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Timing of last deglaciation in the Cantabrian Mountains (Iberian Peninsula; North Atlantic Region) based on in situ-produced ^{10}Be exposure dating

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A B S T R A C T

The Last Glacial Termination led to major changes in ice sheet coverage that disrupted global patterns of atmosphere and ocean circulation. Paleoclimate records from Iberia suggest that westerly episodes played a key role in driving heterogeneous climate in the North Atlantic Region. We used ^{10}Be Cosmic Ray Exposure (CRE) dating to explore the glacier response of small mountain glaciers (ca. 5 km^2) that developed on the northern slope of the Cantabrian Mountains (Iberian Peninsula), an area directly under the influence of the Atlantic westerly winds. We analyzed twenty boulders from three moraines and one rock glacier arranged as a recessional sequence preserved between 1150 and 1540 m above sea level (a.s.l.) in the Monasterio valley (Redes Natural Park). Results complement previous chronologic data based on radiocarbon and optically stimulated luminescence from the Monasterio valley, which suggest a local Glacial Maximum (local GM) prior to 33 ka BP and a long-standing glacier advance at 24 ka coeval to the global Last Glacial Maximum (LGM). Resultant ^{10}Be CRE ages suggest a progressive retreat and thinning of the Monasterio glacier over the time interval 18.1–16.7 ka. This response is coeval with the Heinrich Stadial 1, an extremely cold and dry climate episode initiated by a weakening of the Atlantic Meridional Overturning Circulation (AMOC). Glacier recession continued through the Bølling/Allerød period as indicate the minimum exposure ages obtained from a cirque moraine and a rock glacier nested within this moraine, which yielded ages of 14.0 and 13.0 ka, respectively. Together, they suggest that the Monasterio glacier experienced a gradual transition from glacier to rock glacier activity as the AMOC started to strengthen again. Glacial evidence ascribable to the Younger Dryas cooling was not dated in the Monasterio valley, but might have occurred at higher elevations than evidence dated in this work. The evolution of former glaciers documented in the Monasterio valley seems consistent with previous ^{10}Be chronologies reported in other mountain ranges of the Iberian Peninsula, which have been recalculated according to a common production rate and scaling scheme. However, the re-evaluation of published ^{10}Be chronologies has highlighted the fact that glacial evidence previously ascribed to the Younger Dryas might be more limited than previously thought and the need for additional studies to characterized the extent of glaciers during the Younger Dryas cooling.

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1. Introduction

The Last Glacial Termination led to major readjustments of the Earth's climate in response to the collapse and meltdown of Northern Hemisphere ice sheets, which disrupted ocean and atmospheric circulation globally (Denton et al., 2010). Melt waters poured in the North Atlantic (NA) region triggered a strength

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reduction of the Atlantic Meridional Overturning Circulation (AMOC) and a southward shift of the Polar Front, promoting extremely cold winters with sea ice formation and enhanced seasonality across the NA region (Denton et al., 2005, 2006). Latest temperature reconstructions in Greenland show that seasonality variations closely track changes in strength of the AMOC, suggesting that winter conditions dominated abrupt climate change during the last deglaciation (Buizert et al., 2014). Located at a latitudinal range of 42 to 37°N, the Iberian Peninsula is directly under the influence of the North Atlantic Drift (NAD; Fig. 1a). Comparisons between terrestrial and marine sedimentary proxy records from the Iberian Margin suggest a synchronous response of marine and continental environments and reveal the importance of enhanced winter NA westerly episodes in driving a heterogeneous climate signal during the Last Glacial Termination (Naughton et al., 2016). The Cantabrian Mountains are a maritime mountain range aligned parallel to the northern coast of Iberia with broad areas in the altitudinal range 2000–2500 m a.s.l. (Fig. 1b). Compared to other mountain ranges in the Iberian Peninsula, former glaciers developed on the northern slope of the Cantabrian Mountains were highly sensitive to strength variations in the AMOC. A recent chronological study based on Cosmic Ray Exposure (CRE) dating of moraine boulders suggests that former glaciers in the Cantabrian Mountains may have experienced recession after the global Last Glacial Maximum (LGM), particularly during the Heinrich Stadial 1/Mystery Interval (HS1/MI) period (Rodríguez-Rodríguez et al., 2014, 2016). The MI was described by Denton et al. (2005, 2006) as a shutdown or strength reduction episode in the AMOC recorded at the LGM termination (from 18.5 to 14.6 cal ka BP) that was responsible for enhanced seasonality in the North Atlantic Region. In the Iberian Peninsula, lacustrine records suggest that the HS1/MI corresponds to the coldest and driest conditions of MIS 2 (Moreno et al., 2012). The glacier recession signature has also been found in other Iberian ranges, where previous CRE chronologies reported for recessional moraines provide ages of 19–14 ka for the Pyrenean paleo-glaciers (Calvet et al., 2011; Pallàs et al., 2006, 2010; Palacios et al., 2015a, Palacios et al., 2015b), of 19–16 ka in the Sistema Central (Palacios et al., 2011, 2012a, 2012b), and 19–14 ka in Sierra Nevada (Gómez-Ortiz et al., 2012). In all cases, evidence of several hundreds to thousands of meters of glacier front recession compared to the previous LGM position is shown to occur during the Oldest Dryas or the Greenland Stadial 2a (GS-2a, 17.5–14.7 ka) (Rasmussen et al., 2014). The timing of the last deglaciation in the Cantabrian Mountains remains poorly constrained based on absolute dating of moraine sequences and most chronological constrain comes from glacial-related sediments (Rodríguez-Rodríguez et al., 2015; Serrano et al., 2015b). The last deglaciation also caused a recession of the periglaciation belt towards the highland areas of the summit plateaus and glacial cirques, with the development of block fields, block streams, rock glaciers, protalus ramparts, patterned ground and debris slopes reaching altitudes down to 1400–1300 m, most probably between 25–21 and 14–11 ka (Gómez-Villar et al., 2011; Oliva et al., 2016). Rock glaciers show outstanding preservation close to the back wall of the north-facing glacial cirques that are located on detrital lithology (particularly on quartzite sandstone), but there is a lack of direct chronological constrain of their activity (García-Ruiz et al., 2016; Oliva et al., 2016). At present, only five ^{10}Be CRE dates were obtained from a relict rock glacier in the Porma valley, indicating a minimum age of 15.7 ka for sliding cessation of the foremost ridge (Rodríguez-Rodríguez et al., 2016). Thus, the debate on whether their latest activity was mostly during the Younger Dryas (YD) (GS-1, 12.9–11.7 ka) (Rasmussen et al., 2014) or spanned the entire deglaciation is still open.

