The origin and collapse of rock glaciers during the Bølling-Allerød interstadial: A new study case from the Cantabrian Mountains (Spain)


To cite this version:

HAL Id: insu-03661020
https://hal-insu.archives-ouvertes.fr/insu-03661020
Submitted on 6 May 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution 4.0 International License
The origin and collapse of rock glaciers during the Bølling-Allerød interstadial: A new study case from the Cantabrian Mountains (Spain)

Javier Santos-González a,⁎, Rosa Blanca González-Gutiérrez a, José María Redondo-Vega a, Amelia Gómez-Villar a, Vincent Jomelli b, José M. Fernández-Fernández c,d, Nuria Andrés d, José M. García-Ruiz e, Sergio Alberto Peña-Pérez a, Adrián Melón-Nava a, Marc Oliva f, Javier Álvarez-Martínez g, Joanna Charton b, ASTER Team b, David Palacios d

a Department of Geography and Geology, Universidad de León, Campus de Vegazana s/n, 24071 León, Spain
b Aix-Marseille Université, CNRS, IRD, Coll. France, INRAE, UMR 7278 ECODE, 13545 Aix-en-Provence, France
c Instituto de Geografía y Ordenamento del Territorio (IGOT), Universidad de Lisboa, R. Branca Edmée Marques, 1600-276 Lisbon, Portugal
d High Mountain Physical Geography Research Group, Department of Geography, University Complutense de Madrid, 28040 Madrid, Spain
e Instituto Pirenaico de Ecología (IPE-CSIC), Campus de Aula Dei, D.O. Box 13.034, 50080 Zaragoza, Spain
f Department of Geography, Universitat de Barcelona, C/ Montalegre, 6-8, 08001 Barcelona, Spain
g Department of Agricultural and Forest Engineering, Universidad de Valladolid, Campus La Yutera, 34071 Palencia, Spain

A R T I C L E   I N F O

Article history:
Received 3 October 2021
Received in revised form 12 January 2022
Accepted 12 January 2022
Available online 19 January 2022

Keywords:
Rock glacier
Deglaciation
Paraglacial processes
Cosmic-Ray Exposure dating
Bølling-Allerød interstadial
Cantabrian Mountains

A B S T R A C T

During the Late Pleistocene, the main mountain ranges of the Iberian Peninsula were covered by small icefields and cirque and alpine glaciers. The deglaciation triggered paraglacial processes that generated landforms, mostly within the ice-free glacial cirques. In this research we analyse the deglaciation process in the Muxivén Cirque (42°15′N – 6°16′W), in the upper Sil River Basin, which includes some of the largest relic rock glaciers of the Cantabrian Mountains. We addressed this objective by means of accurate geomorphological reconstructions, sedimentological analysis, Schmidt-hammer surface weathering measurements and a dataset of 10 Be Cosmic-Ray Exposure ages. Results reveal that after ~16 ka, glaciers retreated to the bottom of the cirques at the headwaters of the valley, leaving the walls free of ice and triggering rock avalanches onto the remnants of these glaciers. This paraglacial process supplied debris to a small glacier within Muxivén Cirque, which transformed in two rock glaciers. These debris isolated the ice inside the rock glaciers only for a very short period of time and ended up melting completely before the Younger Dryas. The lower sector of the largest one stabilized at 14.5 ± 1.5 ka, while the upper sector remained active until 13.5 ± 0.8 ka. Previous to the stabilization of the lower sector of the northern rock glacier, at its margin a high-energy debris avalanche occurred at ~14.0 ± 0.9 ka. These data agree with previous research, corroborating the paraglacial origin of most Iberian rock glaciers during the Bølling-Allerød interstadial.

© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Deglaciating landscapes in mountain areas and the polar regions favour the development of permafrost-related landforms, such as rock glaciers, which are thus considered the best geoindicators of permafrost in low- and mid-latitude mountain environments (Oliva et al., 2018). Indeed, there is wide consensus that rock glaciers reflect to some extent major climatic features, as they indicate the occurrence of permafrost and a mean annual air temperature (MAAT) ≤ ~2 °C in the region by the time when they were active (e.g. Haeberli, 1985; Giraudi and Frezzotti, 1997; French, 2017). However, present-day observations on how rock glaciers react to climate warming are complex and still being debated depending on latitude, altitude and aspect. In fact, MAAT increases can provoke either the acceleration of the movement of the rock glacier (Delaloye et al., 2010; Kellerer-Pirkblauer, 2012; Kellerer-Pirkblauer and Kaufmann, 2012; Wirz et al., 2016; Kellerer-Pirkblauer et al., 2017; Eriksen et al., 2018; Kenner, 2019) or, conversely, enhance its subsidence and gradual stabilization (Gómez-Ortiz et al., 2014) prior to their definitive stagnation (Emmer et al., 2015; Campos et al., 2019; Tanarro et al., 2019; Fernández-Fernández et al., 2020; Palacios et al., 2021). Moreover, rock glacier dynamics are not only driven by climate fluctuations, but also modulated by the intensity of the processes occurring on the cirque walls where micro-climatic and geomorphic processes can evolve in a different way than the regional

