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THE DEGLACIATION OF SIERRA NEVADA (SPAIN), SYNTHESIS OF THE KNOWLEDGE AND NEW CONTRIBUTIONS

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ABSTRACT. *The large number of studies of Sierra Nevada's environmental history since the Last Pleistocene glacial period makes it one of the most intensively analysed massifs in the Iberian Peninsula. The early geomorphological descriptions have been complemented in recent decades with absolute dating techniques that have allocated in time the sequence of environmental events occurred in Sierra Nevada during the last millennia. The maximum expansion of the glaciers during the Last Glaciation took place around 30-32 ka, with a subsequent re-advance by 19-20 ka. The process of deglaciation was very fast, and around 14-15 ka the ice had almost completely retreated from the massif. Since then, with greater or less intensity and extent, periglacial processes have driven the environmental change in the massif. The coldest and wettest phases during the Holocene have favoured the development of small glaciers in the highest northern cirques. The last of these phases was the Little Ice Age, where abundant historical sources and sedimentary records exist. During the mid XX century the last glaciers melted, resulting in the complete deglaciation of the massif.*

La deglaciación de Sierra Nevada (España), síntesis del conocimiento y nuevas contribuciones

RESUMEN. *Sierra Nevada es uno de los macizos ibéricos con mayor información de su último periodo glaciar pleistoceno. El análisis geomorfológico de campo se ha ido completando durante las últimas décadas con técnicas de datación absolutas que han permitido localizar en el tiempo los acontecimientos ambientales acontecidos en Sierra Nevada durante los últimos milenios. La máxima expansión de los hielos durante la Última Glaciación tuvo lugar en torno a 30-32 ka, con un reavance posterior en torno a 19-20 ka. La deglacia-*

ción, entonces, fue rápida y en torno a 14-15 ka el macizo estaba ya prácticamente deglaciado. Desde entonces, con mayor o menor intensidad y extensión, los procesos periglaciares controlan los cambios ambientales en el macizo. En la actualidad éstos fijan su límite inferior en torno a los 2500 m. Durante el Holoceno las fases más frías y húmedas han conllevado la aparición de pequeños focos glaciares en los circos septentrionales de mayor altura. De ellas, la Pequeña Edad de Hielo ha sido la última y de la que mayor información se dispone, ya sea a través de fuentes históricas como de registros sedimentológicos. A mediados del siglo XX desaparecen los últimos vestigios glaciares, conllevando la deglaciación completa de Sierra Nevada.

Key words: Sierra Nevada, Quaternary, glacial processes, periglacial processes, absolute dates, historical documents.

Palabras clave: Sierra Nevada, Cuaternario, glaciarismo, periglaciarismo, dataciones absolutas, documentos de época.

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1. Introduction

The deglaciation of the mountains in the European alpine belt is a large-scale process that has taken place at different time periods. Depending on the latitude, altitude and climatic conditions prevailing in the different massifs, this process has already been completed in the Iberian Peninsula or is still currently underway. This is the case of the Pyrenees, where small glaciers in disequilibrium still exist in some cirques, being the legacy of colder and wetter periods in historical times (González Trueba *et al*., 2008).

Most Iberian mountains with altitudes over 2000 m hosted glaciers during the Pleistocene cold stages (Domínguez-Villar *et al*., 2013). The intensity and extent of the Last Glaciation erased the traces of earlier glaciations, so that little geomorphological and sedimentological evidence remains of these, as in e.g. Sierra Nevada (Gómez-Ortiz and Pérez González, 2001). In contrast, the abundant landforms and deposits of glacial and periglacial origin from the last Pleistocene glaciation facilitate a better understanding of both the time scale and of the environmental conditions of the respective morphogenic domains.

Advances in dating techniques in recent years has made it possible to define a timeline for the maximum advance of the glaciers and their gradual retreat. Nevertheless, the wide spectrum of climatic conditions in the Iberian Peninsula –conditioned by its complex orography and altitude, orientation, oceanic and/or continental influence– has determined notable divergences in the age of the maximum ice extent in the different mountain systems, as occurs in the NW quadrant of the Iberian Peninsula in contrast with other glaciated massifs (Delmas *et al*., 2008, 2011; García-Ruiz *et al*., 2010; Palacios *et al*., 2011, 2012, 2014; Serrano *et al*. 2013).

The main aims of this article are:

- to synthesize the chronology of deglaciation phases in Sierra Nevada since the last Pleistocene glacial period and their morphological repercussions;
- to examine the environmental sequence in the natural systems of the Sierra Nevada summit areas during the last glacial period; highlight the glacial behaviour in the Little Ice Age (LIA) in Sierra Nevada, and
- to integrate the environmental dynamics in Sierra Nevada into the evolution observed in other mountains in the Iberian Peninsula and southern continental Europe.

2. Study area

Sierra Nevada, in the SE Iberian Peninsula, forms part of the axis of the Baetic System and is its highest area, with ridgelines exceeding 3300 m (Mulhacén, 3478 m; Veleta, 3398 m; Alcazaba, 3371 m) (Fig. 1). Sierra Nevada is a robust alpine massif, armoured in summit areas by series of metamorphic rocks in a Paleozoic substratum, with interspersed emergent micaschist series (Díaz de Federico *et al*., 1980). The morphostructure of Sierra Nevada is made up of different mantles, which include important faults and fractures that have conditioned the river network layout (Sanz de Galdeano *et al*., 1999), and of the remnants of summit erosion surfaces. The glaciation remained confined within the summit area, where glacial and periglacial landforms are widespread.

