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

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Abstract

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.

**Key words**

$^{10}$Be surface exposure dating; radiocarbon; optically stimulated luminescence; Last Glacial Maximum; Cantabrian Mountains; Iberian Peninsula; Glaciation.

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 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, Sankaya et al., 2014); the Sistema Central in Iberia (Carrasco et al., 2015, Carrasco et al., 2011, Palacios et al., 2012a, Palacios et al., 2012b, Palacios et al., 2011); and some Pyrenean valleys (Pallás 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 (Pallás et al., 2010, Delmas et al., 2011) and the Cantabrian Mountains (Vidal Romani 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 4 (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 Fondria ice-moulded 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 over-deepened
depression close to the San Isidro Pass provided a $^{14}$C age of 9570 ± 200 yr BP at a depth of 775 to 780 cm (Fombella-Blanco et al., 2003, Fombella-Blanco et al., 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.
Figure 1.-(A) Location of the study area in the context of the North Atlantic region [trajectory of the main ocean currents: red- warm, and blue- cold]. (B) Geomorphological map of the Porma valley showing the sampling site locations. The $^{10}$Be CRE dataset includes a new set of 20 boulders sampled from lateral moraines in the Porma, Silván and Respina valleys; and two previous sets of boulders sampled from moraine, erratics and rock glacier boulders in the Porma (27 samples; Rodríguez-Rodríguez et al., 2016), and and Monasterio valleys (19 samples; Rodríguez-Rodríguez et al., 2017) [the acronym of the landform name is given in capital letters; information on boulder type is given by the following abbreviations: m- moraine boulder; e- glacial erratic boulder; rg- rock glacier boulder]. Black stars indicate the location of the new sediment cores and samples taken for OSL and radiocarbon dating; while grey stars indicate cores and OSL samples previously published in the Brañagallones and Tarna sites (Jiménez-Sánchez and Farias, 2002; Jiménez-Sánchez et al., 2013) is also included.
2. Methods

The sampling campaigns were planned considering previous geomorphological map and glacier reconstructions in the Porma valley (Rodríguez-Rodríguez et al., 2015, Rodriguez-Rodríguez et al., 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$^{2}$C) 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
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 $^{10}\text{Be}/^{9}\text{Be}$ 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 $^{10}\text{Be}/^{9}\text{Be}$ ratio of $(2.79 \pm 0.03) \times 10^{-11}$ (Nishiizumi et al., 2007) and a $^{10}\text{Be}$ 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 $^{10}\text{Be}$ concentration in the quartz sample (Balco, 2006) and used to calculate exposure ages with the online exposure age calculator formerly known as the CRONUS-Earth $^{10}\text{Be}$ exposure age calculator (Balco et al., 2008) using version 2.3 (released in June 2016) and considering the global production rate based on the primary calibration dataset in Borchers et al. (2016) and the Lm scaling scheme (Lal, 1991, Stone, 2000) (Table 1). A standard atmosphere was assumed, while topographic shielding was corrected using the Cronus-Earth Geometric shielding calculator version 1.1 and field readings of the horizon’s inclination taken at each sample site (Balco et al., 2008). Moraine minimum exposure ages reported in Table 1 correspond to straight mean of the exposure ages obtained from multiple boulders collected from the same landform, not corrected for neither erosion nor vegetation cover. Similarly, snow shielding corrections were not applied because the historical record of snowpack thickness measurements is too restricted in duration (c. 1991 to present) and spatial distribution
(just 5 control points, all placed along the Porma catchment divide) to ensure reliable corrections for the entire Last Glacial Cycle (Schildgen et al., 2005). Moreover, recent long-term neutron monitoring have shown that snow cover attenuates fast neutrons (0.1–10MeV) much more strongly than predictions based on conventional mass-shielding (Zweck et al., 2013), being necessary to develop further studies to validate the extrapolation of this results to spallogenic neutrons with higher energies (e.g. >50 MeV) like those responsible for $^{10}$Be production (Delunel et al., 2014). Thus, the ages reported in this work must be regarded as minimum exposure ages. The ±1σ analytical uncertainty corresponds to the standard deviation of the mean exposure age when the standard deviation of the age values is greater than the averaged internal uncertainties. Otherwise, the standard deviation of the weighted mean is provided. Errors reported in brackets include uncertainty associated to the production rate.

