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Environmental evolution in Sierra Nevada (South Spain) since the Last Glaciation, based on multi-proxy records

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A B S T R A C T

Our knowledge of the Quaternary landscape evolution in the high mountain areas of the Iberian Peninsula has substantially improved over the last decades. The Sierra Nevada is one of the most studied mountain ranges in southern Europe regarding its environmental evolution. The purpose of the present paper is to integrate and summarize all the studies focused on the reconstruction of the palaeoenvironmental history in this massif since the Last Glaciation. Research has focused both on different sedimentary records and historical sources. A wide range of geomorphological, sedimentological and geochronological techniques have been used to characterize the glacial, periglacial, wetland and lacustrine records for palaeoenvironmental purposes. For the last nine centuries tens of descriptions, maps and sketches describe the landscape of the summit area of the Sierra Nevada, providing evidences of the historical environmental events. Based on a multi-proxy approach, five periods have been identified: Last Glaciation, deglaciation, Holocene, Little Ice Age and recent evolution. Recent studies have detected the maximum expansion of glaciers in the Sierra Nevada around 30–32 ka BP, predating the global temperature minimum. No data about the environmental evolution is available between 20–30 ka BP. Around 19–20 ka BP glaciers advanced significantly. The process of deglaciation was rapid and around 14–15 ka BP the massif was almost free of ice. The Late Glacial promoted the formation of small glaciers in the highest northern cirques and widespread active periglacial processes (i.e. rock glaciers). During the Holocene there has been an alternation of colder/warmer periods and changing moisture conditions. Periglacial processes have been generally widespread in the summit area, with an increasing or decreasing activity depending on climate conditions. Ephemeral reappearance of small glacial cirques occurred in the highest northern cirques during the coldest and wettest phases. This is the case of the Little Ice Age, as revealed by historical documents and sedimentary records. Since the last decades of the XIX century the temperature has increased ~0.93°C leading to a decrease of the intensity of periglacial processes in the high lands of the Sierra Nevada.

1. Introduction

Numerous researchers in recent decades have studied the Quaternary palaeoecological evolution of the Iberian mountains. As in other mountains in the Mediterranean alpine belt, most palaeoenvironmental studies in the Iberian Peninsula have focused on:

(a) Determining the maximum development of the Last Glaciation, its forms and associated glacial modelling.
(b) Chronologically reconstructing particular environmental events in neighbouring sectors of summits and valleys, based on numerical dating.
(c) Sequencing the environmental events of the deglaciation process by studying lacustrine/peaty sediments, especially in mid-mountain areas.

The high-mountains of the Sierra Nevada is probably the best-known sector of the Iberian Peninsula. Naturalists and geographers began to study the area from an environmental perspective in the early 19th century (Rojas Clemente, 1804-1809). By the mid-19th century, much of its flora and glaciers were known (Boissier,

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1845; Madoz, 1849). The traces of Quaternary glaciation were noted by Schimper (1849) and validated by Macpherson (1875), Quelle (1908), and especially Obermaier (1916). Until well into the 1980s, glacial periods were framed within the context of Alpine chronology, and it was almost always deduced that there had been more than one glaciation (Riss-Würm), mostly on the basis of erosion records in cirques and valleys along with sedimentological and edaphic studies in moraines (García Sainz, 1943; Messerli, 1965; Lhenaff, 1977; Gómez Ortiz, 1987; Sánchez Gómez, 1990). Pollen data from the Padul peat bog (785 m, where the Sierra Nevada meets its peripheral depression) presented taxa characteristic of alternating cold phases and hot-humid periods between 46 ka BP and 4.5 ka BP according to ^{14}C dates (Florstchütz et al., 1971; Pons and Reille, 1988). Over the last two decades, studies focusing on the Sierra Nevada's glacial and periglacial geomorphology (Gómez Ortiz, 2002) have been combined with sedimentological and geochronological analyses of numerous natural records located in the summit area (Oliva, 2009; Oliva et al., 2009a, 2011; Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Oliva and Gómez Ortiz, 2012; Gómez Ortiz et al., 2012a). For the last few centuries, the information from natural archives has recently been complemented with environmental evidence interpreted from written historical accounts (Gómez Ortiz et al., 2009).

Lately, there has been growing interest in integrating palaeoclimatic records from a multi-proxy perspective in order to provide a better framework for the climate dynamics of the last few centuries (e.g. Morellón et al., 2012). At longer time scales, however, the use of different sources of palaeoenvironmental information that might complement and broaden our knowledge of glaciation and subsequent deglaciation in the same massif is relatively rare. There is also a need to establish the climate sequence since the Last Glaciation, continuously, so as to gain a better understanding of the natural fluctuations of general atmospheric circulation on the Atlantic seaboard of Europe. That is what this paper intends to do, focusing on the Sierra Nevada massif in the south of the Iberian Peninsula. More specifically, the aims are to:

(a) Integrate and synthesize the various proxies relating to the chronology of palaeoenvironmental evolution during the Last Glaciation and subsequent deglaciation of the massif; and
(b) Relate the trends in the Sierra Nevada to the variations in climate that have taken place in the Mediterranean region since the Last Glaciation.