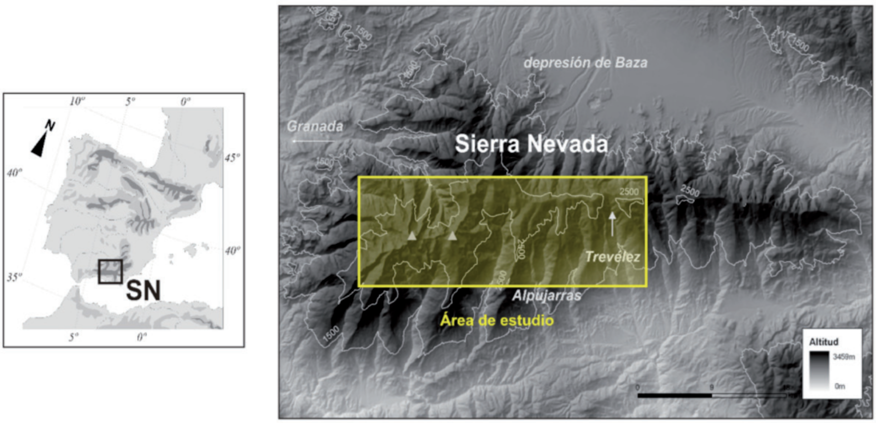

Figure 1. Location of Sierra Nevada within the Iberian Peninsula and study areas in the massif.

The current climatic regime in Sierra Nevada corresponds to a semi-arid cold mountain climate with mean annual temperatures around 0ºC on the summit areas at the highest elevations (Salvador-Franch *et al.*, 2011) and 4.4ºC at 2500 m. The estimated annual precipitation at these levels is around 710 mm (Oliva, 2009). Snow cover starts in November above 2400 m and lasts until May-June, when snow patches only remain at elevations above 2900 m. In snowy years they can persist the whole summer in nivation and glacial cirques, as it occurred in 2010, 2011 and 2013. These climatic conditions suggest that periglacial processes characterize the geomorphic dynamics in the highest lands in Sierra Nevada. Thus, in general terms, the area currently affected today by periglacial activity coincides with the predominantly glaciated surface during the Last Glaciation (Gómez-Ortiz and Salvador-Franch, 1992; Oliva *et al.*, 2014). The current characteristic landscape of these mountain areas is predominantly bare ground or sparse vegetation as open cover, except in topographical depressions well supplied by late snowmelt waters, where grasslands with multiple endemisms are distributed (Molero Mesa and Pérez Raya, 1987). These endemisms are a consequence of the role played by Sierra Nevada as an ecological refuge during the Quaternary cold stages and the subsequent adaptation of the plant species to the prevailing climatic conditions (Blanco-Pastor *et al.*, 2013).

The glaciers in Sierra Nevada, the southernmost glaciers in Europe, remained confined within the high valleys and valley heads, generally above 2500 m, without reaching the low lands surrounding the massif (Fig. 2). Nevertheless, in some cases, such as the alpine-type glaciers in ravines with steep slopes, the ice masses reached altitudes below 2000 m. The glaciated area must have covered around 320 km^2 including the north and the south slopes, from Puerto de Trevélez (2799 m), in the east, to Cerro del Caballo (3011 m), in the west. This area, which coincides with the western fringe of the Sierra, includes the main valleys and their respective headwalls and during this stage was the home of important glacial systems including Trevélez, Siete Lagunas, Poqueira (Cornavaca, Lagunillos, Peñón Colorado, Veleta, Río Seco, Naute), Lanjarón, Dílar, Monachil and Genil (Hoya de la Mora, San Juan, Guarnón, Valdeinfierno, Valdecasillas, Vadillo).

The existence of glaciation in Sierra Nevada was first referred to by Boissier (1845), who mentioned the active cirque glacier enclosed in Corral del Veleta, at the head of the Barranco del Guarnón. References to Quaternary glaciations came soon after from Schimper (1849). From then on, especially after the observations made by Macpherson (1875) on the origin of the lakes in the Sierra, our understanding and explanation of glaciological, morphological and environmental events has gradually continued to evolve up to the present (Obermaier, 1916; Dresch, 1937; García Sainz 1947; Paschinger 1957; Messerli 1965), with the research also becoming gradually more precise and with greater scientific validity (Gómez-Ortiz, 1987, 2002). In this context, it is particularly worth noting the remarkable range of research conducted since the 1980s, with detailed analyses of the glaciated valleys and mapping of the glacial and periglacial morphology of the Sierra Nevada peaks (Gómez-Ortiz, 2002). This enabled a first approach to a precise timeline of glacial records (moraine deposits and abrasion surfaces in valleys and cirques) using cosmogenic techniques (^{36}Cl) (Gómez-Ortiz *et al.*, 2012). In addition, Holocene paleoenvironmental evolution was also approached through sedimentological analyses (lakes and solifluction lobes) and [14]C radiocarbon dating (Oliva, 2009; Oliva *et al*., 2011, 2014). In recent years, with the support of historical documentation and morphological records, the recent evolution of the historical glaciation of the Sierra linked to the LIA has also been confirmed and its spatial extension defined (Gómez-Ortiz *et al*., 2009).

