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Deglaciation in the central Pyrenees during the Pleistocene–Holocene transition: Timing and geomorphological significance

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ABSTRACT

In this study, we document deglaciation in a sector of the southern–central Pyrenees (the Panticosa massif and the upper Gállego and Ossau valleys) using cosmic-ray exposure (CRE) dating methods, which were applied to samples from high altitude polished rock steps and rock glacier boulders. The obtained CRE dates show a coherent spatial distribution and confirm results previously obtained in this study area, thus demonstrating the reliability and robustness of the method. The results of analyses based on two distinct isotopes (^{10}Be and ^{36}Cl) are consistent, although the error is higher for results based on the ^{36}Cl isotope. The study provides evidence for ice extent in the High Gállego Valley during the Oldest Dryas, with glacial advance until the bottom of the valleys, although the main glacier tongues remained disconnected from each other. During this period, the extent of glacier advance was directly related to the elevation of the associated summits. The Younger Dryas glaciers were constrained to cirques or very short ice tongues, and dating of the polished rock steps indicates that the ice masses were present until the first millennium of the Holocene. The Brazato rock glacier developed at the beginning of the Holocene and remained active until the Holocene Thermal Optimum, because of the protective effect of large masses of blocks and boulders.

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1. Introduction

The global Last Glacial Maximum (LGM), which occurred at 26–20 ka (Hughes et al., 2013), marked the beginning of a series of sudden and drastic climatic changes that were closely related to variations in temperature, changes in ocean currents, and the extent of the Atlantic ice sheets. These changes affected global climate evolution because of the influence of the Atlantic ice sheet deglaciation stages on the Atlantic meridional overturning circulation during the Late Pleistocene–Holocene transition (Peck et al., 2006; Clark et al., 2012; Renssen et al., 2012; Gil et al., 2015; Jaccard et al., 2016; Lippold et al., 2016). Recent reports have summarized advances made in the understanding of the changes in the Atlantic ice sheets during the Last Deglaciation (Dyke, 2004; Stokes et al., 2015; Vasskog et al., 2015; Stroeven et al., 2016; Hughes et al., 2016). A close relationship between these changes and the evolution of alpine glaciers has been highlighted in the central European mountains, including the Alps (Ivy-Ochs et al., 2009; Hippe et al., 2014; Ivy-Ochs, 2015) and the Tatras and Carpathian mountains (Makos et al., 2013; Makos, 2015).

Knowledge of deglaciation in Mediterranean mountains is of particular importance, as they occupy a key position in an area that is highly impacted by ocean/atmosphere processes, including latitudinal migration of the Intertropical Convergence Zone, variability in the African monsoon, and runoff from North Africa into the Mediterranean (Tzedakis et al., 2009; Fletcher et al., 2010). These processes also have strong climatic linkages with North Atlantic regions (Dormoy et al., 2009), and are clearly affected by the North Atlantic Oscillation (Ramos-Román et al., 2016). The Pyrenees are a long mountain range (415 km) along the 42°N parallel of latitude, and represents the northern limit of the

Abbreviations: LGM, Last Glacial Maximum; FIS, Fennoscandian Ice Sheet; CRE, Cosmic-Ray Exposure Dating; LIA, Little Ice Age.

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Mediterranean influence in southwest Europe, with increasing Atlantic influence from the east to the west of the range.

Over recent years there have been remarkable advances in knowledge of the chronology of the last deglaciation in the Pyrenees and other Iberian mountains, mostly through the application of cosmic-ray exposure dating (CRE). As a result, various glacial stages that occurred during the Late Pleistocene and Holocene have been differentiated.

a) In the Pyrenees, the Maximum Ice Extent (MIE) occurred prior to the LGM (García-Ruiz et al., 2003, 2010, 2013; Lewis et al., 2009; Delmas, 2015), probably at approximately 60 ka BP, and with some variations the same occurred in the Cantabrian Mountains (Rodríguez-Rodríguez et al., 2015, 2016), the northwest Iberian mountains (Rodríguez-Rodríguez et al., 2014), the Central Range (Domínguez-Villar et al., 2013; Pedraza et al., 2013), and the Sierra Nevada (Gómez-Ortiz et al., 2012, 2015).
b) During the LGM, there was a significant readvance of glaciers in the central Pyrenees (Delmas, 2015; Turu et al., 2016) followed by a rapid retreat; this is consistent with the last major advance of the Fennoscandian Ice Sheet (FIS) between 26 and 21 ka (Marks, 2015; Hughes et al., 2016; Stroeven et al., 2016) and with that of many European mountain glaciers (García-Ruiz et al., 2010; Hughes et al., 2013). A similar situation has been reported for the Cantabrian and northwest Iberian mountains (Rodríguez-Rodríguez et al., 2014, 2015, 2016; Serrano et al., 2015, 2016). In the eastern Pyrenees, relatively stable glacier fronts during the LGM generated large moraine systems (Delmas, 2015), as occurred in the Central Range (Andrés and Palacios, 2014; Carrasco et al., 2015) and the Sierra Nevada (Gómez-Ortiz et al., 2012, 2015; Oliva et al., 2014).
c) During the Oldest Dryas, which is the term used for the GS-2a stadial (17.5–14.5 ka), a major advance occurred at approximately 17 ka in the Pyrenees, in both the eastern (Delmas et al., 2008; Pallàs et al., 2010; Palacios et al., 2015a; Turu et al., 2016) and central parts of the range (Palacios et al., 2015b). The glaciers reoccupied the bottoms of the valleys, but to a significantly lesser extent compared to that which occurred during the LGM (Delmas, 2015; Palacios et al., 2016a). The glaciers retreated and abandoned the valley bottoms at the end of the Oldest Dryas, between approximately 15 and 13.5 ka, coinciding with the Bølling–Allerød interstadial (Delmas, 2015). The process of deglaciation at the end of the Oldest Dryas promoted the formation of rock glaciers in many cirques of the Pyrenees (Palacios et al., 2015a, 2015b, 2016a; Oliva et al., 2016).

