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Timing and new geomorphologic evidence of the last deglaciation stages in Sierra Nevada (southern Spain)

David Palacios [a, *], Antonio Gómez-Ortiz [b], Nuria Andrés [a], Ferrán Salvador [b], Marc Oliva [c]

[a] Research Group of High Mountain Physical Geography, Department of Geography, Complutense University of Madrid, Spain
[b] Department of Geography, University of Barcelona, Spain
[c] Centre for Geographical Studies e IGOT, Universidade de Lisboa, Portugal

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ABSTRACT

The main objective of this research is to improve knowledge of the deglaciation stages in Sierra Nevada (southern Spain) by applying ^{36}Cl cosmogenic exposure dating to 28 samples from moraine and fossil rock glacier boulders and glacial polished surfaces, in 5 glaciated valleys around Veleta Peak (3396 m asl; 37°03′02″N 3°20′54″W). The results show that shortly before the Last Glacial Maximum (LGM) and during the LGM, the heads of the glacial valleys were occupied by ice tongues, with possible glacial transfluence between the valleys. After 19 ka, a major glacial regression started, but glaciers during the Oldest Dryas (OD) expanded again and refilled the valley bottoms. The glacial advances of the pre-LGM, LGM and OD formed polygenic moraine systems. During the Bølling-Allerød the glaciers receded and probably disappeared. Thereafter, the valley bottoms remained ice-free. During the Younger Dryas (YD) small glaciers developed again, but only in cirques shaped on east-facing slopes. Subsequently, these glaciers started retreating towards their valley heads and finally disappeared completely. With the onset of the Holocene, rock glaciers developed inside the deglaciated cirques on the eastern slopes of some valleys, but only under the most active and protected headwalls did large complex rock glaciers develop and remained active until the mid-Holocene.

1. Introduction

Over the last years there have been important advances in the knowledge of the last deglaciation which occurred during the Late Pleistocene (Darnault et al., 2012), as well as its impact on the glacier evolution in Iberian mountain ranges (Fig. 1), mostly through the application of cosmogenic exposure dating (CED). These advances have been summarized in recent publications on:

(i) some mountain ranges such as the Pyrenees (Delmas, 2015), NW Iberian ranges (Rodríguez-Rodríguez et al., 2014), Cantabrian Mountains (Jiménez-Sánchez et al., 2013; Rodríguez-Rodríguez et al., 2016), the Central Range (Domínguez-Villar et al., 2013; Pedraza et al., 2013; Andrés and Palacios, 2014; Carrasco et al., 2015) and Sierra Nevada (Gómez-Ortiz et al., 2012, 2015; Oliva et al., 2014);
(ii) some of the most representative periods, such as the Last Glacial Maximum (LGM) (García-Ruiz et al., 2010; Hughes et al., 2013), Oldest Dryas (OD) (Palacios et al., 2016) and Younger Dryas (YD) (García-Ruiz et al., 2016) and
(iii) the interaction between deglaciation and periglacial activity (Oliva et al., 2016a).

The LGM is defined as the last period in which glaciers reached the maximum global ice volume on Earth (Clark et al., 2009), and consequently, the sea level reached its lowest level between ca. 26 ka until 19 ka (Mix et al., 2001). Recent studies showed evidence that the last major advance of the Fennoscandian Ice Sheet (FIS) occurred between 26 and 21 ka (Clark et al., 2009; Marks, 2015; Hughes et al., 2016; Stroeven et al., 2016) in parallel with many European mountain glaciers (García-Ruiz et al., 2010; Hughes et al., 2013). However this glacial advance was not the greatest of the LGC (Last Glacial Cycle, last 120 ka) in some Iberian mountain ranges. In

Abbreviations: LGM, Last Glacial Maximum; LIA, Little Ice Age; OD, Oldest Dryas; YD, Younger Dryas; CED, Cosmogenic Exposure Dating; LGC, Last Glacial Cycle; FIS, Fennoscandian Ice Sheet; MAAT, Mean Annual Air Temperature; ELA, Equilibrium Line Altitude.