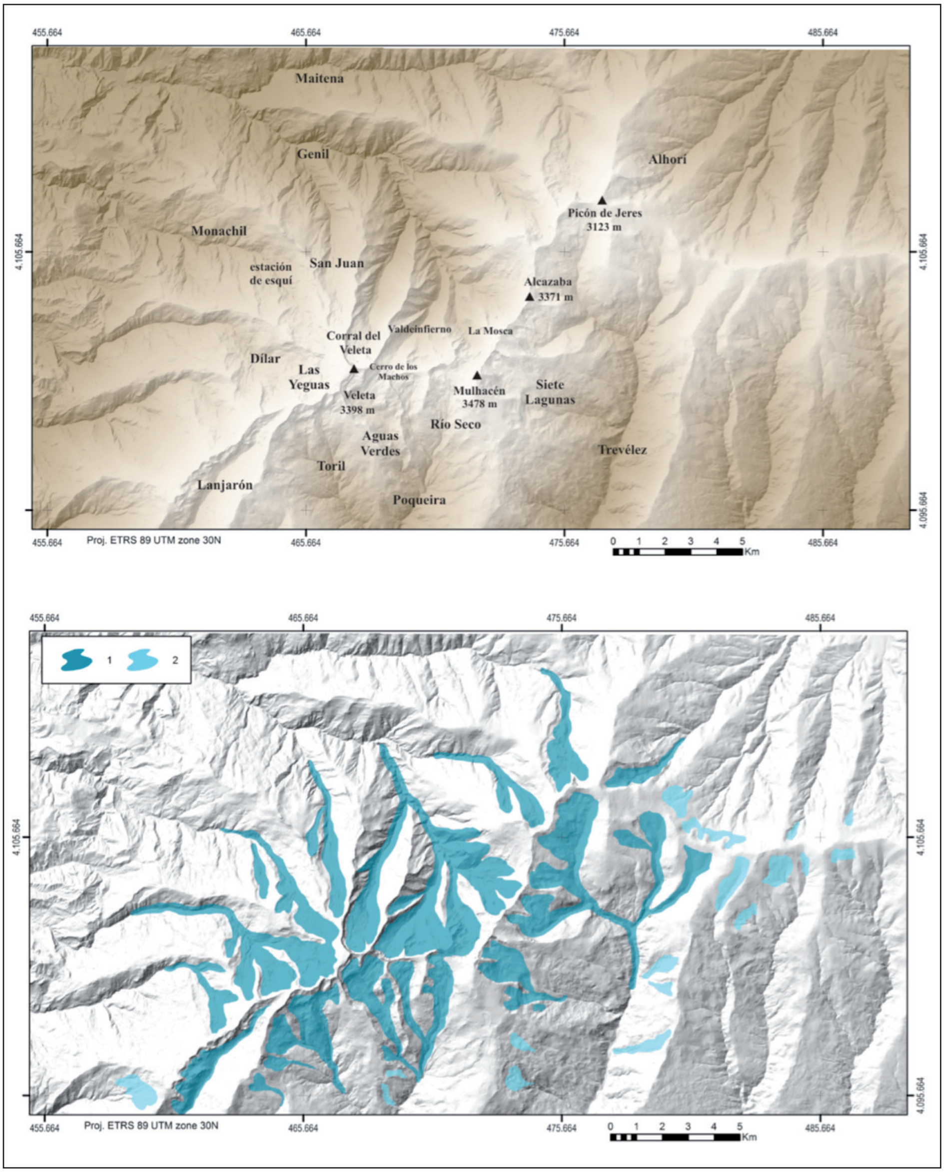

Figure 2. Maximum extension of the glaciers in Sierra Nevada during the Last Glaciation (figure below), and location of the sites mentioned in the text (figure above).

3. Materials and methods

This paper, which is presented as a synthesis and includes new data contributions, takes into consideration all the recent research carried out to date relating to the Quaternary glacial evolution of Sierra Nevada, and in particular to its deglaciation process. Because of its relevance, the highest summit sector has been considered, in particular the Poqueira (side valleys of Mulhacén, Río Seco and Veleta), Dílar and Monachil valleys, as the best representation of the glaciated area in this massif. Abundant geomorphological information on these valleys is available (Gómez-Ortiz, 2002) as well as an absolute chronology of their glacial evolution. Of particular interest here is the updated research by Oliva *et al*. (2014) which compiles the results obtained by absolute dating techniques used up to the present in Sierra Nevada as a whole, including: ^{14}C dating (41 samples - conventional and AMS), cosmogenic dating of exposed glacial surfaces (13 samples), ^{210}Pb dating (3 samples) and ^{137}Cs dating (1 sample). With reference to events in the historical era, above all to the cirque glaciers which developed in the LIA and their evolution over time, information obtained from documentary sources during the Arab era to the mid-20th century has also been analysed and evaluated (Gómez-Ortiz *et al*., 2006, 2009), as well as results obtained from the current disintegration of the remnants of this historical glacial ice (Gómez-Ortiz *et al*., 2014).

4. Results

The most important studies of the glaciation in Sierra Nevada suggest the existence of different glacial periods during the Pleistocene (e.g. García Sainz, 1943; Hempel, 1960; Messerli, 1965; Lhenaff, 1977), although the best documented events in different time periods based on recent absolute dating start with the Last Glaciation (Gómez-Ortiz *et al*., 2012). Therefore, when discussing the history of the different glacial systems affecting the Sierra Nevada during the Quaternary, we differentiate between the glacial events occurring before and those that took place during the Last Glaciation.