The advances during the Oldest Dryas were contemporaneous with others that occurred in the FIS, although they did not exceed the limits of the LGM (Rinterknecht et al., 2012; Greenwood et al., 2015; Marks, 2015; Hughes et al., 2016; Stroeven et al., 2016), in the Alps (Ivy-Ochs et al., 2009; Ivy-Ochs, 2015) and the Tatras Mountains (Makos, 2015). Glacier readvances during this period have also been recently detected in the Cantabrian Mountains and the Trevinca Massif (Rodríguez-Rodríguez et al., 2014, 2015, 2016), and in the Central Range, where the glaciers extended across the valley bottoms near the LGM moraines (Andrés and Palacios, 2014; Carrasco et al., 2015).

As in the Pyrenees, major deglaciation of the valley bottoms in the Sierra Nevada occurred during the Bølling–Allerød interstadial (14.7–12.9 ka; stadial GI-1). This warm period probably resulted in the complete disappearance of Iberian glaciers (Palacios et al., 2016a), as occurred in many European mountain ranges (Dielforder and Hetzel, 2014; Hippe et al., 2014; Ivy-Ochs, 2015); a major retreat also occurred in the FIS (Makos et al., 2013; Marks, 2015; Hughes et al., 2016).

d) During the Younger Dryas (12.9–11.7 ka; stadial GS1), the glaciers expanded within the limits of the glacial cirques in both the central (Pallàs et al., 2006; Calvet et al., 2011; Delmas, 2015; García-Ruiz et al., 2016a, 2016b) and eastern Pyrenees (Pallàs et al., 2010). Many of the rock glaciers that had formed at the end of the Oldest Dryas remained active, and new ones formed at the end of the Younger Dryas (Palacios et al., 2015a, 2015b; Oliva et al., 2016). The presence of a sequence of cirque moraines and rock glaciers in the Cantabrian Mountains have been attributed to this period (Redondo et al., 2010; Gómez-Villar et al., 2011; Pellitero et al., 2011; Serrano et al., 2015, 2016; García-Ruiz et al., 2016a; Oliva et al., 2016; Ruiz-Fernández et al., 2016). The Central Range also has moraines preserved from this period (Carrasco et al., 2015), and the presence of various polished rock surface thresholds testify to the existence of glaciers at the end of this stage (Andrés and Palacios, 2014). In the case of the Sierra Nevada, many cirques were deglaciated at the end of this period (Oliva et al., 2014; Gómez-Ortiz et al., 2015), and were replaced by active rock glaciers (Gómez-Ortiz et al., 2012, 2015; Oliva et al., 2016; Palacios et al., 2016b). The Younger Dryas was the last advance of the FIS (Ballantyne, 2012; Mangerud et al., 2013; Greenwood et al., 2015; Marks, 2015; Hughes et al., 2016; Stroeven et al., 2016), and of alpine glaciers including those in the Alps (Egesen stadial) (Ivy-Ochs, 2015), the Tatras Mountains (Makos, 2015), the Apennines (Giraudi, 2015), and other areas.
e) The extent of the glaciers in the Pyrenees and Iberian mountains during the Little Ice Age (LIA) maximum is relatively well known (González Trueba et al., 2008). However, there is a gap in knowledge concerning the evolution of the glaciers from the end of Younger Dryas and Early Preboreal periods to the LIA. It is possible that the glaciers in the Pyrenees disappeared during the first half of the Holocene, particularly from 7 to 5.5 ka (the Holocene Thermal Optimum), when the conditions were warmer than at present (Wanner et al., 2011; Renssen et al., 2012). It is possible that the relatively large extent of the LIA glaciers in the Pyrenees exceeded most of the previous Holocene advances, as is generally the case in the Alps (Deline and Orombelli, 2005; Schimmelpfennig et al., 2014a; Solomina et al., 2015; Moran et al., 2016a). The only information on pre-LIA Holocene glacial advances comes from the Troumouse cirque (central-northern Pyrenees), where advances assigned to 5190 ± 90 and 4654 ± 60 cal yr BP were determined using radiocarbon dating (Gellatly et al., 1992), and from the Marboré cirque, which is 9 km south of the Troumouse cirque. Based on cosmogenic ^{36}Cl dating, the latter provided evidence for an advance in the middle of the Holocene (5.1 ± 0.1 ka) in a push moraine, and also in polished surfaces at 3.4 ± 0.2 and 2.5 ± 0.1 ka, and a last glacial expansion during the Dark Age Cold Period (1.4–1.2 ka), prior to the LIA (García-Ruiz et al., 2014). In the la Mosca cirque, in the Sierra Nevada, similar advances at 2.8–2.7 and 1.4–1.2 cal yr BP have been detected using radiocarbon dating (Oliva and Gómez-Ortiz, 2012; Gómez-Ortiz et al., 2015).

Despite improved understanding, various aspects of deglaciation in the Pyrenees remain unclear. It is necessary to clarify two important questions. Firstly, did the greatest glacial advance since the Early Holocene occur during the LIA? Secondly, did the end of the Oldest Dryas (OD) and Younger Dryas (YD) stadials promote the development of rock glaciers in many valleys? If so, this would indicate that fossil rock glaciers developed under deglaciation

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