spring (figure 8.6).

In the lowest study area in San Juan (SJC), we found the oldest solifluction deposits that correspond to the Early-Mid Holocene. In this valley, between 2500 and 2800 m, several solifluction pulses took place during the Mid-Late Holocene. San Juan and Rio Seco valleys show a similar solifluction chronology within the Late Holocene.

The most intense solifluction periods in Sierra Nevada correspond to the Neoglacial period (S_6: 3.6-3.4 ky BP) and the LIA (S_2 and S_1: 850-700 and 400-150 years BP). Other relative solifluction advances with minor slope activity occurred between 5-4 (S_7), 3-2.8 (S_5), 2.5-2.3 (S_4), 1.8-1.6 ky BP (S_3).

By contrast, edaphic processes evolve preferably during warm periods; according to water availability in the ground, soils are more or less developed. Dry periods mostly favour regosol formation whereas wet promote well structured histosols. Regosols only developed between 3.4-3.2 ky BP (E_6) and 700-400 years BP (E_2). By contrast, several periods during the Holocene were suitable for peat formation: 8-7.6 (E_9), 7-5 (E_8), 4-3.6 (E_7), 2.8-2.5 (E_5), 2.3-1.8 ky BP (E_4), 1600-850 (E_2) and 150 years BP onwards (E_1).

8.4 Slope dynamics inferred from lake sediments and correlation with solifluction lobes chronology

Sierra Nevada holds the highest lakes in Europe, all of them related to a glacial origin. Four lakes were cored in Sierra Nevada, three of them southern exposed (Aguas Verdes, Rio Seco and Rio Seco lagoon) and only one with northern orientation (San Juan lagoon).

Sedimentological properties of these cores assert evidences of different phases of coarse inputs into the lakes, with low organic matter proportion and high mineral contents. These pulses correspond to geomorphic periods with enhanced slope instability, interfingered in phases with minor sediment transfer onto the lakes. These relative stable periods show a fine grain size texture with less mineral sediments and increases in the organic fraction. The similar evolution of the C/N ratio and C_{org} contents reflects the low productivity of these oligotrophic lakes and the terrestrial origin of the organic matter present in their sediments. Both proxies also confirm a general pattern characterized in Sierra Nevada by an aridity trend since the HWP, when the headwaters of the highest catchments stored a denser vegetation cover.

Despite the relative chronology of environmental changes inferred from lake sediments, due to the small number of datings and resedimentation processes in lakes with extremely low sedimentation rates, several geomorphic periods were determined for the last 6 ky BP. Our relative chronostratigraphy of active slope phases derived from the analyzed cores matches reasonably well with the solifluction chronology presented in section 7.4 (figure 7.7). Periods with high mineral input into the lakes and low vegetation cover in the headwaters of the highest cirques coincide with phases of solifluction activity. By contrast, during those periods with less mineral material being deposited into the lakes, edaphic processes were dominant in favourable topographical emplacements at high altitudes, a dense vegetation cover expanded surrounding the lakes and a patchy and sparse grass vegetation recover could also spread over the gentle slopes covered by debris.

8.5 Sensitivity of geomorphological processes in Sierra Nevada in relation to Holocene palaeoclimatic evolution

The numerous sedimentological changes inferred from terrestrial (solifluction lobes) and aquatic (lacustrine) records suggest the proximity of geomorphological processes in the massif of their climate boundaries and the small climate range necessary to carry environmental changes in the summits of Sierra Nevada.

Holocene climate variability drove remarkable landscape changes in the massif, heightened due to the emplacement of Sierra Nevada at 37ºN in southwestern Europe and, therefore, the different crossing influences in this region: geographical (between Europe and Africa), maritime (between the Atlantic Ocean and the Mediterranean Sea), climatic (between the subtropical high-pressure belt and the mid-latitude westerlies). The enhanced vertical gradients in such an alpine mountain area reinforce the regional climate trend: small changes in the General Circulation of the Atmosphere in the North Atlantic basin determined the geomorphological processes dominating in Sierra Nevada.