4.1. Glacial stages previous to the Last Glaciation

Ever since the studies by Obermaier (1916) the existence of pre-Würm glaciations (using alpine terminology) in Sierra Nevada has been suggested, as occurred in other Iberian massifs, particularly in the Pyrenees (e.g. Solé Sabarís, 1951). In the case of Sierra Nevada these interpretations have always been deduced from the remains of erosive reliefs associated with the action of glacial ice, particularly from striations on slopes, altitude of cirques, erosive traces on gravel and boulders in moraines as well as the state of preservation of the landforms. The presence of some or all of these records in the valley morphology, normally in the lowest glaciated environments, suggested the existence of the Riss, Würm and Late Glacial stages in Sierra Nevada. However, no precise absolute chronology to support this interpretation was produced, only a relative timeline based on morphological and sedimentological differences in the erosive and depositional forms of the glaciated area. From the 1970s onwards there was a tendency to adjust this timeline with pollen record data from the nearby Padul peat bog, which includes paleoenvironmental events from 46,440 BP using analysis of taxa in the biostratigraphic core samples from cold, warm and hot-humid periods (Florstchütz *et al*., 1971; Pons and Reille, 1988; Ortiz *et al*., 2004).

Sánchez Gómez (1990) suggested possible ancient glaciations in Sierra Nevada, by establishing relationships between the geomorphology and soils of the Lanjarón valley where a sequence of four cold periods and glacial advances were differentiated, based on the degree of evolution of the paleosols existing on moraines and bare summit surfaces without glacial till. Each cold phase was interpreted as being followed by different edaphogenic phases, suggesting that glacial events were interspersed with interglacial periods.

4.2. Last Glaciation and Late Pleistocene cold crises

During the Last Glaciation, which can be correlated with the former alpine Würm chronology, the glaciers in Sierra Nevada were restricted to the summit area and adapted to cirque depressions and hollows on the high slopes with occasional transfluence occurring between different cirques. This compartmentalized glaciation was subordinated to the preglacial relief, and left erosive records (U-shaped valleys, polished rock thresholds, arêtes on watersheds, over-deepened basins, etc.) and depositional records (mainly moraines) common throughout the glaciated area, which gave the overall relief in this summit area of Sierra Nevada its alpine morphology (Fig. 3).

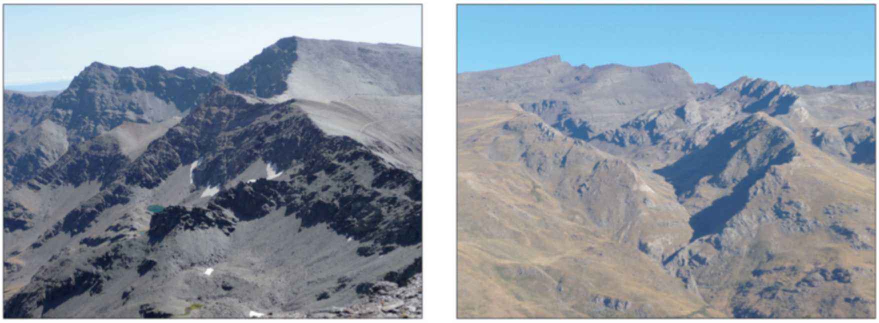

Figure 3. Landscape of the high lands of the massif: Mulhacén (left) and Veleta valley (right).

The valleys sampled for cosmogenic dating purposes were Poqueira (Río Seco and Naute-Mulhacén side valleys), Monachil and Dílar (Table 1). Sampling has also been recently carried out in Lanjarón, San Juan, Hoya de la Mora and Poqueira, Hoya del Capitán sector, downstream from the Poqueira refuge, although chronological data are not available for all these sites.

Table 1. ^{36}Cl exposure ages, sample type and sample location. Ages are reported assuming 0 erosion rates. Errors correspond to the analytical uncertainty of the AMS ^{36}Cl determination (one standard deviation).