* Corresponding author.
E-mail addresses: davidp@ucm.es (D. Palacios), gomez@ub.edu (A. Gómez-Ortiz), nandresp@ucm.es (N. Andrés), fsalvador@ub.edu (F. Salvador), oliva_marc@yahoo.com (M. Oliva).

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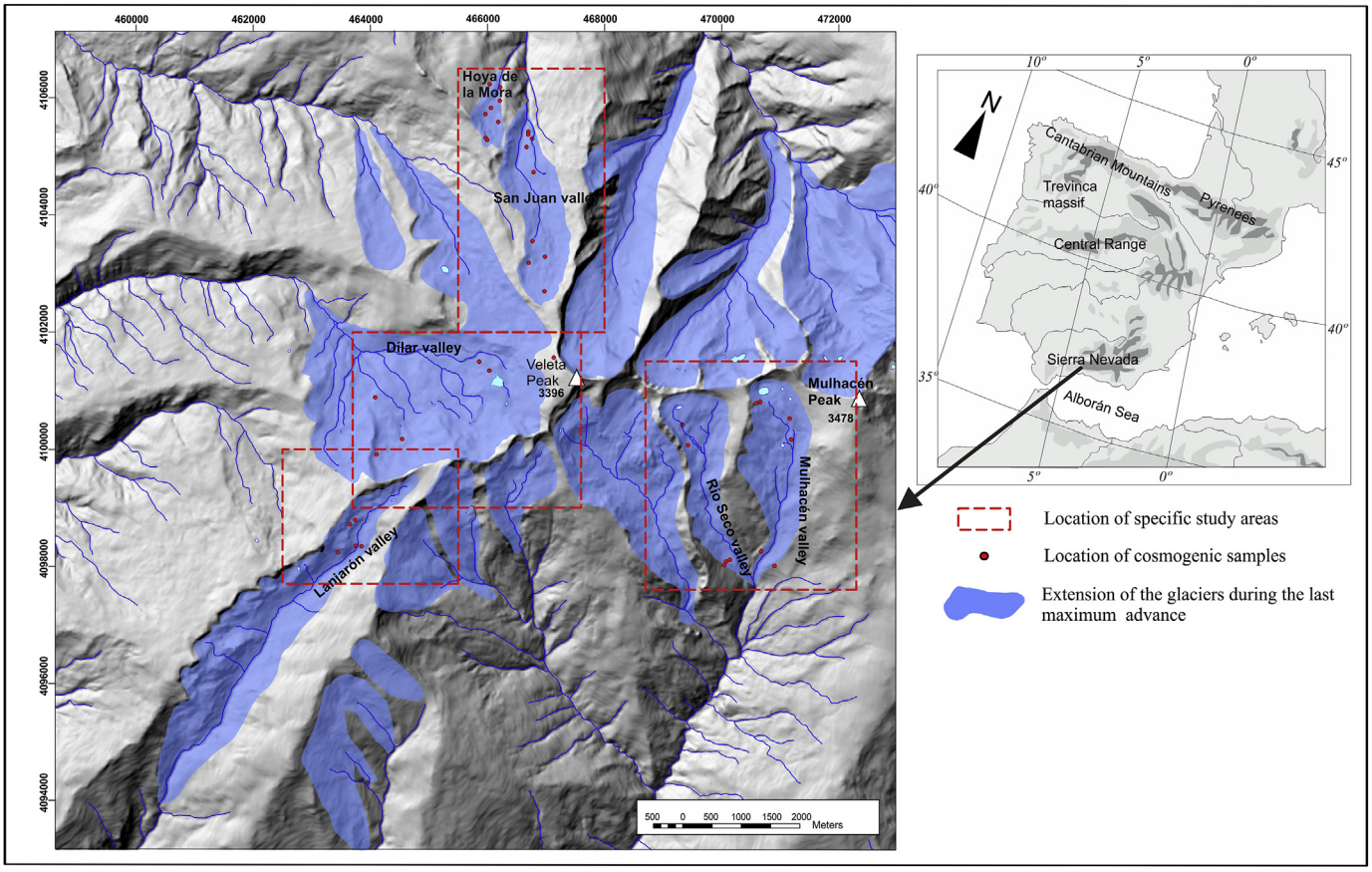