Figure 8.6 resumes the most favourable climate conditions for solifluction, slope instability and edaphic processes in Sierra Nevada. Solifluction and slope dynamics are favoured by low temperatures in summer and substantial snow precipitations in winter, with a decisive role of late-lying snow patches; depending on the range and persistence of this wet cooling trend, glacial conditions and permafrost extension can also return in the highest northern cirques (e.g. LIA). We consider that a weak slope activity could also take place associated with shifts in moisture regimes.

Soil development is enhanced with high precipitations (both in summer and winter) and warm summer temperatures. After a solifluction period, the thermal raise combined with a relative increase in moisture availability induces an incipient soil formation (regosols) and if this climate trend continues well-structured soils can develop (histosols).

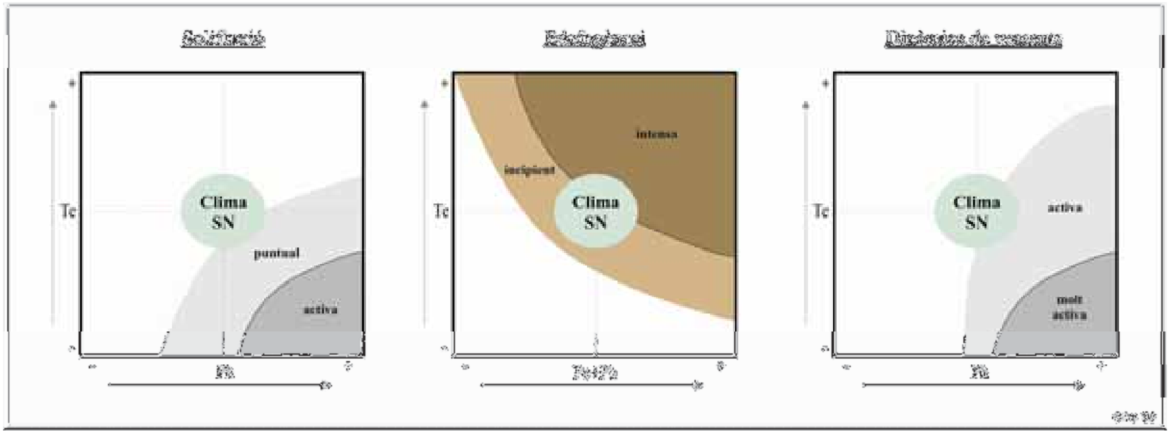

Figure 8.6. Theoretical model of climate conditions appropriate for solifluction, soil formation and slope dynamics in Sierra Nevada (Ts: summer temperature; Ps: summer precipitation; Pw: winter precipitation).

Geomorphological processes in Sierra Nevada respond to variables driven by overlapping different scale climate signals:

- **Global**

  Cold phases, reflected by positive radiocarbon anomalies (Stuiver et al., 1997) coincide with solifluction and slope activity periods, whereas warm stages, driven by negative radiocarbon anomalies, favour soil formation, spread vegetation cover at high altitudes and slow down mass movements.

- **Hemispheric**

  The Greenland ice sheet has played a decisive role since the last deglaciation, ruling the atmospheric circulation in the North Atlantic region with displacements, weakening and deepening phases of the dominant high-pressure or low-pressure systems which affect directly the Iberian Peninsula and, thus, Sierra Nevada. We assert a relative synchrony between periods with more recurring icebergs discharge in the North Atlantic basin (Bond et al., 2001) and phases with slope instability in Sierra Nevada.