Sample	Sample type	Zero erosion age (ka)	Latitude (°N)	Longitude (°W)	Elevation (m)
MULH-M-1	moraine boulder	11.6 ± 0.5	37° 01’ 48.10”	3° 19’ 46.90”	2461
MULH-M-2	moraine boulder	30.0 ± 1.1	37° 01’ 40.10”	3° 19’ 37.60”	2448
MULH-BR-3	polished bedrock	12.0 ± 0.6	37° 02’ 50.05”	3° 19’ 26.47”	2912
MULH-BR-4	polished bedrock	14.6 ± 0.8	37° 03’ 01.71”	3° 19’ 27.49”	3004
MULH-M-5	moraine boulder	14.7 ± 0.7	37° 03’ 10.90”	3° 19’ 47.88”	3036
MULH-M-6	moraine boulder	8.7 ± 0.4	37° 03’ 10.27”	3° 19’ 50.48”	3090
SECO-M-1	moraine boulder	14.2 ± 0.8	37° 01’ 43.40”	3° 20’ 08.50”	2423
SECO-M-2	moraine boulder	13.4 ± 0.7	37° 01’ 42.40”	3° 20’ 11.10”	2437
SECO-M-3	moraine boulder	19.0 ± 1.0	37° 01’ 40.40”	3° 20’ 12.40”	2446
SECO-BR-4	polished bedrock	12.7 ± 0.6	37° 02’ 58.03”	3° 20’ 41.63”	2984
SECO-RG-5	rock glacier boulder	9.6 ± 0.4	37° 02’ 46.75”	3° 20’ 37.84”	2895
DILAR-RG-1	rock glacier boulder	12.0 ± 0.5	37º 03’ 12.57”	3º 24’ 14.25”	2583
DILAR-RG-2	rock glacier boulder	9.1 ± 0.7	37º 02’ 49.57”	3º 23’ 55.41”	2784
DILAR-RG-3	rock glacier boulder	7.5 ± 0.4	37º 02’ 40.99”	3º 24’ 13.17”	2870
DILAR-BR-4	polished bedrock	14.3 ± 0.5	37° 03’ 32.66”	3° 23’ 02.38”	2828
DILAR-BR-5	polished bedrock	15.4 ± 2.2	37° 03’ 27.70”	3° 22’ 55.37”	2873
DILAR-VP-6	bedrock	32.1 0.8	37° 03’ 34.99”	3° 22’ 10.77”	3211
MONA-M-1	moraine boulder	13.9 0.7	37° 05’ 40.17”	3° 24’ 19.49”	2006
MONA-M-2	moraine boulder	19.6 0.8	37° 05’ 42.70”	3° 24’ 22.64”	1975

The oldest dating of moraine remains in valleys on the south face of the Sierra show the maximum expansion of the glaciers during the Last Glaciation at approx. 30-32 ka (the upper Poqueira Gorge, Naute-Mulhacén lateral Valley, 2448 m) (Fig. 4). For the rock substratum, the oldest cosmogenic dating coincides on the western face of El Veleta hörn, (3211 m), obtaining an age of 32 ka (Gómez-Ortiz *et al.*, 2012).

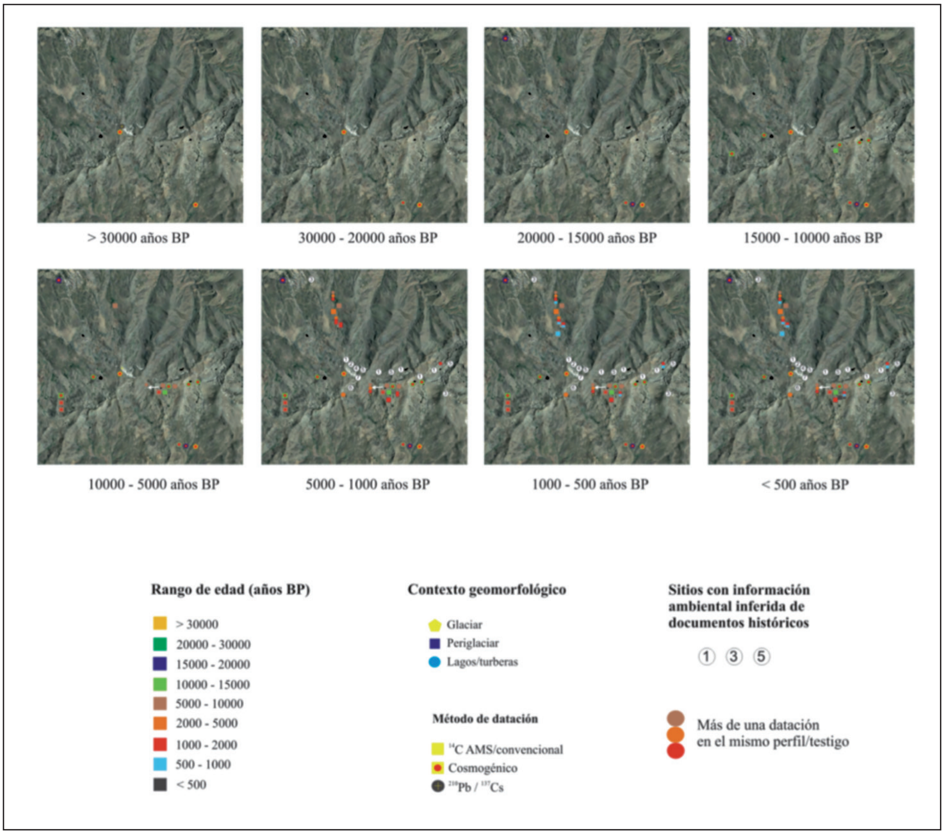

Figure 4. Datings according to the age range, geomorphological environment and dating method.

In all the valleys examined with chronological results there are no ages available between 30 and 20 ka, which prevents any evaluation of the glacial masses on the massif during this period. But from 20-19 ka several records in the glaciated area distributed across valleys and cirques suggested a phase of second glacial re-advance.

The dates obtained from 20-19 ka are repeated in different valleys (Monachil, west-facing and Río Seco, south-facing). In the Monachil valley a left-front lateral moraine segment at altitude 1975 m near the Pradollano winter resort obtained 19.6 ka (Fig. 5). And in Río Seco, in the lowest reach near the confluence with the Naute River, a stepped sequence of lateral moraine segments at different altitudes yielded ages of 19.0; 13.4 and 14.2 ka. Immediately afterwards, the glacier installed in each valley tended to retreat towards the cirque walls leaving erosive records on the bedrock surfaces. This occurred in the interior of the Naute-Mulhacén valley (threshold at 3036 m, 14.6 ka), at the head of the Dílar cirque, in the rocky steps of Las Yeguas (15.4 and 14.3 ka) and in Río Seco (12.7 ka).

