POST-LITTLE ICE AGE PARAGLACIAL PROCESSES AND LANDFORMS IN IBERIAN HIGH MOUNTAINS

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Abstract

Three Iberian mountain ranges encompassed glaciers during the Little Ice Age (LIA): the Pyrenees, Cantabrian Mountains and Sierra Nevada. The gradual warming trend initiated during the second half of the XIX century promoted the progressive shrinking of these glaciers, which completely melted during the first half of the 20th century in the Cantabrian Mountains and Sierra Nevada and reduced by 80% of their LIA extent in the Pyrenees. Currently, the formerly glaciated environments are located within the periglacial belt and still present to a major or lesser degree signs of paraglacial activity. LIA moraines are devoid of vegetation and composed of highly unstable sediments that are being intensely mobilized by slope processes. Inside the moraines, different landforms and processes generated following LIA glacial retreat have generated: (i) buried ice trapped within rock debris supplied from the cirque walls, which has also generated rock glaciers and protalus lobes; (ii) semi-permanent snow fields distributed above the ice-patches remnants of the LIA glaciers, and (iii) small periglacial features such as frost mounds, sorted circles and solifluction landforms generated by processes such as solifluction and cryoturbation. Present-day morphodynamics is mostly related to seasonal frost conditions, though patches of permafrost have formed in some areas in contact with the buried ice. This 'geomorphic permafrost' is undergoing a process of degradation since it is not balanced with present-day climate conditions. This is reflected in the occurrence of multiple collapses and subsidences of the debris cover where the frozen bodies sit. In the highest areas of the Pyrenees there is a permafrost belt next to the small glaciated environments in the highest massifs. Finally, we propose a model for paraglacial activity in Iberian mountain ranges and compare it to other mid-latitude mountain environments as well as to other past deglaciation stages.

Key words: Little Ice Age, paraglacial processes, recent warming, Iberian Peninsula.

1. Introduction

The end of the Little Ice Age (LIA) led to accelerated glacier shrinkage in many mid-latitude high mountain areas promoting a readjustment of geomorphological and hydrological processes in these deglaciated environments. The transition period between the glacier occupation and its disappearance implied the substitution of glacial by periglacial processes that now characterize the highest lands of these mountain ranges. These new ice-free areas following LIA glacial retreat are framed within the paraglacial landsystem (Ballantyne, 2002). The evolution from glacial to periglacial conditions led some authors to use the term "paraperiglacial" as a stage when "Earth-surface processes, sediment accumulations, landforms, landsystems and landscapes are directly conditioned by permafrost thaw-degradation" (Mercier et al., 2008).

The complex geomorphic and geoecological interactions occurring in paraglacial landsystems are very sensitive to climate variability at decadal or centennial scales as well as to the rapidly changing environments in mid-latitude high mountain regions. This is the case of the three mountain ranges encompassing glaciers during the LIA in the Iberian Peninsula (Sierra Nevada, Pyrenees and the Cantabrian Mountains). The formerly glaciated areas in Iberian mountains during the LIA are currently experiencing a paraglacial readjustment due to glacier retreat, with very active periglacial conditions, whereas outside the LIA moraines paraperiglacial dynamics prevail, namely on the slopes and walls surrounding LIA glaciers (Mercier et al., 2008).

The LIA constitutes one of the coldest stages of the Holocene favouring the expansion of glaciers in most of the highest mountain ranges on Earth (Bradley & Jones, 1992). This period spans from the Medieval Climate Anomaly to the recent warming climate started at the end of the LIA (Grove, 2004; Matthews & Briffa, 2005). In the case of the Iberian Peninsula, a recent multiproxy reconstruction based on different natural records, historical sources and early instrumental data points the onset of the LIA around 1300 and its end by 1850 (Oliva et al., *in press*). Climate conditions showed significant spatio-temporal variations across Iberian mountains, with the coldest conditions recorded between 1620 and 1715 coinciding with the lowest solar activity during the Maunder Minimum when mean annual tempertaures were ca. 2ºC lower than present-day values. This colder climate conditioned the expansion of glaciers in massifs above 2600 m, a downslope migration of the periglacial belt, increase of natural hazards and geoecological changes, among others (Oliva et al., *in press*). Since 1850, temperatures have increased by 1ºC which led to significant environmental and geoecological shifts in the highest mountains, reducing the intensity and area affected by cold-climate geomorphological processes. The most visible effect of post-LIA warming climate is the significant reduction in the number of glaciers and the extent of the glaciated domain. Glaciers have disappeared from Sierra Nevada (Gómez Ortiz et al., 2017) and Picos de Europa (González-Trueba, 2006; González-Trueba et al., 2008) as well as from many massifs in the Pyrenees, where 88% of the LIA glaciers have completely melted (Rico et al., 2017a).

The objective of this paper is to examine the LIA and post-LIA environmental dynamics in the three Iberian ranges glaciated during the LIA that are still currently subjected to active paraglacial dynamics in the form of a wide range of processes. With this purpose, we will give answer to the following specific questions:

- What processes and landforms are/were characteristic of the paraglacial stage in each massif?
- What is/was the timing and spatial domain of post-LIA paraglacial activity in Iberian mountains?
- What are/were the interactions between the glacial, paraglacial and periglacial landsystems and what is their impact on present-day environmental dynamics?
- Is it possible to establish a common landscape model for paraglacial processes in Iberian mountains?

2. High mountains in Iberia

The Iberian Peninsula is located in SW Europe, between latitudes 43° 47′ N to 36° 01′ N and longitude 9º 30' W to 3º 19' E, extending over a surface of 582,925 km². The peninsula is divided by several W-E aligned mountain ranges exceeding 2000 m asl: Pyrenees, Cantabrian Mountains, NW ranges, Central Range, Iberian Range and Betic Range (Figure 1). Two Iberian massifs include the highest peaks in Western Europe outside the Alps: the Sierra Nevada, in the Betic Range (Mulhacén, 3478 m), and the Maladeta massif, in the Pyrenees (Aneto, 3404 m).

Figure 1

The Iberian Peninsula is placed in a transitional area between different influences: maritime (Atlantic/Mediterranean), climatic (subtropical high-pressure belt/mid-latitude westerlies) and biomes (Europe/Africa): the interaction between these influences explains the wide spectrum of landscapes and environments existing across Iberian mountains (Oliva et al., 2016). The highly seasonal climate is controlled by the westerlies dominating the winter circulation and by the Azores Anticyclone, which prevails in summer (Paredes et al., 2006). In some mountains the climate regime is more affected by the Atlantic sea with precipitations throughout the year (western Pyrenees, western Central range, NW Ranges, Cantabrian Mountains), whereas others show a Mediterranean influence with most of the precipitation concentrated between October and May (eastern Pyrenees, southern Cantabrian Mountain, Central Range, Betic Range). Consequently, climate variability in Iberia is controlled by both, the North Atlantic Oscillation (NAO) and the Western Mediterranean Oscillation (WeMOi; Martín-Vide & López-Bustins, 2006). From an Iberian perspective, annual precipitations decrease from N to S and from W to E, whereas mean air temperatures increase towards the S and the E. Despite LIA cooled all Iberia, only Sierra Nevada, Pyrenees and the Cantabrian Mountains had enough elevation to develop glaciers in their highest cirques (Oliva et al., *in press*).

Sierra Nevada constitutes a semiarid massif of the Betic Range located in the south of the Iberian Peninsula including the highest peaks in Iberia. The massif stretches along 80 km including several peaks exceeding 3000 m in its western fringe. At summit level mean annual temperatures are 0ºC, with annual precipitations of 700 mm at 2500 m (Oliva et al., 2016). Natural records and historical sources show evidence of the existence of two glaciers at the foot of the highest peaks during the LIA above 2950 m (Gómez Ortiz et al., 2009; Oliva & Gómez Ortiz, 2012). The last glacier, the one existing inside the Veleta cirque, finally disappeared during the first decades of the 20th century (Gómez Ortiz et al., 2017).