The aim of this work is to provide additional constrain on the evolution of glacier fronts and the periglaciation belt during the last deglaciation in the Cantabrian Mountains. This mountain range constitutes a key site to study past glacier responses linked to variations in atmospheric circulation patterns driven by changes in the AMOC strength. A ^{10}Be CRE dataset constraining the timing of last glacier retreat and rock glacier formation on the northern slope of the Cantabrian Mountains is presented in this work and compared to previously published ^{10}Be CRE chronologies from other Iberian mountain ranges and to paleoclimate proxies from nearby areas of the NA Region. A re-evaluation of previously published datasets according to a common ^{10}Be in situ-production rate and scaling scheme was necessary in order to: a) compare the entire CRE age dataset, and b) evaluate the glacier dynamics with regards to regional paleoclimate.

2. Regional setting

The Monasterio river, a tributary of the main Nalón river, flows along the northern slope of the Cantabrian Mountains (Asturias, North Spain). The Monasterio valley is located within the limits of the Redes Natural Park (Biosphere Reserve since 2001) and was sculpted on a Paleozoic sedimentary sequence by fluvial and glacial erosion. The bedrock lithology consists of alternating siliciclastic and carbonate formations, including quartzite sandstone outcropping at the mountain divide (Fig. 1c). The glacial record of this valley was among the first in North Iberia to be dated based on radiocarbon analysis on glacio-lacustrine sediments retrieved from the Brañagallones sequence (Jiménez-Sánchez and Farias-Arquer, 2002). The Brañagallones sequence corresponds to an ice-dammed deposit that has developed behind five lateral moraines deposited along the main valley and that blocked the runoff of an eastern tributary stream of the Monasterio river (Fig. 2). A sediment core drilled in 1998 revealed a total sequence thickness of 36.7 m, mainly composed by alternations of alluvial debris and tills from the lateral moraine talus. An intercalation of clay and silt sediments displaying parallel lamination and normal grading at 35.5–35.6 m depth provided a minimum radiocarbon age of 29.0 ± 0.2 ka BP for the moraine blockage [33.2 ± 0.3 cal ka BP after calibration with Calib Rev 7.0.2 (Reimer et al., 2013)] and thus for the local Glacial Maximum (local GM) (Jiménez-Sánchez and Farias-Arquer, 2002). Optically stimulated luminescence (OSL) analysis carried out on a till sample taken from the second outermost lateral moraine yielded a burial age of 24.0 ± 1.8 ka, consistent with previous radiocarbon results from the ice-dammed sequence (Jiménez-Sánchez et al., 2013). There is no chronology for the remaining moraine sequence, but a radiocarbon date acquired in a peat bog located ca. 760 m north from the Tarna Pass, at the source of the Nalón River (1490 m a.s.l., see location in Fig. 1b), yielded an age of 20.6 ± 0.3 ka BP. The age of the Tarna peat bog suggests a rapid retreat of glaciers towards the mountain divide in the upper Nalón valley after the LGM. This finding is consistent with the OSL depositional age of 23.0 ± 2.3 ka obtained from a complex landslide in the Nalón valley, which toe lies at 1050 m a.s.l. (Jiménez-Sánchez and Farias-Arquer, 2002; Jiménez-Sánchez et al., 2013). However, the upper Nalón valley does not display a sequence of recessional moraines as complete as that found in the Monasterio valley, where three recessional stages followed by a gradual transition to rock glacier activity have been proposed (Jiménez-Sánchez, 1996).

3. Glacier reconstruction and ^{10}Be CRE dating methods

Geomorphological evidence recording past glaciations in the Monasterio valley was reviewed at a scale 1:25,000 and digitalized in ArcGIS using aerial photos, topographic maps, and LIDAR digital elevation models from the Spanish *Centro Nacional de Información*

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