2.2. Radiocarbon dating

Radiocarbon dating was applied to sediments deposited in ponds and peat bogs located outside lateral moraines or in glacially over-deepened hollows (Fig. 1). Eight sediment cores were drilled with a manual sampler manufactured by Eijelkamp®. Pond sequences and peat bogs formed outside lateral moraines (referred as ice dammed or kame terrace deposits) may have been deposited since the glacier advance responsible for the moraine deposition due to the impoundment effect on lateral tributaries, while ponds and peat bogs deposited in glacially over-deepened hollows most likely developed after glacier retreat. Once in the laboratory, each sediment core was split in half to describe the sedimentary sequence and take samples for radiocarbon dating. Ten terrestrial plant macro remains samples were taken from discrete organic-rich levels using laboratory pincers. Additionally, six bulk sediment samples were collected from some inorganic units. A slice ~0.5 cm thick of clay material was
### Table 1
Minimum surface exposure ages reported for lateral moraines sampled in the Porma valley.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Lat (DD)</th>
<th>Long (DD)</th>
<th>Elevation (m)</th>
<th>Height (m)</th>
<th>Thickness (cm)</th>
<th>Shielding factor</th>
<th>Quartz (g)</th>
<th>Be carrier (mg)</th>
<th>$^{10}$Be age (10$^4$ at g$^{-1}$)</th>
<th>$^{10}$Be CRE age (ka)$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Runção lateral moraine</strong></td>
<td></td>
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</tr>
<tr>
<td>RUN-01</td>
<td>43.0368</td>
<td>-5.2835</td>
<td>1328</td>
<td>2.1</td>
<td>3.4</td>
<td>0.9975</td>
<td>14.5852</td>
<td>0.1025</td>
<td>24.574 ± 0.780</td>
<td>21.3 ± 0.7</td>
</tr>
<tr>
<td>RUN-02</td>
<td>43.0364</td>
<td>-5.2832</td>
<td>1331</td>
<td>1.4</td>
<td>2.3</td>
<td>0.9975</td>
<td>14.2067</td>
<td>0.1028</td>
<td>24.519 ± 0.795</td>
<td>21.1 ± 0.7</td>
</tr>
<tr>
<td>RUN-03</td>
<td>43.0357</td>
<td>-5.2825</td>
<td>1307</td>
<td>1.0</td>
<td>2.5</td>
<td>0.9978</td>
<td>14.7240</td>
<td>0.1014</td>
<td>22.965 ± 0.906</td>
<td>20.1 ± 0.8</td>
</tr>
<tr>
<td>RUN-04</td>
<td>43.0347</td>
<td>-5.2814</td>
<td>1278</td>
<td>4.6</td>
<td>2.5</td>
<td>0.9976</td>
<td>14.2754</td>
<td>0.1017</td>
<td>22.481 ± 1.073</td>
<td>20.2 ± 1.0</td>
</tr>
<tr>
<td>RUN-05</td>
<td>43.0338</td>
<td>-5.2807</td>
<td>1277</td>
<td>2.9</td>
<td>2.0</td>
<td>0.9980</td>
<td>15.0259</td>
<td>0.1027</td>
<td>20.414 ± 0.787</td>
<td>18.3 ± 0.7</td>
</tr>
<tr>
<td><strong>Robledo lateral moraine</strong></td>
<td></td>
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</tr>
<tr>
<td>ROB-02</td>
<td>43.0233</td>
<td>-5.3224</td>
<td>1415</td>
<td>2.5</td>
<td>2.8</td>
<td>0.9982</td>
<td>14.6866</td>
<td>0.1024</td>
<td>24.313 ± 0.771</td>
<td>19.7 ± 0.6</td>
</tr>
<tr>
<td>ROB-03</td>
<td>43.0218</td>
<td>-5.3196</td>
<td>1390</td>
<td>1.5</td>
<td>1.8</td>
<td>0.9983</td>
<td>14.2943</td>
<td>0.1024</td>
<td>28.982 ± 0.922</td>
<td>23.6 ± 0.7</td>
</tr>
<tr>
<td>ROB-04</td>
<td>43.0218</td>
<td>-5.3196</td>
<td>1390</td>
<td>1.3</td>
<td>4.6</td>
<td>0.9983</td>
<td>14.1238</td>
<td>0.1023</td>
<td>42.908 ± 1.347</td>
<td>35.2 ± 1.1$^*$</td>
</tr>
<tr>
<td>ROB-05</td>
<td>43.0218</td>
<td>-5.3196</td>
<td>1390</td>
<td>1.9</td>
<td>2.0</td>
<td>0.9983</td>
<td>14.9241</td>
<td>0.1018</td>
<td>28.238 ± 0.899</td>
<td>23.0 ± 0.7</td>
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<td>ROB-06</td>
<td>43.0218</td>
<td>-5.3196</td>
<td>1390</td>
<td>1.4</td>
<td>4.0</td>
<td>0.9983</td>
<td>17.6897</td>
<td>0.1021</td>
<td>21.415 ± 0.729</td>
<td>17.9 ± 0.6</td>
</tr>
<tr>
<td><strong>Respina lateral moraine</strong></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>RES-01</td>
<td>43.0234</td>
<td>-5.3701</td>
<td>1631</td>
<td>1.1</td>
<td>2.0</td>
<td>0.9955</td>
<td>14.6739</td>
<td>0.1033</td>
<td>54.341 ± 1.704</td>
<td>36.4 ± 1.2</td>
</tr>
<tr>
<td>RES-02</td>
<td>43.0233</td>
<td>-5.3696</td>
<td>1644</td>
<td>1.2</td>
<td>3.0</td>
<td>0.9955</td>
<td>14.6324</td>
<td>0.1022</td>
<td>44.374 ± 1.471</td>
<td>29.9 ± 1.0</td>
</tr>
<tr>
<td>RES-03</td>
<td>43.0233</td>
<td>-5.3690</td>
<td>1644</td>
<td>0.9</td>
<td>3.3</td>
<td>0.9851</td>
<td>14.4383</td>
<td>0.1026</td>
<td>37.520 ± 1.329</td>
<td>25.8 ± 0.9</td>
</tr>
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<td>RES-04</td>
<td>43.0233</td>
<td>-5.3698</td>
<td>1644</td>
<td>0.9</td>
<td>1.7</td>
<td>0.9955</td>
<td>14.7452</td>
<td>0.1024</td>
<td>152.789 ± 4.762</td>
<td>101.7 ± 3.4$^*$</td>
</tr>
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<td>RES-05</td>
<td>43.0231</td>
<td>-5.3696</td>
<td>1647</td>
<td>0.4</td>
<td>2.6</td>
<td>0.9955</td>
<td>14.5469</td>
<td>0.1022</td>
<td>23.721 ± 0.777</td>
<td>16.2 ± 0.5</td>
</tr>
<tr>
<td><strong>Silván recessional moraine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>SIL-01</td>
<td>43.0253</td>
<td>-5.3025</td>
<td>1256</td>
<td>0.6</td>
<td>1.6</td>
<td>0.9906</td>
<td>14.3810</td>
<td>0.1009</td>
<td>52.142 ± 1.632</td>
<td>46.3 ± 1.5</td>
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<td>SIL-02</td>
<td>43.0251</td>
<td>-5.3027</td>
<td>1254</td>
<td>0.9</td>
<td>2.5</td>
<td>0.9442</td>
<td>14.4077</td>
<td>0.1031</td>
<td>53.506 ± 2.222</td>
<td>50.4 ± 2.2</td>
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<td>SIL-03</td>
<td>43.0245</td>
<td>-5.3020</td>
<td>1262</td>
<td>0.8</td>
<td>2.0</td>
<td>0.9906</td>
<td>13.0997</td>
<td>0.1020</td>
<td>12.684 ± 0.591</td>
<td>11.6 ± 0.5</td>
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<td>SIL-04</td>
<td>43.0246</td>
<td>-5.3020</td>
<td>1261</td>
<td>0.3</td>
<td>1.7</td>
<td>0.9906</td>
<td>14.8372</td>
<td>0.1028</td>
<td>15.040 ± 0.625</td>
<td>13.8 ± 0.6</td>
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<td>SIL-05</td>
<td>43.0232</td>
<td>-5.3013</td>
<td>1263</td>
<td>-</td>
<td>2.5</td>
<td>0.9943</td>
<td>13.6479</td>
<td>0.1035</td>
<td>12.512 ± 0.720</td>
<td>11.5 ± 0.7</td>
</tr>
</tbody>
</table>

$^a$ Geographical coordinates are referred to WGS84 datum.

$^b$ Samples measured at the French AMS national facility ASTER (Aix-en-Provence, France).

$^c$ CRE ages calculated with the latest version of the online exposure age calculator formerly known as the CRONUS-Earth online exposure age calculator v2.3 (http://hess.ess.washington.edu/math/; November 2016; Balco et al., 2008) considering the default primary calibration dataset of Borchers et al. (2016) and the Lm scaling scheme. No snow and no erosion corrections were applied.

$^d$ Mean CRE age and analytical uncertainty, expressed as the standard deviation of the mean exposure age when the standard deviation is greater than the averaged internal uncertainties, otherwise, the standard deviation of the weighted mean is provided. Errors in brackets include production rate uncertainty (3.5%).

*Outlier boulder ages (see text for details).
taken in each case. Basal ages provide a minimum reference age for the start of the sedimentation and thus for either the glacier advance episode responsible for lateral moraine buildup or the glacier retreat episode that exposed a glacial hollow. All samples were analyzed by the AMS radiocarbon technique in two commercial laboratories. Nine radiocarbon samples were analyzed at Poznan Radiocarbon Laboratory (Poland) and seven samples at Direct AMS laboratory (Seattle) (Table 2). Age results were calibrated with the Radiocarbon Calibration Program Calib Rev 7.0.2 (Stuiver and Reimer, 1993) against the IntCal13 curve (Reimer et al., 2013).