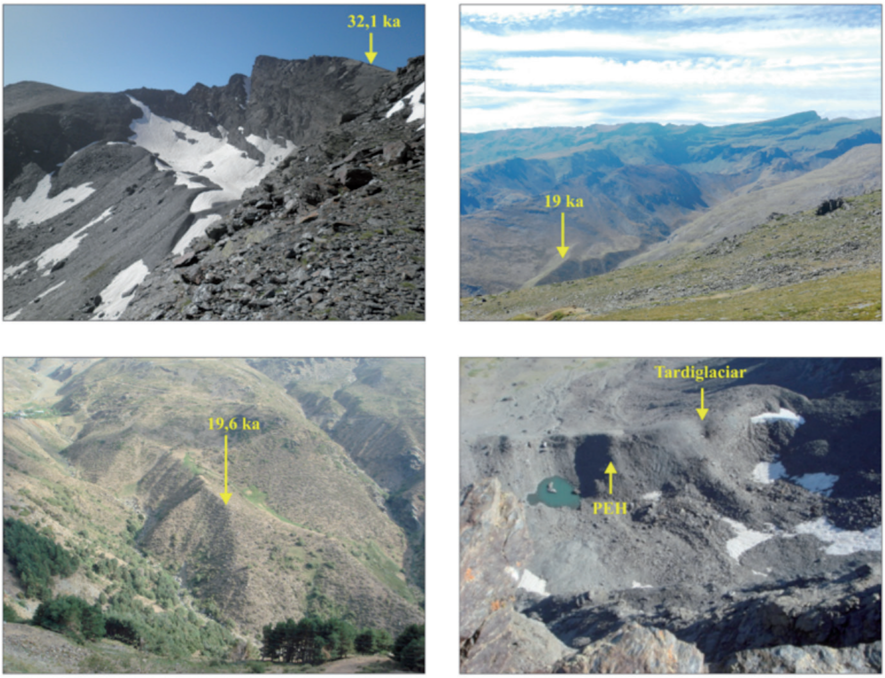

Figure 5. Location and results of the datings in some areas of the massif: Veleta peak (above, left), lateral moraine in Rio Seco valley (above, right lateral moraine in Monachil valley (below, left) and moraine formed during the Late Glacial and LIA in the Veleta cirque (below, right).

The final phase of the Last Glaciation does not seem to show any notable glacial repercussions on the peaks of the Sierra. It must have been most intense on the north face inside the cirques, e.g. in Hoya del Mulhacén and Corral del Veleta, and to a lesser extent on the south face in La Caldera cirque, with all glaciers enclosed by terminal moraine ridges. No absolute dating exists for these morphologies, making it difficult to establish the chronology of their formation. Relevant information is only available for La Caldera, with 14.7 ka, which may be considered coherent if we take into account that for the adjacent Rio Seco cirque a soil formation has been detected at 12.9 ka BP (Oliva, 2009; Oliva *et al*., 2014), suggesting that this glacier cirque remained ice-free during that period.

The deglaciation of the massif was completed immediately afterwards as confirmed by cosmogenic dating carried out on stable blocks located in different generations of rock glaciers. This occurs at the head of the Dílar, in the Cascajares del Cartujo, where the succession of arcs forming the relief offers a range of ages, with 12.1 ka in the oldest generation at altitude 2583 m; 9.1 ka in the intermediate and 7.5 ka in the most recent at 2870 m. These morphologies are also found at similar altitudes on the south face with ages of 9.6 ka obtained for Río Seco and 8.7 ka for Mulhacén valleys.

4.3. The Holocene and the Little Ice Age

At the start of the present interglacial, the increase in temperature conditioned the existing geomorphological dynamics in Sierra Nevada. The Holocene is characterized by the predominance of periglacial processes in the massif, with only ephemeral appearances of glaciers in the highest northern cirques (Oliva *et al*., 2014).The stabilization of the rock glaciers around 7 ka BP occurred in parallel to the formation of histosols with very high organic material content on valley bottoms on both slopes. These conditions predominated during the Middle Holocene, implying prevalent geomorphic stability, extension of scattered vegetation on slopes and formation of grasslands (known here as *borreguiles)* in areas with flat topography and abundant supply of meltwater. During the last 4 millennia the aridity in Sierra Nevada has intensified as shown by lacustrine sediments and distribution of solifluction records in the massif (Oliva *et al.,* 2011). However, the sedimentary sequences show significant changes in the prevailing environmental conditions over 2500 m in Sierra Nevada during these millennia. In this context, a series of cold wet periods is detected, with enhanced periglacial activity extending to lower altitudes. At the same time, warmer periods promoted intense edaphogenesis, resulting in greater geomorphic stability and increased vegetation colonization (Oliva, 2009b).

Based on the analysis of the lacustrine sediments of the Laguna de la Mosca, Oliva and Gómez-Ortiz (2012) have detected the existence of a glacier at three different times over the last three millennia in the Hoya del Mulhacén, between 2800-2700, 1400-1200 and 510-240 yrs cal BP. During these short time periods the climatic conditions must have been colder and wetter than present-day. The most recent and intense of these periods corresponds to the LIA in Sierra Nevada, well documented in historical texts, above all by references to perennial snow patches (cirque glaciers) located below the highest summits of the northern slopes, between the Mulhacén and Veleta peaks (Madoz, 1849).

