Quaternary Science Reviews 195 (2018) 215–231

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Constraining the age of superimposed glacial records in mountain environments with multiple dating methods (Cantabrian Mountains, Iberian Peninsula)

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A R T I C L E I N F O

Article history:
Received 25 May 2018
Received in revised form
13 July 2018
Accepted 16 July 2018

Keywords:
^{10}Be surface exposure dating
Radiocarbon
Optically stimulated luminescence
Last glacial maximum
Cantabrian mountains
Iberian peninsula
Glaciation

A B S T R A C T

Numerous cases of timing differences between glacier advances recorded in mountain environments have been documented over the last decade, usually suggesting potential age conflicts between the different dating techniques. The frequent use of a single technique to date numerically a given glacial sequence makes it difficult to address to what extent age differences can be an artifact related to biased numerical age results or a paleoclimate signature. Here we present a new set of 43 numerical ages based on three dating techniques —^{10}Be surface exposure dating; radiocarbon; and optically stimulated luminescence— that complement the chronology of Pleistocene glacial advances in the Porma valley, in the central Cantabrian Mountains of Spain. Results compliment previous chronologies in the area, supporting an important glacial advance during Marine Isotope Stage 3 (Stage IIa: ~56 ka) that culminated with the Last Glacial Maximum advance (Stage IIb: ~33–24 ka) of MIS 2 in response to increased rainfall and solar insolation minima. Glacier fronts reached elevations as low as 1130 m a.s.l. possibly without overriding evidence related to the previous Pleistocene glacial maximum extent. Glacier recession in the Cantabrian Mountains started at 21–20 ka ago, after the global LGM. We suggest that the recession was initiated by increased insolation followed by hyper-cool and dry conditions during Heinrich Stadial 1 in response to meltwater discharges in the North Atlantic.

1. Introduction

Formerly glaciated landscapes have been a frequent research topic in the last decades to understand the timing, extent and behavior of Quaternary glaciations with regards of past climate change and atmospheric circulation patterns. However, as glacial chronologies grow in number more cases of asynchrony in glacier behavior have been detected around the world for the Last Glacial Cycle, evidencing the limited chronostratigraphical value of some broadly used correlation terms such as the Last Glacial Maximum or LGM (c. 23–19 ka) (Hughes et al., 2013). A recent study proposes new limiting ages for the global LGM event of 27.5–23.3 ka, comprising the peak dust concentration in the polar ice cores, the global sea-level minima, and both the coldest and driest part of the Last Glacial Cycle and the peak in global ice volume (Hughes and Gibbard, 2015).

The timing differences between glacier fluctuations recorded in the different mountain ranges across South Europe and the Mediterranean region received special attention due to age conflicts found between Cosmic Ray Exposure (CRE) chronologies and those derived from other techniques like Optically Stimulated

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https://doi.org/10.1016/j.quascirev.2018.07.025
0277-3791/

Luminescence (OSL) and radiocarbon (Hughes and Woodward, 2008). In one hand, CRE chronologies supported extensive mountain glacier advances during the so-called LGM of Marine Isotope Stage 2 (MIS 2) in the Eastern Alps (Ivy-Ochs et al., 2008); the Carpathians (Makos et al., 2018); most mountain areas of the Anatolian Peninsula (Akçar et al., 2014; Sarikaya et al., 2014); the Sistema Central in Iberia (Carrasco et al., 2011, 2015; Palacios et al., 2011, 2012a, 2012b); and some Pyrenean valleys (Pallàs et al., 2006; Delmas et al., 2008; Palacios et al., 2015). On the other hand, analyses relying on alternative dating techniques (U-Th, radiocarbon, OSL) pointed out to ages older than the LGM of MIS 2 for the most extensive glacial advance locally recorded in areas such as the Swiss Alps (Dehnert et al., 2010); the Pindus Mountains (Hughes et al., 2006; Woodward and Hughes, 2011); the coastal mountains of the Adriatic Sea (Hughes et al., 2010); the Apennines (Giraudi et al., 2011); or the Cantabrian Mountains (Jiménez-Sánchez and Farias-Arquer, 2002; Serrano et al., 2012; Frochoso et al., 2013; Jiménez-Sánchez et al., 2013). In the Iberian Peninsula, only a limited number of sites in the Pyrenees (Pallàs et al., 2010; Delmas et al., 2011) and the Cantabrian Mountains (Vidal Romaní et al., 1999; Rodríguez-Rodríguez et al., 2016) have provided CRE chronologies compatible with a Pleistocene glacial maximum older than the LGM of MIS 2. Timing asynchronies may have paleoclimate significance (Calvet, 2012; Calvet et al., 2011), but can also be an artifact related to the use of different dating techniques applied to samples of diverse nature and context with regards of the glacial environment (Hughes et al., 2013). However, since most local chronologies are relying on a single dating technique, it is difficult to assess which dating method may be providing the most accurate chronology in a particular study area. Here we used three among the most frequently employed techniques in the literature: ^{10}Be CRE, radiocarbon, and OSL, to date the glacial record preserved in a single glacier catchment and to cross-compare the obtained results.