- **Regional**

The Iberian Peninsula has been defined as a very sensitive environment to Holocene climate variability (Esteban Amat, 1995; Martínez-Cortizas et al., 1999; Jalut et al., 2000; Ortiz et al., 2004; Gil García et al., 2006; Carrión et al., 2007). Contrasting our records with proxies of neighbouring areas (Alps, Atlas range, Western Mediterranean), we can not report a synchronous response of geomorphological processes in Sierra Nevada with all of them. There is a light correlation between wet periods in the Western Mediterranean (Jalut et al. 2000), glacial advance in the Alps (Hormes et al., 2006) and phases of enhanced instability in Sierra Nevada. Solifluction prevailed in Sierra Nevada during the Neoglacial period, which coincides with a period of maximum precipitation in northern Africa (Cheddadi et al., 1998) and glaciers advance after several millennia retreating during the HWP (Hormes et al., 2006). In general, aridity phases in the Western Mediterranean region match reasonably well with periods of geomorphic stability and weak soil formation in Sierra Nevada parallel to glacial retreats in the Alps (Hormes et al., 2006).

- **Local**

The circummediterranean relief imposes a complex spatial and microclimatic distribution in southern Europe which determines different environmental responses in European alpine ranges for regional scale climate trends. Different methods were used to establish periods with solifluction activity in the three previous chronologies determined for the Alps (Steinman, 1978; Gamper, 1983; Veit, 1988), showing very different timings among them despite having similar regional climate signals. The comparison of our records in Sierra Nevada with those obtained in the Alps shows evidence of how difficult is to correlate synchronous geomorphic patterns: only periods with climate extremes better defined have similar geomorphological responses (figure 7.8). In Sierra Nevada, as in the Alps, cold periods promote solifluction (e.g. Neoglacial, LIA) and warm periods induce soil formation (e.g. RWM, MWP).

8.6 Holocene alpine environments in Sierra Nevada

Solifluction lobes and mountain lakes prove a complex sequence of environmental changes in the headwaters of the highest glacial cirques of Sierra Nevada. Table 8.2 resumes the chronology, paleoclimatic and palaeoenvironmental conditions dominating in the massif for the last 2 ky BP.

The inexistence of fossil tree or bushy fragments in the studied natural archives suggests that Holocene climate conditions have not permitted the forest expansion to the study area at altitudes over 2500 m. At least for the last 7 ky BP, the timberline have not exceeded this level, which situates the maximum thermal increase in about ~2-2,5ºC respect today's mean annual temperature.

Solifluction records also indicate that the LIA has been the wettest and coldest period during the Mid-Late Holocene, with the most rigorous climate conditions from 1590 to 1650 (Rodrigo et al., 1999). In southern Iberian Peninsula this cold pulse is prior to the MM (1675-1715), with a temperature fall ranging between 0.8 to 1.7ºC with respect to the present values (Martínez-Cortizas et al., 1999; López Moreno, 2000; González Trueba et al., 2008).