Table 2

Radiocarbon results obtained for samples taken from sediment cores drilled in key sites of the Porma valley closely related to past glacier environment. Radiocarbon ages calibrated with Calib Rev 7.0.2 program (Stuiver and Reimer, 1993) against the IntCal13 curve (Reimer et al., 2013).

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Depth (m)</th>
<th>Laboratory reference</th>
<th>Dated material</th>
<th>C-14 age (years BP)</th>
<th>Calendar age (2σ) (years BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fonfría-01</td>
<td>1.73</td>
<td>Poz-76440</td>
<td>9 g wood</td>
<td>7000 ± 50</td>
<td>7712 – 7938</td>
</tr>
<tr>
<td>Fonfría-01</td>
<td>1.78</td>
<td>Poz-76441</td>
<td>3 g plant remains</td>
<td>6970 ± 50</td>
<td>7689 – 7876</td>
</tr>
<tr>
<td>Fonfría-01</td>
<td>4.02</td>
<td>Poz-76442</td>
<td>8 g plant remains</td>
<td>10450 ± 60</td>
<td>12104 – 12554</td>
</tr>
<tr>
<td>Fonfría-01</td>
<td>5.30</td>
<td>Poz-76443</td>
<td>4 g plant remains</td>
<td>9520 ± 60</td>
<td>10653 – 11099</td>
</tr>
<tr>
<td>Isidro-02</td>
<td>2.53</td>
<td>Poz-76447</td>
<td>13 g bulk sediment</td>
<td>33000 ± 500</td>
<td>36014 – 38473</td>
</tr>
<tr>
<td>Isidro-02</td>
<td>5.78</td>
<td>Poz-76448</td>
<td>12 g bulk sediment</td>
<td>40500 ± 1500</td>
<td>41842 – 46746</td>
</tr>
<tr>
<td>Silván-02</td>
<td>1.14</td>
<td>Poz-76450</td>
<td>15 g bulk sediment</td>
<td>6790 ± 50</td>
<td>7569 – 7709</td>
</tr>
<tr>
<td>Silván-02</td>
<td>1.94</td>
<td>Poz-76451</td>
<td>8 g bulk sediment</td>
<td>6950 ± 50</td>
<td>7679 – 7869</td>
</tr>
<tr>
<td>Toneo-01</td>
<td>1.44</td>
<td>Poz-76452</td>
<td>12 g bulk sediment</td>
<td>14450 ± 70</td>
<td>17404 – 17870</td>
</tr>
<tr>
<td>Soportales-03</td>
<td>1.40</td>
<td>DAMS012594</td>
<td>24 g wood</td>
<td>5340 ± 33</td>
<td>6000 – 6211</td>
</tr>
<tr>
<td>Soportales-03</td>
<td>1.90</td>
<td>DAMS012595</td>
<td>13 g wood</td>
<td>7838 ± 39</td>
<td>8542 – 8729</td>
</tr>
<tr>
<td>Soportales-03</td>
<td>2.40</td>
<td>DAMS012596</td>
<td>38 g wood</td>
<td>8201 ± 36</td>
<td>9030 – 9272</td>
</tr>
<tr>
<td>Soportales-03</td>
<td>3.65</td>
<td>DAMS012597</td>
<td>7 g wood</td>
<td>7686 ± 35</td>
<td>8411 – 8543</td>
</tr>
<tr>
<td>Soportales-03</td>
<td>4.20</td>
<td>DAMS012598</td>
<td>3 g wood</td>
<td>8158 ±34</td>
<td>9011 – 9143</td>
</tr>
<tr>
<td>Soportales-03</td>
<td>6.12</td>
<td>DAMS012599</td>
<td>1 g wood</td>
<td>8200 ± 38</td>
<td>9029 – 9274</td>
</tr>
<tr>
<td>Soportales-03</td>
<td>7.63</td>
<td>DAMS012600</td>
<td>8 g bulk sediment</td>
<td>27532 ± 122</td>
<td>31114 – 31531</td>
</tr>
</tbody>
</table>
2.3. Optically Stimulated Luminescence dating

The OSL technique was used to date sandy deposits from glacially-related sedimentary basins and lateral moraines. A total of seven samples were taken (Table 3): (i) four samples correspond to lacustrine sequences deposited in close relationship with lateral moraines, either between moraine ridges (Tronisco site) or behind them (Guarilla site); (ii) two samples correspond to lacustrine or alluvial sedimentary sequences infilling glacial hollows (Fonfría and Remelende sites); and (iii) one sample (Runción site) is from a lateral moraine which was also analyzed for $^{10}$Be CRE dating. Samples were taken using conventional techniques for poorly lithified sediments. Opaque plastic tubes were used to collect the samples and then protected from light with the aid of plastic bags, tape and aluminum foil. Samples were processed in the luminescence dating laboratory of Instituto Universitario de Xeoloxía Isidro Parga Pondal at Universidade da Coruña (Spain). Sandy material of the tube ends (initial ~5 cm) was discarded from the OSL analysis. Samples were dried at 45ºC and sieved to collect the 180–250 μm grain size fraction, which was treated with hydrochloric acid to remove carbonate and organic material. Both quartz and k-feldspar fractions were independently leached with hydrofluoric acid. Quartz purity was ensured through Infrared Stimulated Luminescence (IRSL) analysis of sample aliquots, obtaining negative signals in all cases. The Equivalent Dose (ED) was measured using the Single Aliquot Regeneration (SAR) protocol (Murray and Wintle, 2000), including a final recovery test. Measures were performed in an automated RISØ TL/OSL-DA-15 reader equipped with a photomultiplier EMI 9635 QA and an inner source of $^{90}$Sr/$^{90}$Y that provides a dose of 0.120 ± 0.003 Gy/s. Dose Rates (DR) were determined measuring the activity of $^{40}$K, $^{238}$U, $^{226}$Ra and $^{232}$Th in a high-resolution Canberra spectroscopy at the radioactive laboratory at Universidad de Sevilla (Spain). Results were used to determine the DR considering the conversion factors of Guerin
et al. (2011), while the cosmic dose was determined following Prescott and Hutton (1994). The water content was measured in all samples and an average value was considered to account for its effect over resultant DR. Table 3 compiles the OSL results, including the number of aliquots measured and the over dispersion of the average in the distributions of sample aliquots. The over dispersion shows the possible effect of sedimentation / transport processes in the measured grains, which generally fits to a normal distribution (Galbraith et al., 1999). In general, over dispersion values higher than 30% are related to these processes, but also can result from low radiation rates. The Central Age Model was applied to estimate sample ages (Galbraith et al., 1999). Samples Gua-02-1 and Gua-02-2 show over dispersions above and below than 30% but provide the same burial age using this model. The OSL signal of sample Fonf-01 was in saturated values, so a minimum age estimate is provided following Wintle and Murray (2006).

### Table 3
Optically Stimulated Luminescence results obtained for samples taken in the Porma valley (DR- dose rate; ED- equivalent dose).