https://doi.org/10.1016/j.geomorph.2022.108112
0169-555X/© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
climate (Humlum, 2000; Kirkbride, 2000; Brenning, 2005; Azócar and Brenning, 2010; Deline et al., 2015; Anderson and Anderson, 2016; Mayr and Hagg, 2019).

The use of relict rock glaciers as palaeoclimatic indicators is a complex issue due to the problems posed by the interpretation of the numerical dates obtained by different dating techniques. Nowadays, the most precise –and most commonly used– method for dating relict rock glaciers is the Cosmic-Ray Exposure (CRE) dating (Hipólito et al., 2009; Deline et al., 2015; Moran et al., 2016; Palacios et al., 2016, 2017, 2020; Fernández-Fernández et al., 2017; Crump et al., 2017; Dede et al., 2017; Oliva et al., 2018; Winkler and Lambiel, 2018; Amschwald et al., 2021; Jomelli et al., 2020; Linge et al., 2020; Steinemann et al., 2020; Charton et al., 2021). However, there is still an active scientific debate on the significance of the CRE ages obtained from boulders of a rock glacier. Many observations indicate that the CRE ages of rock glaciers are indicative of absence of flow and not the final stabilization by complete melting of the internal ice body (Mackay and Marchant, 2016; Amschwald et al., 2021; Fernández-Fernández et al., 2020; Scherler and Egholm, 2020; Palacios et al., 2021). In any case, the total melting of core-ice and stabilization age of a rock glacier can only be determined if a large number of CRE samples are taken and an accurate understanding of the geomorphological setting is accomplished (Moran et al., 2016; Crump et al., 2017; Charton et al., 2021).

In the Cantabrian Mountains (northern Iberian Peninsula) there are no longer active rock glaciers, but those in relict state are widespread along the range, where more than 250 features have been identified (Gómez-Villar et al., 2011; González-Gutiérrez et al., 2019). Nonetheless, their age of stabilization and whether they represent a climatic phase within the complex climatic evolution of the Late Pleistocene still remains unknown (Redondo-Vega et al., 2010; Gómez-Villar et al., 2011; Pellitero et al., 2011). The roots of the rock glaciers in the Cantabrian Mountains are mostly located above 1500 m a.s.l. at the foot of quartzite or sandstone walls, being rare in other lithologies. The vast majority are N- or NE-oriented and rock glaciers exposed to the SE to WSW are very scarce (Redondo-Vega et al., 2010; Gómez-Villar et al., 2011). In general, they show a very-well preserved ridge-furrow morphology (e.g. González-Gutiérrez et al., 2019). Almost all these rock glaciers are found in glacial cirques, which suggests their origin related to the interaction between the deglaciation and the subsequent paraglacial processes (Santos-González et al., 2018). In the Cantabrian Mountains, some authors associated the rock glaciers located at different altitudes to different chronological stages (Pellitero et al., 2011; Serrano et al., 2013), but most of the studies proposed a Late Pleistocene age for all of these rock glaciers, either in the Younger Dryas stadial (YD) (GS-1: 12.9–11.7 ka) (Serrano et al., 2015) or in the Bolling–Allerød (B-A) (GI-1: 14.6–12.9 ka) interstadial (Rodríguez-Rodríguez et al., 2016, 2017). However, an accurate chronology is only available for two rock glaciers in the Cantabrian Mountains dated through CRE (10Be cosmogenic) (Rodríguez-Rodríguez et al., 2016, 2017). One is located in the headwaters of the Porma River, at the southern end of the range, with an ENE orientation and a mean stabilization age at its front (1620 m a.s.l.) of 15.7 ± 0.8 ka (n = 5; ranging from 16.6 to 15.5 ka). The other is located at the northern face of the mountains, in the headwaters of the Monasterio River. It is north-oriented, and yielded a mean age of 13.0 ± 0.5 ka (n = 5; from 13.7 to 12.4 ka) in its front (1540 m a.s.l.). The origin of these rock glaciers has been interpreted as the terminal stage of the shrinking Late Pleistocene glaciers that occurred during the B-A interstadial. The CRE age differences in both rock glaciers provide evidence of the importance of the topography controlling their dynamics, with slightly younger ages in the less favourable aspects (Rodríguez-Rodríguez et al., 2017).