Fig. 1. Area of the last glacial maximum extent in Sierra Nevada and location of the valleys studied in this work.

the Pyrenees, the last glacial maximum extent occurred before the LGM, concurrent with the MIS 4 (García-Ruiz et al., 2010). However, during the LGM there was a significant glacier readvance - though of different magnitude across this range - followed by a rapid retreat (Delmas, 2015; Turu et al., 2016). In the Cantabrian Mountains the maximum extent may have taken place at the beginning of the LGC (minimum age of 113.9 ka). Subsequently, several readvances occurred, with the largest dated at a minimum age of 55.7 ka (Rodríguez-Rodríguez et al., 2016). As well as in the Pyrenees, substantial advances occurred before (36–45 ka) and during the LGM (19–23 ka), although the latter was considerably smaller than the former two, and was followed by a major retreat (Serrano et al., 2015, 2016; Rodríguez-Rodríguez et al., 2015, 2016). In the NW Iberian mountains the chronology is rather similar, as inferred from the Trevinca mountains, where a significant glacial advance took place around 33 ka, and a minor one during the LGM which ended at 19 ka (Rodríguez-Rodríguez et al., 2014). In the Central Range the maximum extent of glaciers during the LGC occurred slightly before the LGM (Domínguez-Villar et al., 2013; Pedraza et al., 2013). However, it was during this stage when the relatively stable glacier fronts generated the largest moraine systems (Andrés and Palacios, 2014; Carrasco et al., 2015). In Sierra Nevada, until now, researchers suggested that the maximum glacier extent occurred at 30–32 ka, with an important readvance at 19–20 ka followed by a major deglaciation of the massif (Gómez-Ortiz et al., 2012, 2015; Oliva et al., 2014).

During the OD, the term used for the stadial GS-2.1a (17.5–14.5 ka), there is no geomorphologic or sedimentological evidence of a widespread readvance of the FIS except in some areas in northern Europe and Scandinavia, without reaching the limits of the LGM (Rinterknecht et al., 2012; Marks, 2015; Greenwood et al., 2015; Hughes et al., 2016; Stroeven et al., 2016). However, in many European mountain ranges there is evidence of glacier advance during the OD. This is the case of the Alps (Gschnitz stadial) where glaciers spread across the valley bottoms ca. 100 km upvalleys with respect the limit of the LGM moraines (Ivy-Ochs et al., 2009; Ivy-Ochs, 2015), as well as other European mountain ranges such as the Tatras (Makos, 2015) where the OD glaciers reached halfway of their LGM extent and the Apennines, where the OD glacial advance covered ca. 20% of the Global LGM glacial extent (Giraudi, 2015). Limited information is available about North Africa glacial stages, although preliminary dating suggest a maximum glacial advance during the LGM and the existence of moraines formed during the YD, along with a moraine system in between which has not been dated yet (Hughes et al., 2011).

In Iberia there is also evidence that many mountains interrupted their process of deglaciation and glaciers readvanced significantly during the OD (Palacios et al., 2016). In the Pyrenees an important advance occurred ca. 17 ka, both in the eastern fringe (Delmas et al., 2008; Pallàs et al., 2010; Palacios et al., 2015a; Turu et al., 2016) and in the central part of the range (Palacios et al., 2015b). The glaciers reoccupied the valley bottoms, but to a significantly reduced extent than that during the LGM (Delmas, 2015; Palacios et al., 2016). The last glacier advance took place at the end of the OD period, at ca. 15 ka. After that, glaciers retreated and abandoned the valley bottoms between approximately 15 and 13.5 ka, coinciding with the Bølling and Allerød interstadial (Delmas, 2015). The process of deglaciation at the end of the OD promoted the formation of rock glaciers in many cirques with very active geomorphic dynamics (Palacios et al., 2015a,b; Oliva et al., 2016a). The deglaciation in the Cantabrian