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Depth (m)</th>
<th>Elev. (m)</th>
<th>Hum. (%)</th>
<th>DR (Gy/ka)</th>
<th>ED (Gy)</th>
<th>N</th>
<th>Overdisp. (%)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fonf-01</td>
<td>6.00</td>
<td>1600</td>
<td>20 ± 4</td>
<td>0.59 ± 0.07</td>
<td>&lt; 96</td>
<td>10</td>
<td>-</td>
<td>&lt; 164*</td>
</tr>
<tr>
<td>Gua-02-1</td>
<td>1.00</td>
<td>1350</td>
<td>20 ± 4</td>
<td>0.78 ± 0.08</td>
<td>25.5 ± 0.9</td>
<td>44</td>
<td>28.0 ± 5.8</td>
<td>32.5 ± 3.9</td>
</tr>
<tr>
<td>Gua-02-2</td>
<td>1.40</td>
<td>1350</td>
<td>17 ± 3</td>
<td>0.68 ± 0.06</td>
<td>19.2 ± 1.6</td>
<td>42</td>
<td>38.2 ± 6.9</td>
<td>27.9 ± 3.4</td>
</tr>
<tr>
<td>Tro-02-1</td>
<td>0.50</td>
<td>1500</td>
<td>29 ± 6</td>
<td>1.85 ± 0.22</td>
<td>9.4 ± 0.8</td>
<td>45</td>
<td>48.6 ± 6.1</td>
<td>5.0 ± 0.7</td>
</tr>
<tr>
<td>Runc-01</td>
<td>0.50</td>
<td>1340</td>
<td>20 ± 4</td>
<td>0.88 ± 0.13</td>
<td>29.4 ± 2.0</td>
<td>38</td>
<td>29.6 ± 5.7</td>
<td>33.3 ± 5.4</td>
</tr>
<tr>
<td>REM-02b</td>
<td>1.26</td>
<td>1640</td>
<td>10 ± 3</td>
<td>0.78 ± 0.09</td>
<td>20.6 ± 1.9</td>
<td>30</td>
<td>37.3 ± 8.5</td>
<td>26.5 ± 4.0</td>
</tr>
<tr>
<td>REM-02c</td>
<td>1.26</td>
<td>1640</td>
<td>16 ± 4</td>
<td>0.77 ± 0.09</td>
<td>21.0 ± 2.0</td>
<td>31</td>
<td>34.4 ± 8.4</td>
<td>27.0 ± 4.1</td>
</tr>
</tbody>
</table>

*The OSL signal obtained from quartz was saturated most probably due to insufficient bleaching prior to the final burial event dated. The age provided is a minimum estimate based on Wintle and Murray (2006).

b Aliquot of REM-02 sample that corresponds to the 180-250 μm grain fraction.

c Aliquot of REM-02 sample that corresponds to the 250-300 μm grain fraction.

### 3. Results

Four lateral moraines preserved along the Porma, Isoba, Respina and Silván valleys were sampled for cosmic ray exposure dating (Table 1) and resultant ages have been analyzed against ¹⁴C (Table 2) and OSL (Table 3) results derived from lacustrine sediments closely
related to glacier dynamics and moraine deposition. Results are summarized by sampling areas.

3.1. The Porma valley and the Señales Pass

The Porma valley (~12 km long; up to 1.5 km wide) shows outstanding examples of lateral moraines, particularly well-preserved are those located in the vicinity of the Cofiñal village and at the confluence with the Tronisco tributary valley. The Runción moraine is a 1.2 km-long lateral moraine preserved in the western slope of the Porma valley, hanging ~200 m above the valley floor. The $^{10}\text{Be CRE}$ dating of five boulders from this moraine yielded a mean minimum abandonment age of 20.2 ± 0.5 (0.9) ka, whereas an OSL sample from the sandy till matrix of the same moraine (Runc-01) provide a minimum burial age of 33.3 ± 5.4 ka for the time of moraine deposition (Fig. 2). A sediment core was drilled in the Guarilla kame terrace (ca. 1350 m a.s.l.) deposited behind the Runción lateral moraine and named Guarilla-02. It is made up by alternations of clay, silt and sandy sediments interpreted as lacustrine sedimentation with episodic alluvial inputs from a lateral short tributary (~1.1 km long). Two OSL analysis of the sandy sediment found at 1.0 and 1.4 m depth provide burial ages of 27.9 ± 3.4 and 32.5± 3.9 ka respectively (Table 3), which represent minimum ages for the onset of alluvial sedimentation due to the impoundment of the lateral tributary valley caused by the presence of the Runción lateral moraine.
Figure 2.- (A) Google Earth image showing the location of the Runción lateral moraine and the Guarilla kame terrace in the Porma valley, which were dated through a combination of $^{10}$Be CRE and OSL dating (small blue arrows indicate former ice flow direction). Particle size in the stratigraphic section of the Guarilla-02 core is provided according to the Wentworth scale [C- clay; S- silt; SF- fine sand; Sm- medium sand; Sc- coarse sand; G- gravel]. (B) Detailed pictures of sampled boulders in the Runción moraine and the OSL sample Runc-01 taken from the till matrix in an exposed section of the same moraine (about one-meter depth below surface).

About 2 km up-valley from Cofiñal, five lateral moraines are preserved at different heights across the Tronisco tributary valley, the outermost towering up to 200 m above the floor of the Porma valley. Due to the scarcity of adequate boulders for $^{10}$Be CRE dating, only a
sediment core named Tronisco-02 was drilled in a lacustrine deposit preserved between the two outermost moraine ridges (Fig. 3A). This core reached a depth of 0.8 m, showing a lower unit (~25 cm) made up by matrix-supported angular sandstone cobbles embedded in a sandy-clay matrix interpreted as till sediments; and an upper unit composed by fine sand and silt sediments (~55 cm) interpreted as the result of illuviation from the adjacent moraines. The OSL sample Tro-01 was taken in the Tronisco-02 core at a depth of 0.5 m and yielded a burial age of 5.0 ± 0.7 ka for the alluvial inter-moraine sequence.

A third site was analyzed in the Zampuerna tributary valley close to the Remelende peak (1888 m a.s.l.; Fig. 3B), which is located 0.5 km north from Las Señales Pass (1625 m a.s.l.) and ~2.4 km west from the Tarna Pass (1492 m a.s.l.). Alluvial sand sediments nested within two recessional moraines at ~1640 m a.s.l. were sampled for OSL analysis (sample REM-02). The source area of alluvial sand sediments is located at a distance of 0.5–1 km. The OSL analysis was performed on two different grain size fractions of the REM-02 sample (180–250 μm and 250–300 μm), resulting in ages of 26.5 ± 4.0 and 27.0 ± 4.1 ka, which ideally represent a minimum time reference for the onset of alluvial sedimentations at this setting.