The results recorded for the rock glaciers stabilization in the Cantabrian Mountains are similar to those obtained in other relict rock glaciers throughout the Iberian Peninsula (Oliva et al., 2019). The vast majority of the alpine cirques in Iberian mountains below 2800 m a.s.l. were deglaciated shortly before or during the B-A interstadial, by 15.1 ± 1.3 ka (mean age; n = 21; ranging from 16.3 ± 3.3 ka to 13.2 ± 0.7 ka; Palacios et al., 2020), when MAAT values were similar to present-day according to marine and terrestrial records (Fletcher et al., 2010a, 2010b; Moreno et al., 2014; Rasmussen et al., 2014; López-Sáez et al., 2020; Bernal-Wormull et al., 2021). In many of these cirques, rock glaciers formed shortly after the deglaciation and their fronts became inactive or stabilized within the same interstadial, as it has been reported from the Central (Palacios et al., 2017; Oliva et al., 2021) and Eastern Pyrenees (Andrés et al., 2018), the Iberian Range (García-Ruiz et al., 2020), the Central Range (Palacios et al., 2012), and the Sierra Nevada (Palacios et al., 2016, 2019). On the few cases where boulders from the upper sectors of relict rock glaciers in the Iberian Peninsula have been dated, data confirmed that these features remained active for much longer and only became inactive or stabilized during the mid-Holocene, often during the Holocene Thermal Maximum (HTM; 11–5 ka BP; Renssen et al., 2012) (Palacios et al., 2016, 2017, 2020; Fernández-Fernández et al., 2017; Andrés et al., 2018; Oliva et al., 2021).

Despite these recent advances in the knowledge of the age of the rock glaciers in the Iberian mountains, there still remain major uncertainties about their geomorphological and palaeoclimatic meaning as inactive landforms, methodological issues inherent to the CRE dating. In this work, we will approach these gaps by addressing the following specific questions:

(i) What is the geomorphological meaning of the CRE ages obtained from surface boulders of the rock glaciers? To date, it is still not clear whether they represent the age of the definitive stabilization of the rock glacier or, on the contrary, they indicate a previous period of limited and slow flow towards an inactive state and the complete disappearance of the inner ice.

(ii) What is the palaeoclimatic significance of these formations? The current knowledge is uncertain about (i) if the development of the currently relict rock glaciers was the consequence of a cold, generally dry, climatic phase with the extension of permafrost; or (ii) if they represent a warmer phase that favoured the transformation of the debris-free glaciers into rock glaciers.

These questions are addressed through a study case focuses on the Muxivén glacial Cirque, which has been selected as representative of the Cantabrian Mountains due to the wide variety of glacial, periglacial and paraglacial landforms that it hosts.

2. Study area

The Cantabrian Mountains are located in NW Iberian Peninsula, northern Spain. They run parallel to the Cantabrian coast for ~500 km from W to E and are ~80 to 120 km wide from N to S (Fig. 1A), with the highest altitudes ranging from 1800 to 2648 m a.s.l. At present, this range is fully deglaciated, but small ice patches and isolated permafrost exist in the highest cirques (Serrano et al., 2011; Ruiz-Fernández et al., 2016; Pisabarro et al., 2017). The relief is very steep on the northern slope due to its proximity to the Cantabrian Sea, while on the southern side the valleys are wider and located at higher altitudes.

The study area is located in the western part of the southern slope of this range, in the Sil River headwaters, which flow into the Miño River and the Atlantic Ocean (Fig. 1B). This basin shows gentle relief in the upper part, with extensive surfaces between 1500 and 2100 m, while narrow valleys prevail below this altitude. The Lumajo Valley, drained by the Almozarra River, runs 11.7 km N-S from the Cornón Peak (2188 m a.s.l.) to the Sil River (1050 m a.s.l.).