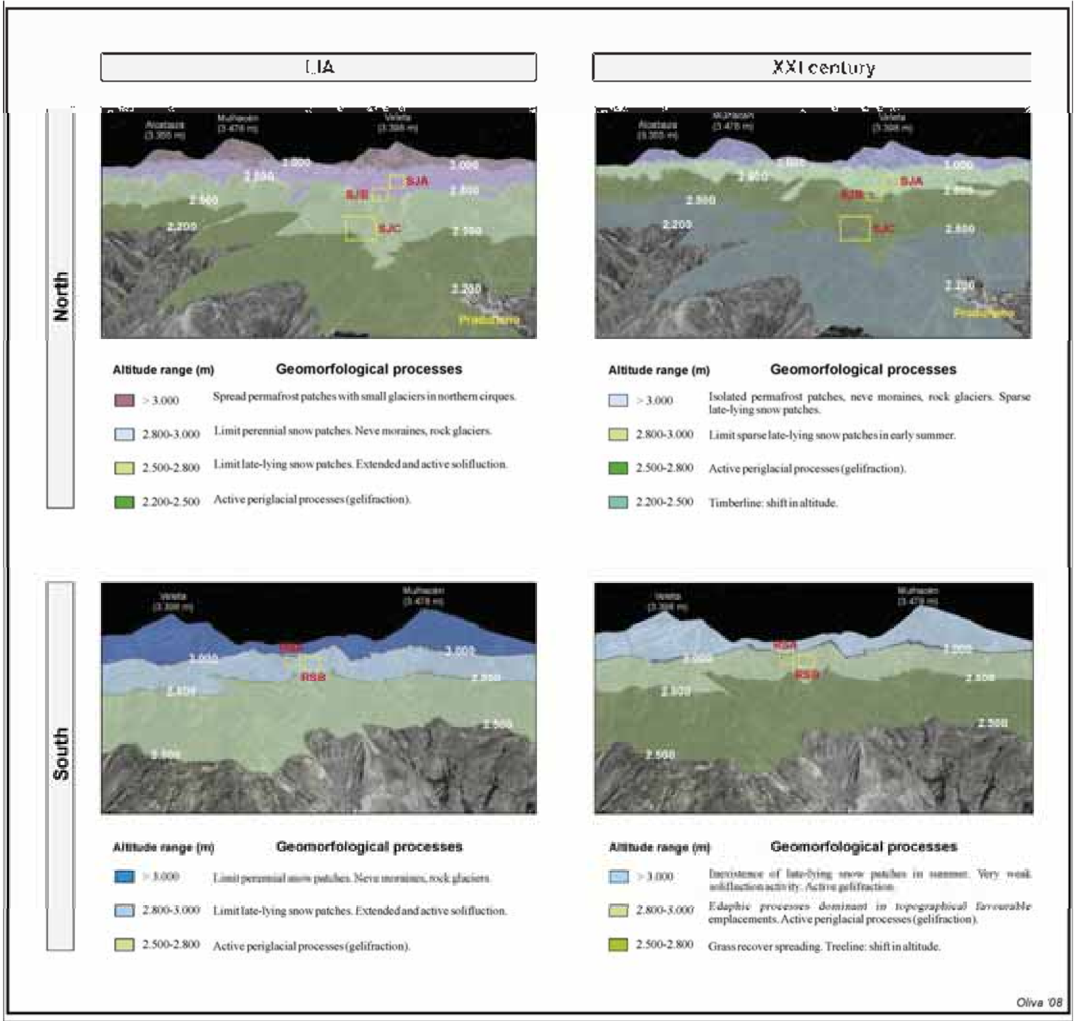

Figure 8.5. Altitudinal changes of dominant geomorphological processes during the LIA and nowadays in northern and southern slopes of the massif.

Therefore, the thermal range that has driven Holocene palaeoecological changes in Sierra Nevada in altitudes between 2500 and 3000 m is estimated around ±2ºC, far away the 4-5ºC mean temperature decay reported for the LGM (CLIMAP, 1981), that kept the massif under glacial conditions, but enough to explain the dominance of periglacial geomorphological processes in the summits of Sierra Nevada during the Holocene.

Thermal variability has shifted vertically the periglacial belt in the massif. During cold and wet periods, our study area was located in the nival ecotone where the scarce vegetation cover enhances erosion and mineral mobilization. By contrast, during warm periods, the nival ecotone moved upwards and our study area was affected by typical processes of the subnival ecotone: soil development was favoured in gentle topographical places with high water availability and the previous sparse vegetation cover became denser, reducing mass wasting effectiveness.

Figure 8.5 exemplifies these vertical shifts by comparing the geomorphological processes dominating during a cold period (LIA) with those prevailing during the present warm phase (XXI century).

Figure 8.7 shows the clear arid trend initiated around ~4-5 ky BP inferred from lake sediments in Sierra Nevada parallel to the same pattern observed in northern Africa and southeastern Spain since the HWP (Gasse, 2000; Burjachs et al., 2007). Previously, climate conditions were favourable for a rather higher vegetation cover than present in the headwaters of Rio Seco and San Juan valleys with more aeolian input of allochthonous carbonates into the high lakes. These conditions suggest a more recurring trajectory of the low-pressure systems over southern latitudes, entering across the Gulf of Cadiz, which explains increased precipitations and high Ca aeolian inputs due to the associated south-southwestern winds coming from the Sahara desert.