3.2. The Isoba valley and the San Isidro Pass

The Isoba valley is an 8.8 km-long valley that extents from the San Isidro Pass (1520 m a.s.l.) to its confluence with the Porma valley. Previous $^{10}$Be CRE chronologies based on analysis of rock glacier boulders and glacial erratics resting on the ice-molded surface of Loma Fonfría were complemented with new radiocarbon and OSL analyses from three glacially-related sedimentary sequences (Figs. 4 and 5). Particularly, sediment cores correspond to: (i) the Isoba valley bottom located between the San Isidro urbanization and the San Isidro Pass (Isidro-02); (ii) the Fonfría peat bog (Fonfría-01) located in the Loma Fonfría surface; and (iii) the Toneo kame terrace (Toneo-01) located East from the San Isidro valley.
Figure 3.- (A) Google Earth image showing the location of lateral moraines preserved in Arroyo de Tronisco and location of the sediment core Tronisco-02 (where the OSL sample Tro-02-1 was taken) between the two outermost lateral moraines. (B) Panoramic Google Earth view of the Señales and Tarna mountain passes. The location of the Tarna core, previously dated with a combination of radiocarbon and OSL techniques, is also provided (Jiménez-Sánchez and Farias, 2002; Jiménez-Sánchez et al. 2013). (C) An OSL sample was taken in alluvial sediments nested by recessional moraines in the vicinity of the Señales Pass. Small blue arrows represent former ice flow directions.
The Isidro-02 core was retrieved from a valley bottom infill sequence deposited in the Isoba glacial valley close to the confluence with the San Isidro valley and located about 450 meters east of the San Isidro Pass (Fig. 4B). This sequence is at least 6.2 m thick, composed of decimeter-sized intervals of grey gravel and sand units, inter-beded with grey silt and clay intervals arranged as normal grading sequences interpreted as alluvial sedimentation related to inputs from nearby tributary valleys. Gravel sediments are mostly made up by bedrock
shale and sandstone fragments up to 2-3 cm in diameter. A thick unit of dark grey clay is preserved at depth between 4.50 and 5.85 m and is interpreted as decantation of fine sediments in a quiet lacustrine environment. A second yellowish to brownish colored clay-silt laminated unit is preserved at depth between 1.80 and 2.55 m and may correspond to glacial varve sediments. Two radiocarbon bulk sediment samples were analyzed at the base of the two clay units. The sample taken at the base of the deepest homogeneous clay unit yields an age of 41.8–46.7 cal ka BP, while the bulk sediment sample at the base of the varve interval yields an age of 36.0–38.5 cal ka BP.

The Fonfría-01 core corresponds to a peat bog sequence deposited in a glacially overdeepened depression that was excavated in the Loma Fonfría ice-molded surface (~1520–1670 m asl; ~3.3 km SE of the San Isidro Pass Fig. 4C). The Fonfría-01 core reached a drilling depth of 6.3 m, showing a sequence constituted of 0.7 m-thick lower unit of alluvial quartz-rich sands overlaid by alternations of lacustrine clay-silt sediments and peat bog material. The source area of the basal sandy unit is located just 300 to 600 m south from the Fonfría sequence, in the quarztarenite sandstone that outcrops along Sierra de Sentiles. Given the absence of alluvial sands in the upper part of the core and the dominance of muddy and peat bog intervals, a glacio-fluvial origin is assumed for the basal sandy unit, which was probably deposited when glaciers were retreating from the Loma Fonfría surface. In fact, the OSL sample taken at 6 m depth provided a saturated OSL signal for quartz, most likely due to insufficient bleaching prior to burial. Four radiocarbon samples from the upper peat bog intervals were analyzed for radiocarbon, and the oldest minimum depositional age for the lacustrine sedimentation is 12.1–12.6 cal ka BP. However, this result does not correspond to the deepest sample in this core.
Figure 5.- Sedimentary sequences of the Isidro-02, Fonfría-01, Soportales-01, Toneo-01 Silván-02 and Tronisco-02 cores [particle size according to the Wentworth scale: C- clay; S- silt; Sf- fine sand; Sm- medium sand; Sc- coarse sand; G- gravel]. The position of radiocarbon and OSL samples in the sedimentary sequences is indicated and results are provided in Tables 2 and 3. Core locations are shown in Figure 2.
Finally, the Toneo-01 core was drilled in a kame terrace deposited behind the lateral moraine located along the eastern slope of the San Isidro valley (Fig. 4D). The sequence is at least 1.7 m thick and mostly comprises grey massive clay sediments. A bulk sediment sample taken close to the base of the Toneo-01 core gives a minimum radiocarbon age of 17.4–17.9 cal ka BP.

3.3. The Silván and Respina valleys

The Silván valley is the main tributary of the Porma valley in the study area (Fig. 6). This 9.8 km-long glacial valley extends from the vicinity of Lago Ausente to Puebla de Lillo village. Well-preserved lateral moraines on both valley sides can be observed continuously over 2 to 3.6 km. The lateral moraine preserved along the western side of the Silván valley is merged with the lateral moraine that runs along the northern slope of the Respina valley (also known as Iyarga valley). The Respina valley is a 7.7 km-long glacial valley that starts at the southern side of Sierra de Sentiles. Former glaciers that flowed along the Silván and Respina valleys joined at the Soportales area, where multiple medial moraines were deposited and preserved. The Soportales-03 core corresponds to a 7.9 m thick lacustrine sequence deposited between moraine ridges preserved at the former water divide between the Rebueno and Celorno valleys. The core is located at 1270 m a.s.l., ~58–74 m above the modern Celorno river. The sequence alternates lacustrine grey clay and dark-brown peat bog material intervals with multiple plant macro remains such as wood fragments, pine corns, and hazelnuts. The lowest unit corresponds to clay and angular shale fragments interpreted as weathered bedrock. Seven radiocarbon ages were obtained from the Soportales-03 core, six correspond to wooden fragments, whereas the deepest sample corresponds to bulk sediment. Radiocarbon ages obtained from woody fragments sampled at depths between 1.42 and 6 m
yield ages in the range 6.0–9.3 cal ka BP. However, the lowest bulk sediment sample taken at 7.6 m depth yields an age of 31.1–31.5 cal ka BP.

Figure 6.- (A) Google Earth view of the Silván, Respina and Rebueno-Celorno tributary valleys in the Porma basin, showing former ice flow directions (blue arrows) during the local Glacial Maximum and the location of the Robledo and Respina moraines sampled for $^{10}$Be CRE dating (detailed pictures of the sampled boulders are also provided). The location of the sediment cores Silván-02 and Soportales-03 drilled in lacustrine infill deposited in glacially over-deepened depressions and between lateral moraines is also indicated. (B) Panoramic view of the Respina moraine and detailed pictures of the sampled boulders. The ridge of a recessional moraine placed inside the Respina moraine is also indicated but was not sampled for CRE dating.
Two lateral moraines were sampled for $^{10}$Be CRE dating in the Respina valley. These were informally named Robledo and Respina moraines in this work (Fig. 6). The Robledo lateral moraine is a 2.2 km long lateral moraine preserved along the northern slope of the Respina valley, hanging ~160 m above the valley floor. A mean minimum exposure age of $21.0 \pm 0.3$ (0.8) ka is reported based on $^{10}$Be CRE analysis of four boulders. Boulder ROB-04 was excluded from the moraine mean exposure age because it is more than two standard deviations older than the other four boulders. The Respina lateral moraine is 380 m long, ~37 m high, and is perched 208 m above the Respina valley floor close to the old Respina talc mine. A minimum $^{10}$Be CRE age of $27.1 \pm 4.2$ (4.3) ka is estimated for the Respina lateral moraine based on ages from four boulders. The age of boulder RES-04 was excluded from the moraine mean exposure age because it is more than two standard deviations older than the mean exposure age of the other four boulders.