The Pyrenees extend along 440 km between the Biscay Gulf in the west (Atlantic Ocean) and the Creus Cape at the east (Mediterranean Sea). The highest massifs exceeding 3000 m are located in the central areas of the range and the altitude decreases towards the west and the east, as well as towards the north and south. The Pyrenees show a high climatic heterogeneity with the 0ºC isotherm placed at approximately 2850 m and with annual precipitations between 600 mm and more than 2000 mm at summit level (López-Moreno et al., 2008). The ice in the Pyrenees, both in the form of glaciers and ice-patches, has significantly decreased since the last LIA glacier advance. There is evidence of LIA moraines and proglacial sediments of LIA age in more than 100 cirques in the Pyrenees, both in the current glaciated and non-glaciated massifs (Serrano and Martínez de Pisón, 1994; Grove and Gellatly, 1995; Chueca et al., 1998a, 1998b). From all of them, 90 glaciers melted completely from 1880 to 1980, and 20 more disappeared since the 1980s (Rico et al., 2017a). The last remnants of LIA glaciers in the Pyrenees glaciers are currently located in the highest massifs, below summits above 3000 m and inside northern cirques sheltered by steep ridges. Today, there are 19 glaciers (244.6 ha), 8 (159.3 Ha) in the Spanish side and 11 (89.7 ha) in the French side, and all of them are exhibiting a very fast degradation in the last few years (López-Moreno et al., 2016; Rico et al., 2017a).

The Cantabrian Mountains extend along the 380 km between the NW ranges (Galicia) in the west and the Pyrenees in the east. The highest massifs are located in the central areas of the range where the highest peaks exceed 2500-2600 m. The Cantabrian Mountains show a climatic dissymmetry between the very wet northern side with precipitations above 1800 mm - even 3000 mm at summit level - and the southern slope characterized by relatively dry summers and annual rainfall around 600 mm. The highest lands show a bare landscape formed by limestone, with human pastures in the subalpine and alpine belts. Six glaciers existed during the LIA in the Picos de Europa, all north exposed and above 2200 m, which melted during the early 20th century (González-Trueba, 2007). Currently, there are no glaciers, with only 4 ice patches located in glaciokarstic depressions at the foot of vertical cirque walls.

3. Methodology

Several new scientific findings have been recently published about the number and extent of current glaciers, periglacial environments and glacial evolution in Iberian mountains (e.g. González-Trueba et al. 2008; López-Moreno et al., 2016; Oliva et al., 2016; Rico et al., 2017a). Taking into account this new literature, we examine the processes, environments and timing of paraglacial post-LIA activity in the small cirques and valleys glaciated during the LIA in the highest Iberian ranges: Sierra Nevada, Pyrenees and Cantabrian Mountains.

For each of these ranges, we have performed an accurate review of the existing scientific literature focusing on the LIA geomorphological complexes based on natural records (glacial, periglacial, lacustrine, alluvial) and historical documents. Based on the distribution of LIA moraines, we have reconstructed the different stages of glacier advance and retreat, together with their interaction with periglacial, slope and proglacial processes as well as geoecological changes. Besides, we have also analysed the geomorphological aspects related with hydrology and mass movements occurring in these response that have modified the environmental dynamics within LIA moraine complexes and surrounding areas in the highest mountains. The available data were summarized in a table for each range, including the different stages within the LIA.

4. Paraglacial systems in Iberian ranges

4.1 Sierra Nevada

Timing

Historical documents and lake sediments have shown evidence that Sierra Nevada hold the southernmost glaciers in Europe during the LIA (Gómez-Ortiz et al., 2009; Oliva & Gómez-Ortiz et al., 2012). Some of the highest northern cirques shaped during the Quaternary period in the western fringe of the massif encompassed small glaciers that melted completely during the early 20th century (Gómez-Ortiz et al., 2017).

Lake records revealed the existence of a small glacier existing at the foot of the highest mountain in Iberia, the Mulhacén peak, between 1440 and 1710 AD. The location of the cirque, ca. 150 m lower than the Veleta cirque and its NNW aspect (Figure 2), led to its melting at the end of the Minimum Maunder cold stage. By contrast, the floor of the Veleta cirque placed at 3100 m and its prevailing N aspect determined a longer persistence of the glacial ice masses until 1940s (Gómez-Ortiz et al., 2009). During the coldest and wettest stages of the LIA permanent ice patches probably developed inside other glacial cirques located at relatively lower elevations in northern aspects as well as in south-exposed hollows above 3200 m, where wind redistribution accumulated large amounts of snow that persisted throughout the summer.

Figure 2

Landforms and processes

The timing of post-LIA paraglacial activity in Sierra Nevada followed a different calendar in the Veleta and Mulhacén cirques as a consequence of the different glacial evolution, which therefore conditions the type and intensity of present-day geomorphological processes (Figure 3). While the Mulhacén cirque has been glacier-free over the last three centuries, glacial ice in the Veleta cirque melted entirely only 70 years ago (Table 1). The gradual melting of the glaciers exposed the bedrock surface and favoured slope instability. Even if present-day ground temperatures indicate that permafrost was probably inexistent in the northern cirque walls during the LIA (Oliva et al., 2016b), rock fall activity associated to paraglacial dynamics was very intense, with the development of a thick debris mantle on the slopes connecting the cirque walls with the cirque floors, and burying also the last remnants of glacial ice and snow. The ice trapped under the debris cover favoured the development of a permafrost layer in contact with these frozen masses (Gómez-Ortiz et al., 2014). In some cases, within the last glaciated spots during the LIA in each cirque, these frozen layers favoured the development of permafrost-derived features, such as a rock glacier in the Veleta cirque and a protalus lobes in the Mulhacén cirque (Oliva et al., 2016b).

Figure 3

Table 1

The rock glacier existing inside the Veleta cirque is one of the most studied permafrost landforms in southern Europe (Figure 4). Ground temperatures, geophysical and geomatic measurements show evidence of the degradation of the frozen masses placed beneath the rock glacier, which tends to stabilize as the shrinking of the frozen bodies accelerates (Gómez-Ortiz et al., 2014). In fact, a significant reduction of the volume of the frozen mass was detected over the last 15 years, with permanently frozen bodies located now at deeper levels and becoming spatially disconnected (Gómez-Ortiz et al., 2014). A high interannual variability of the rock glacier movement has been also observed depending on the duration of the snow cover, with increased vertical and horizontal displacement rates in years with no or little snow cover in the Veleta cirque during the summer season (Gómez-Ortiz et al., 2014). The degradation of these permanently frozen conditions in this area is also inferred through geomorphic evidence, such as the existence of multiple collapses and subsidence depressions spread across the debris cover. This fact is also observable in the formerly glaciated environment in the Mulhacén cirque, where geophysical surveying in the late 1990s also reported evidence of permafrost existence (Gómez-Ortiz, personal communication).

Figure 4

Some of the slopes in these recently deglaciated environments show a wide range of hillside processes typical of paraglacial environments, such as debris flows, solifluction and mudflows on fine-grained soils. Nival processes are also shaping the highest lands through avalanche activity within the cirques as well as the formation of some pronival ramparts at the foot of slopes. Besides, in relatively flat areas, centimetric patterned ground features form under present-day climate conditions. The new ice-free environments have been also subjected to hydrological changes since their deglaciation, with the formation of permanent and semi-permanent lagoons that are being infilled by the intense remobilization of sediments characteristic of the paraglacial stage. The drainage network has also adapted to the new geomorphological setting, with seasonal streams crossing the moraine ridges. Besides, in summer a continuous subsurface runoff is observed across the debris-covered slopes connecting the cirque walls with the cirque floors.

4.2 The Pyrenees

Timing

The LIA glacier evolution in the Pyrenees includes three major glacial advances and retreats until around 1850, when glaciers started the definitive retreat, only interrupted by short equilibrium periods (Table 2). The first glacial advance known, the LIA glacier maximum, took place during last decades of the 17th century and the first decades of the 18th century. The morphological record is represented by frontal and lateral moraines, although the most external ones are not very well preserved in some massifs. The age of this glacial advance is known by the chronicles of Ramond de Carbonnières from 1789 (de Carbonnières, 1802), and coincided with the coldest climate conditions of the Maunder Minimum (Creus, 1991; Saz and Creus, 2001; Oliva et al., *in press*). However, lichenometric measurements in the Aneto moraines suggests that it occurred slightly before, between 1600 and 1620 (Julián and Chueca, 1998). Some re-advances took place during the widespread glacier retreat occurred between 1750 and 1800, building several small moraines. Historical sources reported another glacial advance during the two first decades of the 19th century in parallel to cold extreme events described for several areas in the Iberian Peninsula (Oliva et al., *in press*). In this sense, in the Maladeta massif the glacial expansion forming the big frontal and lateral moraines behind the external system was dated by lichenometry between 1820 and 1830 (Julián and Chueca, 1998). Subsequently, glaciers started retreating, though in at least 16 cirques there was a period of glacier expansion after ca. 1830 and prior to 1850 that formed moraine complexes with flutes, push and hummocky moraines that deformed the previous ones. This has been interpreted as a short stage of fast flow glacier advance or surging glaciers occurred before post-LIA warming favoured the massive glacier retreat (Serrano and Martín-Moreno, 2017). However, at the end of 19th century there was small glacial advances as illustrated by naturalists and cartographers, with glaciers next to the frontal moraines at Vignemale, Infierno, Maladeta, Posets and Monte Perdido massifs (Wallon, 1874; Russell, 1908; Schrader, 1936). At this time starts the most intense paraglacial dynamics in the Pyrenees, when periglacial, slope and alluvial processes started reworking the moraines and cirque walls were strongly affected by glacial debuttressing and permafrost degradation. Some landforms existing today in the firstly deglaciated ice-free areas in the Pyrenees are inherited from this stage, such as patterned ground, protalus lobes or debris flow on the external side of moraines.