Table 8.2. Sketch resume of palaeoclimate and palaeoenvironmental conditions derived from research on solifluction lobes and mountain lakes in Sierra Nevada.

PHASES OF SLOPE DYNAMICS/GEOMORPHIC STABILITY, PALAEOECOLOGY AND CLIMATE CONDITIONS INFERRED FROM SOLIFLUCTION LOBES AND MOUNTAIN LAKES IN SIERRA NEVADA						
ky cal BP	**Sedimentary records**				**Climate conditions**	**Palaeoenvironmental reconstruction**
	Solifluction lobes		**Mountain lakes**			
	Solifluction	**Soil formation**	**Activity**	**Stability**		
1,8-1,6	**S_3:** ↑		**F_3:** ↑		~↑ P, ~↓ T	~↑ erosion / ~↑ detrital input, solifluction, ↓ vegetation cover
1,6-0,85		**E_3:** ↑ (histosol)		stability	↓↓ P, ↑↑ T, aridity	↓↓ erosion, ↑↑ lake productivity, geomorphic stability,↑ vegetation cover
850-700	**S_2:** ↑↑		**F_2:** ↑		↑ P, ↓ T	↑ erosion / ↑ detrital input, solifluction, ↓ vegetation cover
700-400		**E_2:** ~↑ (regosol)		stability	↓ P, ~↑ T	↓↓ erosion, ↑ lake productivity, geomorphic stability,↑ vegetation cover
400-150	**S_1:** ↑↑		**F_1:** ↑↑		↑↑ P, ↓↓ T	↑↑ erosion / ↑↑ detrital input, solifluction, ↓ vegetation cover
150-s. XXI		**E_1:** ↑ (histosol)		stability	~↓ P, ↑↑ T	↓↓ erosion, ↑↑ lake productivity, geomorphic stability,↑ vegetation cover human impact, transhumance

S: solifluction phase; E: soil formation phase; F: slope instability phase
P: precipitations; T: temperatures
~ stability; ~↑ weak increase; ↑ increase; ↑↑ substantial increase; ~↓ weak decrease; ↓ decrease; ↓↓ substantial decrease