We analyse a small cirque located between the eastern slope of the Muxivén Peak (2027 m a.s.l.) and the Lumajo village (1390 m a.s.l.), at 42°15’N and 6°15’ – 6°16’W (Fig. 1C). The study area is located in the
A geological unit of the Cantabrian Zone (Alonso et al., 2009), which is part of the Astur-Galician region of the Alpine-Pyrenean Orogen (Martín-González and Heredia, 2011). Palaeozoic siliceous materials are dominant. The Muxivén Cirque is composed of Ordovician white quartzites (Barrios Fm.), while Silurian black slates (Formigoso Fm.) and Silurian ferruginous sandstones (San Pedro Fm.) appear to the...
east, and Devonian limestones, dolomites and slates close to Lumajo Valley (Jiménez-Sánchez et al., 2013; Santos-González et al., 2013a, 2021; Rodríguez-Rodríguez et al., 2015; Serrano et al., 2017). The lowest glacial deposits in this catchment are located at 750 m, i.e. 52 km downstream from the headwaters (Santos-González et al., 2013b). The Lumajo Valley was part of the transfluent and icefield glaciers of the upper Sil palaeoglacier, where few palaeoanantasak, such as the Muxivén Peak, stand out (García de Celis and Martínez Fernández, 2002; Alonso and Suárez Rodríguez, 2004; Jalut et al., 2004, 2010; Santos-González et al., 2013a, 2021). The ice thickness exceeded 350 m. 14C dates in Villaseca and La Mata lakes, in the lower part of the Lumajo Valley (Fig. 1B), revealed that glacier recession from the local glacial maximum started between 44 and 35 cal ka BP (Jalut et al., 2004, 2010). The same authors pointed out that the final deglaciation in main valleys probably occurred around 16 cal ka BP (Jalut et al., 2010).

Following the glacier retreat, rock glaciers formed on the eastern slope of the Muxivén Peak (Gómez-Villar et al., 2011). Vidal Box (1958) was the first author who described the glacial morphology, the rock deposits and the geology of the Lumajo Valley and the Muxivén Peak. However, the first reference to the existence of a rock glacier was made by García de Celis (1997), who pointed out its geographical extent and major characteristics. Jalut et al. (2004, 2010) reconstructed glacial dynamics from the lacustrine deposits in Villaseca and La Mata lakes, in the Lumajo and Sil valleys respectively, very close to the Muxivén Peak. They proposed that glacial retreat in Lumajo valley took place at ~16 cal ka BP, although they did not analyse the subsequent geomorphological evolution. Due to the large size and complex development of the rock glaciers at the foot of the Muxivén Peak in comparison with other landforms in this range (Redondo-Vega et al., 2004; Gómez-Villar et al., 2011), they were included as geomorphosites in the inventory of the Alto Sil Natural Area (Santos-González and Redondo-Vega, 2006), and some years later in the Lumajo Valley geosite, in the geosites inventory of the León Province (Fernández Martínez et al., 2009). Therefore, it is included in the viewer of the national inventory of geosites (http://info.igme.es/igls/). The inclusion of these landforms has recently attracted the scientific interest for understanding their formation and subsequent landscape evolution in the area (Rodríguez et al., 2020).

3. Methods

3.1. Geomorphology and sedimentology

A detailed geomorphological map of the Muxivén Cirque was constructed using the Geographic Information System (GIS) ArcMap 10.7 (Esri), based on extensive fieldwork, photointerpretation and previous geomorphological studies. The map has been used as a framework to place the development of the Muxivén rock glacier in a broader geomorphological context. The characterization of the different types of landslides has followed the classification of Hung et al. (2014).

Using an unmanned aerial vehicle (UAV) we obtained an updated cartographic base from orthophotos and a Digital Surface Model (DSM) with great detail (between 6 and 20 cm resolution). The use of a DJI Phantom 4 Multispectral model, equipped with a Global Navigation Satellite System (GNSS), Real-Time Kinematic (RTK) system, allowed achieving very accurate images thanks to this positioning system (STRONER et al., 2020). With a proper overlap configuration (75% frontal and 60% lateral) and the use of few Ground Control Points (GCP), we were able to improve small errors and distortions to ensure the highest possible accuracy (ONIGA et al., 2020). The images obtained were processed through Structure from Motion (SFM) techniques, which are based on the elaboration of a 3D structure from the overlapping of all the obtained images (WESTOBY et al., 2012).

Boulders over 4 m long (maximum diameter) have been identified in the entire study area using different ortophotos (Spanish National Orthophoto Program ortophotos of 2017 and 2020, and the UAV-derived one), UAV oblique photographs from the different sectors and the Digital Terrain Model (DTM) at 2 m resolution obtained by the Spanish National Geographic Institute LiDAR. Such boulders were vectorized as polygon shapefiles in the GIS work environment and their axis were retrieved through the “Minimum Bounding Geometry”.

Grain size analyses were also performed in the main deposits, according to geomorphological results. In each of them, we measured the three axis of 50 clasts in a representative section of the deposit. For a better interpretation of the landforms, macrofabric analysis has been performed in 10 sites including different types of deposits (rock glaciers, talus slopes and debris avalanche). Sectors with homogeneous morphology and representative of each landform have been selected for sampling. In each of them, 50 clasts exceeding 20 cm in size (KJÆR and KRÜGER, 1998) were measured considering the main axis declination and dip for each clast, covering surfaces of 2–5 m² depending on the availability of clast. These measures were carried out using the clasts AB plane and only elongated clasts were chosen (a long/intermediate axis ratio > 1.5) with the two major axes well-defined because these clasts shape better reflect unidirectional fluxes in their transport and sedimentation (ANDREWS, 1971; BENN and EVANS, 1996; BENN and RINGROSE, 2001; EVANS, 2017).