In the Silván valley, a 430 m-long recessional moraine draping a bedrock step ~70 m-high above the valley floor was sampled for $^{10}$Be CRE dating (Fig. 7). The results clearly show two distinct groups of boulder exposure ages (Table 1). Two boulders provide ages of $46.3 \pm 1.5$ ka (SIL-01) and $50.4 \pm 2.2$ ka (SIL-02), and are older than expected according to the relative age sequence and comparable to ages previously reported for the Redipollos erratics 4 km down-valley (Rodríguez-Rodríguez et al., 2016). The remaining three boulders yielded results in the range 13.8 to 11.5 ka (SIL-03 to 05) which are considerably younger than expected according to previous ages reported for glacial erratics resting on the Fonfría surface (17.7 ± 0.4 ka) and the Requejines rock glacier (15.7 ± 0.3 ka) (Rodríguez-Rodríguez et al., 2016). Thus, it is not possible to calculate a mean CRE age representative for the time of moraine abandonment. Considering the minimum exposure ages obtained from the Runción, Robledo and Respina lateral moraines and the ages of glacial erratics lying on top of the
Loma Fonfría surface, the most probable abandonment age of the Silván moraine should lie between 20 and 17.7 ka. An alternative interpretation is that instead of a recessional moraine, the Silván ridge is not a recessional moraine but draping till partly preserved on a topographic high that was overridden by glaciers during multiple glacial stages. Then, the inherited boulders reflect a reference age for the glaciers overriding this site and flowing down to the terminal zone.

Figure 7.- The Silván moraine (ca. 1263 m a.s.l.) is draping a bedrock step ~70 m-high above the Silván valley floor. This site was exposed when the Silván outlet glacier had thinned about 60 m compared to the previous glacial stage marked by the ROB lateral moraine, in the opposite hillslope.
Located on the distal side of the Silván moraine, a sediment core named Silván-02 (1.76 m thick) was drilled in a glacially over-deepened hollow excavated in the Carboniferous shale bedrock. The Silván-02 sequence is mostly composed of laminated clays of lacustrine origin and coarser sediment intervals washed from the nearby SIL moraine (Fig. 5, Fig. 6A). Two radiocarbon samples were analyzed, providing a minimum reference age of 7.7–7.9 cal ka BP for the onset of lacustrine sedimentation at this site.

4. Discussion

The application of the three most frequently used dating techniques for studying glacial and glacial-related deposits in a single study area offers a unique opportunity to: (i) analyze dating results relying on different techniques; and (ii) improve the chronological framework of Quaternary mountain glaciations in the Cantabrian Mountains, and (iii) identify potential forcing involved in the glacial history of the studied area.

4.1. Similarities and discrepancies between dating results relying on the different techniques

The new $^{10}$Be CRE chronology presented in this work is generally time-consistent with previous $^{10}$Be CRE ages reported for the glacial sequence in the Porma valley (Rodríguez-Rodríguez et al., 2016). The minimum abandonment ages obtained in the Runción (20.2 ± 0.9 ka), Robledo (21.0 ± 0.8 ka) and Respina (27.1 ± 4.3 ka) lateral moraines support our previous hypothesis that glaciers were still filling the main valleys during MIS 2, flowing down to an elevation of 1130 m a.s.l. Particularly, glacier tongues flowing along the Porma, Silván and Respina valleys would have reached ice thickness values comparable to those recorded during the previous Pleistocene glacial maximum, adding new till deposits to the already existing lateral moraines. Only the Silván recessional moraine yielded an anomalous mixture of boulder exposure ages that are either too old or too young compared to the
moraines and rock glacier sequence dated up and down-valley. According to previous analyses of large global datasets, partial exposure due to post-depositional shielding occurs more often than over-exposure with respect to the deposition time due to prior exposition (Heyman et al., 2011). In the present study, boulder ages that are more than two standard deviations older than the rest of the group mean age are considered too old and excluded from the average moraine age calculation (time of moraine abandonment). They are probably related to either insufficient erosion prior to exposure, e.g. the minimum travelling distance estimated for these boulders varies between 2 and 0.1 km; or inherited nuclides from previous episodes of exposure during glacier advance and retreat in the area, e.g. boulders RES-04, SIL-01 and SIL-02 yield ages that are comparable to those previously found at the glacier front area and attributed to past glacier advances during MIS 5d and MIS 3.

Radiocarbon dating in lacustrine environments may be affected by contamination related to: (1) sediment reworking of old organic matter; (2) freshwater reservoir or hard-water effect (lake freshwater contaminated by old carbon from bedrock can cause the aging of new organic matter synthetized in the aquatic environment); and (3) inorganic carbon contamination as fine-grained sediments derived from bedrock (Pallàs et al., 2006). Radiocarbon samples were preferentially taken from terrestrial plant macro remains to minimize the freshwater effect (Rixhon et al., 2017). Our results show that in general bulk sediment samples provided results considerably older than those obtained from plant macro remain samples. In multiple cases, these virtually old radiocarbon results do not conflict with numerical ages obtained with $^{10}$Be CRE and OSL techniques in adjacent settings, respecting the relative age sequence. In contrast, the Isidro-02 sequence deposited as a valley bottom infill at the confluence between the San Isidro and Isoba valleys, reveals two unexpectedly old radiocarbon results, both derived from bulk sediment samples. They suggest that the
valley was ice free and was recording alluvial and lacustrine sedimentation since 41.8–46.7
kal ka BP, which is incompatible with chronological evidence based on both $^{10}$Be CRE and
OSL. The age differences between plant-macro remain and bulk sediment samples are more
evident when we compare the sedimentation rate at the different sites (Fig. 8). Toneo-01 and
Isidro-02 (bulk sediment samples) suggest low and relatively uniform sedimentation rates,
whereas Fonfría-01, Soportales-03 and Silván-02 show higher sedimentation rates,
particularly during the Early Holocene. In the Soportales-03 core, the basal age based on bulk
sediment provides an age ~22 ka older than the numerical ages derived from plant macro
remain samples at lower depths. The fact that all bulk sediment samples display radiocarbon
ages that are too old strongly suggests a possible aging effect due to inorganic/mineral
(‘fossil’) carbon contamination similar to the one previously observed in multiple lacustrine
sequences in the Pyrenees (Pallàs et al., 2006). In addition, all potentially aged bulk sediment
samples correspond to lacustrine environments developed on top of Carboniferous bedrock,
consisting on shale and sandstone alternations that can sporadically present inter-bedded thin
coal layers. Radiocarbon analysis based on pollen concentrates could be the best alternative
to get reliable numerical results. Regarding age inversions in radiocarbon results, they were
mostly found in Soportales-03 core between 2 and 6 m depth and could be related to soil
carbon reservoir effect (Jull et al., 2013) or to duplicated material accidentally resampled
from the well walls during successive drilling maneuvers.
Figure 8.- Comparison between sedimentation rate trends observed in the different cores based on radiocarbon numerical ages. The sequences Silván-02, Fonfría-01 and Soportales-03 show similar tendency in sedimentation rate during the Holocene. In contrast, Toneo-01 and Isidro-02 (ages exclusively obtained on bulk sediment samples) suggest markedly lower sedimentation rates, probably because results are contaminated by dead carbon effect inherited from local bedrock. Isidro-02, Toneo-01 and Soportales-03 ponds developed on top of Carboniferous shale and sandstone with eventual coal intervals. Thus, inorganic ‘fossil carbon’ may have incorporated to these sequences as fine-grained particles. The same is observed for the basal age of the Soportales-03, also obtained from a bulk sediment sampled.