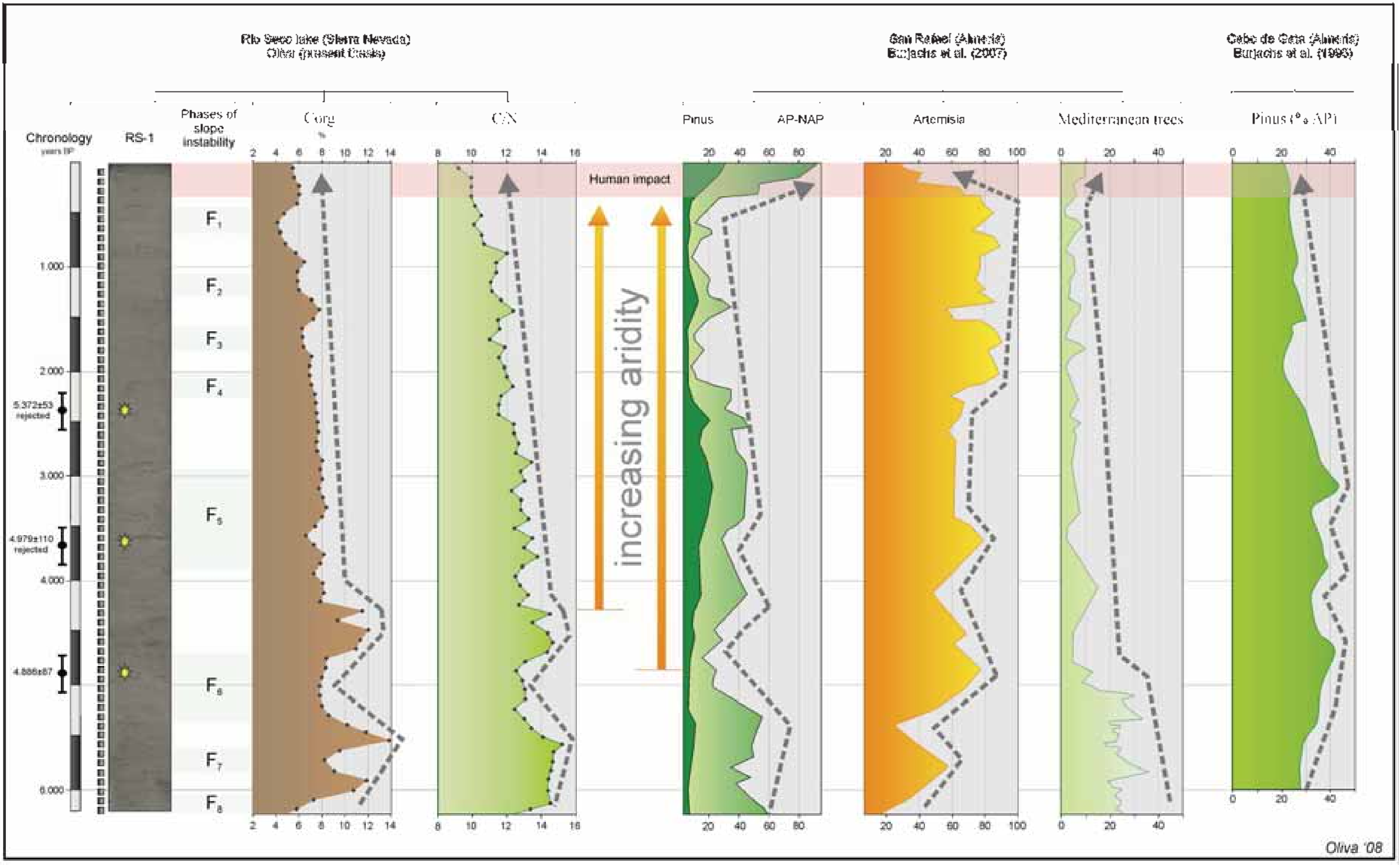

Figure 8.7. Correlations between two pollen diagrams from the southeastern corner of the Iberian Peninsula (Burjachs et al., 1996, 2007) and our lake records in Sierra Nevada. From the Mid Holocene (4-5 ka BP) onwards, both records detect a clear arid trend.

Until the Late Holocene, conditions were more suitable to higher vegetation cover over the headwaters of the southern cirques, which in turns made more difficult solifluction movements. In effect, according to our findings, solifluction activity in Rio Seco started during the last 1500-2000 years BP: we have no evidences of previous solifluction processes during the Holocene. The existence of a G0 soil layer dated 12.973 ± 112 years BP suggests that solifluction processes prevailed during the Lateglacial cold pulses but stopped during the Early to Mid Holocene, with no sedimentological records of mass wasting activity in Rio Seco before the last two millennia.

The increasing climate variability of the last millennia in southern Iberian Peninsula is reflected in the southern slope of Sierra Nevada in three cycles of alternated solifluction and soil formation phases. The southern exposition of Rio Seco cirque, with extremely low vegetated hillsides, is crucial to explain a relative major geomorphic stability in contrast to northern slopes, as in San Juan valley, where dynamism was enhanced due to more water availability: increased slope instability is reported both in solifluction lobes and glacial lakes.

During cold and wet periods, a longer persistence of snow patches in northern valleys turned on feed-back mechanisms that played a decisive role in Holocene landscape changes (providing more water supply, prolonging the frozen ground, shortening the vegetation growing season, etc), crucial to trigger slope instability in the massif, entailing slopes with scarcer vegetation cover and activating solifluction. Depending on temperature and moisture conditions, this pattern could also favour the existence of small glaciers in the highest northern cirques. The reinforced periglacial activity made also more efficient gelifraction which provided further material to be mobilized to valley floors by solifluction when snow cover melted.

On the other hand, warmer periods tend to slow mass wasting and induce soil formation: during arid phases poor developed soils prevailed (regosols) and in those periods with wetter conditions highly organic soils formed (histosols).