5. Discussion

The glaciers in Sierra Nevada shaped the summits of this massif above 2500-2600 m. The areas affected by glacial processes were conditioned by the preglacial relief, namely by the valley network and its tributaries and their exposition to the Atlantic or Mediterranean influences. The Last Glaciation generated cirque and alpine valley glaciers and also hanging glaciers on valley sides, disconnected from the main glacial valley. The summit surfaces did not host ice fields, as shown by the lack of traces of glacial abrasion as well as the sediments overlaying older edaphic horizons than those found in the valley moraines (Sánchez-Gómez, 1990). These high plateaus must have acted as cryoplanation surfaces during the Last Glaciation.

The abundant depositional and erosive glacial, periglacial, lacustrine and peat records distributed in the glaciated domain of the valleys studied makes possible to establish a detailed timeline regarding the environmental evolution of Sierra Nevada since the Last Glaciation.

The maximum extent of the glacial ice in Sierra Nevada (32-30 ka at the Poqueira and Naute/Mulhacén valleys) precedes the global Last Glacial Maximum, probably in response to higher precipitation indices in the massif than those recorded during the global temperature minimum (Gómez-Ortiz *et al*., 2012). However, it is uncertain what happened with the glacier systems between 30 and 20 ka. The permanence of cold temperatures during the final millennia of the last North Atlantic glaciation –also detected in isotopic records of the Mediterranean Sea (Hayes *et al*., 2005; Mikolajewicz, 2011)– suggests that the glaciers may not have disappeared in this phase, although they did experience minor advances and retreats (Oliva *et al*., 2014). In fact, these must have been of less spatial significance than the advance recorded in 19-20 ka BP, close to the maximum extent reached around ten millennia earlier (Gómez-Ortiz *et al*., 2012). This second maximum advance phase is detected in other Iberian massifs with Atlantic climatic influence (Moreno *et al*., 2010; Ruiz-Fernández, 2013; Serrano *et al*., 2013). It corresponds to the maximum expansion of glacier ice in central and northeastern Iberian massifs (Palacios *et al*., 2011, 2012, 2015).

The main deglaciation in Sierra Nevada started around 19-18 ka, and occurred synchronically in most of the glaciated mountains in the Northern Hemisphere during the Last Deglaciation (Clark *et al.,* 2009). In Sierra Nevada, the ice retreated rapidly towards the headwalls. This was the case of the Río Seco cirque near the lake, where polished rock at an altitude of 2984 m yielded an age of 12.7 ka, and 12.9 ka BP for the deepest edaphic layer in a solifluction lobe of the same cirque (Oliva, 2009). The same occurred in the Poqueira basin, downstream from the Caldera cirque, where the polished rock thresholds of the river bed at elevations around 3000 m resulted in ages of 14.6 and 12 ka. This also occurred in the Dílar valley, where the base of the cirque at an altitude of 2850 m became ice-free at 15.4 ka and 14.3 ka, according to the age of the polished rock near Las Yeguas Lake (15.4 ka and 14.3 ka). (Gómez-Ortiz *et al*., 2012). Terrestrial (Ortiz *et al*., 2004) and marine (Cacho *et al*., 2000; Fletcher *et al*., 2010) records of the Sierra Nevada regional area indicate a notable temperature increase during this period, which would have led to a rapid reduction of the glaciated area and the implementation of periglacial processes in the summit areas of the massif.

The glacial imprint left by the Late Glacial cold phase in Sierra Nevada is limited to the development of small moraine ridges in the highest northern cirques and to the formation of rock glaciers (Gómez-Ortiz *et al*., 2012). In contrast to what occurred in the Pyrenees or in the Alps where the Younger Dryas resulted in significant glacial advance (Pallàs *et al*., 2006; Ivy-Ochs *et al.,* 2008, 2009), in Sierra Nevada the glacial ice was confined, particularly at the head of the steep northern valleys, conditioned by the morphotopographic restrictions of the relief and the prevailing cold and dry conditions (Oliva *et al*., 2014). These conditions led to a general reactivation of periglacial processes, very active in the interior of the cirques (Palade *et al*., 2011; Gómez-Ortiz *et al*., 2013). The most significant morphologies created during this phase correspond to the rock glaciers located on the cirque walls. In the Dílar cirque, where these are most well developed, they were active between 12 and 7.5 ka.

The onset of the Holocene conditioned an increasing altitude of the periglacial activity in Sierra Nevada, now located in the highest summit belt, while vegetation began to colonize valley sides and slopes above 2500 m, forming the current grasslands (Oliva, 2009). However, during the Early Holocene some rock glaciers at altitudes of 2800 m on the north face, e.g. in the Dílar cirque, maintained a certain dynamism until 7.5 ka, when they stabilized (Gómez-Ortiz *et al*., 2012). Since then, the prevalence of less rigorous climatic conditions has allowed the periglacial domain to control the biophysical dynamics in the massif (Oliva, 2009). Nevertheless, sedimentological and geochronological analysis of the solifluction landforms revealed alternating climatic periods from the Mid-Holocene until the present, characterized by warmer/colder phases with oscillating moisture conditions. The warmer phases resulted in a relative extension of the scattered vegetation cover and intensification of the edaphic processes; the colder phases meant a reactivation of the periglacial slope processes (e.g. solifluction), with greater mineral remotion and mechanical activity on the slopes (Oliva *et al*., 2011). This occurred parallel to intensifying aridity in Sierra Nevada from 4.2 ka cal BP (Oliva *et al*., 2011) and to the increasing desertification in northern Africa during the Middle Holocene (Gasse, 2000) together with increased variability of the Earth's climate (Mayewski *et al*., 2004). The last of these cold phases occurred in historical times and corresponds to the LIA.