Table 2

Although it was not uniform for each cirque, the main deglaciation following the last advance and the massive ice melt occurred generally during the second half of 19th and the early 20th century. This retreat separated the glaciers from the moraines, as witnessed by contemporary observers (Trutat, 1875; Gaurier, 1921; Schrader, 1936) and it has been deeply examined in the Vignemale massif (Grove, 2004; René, 2011). The retreat was interrupted by minor advances and glacier equilibrium until 1930s, when many glaciers disappeared and others evolved to ice patches. In the Maladeta massif, an equilibrium phase was recorded between 1915 and 1925 (Julián and Chueca, 1998; Chueca et al, 2005). Consequently, post-LIA warming trend until 1930s promoted paraglacial dynamics that extended across the environments occupied by melting LIA glaciers and favoured the development of frost mounds, protalus lobes, patterned ground, debris talus, solifluction lobes, alluvial cones and thermokarst features.

Since 1930 the continuous glacier retreat led to either their extinction or their transformation into ice patches in most of the cirques affected by the LIA glacial and periglacial dynamics. Despite some cases of intermittent small advances, such as Oulettes of Gaube in 1945 and 1964 (Grove and Gellatly, 1995), the drastic retreat since 1980s conditioned an accelerated mass loss after the last episodes of expansion and equilibrium recorded at the end of the 1970s and early 1980s (Martínez de Pisón and Arenillas, 1988; Martínez de Pisón et al., 1995; Grove and Gellatly, 1995; René, 2011; Martí et al., 2015). Since then, the paraglacial landsystem occupies the formerly glaciated highest lands, where changing environmental dynamics are changing the landscape of the highest Pyrenean massifs.

Landforms and processes

Post-LIA paraglacial landsystems in the Pyrenees are located in small areas above 2400 m inside the LIA moraine complexes, showing complex interactions between the topography, microclimate conditions and the different types of moraines (frontal, lateral, hummocky, push), flutes, proglacial deposits and glaciers. Currently, there are only 19 glaciated cirques (Rico et al., 2017a), although there is geomorphic evidence of LIA glacial features in more than one hundred cirques (González-Trueba et al., 2008). Present-day paraglacial dynamics is mostly driven by seasonal frost conditions, with mountain permafrost above 2750 m mainly outside LIA moraines.

Up to sixteen different processes-landforms interactions have been identified in paraglacial environments in the Pyrenees, noting the existence of different subsystems (Table 3). The transition from glacial to periglacial environments includes the deglaciation of the lowest areas and the evolution of glaciers into ice-patches. Present-day glaciers show evidence of fast degradation features, such as frontal collapses, ice thinning, debris-cover occurring at the distal part of the glaciers and burying snow and ice; this generates processes related to melting water and ice blocks falls. Ice patches are also thinning, with steeper slopes favouring the sliding of rocks released from the cirque walls. Rock fall activity is particularly intense in walls higher than 300 m, though in general is widespread in all cirques, lithologies and aspects between the ridges and the cirque floors above 2500 m (Figure 5). Very frequent freeze-thaw cycles favour intense frost shattering in the cirque walls that is also enhanced by glacial debuttressing and permafrost degradation, as it has been confirmed for the north face of the Vignemale peak (Rico et al., 2017b). Large talus slopes up to 50-100 m long accumulate at the lowest parts, mainly in granite and metamorphic massifs.

Table 3

Figure 5

The current distribution of permafrost in the Pyrenees is also spatially connected with the existence of glaciers during the LIA. Generally, permanently frozen ground occurs above 2700-2750 m, and therefore geomorphological processes in ice-free environments above this elevation are related to active layer dynamics. Here, water flow in contact with frozen bodies and glacier ice enables ice segregation and refreezing processes that favour the formation of frost mounds and protalus lobes (Serrano et al., 2010; González-García, 2013; González-García et al., 2016). Frost mounds are metric size landforms linked to the presence of buried ice, located between 2700 and 3050 m and are always indicative of permafrost environments. The cirques concentrating buried ice (e.g. Alba, La Paúl) and hummocky moraines (e.g. Posets, La Paúl) include these landforms on landforms and deposits formed between 1830 and 1850, or deglaciated after 1850 (Figure 6). Therefore, these frost mounds must have generated after 1850. Protalus lobes are located in the distal part of debris talus, where a frozen body exists and favours the creeping of the sediments. They are scarce features, and have been only identified in Frondiellas, Alba and La Paúl cirques, inside LIA moraines at 2800, 2920 and 3000 m, respectively, formed during the deglaciation started by 1850. In contrast to frost mounds, protalus lobes are common landforms in non-glaciated environments during the LIA in the Pyrenees, suggesting past permafrost conditions (Serrano et al., 2000, 2001, 2009; González-García et al., 2016; Fernandes et al., 2017).

Figure 6

Inside the moraine systems there are other periglacial landforms related to seasonal frost, such as solifluction and patterned ground features. Solifluction landforms are widespread above 2750 m, reaching ca. 3000 m in the Monte Perdido massif. Even if some are located within the permafrost belt, their formation is not strictly linked to permafrost, such as in Alba massif where these landforms appear at 2920 m with frozen ground conditions lasting six months per year (González-García, 2013). Patterned ground features up to 2-3 m long developed on LIA moraines above and below the permafrost elevation limit, at altitudes around 2650-2900 m in Alba, at 2750-2800 m in La Paúl and at 2600-2700 m in Infierno massifs (Serrano et al., 2000; Martín-Moreno et al., 2012; González-García, 2013). Some features are also distributed at higher elevations within the mountain permafrost belt inside the moraine complexes, at 2950 m in Alba, at 2850 m in La Paúl and at 3035 m in Posets massifs. Consequently, there are two generations of patterned ground features: those very recent associated to permafrost environments and those related to seasonal frozen ground formed prior to 1850 (Martín-Moreno et al., 2012).

The unconsolidated sediments of LIA moraines favour frequent fast and slow mass movements on the slopes of these complexes as well as inside the cirques. Debris flows are common on the internal and external slopes both of lateral and frontal moraines, caused by the fast melt of snow patches and snow cover and intense rainfall events on the saturated till as well as by permafrost degradation. Debris flows originated on the LIA moraines in Maladeta, Tendeñera or Infierno massifs can go well below the glaciated environments, reaching elevations of 2550-2700 m. In fact, the occurrence of rapid mass movements is accelerating in response to the recent warm summers recorded in the Pyrenees, as reported by the major geomorphic event affecting LIA moraines this summer (Figure 7). A glacial lake outburst flood (GLOF) episode in the Maladeta massif has shown evidence of current paraglacial dynamics linked to the small glaciers still existing in the Pyrenees. The removal of sediments and redefinition of the landforms caused by fast melt and surface runoff was driven by intense precipitations that led to a sudden hydrological response in the proglacial environment. In 6th August, after a hot day a storm event took place in the Maladeta massif accumulating 75.2 mm at the Renclusa hut (2140 m). The intense precipitations together with snow and ice melt of the glacier triggered a GLOF event from a semi-permanent lake formed inside the LIA frontal moraine complex. We do not know how long the lake lasted, its depth and extension, though there is evidence of sand and coarse sediments infilling a small depression previously occupied by an alluvial fan. The accumulated water broke the frontal moraine located at an elevation of 2650 m, forming a 3-4 m scarp on the moraine, removing sediments and triggering a debris flow moving 1.4 km downslope until around the Renclusa hut, where a 140 m long debris fan was deposited. Along the debris channel there is evidence of intense abrasion on rock outcrops and deposition of levees at both margins. Consequently, although until now there was no evidence of other GLOF episodes in the Pyrenees, the presence of alluvial fans, incision features in moraines as well as dispersed blocks on relative flat surfaces can be thus attributed to other fast flow events by lake outbursts or sudden torrential events originating from LIA moraine complexes.