The data were plotted using the software Orient 3 (VOLLMER, 1995, 2015) and represented in a stereonet or Lambert equal-area spherical projection, using the lower hemisphere, where the area is preserved and the densities are not distorted. The data were contoured following the method of DIGGLE and FISHER (1985) so that areas with the same density concentration are presented. Thus, the contours show whether the fabric is isotropic (without a main direction), girdle (points distributed around a circle) or cluster (the majority of the points are grouped).

The directional data have been quantified by calculating the average values through the factorial analysis of the eigenvalues (WOODCOCK, 1977; BENN, 1994). Each fabric is summarized in three values, the eigenvectors (V1, V2, V3) describing the maximum, the intermediate and the minimum preferred directions and dips in three perpendicular axes. Also, the eigenvalues (S1, S2 and S3) were identified showing the concentration degree around their respective axis. The relationship between the three eigenvalues allows the fabric shape identification in each sample: the cluster fabric (S3 is predominant), the girdle fabric (the S1 and S2 values are similar) and the isotropic shape (the three values are close to each other) (WATSON, 1966; MARK, 1973; JOHNSON, 1990; EVANS and BENN, 2004).

3.2. Schmidt-hammer dating

The Schmidt-hammer has been applied to estimate the (relative) exposure time of rock glacier boulder surfaces, through weathering measurements with a scale up to 100 of the rebound value (Goudie, 2006), which helps to differentiate relative chronological stages. Hence, when combined with other dating techniques, it is possible to establish a Schmidt hammer-derived chronology (e.g. TOMKINS et al., 2018a, 2018b, 2021; WINKLER and LAMBIEL, 2018; MARR et al., 2019; MATTHEWS et al., 2019; WINKLER et al., 2020).

We measured Schmidt-hammer rebound (SH-R) values using the electronic Proceq® RockSchmidt (Type N), with an impact energy of 2.207 Nm for its plunger. A total of 14 sites (84 boulders) were selected

The Schmidt-hammer has been applied to estimate the (relative) exposure time of rock glacier boulder surfaces, through weathering measurements with a scale up to 100 of the rebound value (Goudie, 2006), which helps to differentiate relative chronological stages. Hence, when combined with other dating techniques, it is possible to establish a Schmidt hammer-derived chronology (e.g. Tomkins et al., 2018a, 2018b, 2021; Winkler and Lambiel, 2018; Marr et al., 2019; Matthews et al., 2019; Winkler et al., 2020).

We measured Schmidt-hammer rebound (SH-R) values using the electronic Proceq® RockSchmidt (Type N), with an impact energy of 2.207 Nm for its plunger. A total of 14 sites (84 boulders) were selected.
covering different geomorphological contexts from 1380 to 1735 m a.s.l. and including different coarse periglacial and slope deposits. We select the locally higher parts of the deposits (i.e. ridges) in order to minimize the possible snow influence (Ballantyne et al., 1990). Only boulders over 50 cm in the long axe (most of them between 100 and 200 cm) and in stable and prominent locations were chosen. In each boulder, we restricted the impacts to flat surfaces on lichen-free quartzite, considered to be the most reliable areas (Guglielmin et al., 2012). Boulders with visible cracks or weaknesses were avoided.

There is no agreement on the recommended number of impacts between researches. Some authors recommended select the upper values. For example, the International Society for Rock Mechanics (1978) recommends the upper 10 values of 20 rebound values. The low impact values usually reflect ‘that the rock was weakened by the actual impact of the hammer on the rock surface, or to small rock flaws that were not spotted visually before the impact was applied’ (Goudie, 2006). For that reason, we test all boulders with previous impacts in some areas to find the best location. This procedure could reduce the sample size necessary to have enough statistical significance (Niedzielski et al., 2008). In each site we performed 72 impacts, spread over six boulders with 12 impacts on each one, discarding the two lowest values, using a total of 60 impacts in each site.

Data collection was introduced in a spreadsheet where the mean values and their 95% confidence intervals were calculated, and then, the data of each boulder was represented through box-plots including the mean value of each location.