During the LIA (14th -19th cent.) Sierra Nevada hosted the southernmost glaciers in Europe. These were small glaciers enclosed in the highest basins at the valley cirques, especially in the Picón de Jeres and Picacho del Veleta areas. The existence of these glaciers is well documented in palynological and lake sediment records (Esteban, 1995; Oliva, 2009a), as well as in contemporary writings (Boissier, 1845; Madoz, 1849). The Corral del Veleta glacier was the most important and longest lasting of all these historical glaciers, with its remnants persisting until the mid-20th century (García Sainz, 1947). Precise information on its existence and evolution is available since 1754 (Ponz, 1754).

There is currently no visible trace of this historical glaciation but frozen remains of the glacier hosted inside the Corral de Veleta at that time are still preserved in the ancient Quaternary cirque of the Guarnón glacier, where relict glacier ice and permafrost persist under a rock glacier at an altitude of 3100 m (Gómez-Ortiz *et al*., 2013). Physical monitoring of these frozen bodies has been carried out since the year 2000, confirming an ongoing process of deterioration resulting in reduction and compartmentalization, both in surface area and thickness. This deterioration is basically related to the lack of snow on the ground during the summer, which allows the external thermal wave to penetrate the active layer reaching the glacial ice and permafrost table (Gómez-Ortiz *et al*., 2014).

6. Conclusions

Sierra Nevada forms a high semi-arid massif located in the extreme SW of the Mediterranean alpine belt, which has been affected by ancient glaciations although absolute dating of their traces has not yet been obtained. The available environmental and chronological information does however enable the reconstruction of the precise environmental sequence that took place from the maximum ice extent during the Last Glaciation. This is explained by the abundant natural records analysed (erosive and depositional landforms in summit areas) facilitating information and timing of glaciological and geomorphological events in this glacial period and during the Holocene. The geomorphological significance of the LIA on the summits of this mountain in historical times has also been determined in this case from complementary written documents of the time and also again from natural records.

The maximum advance of the alpine glaciers channelled through the steep valleys of Sierra Nevada occurred around 30-32 ka, with a later re-advance at 19-20 ka. Based on the erosive records on the valley bottoms, the glacial retreat towards the headwall must have been rapid at around 14-15 ka. From this date onwards the glacier ice was already retreating to the area next to the cirque walls with a favourable orientation. This can be seen in Río Seco where the glacial erosion of the bedrock has been dated at 12.7 ka, and paleosol at 12.9 ka BP. This environmental change must have led to prevailing periglacial processes on the summit areas of Sierra Nevada, which extended over the areas that had recently become ice-free.

The Late Glacial in Sierra Nevada promoted an ephemeral presence of small glaciers in the highest cirques, and the widespread presence of rock glaciers favoured by the prevailing cold and dry climate conditions. The orientation of the mountain slopes and the higher amounts of precipitation in the area of the massif with greater climatic influence of the Atlantic Ocean explain this fact. This can be seen in the north face of the Sierra, where rock glaciers developed inside the cirque walls; in the case of El Dílar site, rock glaciers must have remained active until 12-7.5 ka, although with decreasing intensity.

Periglacial processes gradually retreated to higher levels during the Holocene, with decreasing intensity, especially in the lower areas of the Sierra, where the vegetation started to stabilize. Nevertheless, during the Holocene there is evidence of alternating colder/warmer periods with fluctuating humidity conditions. Above 2500 m this is reflected in greater geomorphic activity linked to periglacial dynamics with less vegetation presence during cold phases and an expansion of the vegetal colonization during warm periods with the formation of highly organic soils on the valley bottoms. All this occurred in spite of the trend towards greater aridity on a millennium scale in the south of the Iberian Peninsula.

The coldest and wettest Holocene phases facilitated the secular reappearance of small cirque glaciers in the north facing cirques at the highest altitudes. This is confirmed by sedimentological data from Laguna de la Mosca in the Hoya del Mulhacén, where a small glacier was active between 2800-2700, 1400-1200 years. ago and during the LIA. Cirque glaciers were also generated precisely in these enclosed areas during the LIA as a result of the combined action of ice, snow, cold and wind. The most representative of these glaciers, in the Corral del Veleta, was described repeatedly in the contemporary literature. From the information provided by these documents and by the lacustrine sediments from the La Mosca lake, we can deduce that the LIA was the coldest and

CIG 41 (2), 2015, p. 409-426, ISSN 0211-6820

wettest phase of the last three millennia in Sierra Nevada, with annual mean temperatures at least 0.93ºC lower than those presently recorded.

Since the late 19th century the temperature increase conditioned the gradual shrinkage of the glacier that existed in the Corral del Veleta. Its remains were visible until the mid-20th century, thus culminating the complete deglaciation of Sierra Nevada.

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