Figure 7

Landslides are also frequent inside the lateral and frontal moraines where glacial melting and basal wetting generate slope instability. Some examples have been identified at 2650 m in Frondiellas (Balaitous), 2490 m in Tendeñera, 2600 m in Bardamina (Posets) or 2850 m in Coronas (Maladeta). They occur on moraine slopes, sliding over the snow or ice and forming a debris cover where frost mounds, patterned ground or even melt hollows can develop. Rock falls are very frequent in the cirque walls forming block accumulations on glacier, ice patches, snow patches and slopes (Figure 8). They are shaped at any lithology, generally above 2500 m, being very abundant above 2750-2900 m, mainly in N orientations. Sometimes blocks falling on the ice or snow and sliding through the frozen surface form elongated blocks accumulations when snow or ice melts. The altitudinal range (from 2750 m to the summits) and prevailing aspect (N) shows also a possible connection with permafrost degradation on the cirque walls characteristic of the disequilibrium typical of the paraglacial readjustment stage, which also favours ice patch covering by debris that delays ice melting.

Figure 8

In the low areas of the moraine complexes there are thermokarst features (subsidence and chaotic topographies) inherited from the last glacial advances occurred between 1830 and 1850 when surging glaciers formed push and hummocky moraines, with ice still preserved today in complexes as La Paúl (Serrano and Martín-Moreno, 2017). These features are visible in the Tucarroya, Infierno and La Paúl cirques in the external and low areas of moraine complexes at 2520 and 2700 m, respectively.

Glacier retreat has also promoted changes on hydrological changes in recently glaciated environments, particularly in granitic massifs where the melt water is changing the landscape of the proglacial area. Surface concentrated runoff can erode the moraines slopes, forming lineal rill on steep moraines at altitudes between 2600 and 2900 m. The till structure and texture determine the existence of rills, which are abundant on metamorphic and granite massifs. They have formed during every deglaciation stages occurred during the LIA. Alluvial processes can degrade lateral and frontal moraines, transferring sediments downslope the moraines. In some cases, proglacial streams can form alluvial fans at the foot of frontal moraines in granite massifs at altitudes between 2400 and 2700 m. Alluvial processes or landforms are inexistent in calcareous massifs because of the absence of surface runoff.

Finally, several new lakes have occupied overdeepened basins when glacier disappeared (e.g. Soum de Ramond, Marboré, Tucarroya, Soulano or Literola). Their age depends on their position with respect to the glacier front: some of them appeared less than ten years ago (e.g. Soum de Ramond), whereas others appeared more than 150 years ago (Tucarroya or Soulano).

4.3 Cantabrian Mountains

Timing

Picos de Europa was the only massif encompassing glaciers during the LIA in the Cantabrian Mountains because of the moderate altitude of the other massifs. Eight small glaciers developed at the foot of the highest peaks strongly influenced by local topoclimatic factors. There is no clear age control on the development of glaciers in the Picos de Europa. Probably, they expanded during the first stage of the 19th century and started retreating during the second half of this century in parallel to what happened in other Iberian massifs (Oliva et al., *in press*). During the first decades of the 20th century all LIA glaciers turned into ice patches (González-Trueba, 2006, 2007). Currently, they are several totally or partially buried ice patches, some of them recently completely melted, such as Cemba Vieya and Peña Santa ice patches (González-Trueba, 2007). Climate conditions also favoured the preservation of ice blocks preserve inside ice caves (Gómez-Lende, 2016). During the last decades of the 20th century and the early 21sth century the loss of ice area has been around 65%, and at the same time the ice volume stored in in some ice caves has significantly reduced (Serrano et al., 2011; Gómez-Lende, 2016).

Landforms and processes

Paraglacial processes follow the timing of glacial retreat, thus periglacial dynamics started to occupy the LIA glaciated cirques during the second half of the 19th century (Table 4). However, it must be taken into account that in the high lands of Picos de Europa there is very limited surface drainage network because of karstification and this conditions the intensity and type of soil, hydrological and periglacial processes prevailing in these environments. Consequently, cirques are mainly shaped by both glacial and karst processes, with glaciokarstic depressions inside LIA moraine systems (Figure 9). The hypogea drainage is dominant, with remarkable subsurface ice masses, both seasonal and permanent, until ca. 160 m depth (Gómez-Lende, 2016).

Figure 9

Within the LIA moraine systems, small frost mounds constitute the most extended landforms. They are developed on the debris covering the ice patches, such as in Jou Negro, Palanca and Forcadona (González-Trueba, 2006, 2007; Ruiz-Fernández et al., 2016). Occasionally, the melting of these frost mounds can trigger mudflows. Patterned ground features, such as centimetric sorted circles, have been observed in LIA moraines in several cirques, such as in Jou Negro, Jou Trasllambrión, Palanca, Forcadona, Hoyo del Llambrión, Torre de la Párdida, as well as incipient stripes above 2280 m (González-Trueba, 2006). On LIA moraine complexes and cirque walls, landslides and rock falls have been detected favoured by glacial debuttressing following deglaciation (Figure 10). Debris accumulations can be, occasionally, reworked by other slope processes, such as debris flows triggered by intense rain or snow melt events.

Figure 10

Isolated patches of permafrost are associated with the presence of ice patches (González-Trueba, 2006, 2007; Pisabarro et al., 2016; Ruiz-Fernández et al., 2016). In the Jou Negro cirque there are sporadic permafrost phenomena, located at a very low altitude (2150-2200 m) due to topoclimatic factors. It is likely that permafrost existed during the LIA in sheltered environments above 2350 m (González-Trueba, 2007). Today, there is subsurface mountain permafrost conditions in ice caves (Gómez-Lende and Serrano, 2014; Gómez-Lende, 2016). Periglacial dynamics prevails today in the Picos de Europa from 1900 m to the summit level mostly associated to seasonal frozen ground (González-Trueba, 2006; Serrano et al., 2011; Pisabarro et al., 2016), with intense nival processes reshaping LIA moraines and inside the cirques. Very frequent solifluction processes driven by snow melt and shallow freezing. Snow patches and nivation niches formed by wind drift and snow avalanches are favoured by topoclimatic and geomorphological factors, with snow accumulations in dolines and pits, closely related to karst processes. Also, in the debris cover channels and moulins can be observed (Alonso & González Suárez, 1998; González-Trueba, 2007; Serrano et al., 2011).

Table 4

5. The Iberian post-LIA paraglacial landsystems

Following LIA glacier retreat, the new ice-free environments in the highest Iberian ranges were occupied by periglacial processes and mass movements, reshaping LIA complexes and favouring the development of different landforms and processes inside the moraines.

5.1 Timing of paraglacial dynamics

The post-LIA paraglacial response in Iberian mountains shows different spatio-temporal patterns depending on the timing of glacial advances. Whereas in Sierra Nevada and Picos de Europa there is only evidence of the last LIA glacial advance, in the Pyrenees the existence of several non-glacial landforms within the LIA glaciated areas distributed across the slopes, cirque bottoms and moraines suggest the existence of three glacial advances during the LIA (Oliva et al., 2016; Serrano and Martín-Moreno, 2017).

In the case of the Pyrenees, the first paraglacial phase occurred immediately after the LIA maximum advance (late 17th-early 18th centuries) with small subsequent advances between 1750 and 1800 (Grove and Gellalty, 1995; González-Trueba et al., 2008; René, 2011; Martí et al., 2015). The melting of glaciers promoted increased runoff and mass movements (solifluction, debris flows), erosion of the external side of the LIA moraine systems and rock falls in the cirque walls that generated that debris covered the ice patches and snow patches existing at their foot. Documentary records in Mediterranean mountains, including the Pyrenees, point to a greater frequency of severe floods at times of LIA Alpine glacier advances, favoring reworking of unstable deposits after LIA glacier retreat (Grove, 2001).