3.3. Sample collection, processing and exposure age calculation

We collected 10 samples for CRE dating by means of a hammer and a chisel following the procedures outlined at Gosse and Phillips (2001). We targeted boulders belonging to the rock glacier and the derived debris avalanche, according to geomorphological results. As a reliability criterion for sampling in the rock glacier, we preferred well-anchored boulders and far from the rock walls so that the risk of sampling rock fall boulders is minimized. Also, aiming to avoid the problems typically associated to the topographic and snow shielding and to optimize the cosmic-ray flux reception: (i) we preferred boulders located at the top of the ridges from which the snow is expected to be easily blown away; and (ii) we sampled flat-topped and gentle-sloping surfaces (<35°). The thickness of the extracted samples ranged from 1.5 to 7 cm (Table 1). In addition, in order to account for any partial shielding due to the surrounding topography, we calculated the topographic shielding factor for every sampling site through the ArcGIS toolbox designed by Li (2018), which implements well-known routines explained in Dunne et al. (1999); it only requires a point shapefile of the sample locations including the strike and the dip of the sampling surfaces, and a digital elevation model from which the skyline is created.

Before conducting the chemical processing of the samples, they were crushed and sieved to the 0.25–0.8 mm fraction at the ‘Physical Geography Laboratory’ of the Universidad Complutense de Madrid (Spain). Following this initial stage, we processed the rock samples at the ‘Laboratoire National des Nucléides Cosmogéniques’ (LNC) of the ‘Centre Européen de Recherche et d’Enseignement des Géosciences de l’Environnement’ (CEREGE; Aix-en-Provence, France). According to the quartz-rich lithology of the samples, i.e. quartzite, they were processed for the extraction of the in situ-produced cosmogenic nuclide beryllium-10 (hereafter 10Be).

Aiming to remove magnetic minerals, samples passed through a Frantz LB-1’ magnetic separator. Once the non-magnetic fraction was concentrated, it underwent several chemical attacks with a concentrated mixture of hydrochloric (HCl; 1:3) and hexafluorosilicic (H2SiF6; 2:3) acids to dissolve and discard the non-quad minerals (e.g. feldspars). Subsequently, some successive partial dissolutions of the remaining minerals with concentrated hydrofluoric acid (HF) helped to dissolve the remaining impurities (e.g. non-dissolved feldspar minerals) and to decontaminate the quartz from atmospheric 10Be. These procedures resulted in pure quartz masses ranging from 8 to 20 g (Table 4).

Just before the total dissolution of quartz, ~150 µL of an in-house manufactured (from a phanekite crystal) 10Be carrier solution (spike, concentration: 3025 ± 9 µg g⁻¹; Merchel et al., 2008) were added to the samples. The purified quartz was subsequently dissolved by acid leaching with 48% concentrated HF (3.6 ml per g of quartz + 30 ml in excess). The Be samples were then precipitated to beryllium hydroxide (Be(OH)2) at pH = 8 by means of ammonia (NH3). Subsequently, Be was separated from other elements through resin columns: a Dowex 1 × 8 anionic exchange column was used to remove elements such as Fe, Mn and Ti, while a Dowex 50WX8 cationic exchange column was used after that aiming to discard B and recover Be (Merchel and Herpers, 1999). Following the final elution, Be was precipitated again, dried and oxidized to BeO at 700 °C. Finally, the targets for accelerator mass spectrometer (AMS) measurements were prepared by mixing the BeO with niobium powder keeping an approximate 1:1 proportion, and the mixture was pressed into copper cathodes.

The targets were analysed at the ‘Accélérateur pour les Sciences de la Terre, Environnement et Risques’ (ASTER) French national AMS facility at CEREGE in order to measure the 10Be/9Be ratio from which the 10Be concentration was later inferred (Table 2). The AMS measurements were calibrated against the in-house standard STD-11 with an assigned 10Be/9Be ratio of (1.191 ± 0.013) × 10⁻¹¹ (Brucher et al., 2015). Analytical 1σ uncertainties include uncertainties in the AMS counting