Regarding OSL results, insufficient light exposure prior to burial is the commonest source of biased results when this technique is applied to date glacial and glacio-fluvial sediments. In the case of glacio-fluvial materials, glacial meltwaters usually have large amounts of suspended sediments that can prevent light-rays to efficiently penetrate through the water column (Stockes, 1999, Klasen et al., 2007). Meanwhile, tills can potentially be transported within the glacier or close to its base (sub-glacially) without necessarily being exposed to light-rays prior to burial. In our case study, all samples gave poor luminescence intensities (highly insensitive to irradiation) and required a large amount of aliquots to get an age determination. The results obtained from the till samples of the Runción lateral moraine (33.3 ± 5.4 ka) and the Guarilla kame terrace deposited behind (27.9 ± 3.4 and 32.5 ± 3.9 ka) yield burial ages that are time-consistent with the ^{10}Be CRE chronology of the Runción moraine. Additionally, results are comparable to the previous OSL age of 24.0 ± 1.8 ka reported for
one of the outermost lateral moraine ridges that dammed the Brañagallones kame terrace sequence in the north-facing Monasterio valley (Jiménez-Sánchez et al., 2013), which also shows burial age few thousands of years older than the $^{10}$Be CRE ages obtained for the recessional moraine sequence preserved inwards (Rodríguez-Rodríguez et al., 2017). In contrast, OSL burial ages obtained in an alluvial fan close to the Remelende peak (26.5 to 27 ka) suggest that some areas along the North-South divide of the Cantabrian Mountains may have remained ice-free during the LGM. This is also supported by material dated in the Tarna valley, where radiocarbon analysis at the base of the Tarna sequence (~600 m North from the Tarna Pass) and OSL analysis of a post-glacial landslide deposit yielded results of $24.6 \pm 0.4$ cal ka BP and $23.0 \pm 2.3$ ka, respectively (Jiménez-Sánchez and Farias-Arquer, 2002, Jiménez-Sánchez et al., 2013). However, both the Guarilla and Remelende sequences were deposited by steep alluvial streams as short as ~1.1 km, so these sandy units were potentially deposited by turbid water currents, an environment more prompt for insufficient bleaching prior to burial (Rixhon et al., 2017). In the case of the basal sandy unit at the base of the Fonfría sequence, the OSL saturated signal obtained for quartz confirms that this unit was not fully bleached before burial. The absence of other sand intervals in the rest of the Fonfría infill sequence could be consistent with a glacio-fluvial origin related to meltwaters sourced from receding glaciers.

4.2. The long-term evolution of glaciers in the central Cantabrian Mountains deduced from the Porma and Monasterio datasets

Together, the Porma and Monasterio sequences provide a complete picture of the Last Glaciation in the central Cantabrian Mountains in northern Spain. Although the terminal moraines are not preserved in the Porma catchment, the remaining glacial evidence suggests that the first glacial stage (Stage I, Fig. 9) of the Last Glacial Cycle took place early (~ 110
ka) coevally with MIS 5d. Some boulders provide even oldest ages (~170–150 ka) that might be inherited from a previous glaciation during MIS 6 (Rodríguez-Rodríguez et al., 2016). In contrast, evidence of these old glacial advances has not been found in the northern slope yet, probably because the topography is generally steeper and the valleys are narrower, conditions that did not favor the preservation of glacial evidence.

The Porma glacier margins remained in positions close to the previous stage during MIS 3 and MIS 2 (~56–22 ka; Stages IIa to IIb), as indicate the presence of diachronous boulders (like RES-04) in various lateral and medial moraines (e.g. RES, ROB and LIL moraines) that suggest moraine build-up during several glacial stages or even during long-time periods. The burial OSL ages obtained in the Runción lateral moraine (c. 33.3 ka) and the Guarilla kame terrace (ca. 32.5 ka) also support continuous glacial occupation of the Porma catchment during MIS 3 (Stage IIa) until the LGM culmination (Stage IIb). The radiocarbon basal age of the Soportales-03 sequence (31.1–31.5 cal ka BP) is consistent with minimum deglaciation ages obtained in the CEL erratic boulders and suggest glacier free conditions for the Celorno valley by the time of the LGM culmination (Stage IIb; Fig. 9). In the northern slope of the range, Stage IIb is recorded by the minimum radiocarbon age of ~33.5 cal ka BP obtained close to the base of the Brañagallones kame terrace sequence, outside the outermost lateral moraine (Jiménez-Sánchez and Farias-Arquer, 2002), while a burial OSL age of c. 24 ka (Brañag-1) has been reported for an inner moraine ridge of the same complex (Jiménez-Sánchez et al., 2013). Evidence for glacier oscillations through MIS 3 have been previously reported to the East, in the glacio-lacustrine sequences of Comeya (~45 ka; Jiménez-Sánchez et al., 2013), Belbín (~37.2 cal ka BP; Ruiz-Fernández et al., 2016) and Campo Mayor (~35.3 cal ka BP; Serrano et al., 2012) in Picos de Europa. Minimum radiocarbon ages reported for Laguna del Castro (~44 cal ka BP) and Laguna del Miro (>35 cal ka BP) in Laciana (Jalut et
al., 2010) and the OSL age of supraglacial till sediments from Vega del Naranco terminal moraine at Fuentes Carrionas Massif (~36 ka; Serrano et al., 2013) are equally consistent with the glacial record documented here for the central Cantabrian Mountains. The minimum exposure ages of the RUN and ROB lateral moraines suggest that the last deglaciation started at c. 21–20 ka in the central Cantabrian Mountains, consistently with the evolution of the Sanabria Lake record (Rodríguez-Rodríguez et al., 2014). The $^{10}$Be CRE age dataset of the Monasterio valley indicates a consistent deglaciation sequence with recessional stages at minimum ages of c. 18.1 ka; 16.7 ka; and 14 ka (Rodríguez-Rodríguez et al., 2017). In the Porma valley, a population of erratic boulders resting on top of Loma Fonfría ice-molded surface suggest remarkable ice thinning of local glaciers by c. 17.7 ka (Rodríguez-Rodríguez et al., 2016) that are consistent with the new minimum radiocarbon ages reported in this work for the Fronfría-01 (12.1–12.6 cal ka BP) and Toneo-01 (17.4–17.7 cal ka BP) sequences (Fig.9). Regarding the timing of rock glacier activity (periglaciation), available $^{10}$Be CRE chronologies for two rock glaciers suggest the stabilization of the foremost ridge during the time interval ~15.7–13 ka (Rodriguez-Rodríguez et al., 2017, Rodriguez-Rodríguez et al., 2016). The available deglaciation datasets show apparently longer time resilience of glaciers in the northern slope of the range compared to the southern slope, possibly favored by topo-climate conditions (although further studies are required to confirm this).
Figure 9.- Glacial stages and sample site locations of available $^{10}$Be CRE, radiocarbon, and OSL ages in the Porma and Monasterio valleys (white arrows indicate ice flow directions). $^{10}$Be CRE dataset is classified in: Last Glaciation (blue); Last Deglaciation (red); and Periglaciation (green) [lowercase letter next to landform acronym indicates the type of boulder: m- moraine; e- erratic; rg- rock glacier]. The probability density
functions of $^{10}$Be CRE results are provided by mountain slopes following the same color key (grey curves represent $^{10}$Be CRE ages of individual boulders).