Increasing temperatures since 1850 led to glacier retreat in all ranges – and the complete melting in some cases –, with the appearance of proglacial environments between the glacier fronts and the moraines. Paraglacial dynamics were very intense during this time, with mass movements and intense periglacial processes extending gradually from the external moraines to the inner ridges and also affecting the lower stretches of the walls. Glaciers transformed into ice patches in Sierra Nevada (Gómez-Ortiz et al., 2017), Picos de Europa (González-Trueba, 2006) and in several cases in the Pyrenees (Martínez de Pisón and Arenillas, 1988; Serrano et al. 2001, 2002). In topographically sheltered environments, topoclimatic conditions favoured the existence of ice patches and small glaciers inside the most elevated cirques until the first decades of the 20th century. However, retreating ice favoured the formation of debris accumulations at the lowest areas of the slopes connecting with the bottom of the cirques, together with protalus lobes, solifluction landforms, frost mounds, patterned ground and thermokarst features (Feulliet, 2011, Feuillet and Mercier, 2012).

Paraglacial dynamics accelerated with continuous glacier retreat that led to the extinction of some of them. The interaction between glacial-derived landforms, mass movements, periglacial activity, nivation, karstic and alluvial processes shaped the landscape of the recently deglaciated areas, together with permafrost degradation in moraines and cirque walls. The warm-based character of the glaciers in these mid-latitude mountain regions explains why the deglaciated environments do not always record nowadays permafrost conditions, which only persist outside the LIA moraine systems (González-García, 2013). Permafrost-related landforms in LIA glaciated domain are only distributed in areas where buried ice still exists below the debris cover (Serrano et al., 2001, 2009; Lugon et al., 2004). The dramatic glacial retreat accelerated since 1980s was parallel to the disappearance of many ice patches as well as a reduction of the snow patches persisting throughout the summer (López-Moreno et al., 2016). Consequently, since then paraglacial processes have extended across the highest lands, in most of the cases associated to nivation and seasonal frozen ground conditions, and to a lesser degree to mountain permafrost.

These sequences have been found in recently deglaciated LIA complexes, both in the Arctic and the Alpine environments. In Svalbard, the most significant set of landforms related to paraglacial dynamics were formed some 100 years after the LIA maximum recession, and the paraglacial sequence began during the first years of the 20th century (Rachlewicz, 2010). The glacial retreat intensified glaciofluvial processes with unstable sediments settled on ice, mass movements and proglacial accumulation, involving washing out sediments in conditions of a shallow permafrost table (Rachlewicz, 2010). In the case of Svalbard, although here the presence of permafrost implies different geomorphological dynamics with respect to Alpine environments, three stages have been differentiated: (i) development of kame terraces and lacustrine deposits by a differential response between small and large glaciers, with meltwater damned, (ii) a GLOF reworking sediments on the deglaciated foreland, and (iii) the current landscape is characterized by moraines being destroyed and slopes modified by the paraglacial adjustment, with intense mudflows and debris flows building some alluvial fans and cones downstream (Etienne et al. 2006). Compared to the Pyrenees, the paraglacial sequence is coetaneous with Arctic post-LIA glacial environments, with some common processes, such as the development of lakes, GLOF and slope processes, with very active mudflows and debris flows.

5.2. Paraglacial processes and landforms

The newly exposed land surface by retreating glaciers as well as permafrost degradation have promoted changes in the geomorphological processes prevailing in Iberian mountains as well as originated new landforms on cirques, both inside and outside the LIA moraine complexes (Table 5).

Table 5

The most widespread processes linked to post-LIA paraglacial stage in Iberian mountains are related to mass movements derived from glacial debuttressing and permafrost degradation in cirque walls. Landslides and rock falls are widespread and supply abundant debris that cover ice and snow patches, which in turn enhance periglacial dynamics in these sites (i.e. rock glaciers, protalus lobes). Post-LIA glacial retreat is one of many factors influencing landslide and rock fall activity in Alpine environments. In the British Columbia, the shrinking of glaciers following the_LIA has increased the spatial frequency of surface failures and rock fall occurrence, with very frequent debris slides or debris avalanches on lateral moraines and glacial trimlines (Holma et al., 2004). In the Mont Blanc massif, French Alps, interactions between rock avalanches and glaciers are linked to glacier thinning and retreat (i.e. paraglacial stage) generating rock avalanches with effects on permafrost, the degradation of which can also trigger massive rock falls (Ravanel et al., 2017). Besides, the debris displaced by these avalanches can also incorporate ice and snow favouring the accumulation of chaotic piles of angular rock debris at the foot of slopes, even contributing to insulate and preserve small glaciers (Deline, 2009). In the Pyrenees, Sierra Nevada and Picos de Europa the increase of paraglacial activity is linked to rock fall and slope activity from walls and moraines by glacier thinning and retreat, preserving also ice patches by insulating debris-cover (Gómez Ortiz et al., 2014). Besides landslides and rock falls, other periglacial processes are also frequent in LIA glaciated environments such as mudflows, debris flows, solifluction or patterned ground. These processes are enhanced by cryoturbation activity and soil saturation by melt water and rain remobilizing sediments.

The existence of LIA frontal and lateral moraines has also conditioned minor hydrological changes characteristic of the paraglacial stage (Ballantyne, 2002). In the Pyrenees, seasonal streams redefine glacial and proglacial landforms, with some erosional features on moraines and accumulation of alluvial deposits at the foot of the larger LIA moraine systems. These processes do not exist in Sierra Nevada and Picos de Europa, where alluvial dynamics is very limited due to the small glaciated environments during the LIA (Oliva et al., 2016). Only small drainage changes as well as subsurface runoff from the walls to the cirque bottoms are common processes in all studied massifs. In addition, in the case of Sierra Nevada and the Pyrenees small lakes and ephemeral lagoons occupied some ice-free glacial overdeepened basins. In the Pyrenees, these lagoons are distributed from 2500 m (early LIA glacial retreat) to 2800-3000 m (recent retreat) following the age of glacial retreat.

Sediment transfer associated to paraglacial activity during the LIA and post-LIA period has been very small. High intensity-low frequency processes, such as rock fall, landslides and debris flows, are limited to the inner part of the glacial cirques, with limited transport from moraines and walls to the cirque bottoms. Other processes linked to karstification, subsurface runoff, cryoturbation, solifluction or nivation processes show a limited capacity of remobilizing sediments, but always within the paraglacial spatial domain. There are only a few processes, such as debris flows, mudflows and alluvial dynamics that can mobilize sediments beyond the LIA moraines, though reduced in space and not frequent in time.

5.3. Spatio-temporal paraglacial morphosequences in the Iberian mountains

At present, the highest lands in Iberia highest ranges are occupied by the periglacial belt, which now includes the LIA glaciated environments distributed between the moraines and cirque walls. Nowadays, the landscape dynamics in these environments is largely controlled by paraglacial processes, namely by the presence of buried ice under the debris cover. Paraglacial processes are particularly active in northern cirques, at the foot of steep slopes where there are subsurface frozen bodies under the debris cover. In the Pyrenees, paraglacial dynamics generally occur above 2700 m (González-García, 2014), increasing to 3100 m in the semiarid range of Sierra Nevada (Gómez-Ortiz et al., 2014), but at only 2100 m in the very humid Picos de Europa, where the presence of frost mounds and patterned ground shows evidence of the existence of frozen bodies beneath (González-Trueba, 2007; Serrano et al. 2011).

Several processes and landforms are common nowadays in the cirques of the three mountain ranges encompassing glaciers in Iberia during the LIA: (i) buried ice trapped within rock debris supplied from the cirque walls, (ii) semi-permanent snow fields distributed above the ice-patches remnants of the LIA glaciers, and (iii) small periglacial landforms related to both seasonal frost and permafrost conditions. Concerning the interaction between different landforms, three different spatio-temporal paraglacial morphosequences can be distinguished (Figure 11):

Figure 11

1. **From buried ice to frost mounds.**
   It occurs in ice patches covered by debris showing frequent frost mounds and patterned ground features (Figure 12). These sediments can come from two different sources:
   (a) The ice patch is buried by debris supplied by the walls by periglacial processes (frost shattering, permafrost degradation) or glacial debuttressing. The debris cover isolating the ice can range from some centimetres to a few meters thick, and it is composed of heterometric sediments dominated by coarse particles.
   (b) The burial of the ice patch is generated by a slide of the LIA moraine falling on the ice and covering it. These deposits can be several meters thick formed by heterometric particles (till), including fine sediments and coarse material.

   Figure 12

   In both cases, the melting water from snow and ice patches flowing across the sediments and between the ice and sediments favours water refreezing and ice segregation. The presence of ground ice enhances cryoturbation processes with the development of small patterned ground features as well as ice growth in flat areas forming frost mounds. Both sequences are common in the Pyrenees and Picos de Europa, related to karstic, granite and limestone massifs and widespread at very different altitudes outside and inside the LIA complexes.