Table 1
Field data of the sampling sites, topographic shielding factor, sample thickness and distance from the headwall.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Latitude (DD)</th>
<th>Longitude (DD)</th>
<th>Elevation (m a.s.l.)</th>
<th>Map and ground distance from the headwall (m)</th>
<th>Topographic shielding factor</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper northern rock glacier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX-1</td>
<td>42.9834</td>
<td>−6.2715</td>
<td>1669</td>
<td>534 [1038]</td>
<td>0.9644</td>
<td>3.5</td>
</tr>
<tr>
<td>MUX-2</td>
<td>42.9837</td>
<td>−6.2714</td>
<td>1668</td>
<td>544 [1051]</td>
<td>0.9542</td>
<td>4.0</td>
</tr>
<tr>
<td>MUX-3</td>
<td>42.9832</td>
<td>−6.2713</td>
<td>1667</td>
<td>555 [1060]</td>
<td>0.9658</td>
<td>5.5</td>
</tr>
<tr>
<td>Lower northern rock glacier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX-4</td>
<td>42.9844</td>
<td>−6.2665</td>
<td>1559</td>
<td>921 [1541]</td>
<td>0.9891</td>
<td>3.2</td>
</tr>
<tr>
<td>MUX-5</td>
<td>42.9844</td>
<td>−6.2665</td>
<td>1559</td>
<td>924 [1544]</td>
<td>0.9891</td>
<td>3.1</td>
</tr>
<tr>
<td>MUX-6</td>
<td>42.9842</td>
<td>−6.2668</td>
<td>1563</td>
<td>899 [1515]</td>
<td>0.9879</td>
<td>1.5</td>
</tr>
<tr>
<td>Debris avalanche</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX-7</td>
<td>42.9857</td>
<td>−6.2605</td>
<td>1402</td>
<td>1409 [2217]</td>
<td>0.9868</td>
<td>2.1</td>
</tr>
<tr>
<td>MUX-8</td>
<td>42.9857</td>
<td>−6.2605</td>
<td>1401</td>
<td>1409 [2217]</td>
<td>0.9868</td>
<td>4.0</td>
</tr>
<tr>
<td>MUX-9</td>
<td>42.9857</td>
<td>−6.2605</td>
<td>1401</td>
<td>1409 [2217]</td>
<td>0.9854</td>
<td>6.9</td>
</tr>
<tr>
<td>MUX-10</td>
<td>42.9856</td>
<td>−6.2607</td>
<td>1400</td>
<td>1397 [2205]</td>
<td>0.9869</td>
<td>4.6</td>
</tr>
</tbody>
</table>

* Elevation data were taken from the LIDAR 5 m digital elevation model produced by the Spanish ‘Instituto Geográfico Nacional’ (vertical accuracy of ±5 m); available online at: http://centrodescargas.cnig.es/CentroDescargas/index.jsp
glaciers. Consequently, the following units were differentiated, stand the postglacial evolution of the cirque and the genesis of the rock on the northern rock glacier.

We calculated $^{10}$Be exposure ages by using the CREp online calculator (Martin et al., 2017; available online at: http://crep.crpg.cnrs-nancy.fr/#/), where we selected the following settings: Lal/Stone time dependent (Lal, 1991; Stone, 2000; Balco et al., 2008), scaling scheme, ERA40 atmospheric model (Uppala et al., 2005) and the geomagnetic record of Atmospheric $^{10}$Be-based VDM (Muscheler et al., 2005; Valet et al., 2005). We chose the ‘European mean’ production rate derived from the ICE-D online calibration dataset (Martin et al., 2017; available online at: http://calibration.ice-d.org/), which yielded a sea level high latitude superposition of the main U-shaped valley and falls towards the bottom of the cirque, showing a chaotic morphology, without clast sorting, and includes some depressions (Fig. 4). The deposit is partially dismantled in its distal part, where it connects with other non-active landforms, particularly the rock glaciers.

### Table 2

<table>
<thead>
<tr>
<th>Samples</th>
<th>Orientation slope (°)</th>
<th>Eigenvalue 1</th>
<th>Eigenvalue 2</th>
<th>Eigenvalue 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V$_1$ (°) Dip (°)</td>
<td>S$_1$</td>
<td>V$_2$ (°) Dip (°)</td>
<td>S$_2$</td>
</tr>
<tr>
<td>Talus slope</td>
<td>120</td>
<td>110 28 0.70</td>
<td>208 15 0.22</td>
<td>322 57 0.07</td>
</tr>
<tr>
<td>Rock fall scree</td>
<td>82</td>
<td>52 14 0.56</td>
<td>144 9 0.31</td>
<td>266 73 0.12</td>
</tr>
<tr>
<td>Upper Northern rock glacier, ridge</td>
<td>127</td>
<td>317 8 0.46</td>
<td>48 7 0.39</td>
<td>179 79 0.15</td>
</tr>
<tr>
<td>Upper Northern rock glacier, depression</td>
<td>132</td>
<td>62 23 0.72</td>
<td>156 8 0.20</td>
<td>265 65 0.09</td>
</tr>
<tr>
<td>Lower Northern rock glacier, external ridge</td>
<td>59</td>
<td>132 7 0.47</td>
<td>41 5 0.37</td>
<td>279 81 0.16</td>
</tr>
<tr>
<td>Lower Northern rock glacier, ridge</td>
<td>57</td>
<td>119 10 0.48</td>
<td>29 4 0.33</td>
<td>278 79 0.19</td>
</tr>
<tr>
<td>Lower Northern rock glacier, furrow</td>
<td>57</td>
<td>269 11 0.47</td>
<td>0 4 0.33</td>
<td>110 79 0.20</td>
</tr>
<tr>
<td>Debris avalanche, lowest part</td>
<td>73</td>
<td>29 3 0.52</td>
<td>297 30 0.31</td>
<td>123 60 0.17</td>
</tr>
<tr>
<td>Debris avalanche (opposite slope)</td>
<td>252</td>
<td>89 16 0.48</td>
<td>184 17 0.30</td>
<td>319 66 0.22</td>
</tr>
</tbody>
</table>