Our study focuses on the Porma catchment, located on the southern slope of the central Cantabrian Mountains that extend along the northern coast of the Iberian Peninsula. Along the coast the maritime climate is strongly influenced by the North Atlantic Ocean (Fig. 1). In the Porma catchment, a previous set of 27 dated samples taken from glacial erratics and moraines support a local Pleistocene glacial maximum coeval with MIS 5d (minimum ^{10}Be CRE age of 113.9 ± 7.1 ka, based on boulders ages from MUR, LIL and CEL sites) and a subsequent glacial advance of similar extent during MIS 3 (minimum ^{10}Be CRE age of 55.7 ± 4.0 ka, based on boulders from RED, LIL and CEL sites) (Rodríguez-Rodríguez et al., 2016). In addition, a limited number of boulders from the LIL composite moraine suggests a possible of a re-advance of the Porma glacier during MIS 2, at the same time as the growth of continental ice sheets to their maximum LGM positions (Clark et al., 2009). In favor of this hypothesis, a group of glacial erratics sampled on top of the Loma Fondría ice-molded surface (FRIA samples) placed the beginning of the last glacial retreat at a minimum ^{10}Be CRE age of 17.7 ± 1.0 ka ($n = 5$), which is consistent with the minimum ^{10}Be CRE age of 15.7 ± 0.8 ka ($n = 5$) obtained for the foremost ridge of a rock glacier (REQ samples) at 1620 m a.s.l. Additionally, a previous palynology study carried in a peat bog deposited in a glacially overdeepened depression close to the San Isidro Pass provided a ^{14}C age of 9570 ± 200 yr BP at a depth of 775–780 cm (Fombella-Blanco et al., 2003, 2004). Calibrated with Calib Rev 7.0.2 using IntCal13 (Stuiver and Reimer, 1993; Reimer et al., 2013), it provides a minimum age of 10.3–11.4 cal ka BP (2σ interval) and suggests glacier retreat from this area at the beginning of the Holocene. On the northern slopes of the central Cantabrian Mountains, the sequence of recessional moraines dated in the nearby Monasterio valley (BRA-VAL samples in the north slope of the range) yield minimum ^{10}Be CRE ages in the range 18.1–16.7 ka that are equally consistent with glacier retreat after the LGM of MIS 2 (Rodríguez-Rodríguez et al., 2017). Based on the preexisting datasets, we have performed new ^{10}Be CRE analyses on twenty samples taken from lateral and recessional moraines along the Porma valley and its main tributaries to check our hypothesis that glaciers remained close to their maximum extent position during the LGM of MIS 2. Additionally, we report sixteen radiocarbon and seven OSL ages obtained on glacial, glacial-related and post-glacial deposits to cross-check if timing asynchronies exist between the results of the different dating techniques and to discuss eventually their possible causes.

2. Methods

The sampling campaigns were planned considering previous geomorphological map and glacier reconstructions in the Porma valley (Rodríguez-Rodríguez et al., 2015, 2016).

2.1. Cosmic ray exposure dating

Surficial samples were collected from a total of twenty boulders from lateral moraines in the different tributaries of the Porma valley for ^{10}Be CRE analysis (sites ROB, RES, RUN and SIL in Fig. 1; Table 1). Five boulders per moraine were sampled with a manual jackhammer. Selected samples correspond to massive sandstone boulders embedded firmly at the top of moraine ridges, which represent statistically the best candidates for CRE dating (Heyman et al., 2016). All samples correspond to quartzarenite sandstone boulders with an estimated rock density of 2.65 g cm^{-3}. This lithology is only present within the study area in the Cambro-Ordovician Barrios Formation (Barrois, 1882), allowing us to use the geological map of the area (available at http://info.igme.es/visorweb/; last access on May 2018) for tracking the distance from potential source areas with regards to possible inherited concentrations of cosmogenic ^{10}Be. Samples were treated at the *Laboratoire National des Nucléides Cosmogéniques (LN_2C)* at *Centre Européen de Recherche et d'Enseignement des Géosciences de L'Environnement* (CEREGE, France). Physical sample pre-treatment included sample grain size lowering by mechanical crushing and magnetic separation with a Franz. Chemical treatment included three leaching batches (2 days duration each) in hydrofluoric acid to isolate and ensure quartz purification (Kohl and Nishiizumi, 1992). An amount of 14–18 g of pure quartz was spiked with ~0.1 g of Beryllium standard solution and digested in hydrofluoric acid. The Beryllium standard is an in-house solution (3025 ± 9 ppm ^{9}Be) prepared from a phenakite crystal mined at great underground depth (Merchel et al., 2008; Braucher et al., 2015). Beryllium extraction was done using column chromatography and precipitation by neutralization. Beryllium hydroxides were dried after rinsing with pH 8 MQ water in order to remove isobar boron, and finally oxidized at 800 °C to BeO in porcelain crucibles. The isotopic ratio ^{10}Be/^{9}Be of each sample was measured at the French 5 MV AMS facility ASTER (Aix-en-Provence) (Arnold et al., 2010; Klein et al., 2008). Data were calibrated against three targets of reference material SRM4325 using an assigned ^{10}Be/^{9}Be ratio of $(2.79 \pm 0.03) \times 10^{-11}$ (Nishiizumi et al., 2007) and a ^{10}Be half-life of $(1.36 \pm 0.07) \times 10^{6}$ (Korschinek et al., 2010; Chmeleff et al., 2010). Reported analytical uncertainty includes external uncertainty of 0.5%, which accounts for all effects contributing to ASTER's variability and is based on long-term standard measurements (Arnold et al., 2010); counting statistics uncertainty of ca. 3% (~1000 events) and chemical blank correction uncertainty. The isotopic ratios measured for each sample were converted to ^{10}Be concentration in the quartz sample (Balco, 2006) and used to calculate exposure ages with the online exposure age calculator formerly