2. **From buried ice to permafrost-related landforms.**
   When the ice patches are covered by debris generated from the cirque walls by physical weathering processes, including permafrost degradation, the water flowing across the sediments can refreeze and form frozen bodies of sediments and ice layers. The frozen bodies can creep down-slope forming protalus lobes or even small rock glaciers flowing towards the bottom of the cirques. Therefore, permafrost exists in these environments even if temperatures are near 0ºC (González-García et al., 2016). However, changes in atmospheric conditions (e.g. post-LIA warming) can led to the degradation of these frozen bodies and led to a shrinking and reduction of their volume, the spatial disconnection between frozen bodies and surface collapses and subsidences (Gómez-Ortiz et al., 2014). This morphosequence is found in all massifs, with more development in high altitudes of the Sierra Nevada and the Pyrenees.

3. **From screes to solifluction landforms.**
   The coarse particles existing in talus and debris cones favour the fast flow of water that accumulates in the basal part of the screes, where it can freeze. Besides, the snow trapped between the boulders can be integrated within the debris talus, forming small and seasonal frozen bodies creeping at the distal portion of the debris slopes in moraines or at the foot of cirque walls. Here, the uppermost part of the soil can move down-slope by solifluction processes associated to seasonal frozen conditions inside the LIA moraine complexes.

4. **Appearance of lakes next to glaciers and ice patches.**
Some lakes appeared inside the LIA moraine ridges and small overdeepened basins following glacier retreat and ice patches melt. This is the case of several lakes in the Pyrenees (i.e. Soum de Ramond, Literola, Marboré, Tucarroya or Soulano) and one in Sierra Nevada (Veleta cirque lagoon), but not in the Picos de Europa where karstic processes impede water retention.

6. Conclusions

By analizing the present-day distribution of landforms and processes in the highest Iberian massifs glaciated during the LIA, we have examined the deglaciation process focusing on the paraglacial stage, which still continues. Climate conditions, topography and the geomorphological settings condition the distribution of the paraglacial landsystem in the Iberian Peninsula, located in the high mountain above 2200 m in the humid Picos de Europa, 2700 m in the Pyrenees and 3100 m in the semi-arid Sierra Nevada, where glaciers exist during the LIA. Topography and climatic conditions determined the existence of glaciers during the LIA, and therefore control the paraglacial response following their disappearance or massive retreat. Paraglacial environments occupy small areas, generally north exposed at the foot of steep walls in several cases higher than 300 m.

Several paraglacial phases have been inferred in the Pyrenees, where evidence of three glacial stages has been detected. In contrast, paraglacial response in Sierra Nevada and Picos de Europa results from the landscape evolution since the last glacial advance during the 19th century. In all cases, the paraglacial system is very young, of less than 200 years, with active paraglacial dynamics occurring in environments deglaciated less than 100 years ago, mainly in the Pyrenees, and ca 80 years old in Sierra Nevada and Picos de Europa. The most intense processes are observed in the Pyrenees, in those areas that become ice-free following the massive glacial retreat occurred during the last decades.

The most active processes currently in these paraglacial environments promoting sediment redistribution are related to glacial debuttressing and permafrost degradation, generating rock falls and landslides from cirque walls and moraines. Periglacial processes linked to the existence of buried ice trapped within the debris cover are widespread in the three massifs. Permafrost developed in contact with these LIA glacial remnants, forming layers of frozen sediments alternated with ice layers. These frozen bodies favoured the development of permafrost-derived features (rock glaciers, protalus lobes) and other features related to segregation ice (frost mounds) and cryoturbation (patterned ground). Debris flows and rockfalls are responsible of the larger mobilization of sediment. This material is subsequently remobilized by slope, periglacial (cryoturbation and solifluction) and hydrological processes, generally at slower velocity and for much shorter distances.

The spatio-temporal evolution in these paraglacial environments followed three different patterns triggering diverse processes and landforms: (i) formation of frost mounds developed on a debris cover with buried ice beneath, (ii) formation of permafrost-related features above these frozen bodies, and (iii) formation of solifluction landforms at the foot of talus cones with abundant supply of snow.

Paraglacial landsystems in these high mountain ecosystems where mean annual temperatures are close to 0ºC are very sensitive to climate shifts, such as variations on snow regime, isotherm changes or permafrost degradation. In the present-day climate scenario where temperatures are expected to significantly increase in the Iberian Peninsula (IPCC, 2014), paraglacial activity is expected to decrease in the deglaciated areas during the early stages of the LIA but to significantly increase in the still glaciated environments in the Pyrenees.

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Figure captions

Figure 1. Location of the main mountain ranges in the Iberian Peninsula examined in research.

Figure 2. Examples of post-LIA paraglacial environments in the Iberian Peninsula: (A) Maladeta and Aneto proglacial LIA moraine systems located between 2600 and 3100 m, Central Pyrenees; (B) Besiberri massif (3008 m), Central Pyrenees; (C) Northern wall of the Mulhacen with La Mosca lake at its foot, Sierra Nevada; (D) Veleta cirque, with the LIA moraine complex located at 3100 m, Sierra Nevada; (E) Los Campanarios peak (2569 m), with the LIA glacial complex located at 2360 m in its northern cirque, Picos de Europa; (F) Jou Negro cirque in the northern face of the highest peak of the Picos de Europa (Torre Cerredo, 2648 m) with the LIA moraine located at 2230 m.

Figure 3. Geomorphological sketch of paraglacial environments in Sierra Nevada.

Figure 4. Examples of landforms generated during the paraglacial stage in Sierra Nevada: (A) Front of the rock glacier existing inside the Veleta cirque; (B) Protalus lobe located at the foot of the northern wall of the Mulhacén peak; (C) Vertical view of the Veleta cirque with the lake dammed by the LIA moraine.

Figure 5. Geomorphological sketch of two paraglacial environments in the Pyrenees: Tucarroya cirque and Monte Perdido-Marboré north face (left); La Paúl LIA moraine complex in the Posets massif (right).

Figure 6. Examples of landforms generated during the paraglacial stage in the Pyrenees: (A) Frost mound developed on the LIA moraines in La Paúl at 2710 m; (B) Cryoturbation landforms in the proglacial area of the Monte Perdido glacier, at 2550 m; (C) Patterned ground section in Posets, at 3020 m (1- Coarse and fines with blocks in planar position, 2- Blocks with their long axis vertical, 3- Clast-supported formation. 4- Fine sediments, 5- Hollows below the debris cover); (D) Rills on the lateral moraine of La Paúl at 2800 m; (E) LIA moraine of Frondiellas (Balaitus massif), with landslides, debris flows and talus developed on it; (F) Rock fall in the north slope of Marboré at 2800 m, with the rocks sliding down slope on the snow cover.

Figure 7. Geomorphological sketch of the GLOF features produced in the Maladeta glacier front during the event occurred in 6th August 2017.

Figure 8. Altitude distribution of landforms generated during the paraglacial stage in the Pyrenees, with the grey box marking the limit of mountain permafrost and showing evidence of the existence of permafrost-related landforms and periglacial phenomena related to seasonal frost (left); Approximate age of the landforms developed in the paraglacial areas in the Pyrenees, with several groups of landforms formed around 19th century, from 19th to 20th centuries, and during the 20th century, with an increase in landforms elevation towards more recent times. Abbreviations: T: thermokarst features, FM: frost mounds, PL: protalus lobes, PG: patterned ground, DT: debris talus and cones, GL: solifluction and debris lobes, DF: debris flows, SS: slide slopes, RF: rock falls, R: rills, AF: alluvial fans, L: lakes.

Figure 9. Geomorphological sketch of the LIA moraine complex and ice patch in the Jou Negro cirque (Picos de Europa).

Figure 10. Examples of landforms generated during the paraglacial stage in the Jou Negro cirque, Picos de Europa: (A) Debris covering the ice patch by rock fall and debris flows with distal deformation; (B) Landslide generated on the LIA moraine slope and debris accumulation on the ice patch; (C) Debris accumulation on the ice patch with development of frost mounds.

Figure 11. Sketch of the more frequent paraglacial sequences in the small LIA complexes of the Iberian Peninsula mountains: (1) From buried ice to frost mounds develops inside moraine complexes; (2) From buried ice to permafrost-related landforms such as small rock glaciers or protalus lobes; (3) From wall or moraine screes accumulations to solifluction landforms; (4) Lakes formed by glacial retreat and ice patches melt.