2. Regional setting

The semi-arid high mountain region of the southern Iberian Peninsula reaches its highest point in the Sierra Nevada massif. This massif forms part of the Baetic System and stretches for 80 km from W to E at 37°N. Its western third, which is the area studied in this paper, includes some of the Iberian Peninsula's highest peaks, such as Mulhacén (3478 m asl) and Veleta (3398 m).

Climate conditions in the Sierra Nevada are characteristic of a Mediterranean semi-arid high-mountain environment, with a marked contrast between the hot, dry season (June–September) and the cold, wet season (October–May). The climate also presents significant interannual and intra-annual variability in rainfall. Its zonal setting and compartmentalized relief determine the existence of numerous topoclimates throughout the massif (Oliva and Moreno, 2008). Along with the Atlas Mountains, the Sierra Nevada is the gateway to the Mediterranean for the humid Atlantic flows associated with westerlies in middle latitudes, affecting the Sierra from October to April. From May to September, a predominance of subtropical high pressure systems brings atmospheric stability and high insolation. The average annual temperature at 2507 m is 4.4 °C, with negative monthly averages between December and April at this height, the 0 °C isotherm being located at around 3300–3400 m (Salvador-Franch et al., 2010). Annual rainfall at 2500 m is around 700 mm; around 80% of the total is concentrated between October and April (Oliva and Gómez Ortiz, 2012).

The core of the Sierra Nevada is basically made up of thick packets of graphite schists and mica schists that form the Nevado-Filabride complex, the main geological unit of the Baetic system. The structure of this core is a succession of nappes lying to form a vast anticline that is fractured and uneven because of a dense network of faults of alpine origin aligned in a SW–NE and NW–SE direction. The schists and mica schists are strongly tectonized (Díaz de Federico et al., 1980; Sanz de Galdeano and López Garrido, 1999). Glacial morphology associated with the Last Glaciation is very evident above 2500 m on the north face and 2700 m on the south face. Unlike in the Alps and to a lesser extent the Pyrenees, the glaciers of the Sierra Nevada were confined to the interior of the mountains, as their diminished length did not enable them to spread to neighbouring plains (Gómez Ortiz, 2002). Evidence of periglacial processes for this cold phase can be found at levels up to 1000–1100 m (Gómez Ortiz and Salvador-Franch, 1992). The current periglacial belt is above 2500 m.

The high altitude and latitudinal position of the Sierra to a great extent explains its richness in flora. During the cold periods of the Quaternary, the highest mountains in the south of the European continent acted as a genetic refuge for many plant species (Brewer et al., 2002; Médail and Diadema, 2009), and this is what happened in the Sierra Nevada. After deglaciation, these species grew at higher levels and adapted to the altitude and summer aridity. This explains the large number of species endemic to the massif (Molero Mesa and Pérez Raya, 1987). Because of the richness of its flora and the geomorphological wealth of the summit areas, the Sierra Nevada has been declared a Biosphere Reserve (1986), Nature Reserve (1989), and National Park (1999) (Gómez Ortiz et al., 2013a).

The combination of dryness and high temperatures in the warm season results in very high evapotranspiration, a key factor limiting plant development in the Sierra Nevada. Along with the barrenness of the ground at the highest levels, this provides conditions for the physical weathering of the rocks and limits the formation of soils and plant cover. Above 2500 m, edaphic processes are restricted to sectors with late-melting snow, in cirques and valley bottoms with flat topography, which encourages the development of dense, compact pasture. Histosols develop in these areas (known locally as *borreguiles*), while on slopes without vegetation or with scattered xerophyte species there is mainly stone cover and scree with only very incipient soils, including especially cambisols, inceptisols and regosols (Martín García et al., 2004).

3. Materials and methods

All the bibliographical sources dealing with Quaternary environmental evolution in the Sierra Nevada have been consulted for this paper. For historical times, starting in the 12th century but especially from the 18th century onwards, information obtained from contemporary documents has been taken into account. Written descriptions of the landscape help to interpret the evolution of the predominant morphogenetic environments in the summit area of the Sierra Nevada. The historical sources consulted consist of original books, facsimiles and historical maps from various libraries and documentary archives at local, regional, and national levels (Oliva and Gómez Ortiz, 2012).