### 4.3. Comparisons with other continental and marine paleoclimate records

The new set of numerical ages presented here supports long-standing glacial conditions in the central Cantabrian Mountains from ~56 to 22 ka (Glacial Stages IIa to IIb) spanning MIS 3 to MIS 2. Similar evolution has been reported in other Atlantic settings like the British Isles, glaciated prior to ~35–40 ka and during the LGM (culminating at ~26–21 ka) (Rolfe et al., 2012); or the Marrakech High Atlas, extensively glaciated from ~50.2 ka to 22 ka (Hughes et al., 2018). Remarkable glacier oscillations through MIS 3 before the LGM have been also documented in multiple mountain settings across the Mediterranean, like Peloponnesus in Greece (~40–30 ka; Pope et al., 2015) or Mount Akdağ in SW Turkey (~31.5 ka; Sarikaya et al., 2014). Burial ages from the Monasterio and Porma moraines suggest that the local LGM advance occurred between 33 and 24 ka, consistently with the new LGM definition proposed by Hughes and Gibbard (2015). Meanwhile, $^{10}$Be CRE ages obtained from the lateral moraines indicate that glacier recession started at ~21–20 ka, after the LGM. This pattern is time consistent with the growth of continental ice sheets to their maximum positions between 33 and 26.5 ka, and their subsequent retreat due to a rise of northern summer insolation between 20–19 ka (Clark et al., 2009). The close synchronicity between Greenland coolest temperatures and the insolation minima at c. 24 ka BP suggests the strong northern-insolation control of Ice-Age Cycles (Alley et al., 2002).

Mountain glaciers in central Spain reached their maximum areal extent at 26.1 ± 1.3 ka in response to a period of rainfall increase (from 25 to 29 ka) under insolation minima conditions (Domínguez-Villar et al., 2013). The available framework of numerical ages in the Pyrenees suggests that more extensive glacier re-advances occurred during MIS 2 in the
Mediterranean influenced end of the range compared to the Atlantic influenced end of the range (Delmas, 2015). This pattern could probably be related to a more active Balearic low atmospheric pressure (Calvet et al., 2011). Iberian mountain glacier growth during MIS 2 was favored by the occurrence of relatively cold and humid conditions, as indicated in lacustrine records from the Iberian Peninsula that show periods of positive hydrological balance linked to reduced summer insolation (Moreno et al., 2012).

Marine records indicate that the Polar Front did not migrate as far south as the Iberian Margin during the LGM (Eynaud et al., 2009) and Sea Surface Temperature (SST) cooled only slightly down (1–2°C temperature difference) reaching average Holocene temperature (Sánchez Goñi et al., 2008). In contrast, massive iceberg calving caused more pronounced southward shifts of the Polar Front during Heinrich Stadials than during the LGM, reaching as far south as 40°N latitude during HS1 (15.9 to 18.3 cal ka BP) (Eynaud et al., 2009).

Continental ice sheet collapses during Termination 1 resulted in massive meltwater and iceberg discharge into the North Atlantic Ocean (Toucanne et al., 2015), perturbing the northern overturning circulation and causing global changes in ocean and atmospheric circulation patterns (Denton et al., 2010). Particularly, the southward shift of the Polar Front during HS1 and the extensive sea ice coverage prevented the readvance of the southern Scandinavian Ice Sheet margin due to moisture starvation (Rinterknecht, 2006). The extremely cold and arid conditions (winter signature) that prevailed during HS1 in the North Atlantic region due to extensive winter sea ice formation seem to have also forced the Iberian Mountain glaciers to reduce their areal extent in response to moisture starvation.

5. Conclusions
Multi-dating approaches are the best options to provide a detailed view of mountain glacier evolution and identify potential age conflicts between numerical ages derived from the
different techniques. Combined or alone, the results of the three techniques applied in the Porma basin highlight the importance of: (i) developing statistical CRE analysis of multiple boulders from the same landform (preferably more than 3 boulders per landform); (ii) working preferentially with plant macro remain samples or pollen concentrates to avoid radiocarbon aging effects; and (iii) giving priority to the water-transported sediments (glacio-fluvial and alluvial) that show the longest travel distances to minimize cases of quartz saturated OSL signals.

The glacial sequence preserved in the Porma valley, southern slope of the central Cantabrian Mountains, provides consistent evidence that glaciers oscillated at various times throughout the Last Glacial Cycle (from MIS 5d to MIS 2). Diachronous $^{10}$Be CRE ages in lateral moraines match the age of erratic and moraines boulders from the terminal zone, suggesting that deposition of lateral moraines took long periods of time or even occurred during several glacial stages. The combination of $^{10}$Be CRE ages with other dating techniques (radiocarbon and OSL) applied to moraine, and kame terraces suggest glacial occupation through MIS 3 (Stage IIa: ~56 ka) and MIS 2 (Stages IIb: ~ 33–24 ka). Numerical ages support a significant advance of glaciers in the central Cantabrian Mountains during MIS 2 (33–24 ka) in response to rainfall increases under cooling conditions related to insolation minima. Glacier retreat started at ~ 21–20 ka due to orbital forcing and continued during HS1 as consequence of moisture scarcity under hyper-cool conditions due to iceberg and meltwater discharges in the North Atlantic Region. Like in the western end of the Pyrenees, the advance of glaciers during MIS 2 recorded inward glacier front positions respect to the local Pleistocene glacial maximum in the southern slope of the Cantabrian Mountains. Further studies from other Cantabrian valleys are required to draw more detailed conclusions about differences in atmospheric circulation patterns between the Atlantic and Mediterranean domains.
Author contributions
Samples for surface exposure dating were taken in the field by LRR, MJDC, MJS and VR. 

$^{10}$Be targets were prepared at the Laboratoire National des Nucleides Cosmogéniques (LN2C-CNRS) by LL. The isotopic ratio $^{10}$Be/$^9$Be was measured at the ASTER AMS facility (CEREGE) by the ASTER Team [GA, KK, and DB]. Exposure ages were calculated and interpreted by LRR and VR. Sediment cores were drilled in the field by LRR, SGL, DB, MJDC, MJS and PV. Detailed laboratory descriptions and sampling for radiocarbon dating were done by LRR and SGL. OSL samples were taken in the field by SGL, LRR, DB and MJDC, while lab processing and age estimations were done by JS. The paper was written by LRR and all coauthors contributed to the discussion.

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