Figure 12. Formation of frost mounds by subsurface melt water flowing through the debris cover. When it freezes, ice segregation favours the development of frost mounds on debris accumulations on ice or frozen ground: (A) Frost mounds distributed in the Jou Negro cirque (Picos de Europa) at 2230 m (modified from González-Trueba, 2007); (B) Frost mounds formed in the external side of La Paúl LIA moraine complex, Central Pyrenees, at 2680 m in a permafrost environment (modified from González-García, 2014). (C) Frost mounds developed on debris covering relict ice in Alba cirque (Maladeta massif, Pyrenees) at 2950 m (modified from González García, 2014).

Table 1. Post-LIA paraglacial processes in Sierra Nevada.

Landsystems			Sierra Nevada	
			Processes and landforms	**Elevation (m)**
Glacial to paraglacial	Glacial		Glacial spots formed in the highest northern cirques stretching from Mulhacén to Veleta peaks. The Mulhacén glacier disappeared by 1710 (Oliva & Gómez Ortiz et al., 2012) and the Veleta cirque shrunk gradually until 1940s, when it finally melted (Gómez-Ortiz et al., 2009).	3100-3200
	Ice patches		Ice patches probably existed during the LIA at relatively lower cirques (e.g. Valdeinfierno) below the ELA as well as in concavities in southern slopes above 3000 m.	2900-3000 (N), 3000-3200 (S)
Periglacial	Active processes	Permafrost	Permafrost only exists nowadays as isolated patches at the foot of the northern cliffs in glaciated environments during the LIA. Nowadays is covered by debris and is showing evidence of rapid degradation as shown by multiple collapses and subsidence (Gómez-Ortiz et al., 2014).	3100-3200
		Seasonal frost	Seasonal frozen ground is widespread at elevations above 2500 m from November to May/June, and shorter-lasting at elevations until 1800-2000 m (Oliva et al., 2014b).	Above 2500
		Nivation	Formation of pronival ramparts at the foot of slopes where long-lying snow patches are distributed. Snow avalanche channels in steep slopes.	Above 2800
	Landforms	Active	Permafrost: protalus lobe (Mulhacén cirque), rock glaciers (Veleta cirque). SFG: solifluction landforms, debris flows, centimetric patterned ground features.	3100-3200 Above 2500
		Relict	Pronival ramparts at the foot of slopes where long-lying snow patches existed during the LIA.	Above 2650
Mass movements	Active processes		Rock falls in LIA glaciated environments, debris flows, screes deposits, mudflows. Slow periglacial slope processes related to permafrost creeping and seasonal frost (Oliva et al., 2009, 2014a).	Above 2500
	Landforms	Active	Permafrost: rock glaciers, protalus lobes. SFG: solifluction landforms, debris flows, snow avalanches.	3100-3200 Above 2500
		Relict	Some solifluction landforms at elevations down to 2500 m reactivated during the LIA but they are no longer active under present-day conditions (Oliva et al., 2011; Oliva & Gómez-Ortiz, 2011).	2500-2800
Hydrology	Recent hydrological changes		Formation of one permanent and two semi-permanent lagoons at the LIA glaciated cirque floor of the Veleta cirque. The drainage network adapted to the new geomorphological setting conditioned by the LIA moraines.	3100-3200
	Active processes		Development of short streams within the glaciated environments. Subsurface runoff across the debris-covered slopes connecting the cirque walls with the cirque floors.	3100-3200
	Landforms	Active	Seasonal streams.	
		Relict	Two small lagoons are becoming infilled with sediments.	
Timing	LIA paraglacial processes (XVIII-XIX centuries)		Glacial disappearance of the Mulhacén glacier, which favoured paraglacial activity in this cirque (Oliva & Gómez-Ortiz, 2012).	

	Post-LIA processes (1850-1900)	Progressive shrinking of the Veleta cirque during the XIX century, which remained confined to the NE corner of the cirque (Gómez-Ortiz et al., reviewed).	
	Recent processes (XX century)	Disappearance of the Veleta glacier by 1940s. The last glacier remnants were trapped by paraglacial dynamics (ie rock falls), covering the ice masses. The contact of the debris with the ice mass favoured the formation of isolated permafrost patches that led to the development of a rock glacier at the NE fringe of the cirque.	
	Present-day processes	Degradation of these frozen masses as reported by ground temperatures, geophysical and geomatic measurements (Gómez-Ortiz et al., 2012, 2014). Permafrost and buried ice degradation is also testified by the presence of subsidence and collapse features within the debris cover together with the slowdown movement and vertical shrinking of the rock glacier (Gómez-Ortiz et al., 2014). No permafrost exists at summit level surfaces, at 3400 m (Oliva et al., 2016b).	

Table 2. Main glacial stages in the Pyrenees during the LIA.

Climate stages			**Glacial Stages**		**Paraglacial stages**
Stages (yr AD)		**Climate**	**Advance/Retreat**	**Geomorphic evidence**	
1300-1480		Moderate cooling with increasing climate variability			
1480-1570		Relatively warmer conditions. Low frequency of extreme events.			
1570-1620		Gradual cooling with increasing occurrence of cold spells, snowstorm and enhanced storminess.			
1620-1715	**1620-1680**	Coldest climate conditions Maunder Minimum.	LIA glacier maximum	Frontal and lateral moraines within the cirques and, in some cases, exceeding their limits	
	1680-1715	Severe cold, temperatures ca. 2ºC below present-day values. Prolonged droughts	LIA glacier maximum		F1
1715-1760		Warmer conditions. Low frequency of extreme events.	Glacier retreat		F1
1760-1800		Climate deterioration. Alternation of cold and heat waves. Floods and droughts.	Readvances during the long-term retreat	Formation of numerous small moraine ridges.	F1
1800-1850	**1800-1815**	Highly variable climate.	Glacier advance	Frontal and lateral moraines inside the cirques	

	1815-1835	Cold extreme events.			
	1835-1850	Warming trend. Intense hydrometeorological events.	Glacier advance. Surge glaciers	Flute, push and hummocky moraines	F2
1850-1900		Temperature increase, with short cold phases and extreme events.	Glacier retreat	Minor moraines complexes	F2
1900-1930			Glacial equilibrium		
1930-1970			Glacier retreat with intermittent readvances	Disappearance of several glaciers or transformation into ice patches. Formation of minor moraines around 1945 and 1964	
1970-1980			Last episodes of expansion and equilibrium		
1980-2016			Drastic retreat	Disappearance of tens of glaciers and transformation of others into ice patches.	F3?

Table 3. Post-LIA paraglacial processes in the Pyrenees.

Landsystems			Pyrenees: Processes and landforms	Pyrenees: Elevation (m)
Glacial to paraglacial	Glacial		Glaciers formed in the highest northern cirques above 2700 m. Glacier degradation in the cirques began around 1840, after the last advance. Hummoky moraines in some spots of LIA moraine complexes (González-Trueba et al. 2008; Oliva et al. 2016; Serrano and Martín-Moreno, 2017).	Above 2750.
Glacial to paraglacial	Ice patches		Ice patches derive from LIA glacier shrinking in southern and lower cirques above 2700 m.	Above 2700
Periglacial	Active processes	Permafrost	Nowadays, discontinuous permafrost is located above 2750 in northern slopes and 2850 in southern ones. Nowadays inside LIA moraines permafrost is patched and shows degradation evidences. On north walls the permafrost existence and the recent degradation can be generating rock fall and slides (Serrano et al. 2001; 2009; 2017; Lugon et al. 2004; González-García, 2014; Rico et al. 2017).	Above 2750 until 3000
Periglacial	Active processes	Seasonal frost	Seasonal frozen conditions are widespread between 2100 and 2800 m, lasting ca. 6 months above 2300 m. Patterned ground features related to a seasonal frost regime are located above 2700 m (González-García, 2014).	Above 2100
Periglacial	Active processes	Nivation	Active pronival ramparts form at the foot of slopes where (semi)permanent snow patches exist. Very intense snow avalanche activity in the cirque walls. Nival pavements are distributed inside moraine complexes.	Above 1800
Periglacial	Landforms	Active	Rock glaciers, protalus lobe and frost mounds linked to frozen bodies, the two first permafrost-related landforms. Gelifluction lobes and patterned ground features related to seasonal frozen grounds Debris talus and cones, debris flows, pronival ramparts and snow avalanches channels as nivation and complex landforms. (Serrano et al. 1999; 2002, 2004, González-García, 2014).	Above 2750 Above 2100 Above 1500
Periglacial	Landforms	Relict	Pronival ramparts.	
Mass movements	Active processes		Slope slides on moraines, rock falls, debris flows, scree deposits, mudflows, solifluction.	Above 2500
Mass movements	Landforms	Actives	Landslides features, rock accumulations on ice and slopes, debris flows (channels, levees and fans), solifluction landforms.	Above 2500
Mass movements	Landforms	Relict	Solifluction and nival, recent debris flow features.	Above 1200
Hydrology	Recent hydrological changes		Runoff on moraines, subsurficial runoff through ice and the permafrost table. Formation of lakes and semi-permanent lagoons inside the cirques.	Above 2700
Hydrology	Active processes		Small proglacial and pronival streams with surficial runoff. Subaerial runoff across the sediment cover, with washing out processes.	Above 2550
Hydrology	Landforms	Active	Incisions on deposits, torrential deposits and small alluvial fans, rills and a GLOF.	2100-3000
Hydrology	Landforms	Relict	-	--

Timing	LIA paraglacial processes (XVIII-XIX centuries)	Glacial retreat with proglacial processes and surface runoff on moraines. Hummocky moraines and flutes on saturated ground sediments.	
	Post-LIA processes (1850-1900)	Disappearance of glaciers, ice patches processes and ice degradation on hummocky moraines.	
	Recent processes (XX century)	Disappearance of glaciers and transformation into ice patches. Slope slides and rock falls covering glaciers and ice masses due to very intense freeze-thawing on walls. Isolated permafrost patches and subaerial runoff with creep of frozen bodies, develop of frost mounds and patterned ground features.	
	Present-day processes	Degradation of frozen ground conditions with subsidence and collapses on frost mounds, protalus lobes and moraines. Presence of ice bodies covered by screes and inexistence of permafrost inside the LIA moraines.	

Table 4. Post-LIA paraglacial processes in the Picos de Europa.

Landsystems			Picos de Europa: Processes and landforms	Picos de Europa: Elevation (m)
Glacial to paraglacial	Glacial		Glaciers formed in the highest northern cirques on peaks above 2300 m. Glacier degradation began around 1850 (González Trueba et al. 2006, 2007).	Above 2300
	Ice patches		Ice patches derive from LIA glacier shrinking in southern and lower cirques above 2200 m (González Trueba et al. 2006, 2007; Serrano et al. 2011).	Above 2200
Periglacial	Active processes	Permafrost	There is not climatic/altitudinal permafrost environments, only sporadic permafrost patches and ice caves as subsurface permafrost (González-Trueba, 2006, 2007, Gómez-Lende and Serrano, 2014).	Above 2200-2300
		Seasonal frost	Seasonal frozen conditions are widespread between 1900 and 2600 m, with very active physical weathering processes on cirque walls and moraines. Active cryoturbation and solifluction processes (Pisabarro et al. 2016).	Above 1900
		Nivation	Very intense snow avalanche activity in the cirque walls.	Above 1700
	Landforms	Active	Frost mounds develop on debris cover of LIA ice patches. Patterned ground and solifluction features form on moraines. Talus and debris cones, debris flows. Nivation landforms are very commons, such as pronival ramparts, niches, pavements in snow avalanches channels, and nivokarst microdolines (Góndález-Trueba, 2007). Ice caves are also abundant in the massif (Gómez-Lende, 2016).	Above 2300 Above 2200 Above 1850
		Relict	Patterned ground phenomena exist on flat environments, and solifluction lobes and ploughing boulders develop on gentle slopes in non-calcareous lithologies (González-Trueba 2007; Serrano et al. 2011).	Above 1800
Mass movements	Active processes		Solifluction processes related to snow melt and water availability are very frequent at any altitude, along with debris and mudflows and rock fall on cirques (Brosche, 1994, González-Trueba, 2007; Sanjosé et al. 2016; Pisabarro et al., 2016).	above 1700 Above 2200
	Landforms	Actives	Block accumulations, landslides, debris flows, terraces, turf-banked lobes and debris lobes, widespread at all slopes, aspects and rock type (González-trueba, 2007; Serrano and González-Trueba, 2011; Sanjosé et al. 2016; Pisabarro et al., 2016).	Above 1400
		Relict	Solifluction and debris lobes, ploughing blocks on gentle slopes.	Above 1380
Hydrology	Recent hydrological changes		Drainage changes in glaciokarstic depressions with accelerated ice loss in ice caves (Gómez-Lende, 2016).	Above 2200
	Active processes		Nivokarstic erosion and torrential runoff.	
	Landforms	Active	Supra-ice runoff.	
		Relict	-	
Timing	LIA paraglacial processes (XVIII-		Glacial retreat.	

	XIX centuries)		
	Post-LIA processes (1850-1900)	Disappearance of glaciers, ice patches processes and ice degradation.	
	Recent processes (XX century)	Slope slides and rock falls covering glaciers and ice masses due to very intense freeze-thawing on walls. Isolated permafrost patches and subsurface runoff with creeping of frozen bodies, development of frost mounds and patterned ground features.	
	Present-day processes	Ice patches degradation with ice and snow burial by rock fall, debris flows and slope slide, collapses on frost mounds, rock fall and landslides on moraines slopes.	

Table 5. Summary of the landsystem tipology involved in the Iberian Peninsula high mountain.

	Topography	Thermal Regime		
Glacial landsystem	Plateau icefields	Active temperate glaciers	Polythermal glaciers	Polar continental
	Glaciated valleys			
	Mountain icefields			
	GLOF dominated			
	Surging glaciers			
	Fjords			--
Paraglacial landsystems	Rock slopes			
	Drift-mantled slope			
	Glacier forelands			
	Alluvial			
	Lacustrine			
	Coastal			
Periparaglacial landsystem	Plains	Temperate environments	Seasonal frozen ground	Polar permafrost
	Mountains			

* Gray boxes represent paraglacial dynamics observed in Iberian high mountains.

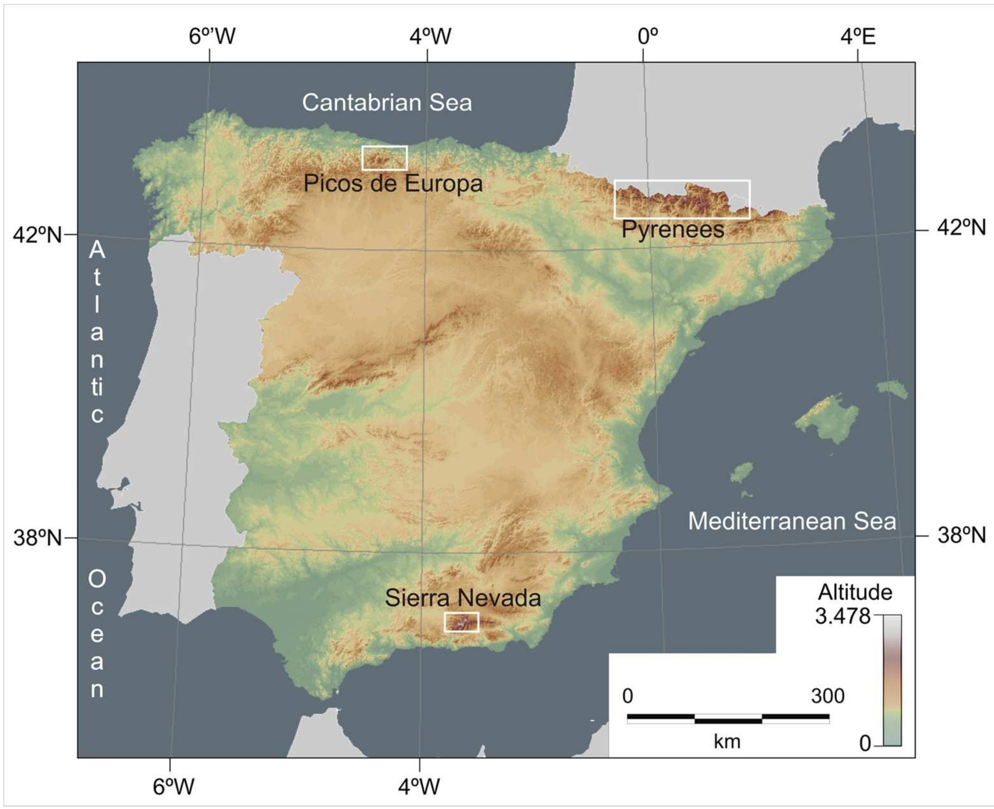

Figure 1. Location of the main mountain ranges in the Iberian Peninsula examined in research.

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