Statistics and an external 0.5% AMS error (Arnold et al., 2010) and the uncertainty related to the chemical blank correction. The $^{10}$Be half-life was considered was $(3.871 ± 0.0012) × 10^6$ years (Chmeleff et al., 2010; Korschinek et al., 2010).

We chose the ‘European mean’ production rate derived from the ICE-D online calibration dataset (Martin et al., 2017; available online at: http://calibration.ice-d.org/), where we selected the following settings: Lal/Stone time dependent (Lal, 1991; Stone, 2000; Balco et al., 2008), scaling scheme, ERA40 atmospheric model (Uppala et al., 2005) and the geomagnetic record of Atmospheric $^{10}$Be-based VDM (Muscheler et al., 2005; Valet et al., 2005). We chose the ‘European mean’ production rate derived from the ICE-D online calibration dataset (Martin et al., 2017; available online at: http://calibration.ice-d.org/), which yielded a sea level high latitude superposition of the main U-shaped valley and falls towards the bottom of the cirque, showing a chaotic morphology, without clast sorting, and includes some depressions (Fig. 4). The deposit is partially dismantled in its distal part, where it connects with other non-active landforms, particularly the rock glaciers.

### Results

#### 4.1. The Muxivén rock glaciers and its geomorphological context

The eastern face of the Muxivén Cirque is dominated by the presence of two rock glaciers: the northern and the southern ones. The northern shows more mature and better-preserved morphology, including two different sectors (lower and upper part), while the southern one shows less-defined morphology. Therefore, this work focused mainly on the northern rock glacier.

These rock glaciers are located in a context of varied past and current geomorphological processes and landforms, that are relevant to understand the postglacial evolution of the cirque and the genesis of the rock glaciers. Consequently, the following units were differentiated, chronosтратigraphically ordered from oldest to the youngest (Fig. 2):

(i) A short remnant of a lateral moraine ridge runs from NW to SE, descending from 1540 to 1500 m a.s.l. (Fig. 3). It is located down valley of the glacial cirque, oriented from NW to SE, and covered by dense scrub. No visible sections or large blocks were detected, but all visible (small) boulders were of quartzite lithology.

(ii) Rock avalanche deposits, probably from polygenic origin, are located under a scar in the main cirque rock wall and reach the

The sedimentological analysis was carried out in two sectors of the northern rock glacier, the debris avalanche and the talus slopes (Fig. 2B), in order to establish potential geomorphic connections and temporal relationships with the rock glacier. In addition, Schmidt-
Fig. 2. Geomorphological map of the study area (A), including samples location and Cosmic-ray, Schmidt-hammer and macrofabric ($S_1$) data (B).
Fig. 3. UAV photograph of the eastern slope of the Muxivén Peak including the main deposits and samples examined in the text.

Fig. 4. UAV image from the upper sector of the northern rock glacier showing the well-defined ridge-and-furrow morphology contrasting with the rock avalanche deposit located in the lower part of the image.
hammer stations were established in the main units (units ii to vii) to verify possible differences in their SH-R ages (Fig. 2B).

The two sectors of the northern rock glacier were sampled for CRE dating (Fig. 2B). In the upper sector, the sample MUX-1 was collected from an internal ridge, and samples MUX-2 and MUX-3 in the next external one (Fig. 5A). Samples MUX-4, MUX-5 and MUX-6 were collected (Fig. 5B) from the top of a lateral ridge of the lower sector. Finally, given the spatial relationships with the rock glacier, four samples were taken in the frontal deposit of the debris avalanche which come from the margin of the northern rock glacier (MUX-7, MUX-8, MUX-9, MUX-10) (Fig. 5D).

4.2. Sedimentological results

The results of the macrofabric analysis in the sampled sites of the rock glacier and the debris avalanche show similar characteristics. The main vector (V1) slightly matches the slope orientation in all cases (parallel or sub-parallel to the slope in 6 samples and perpendicular to this direction in 3 samples, Fig. 6) and shows a sub-horizontal inclination (dip). In the distal part of the debris avalanche the V1 dips 16° towards the Muxivén Cirque despite it is located on the opposite slope, in the Lumajo Valley.

The values of S1, — degree of concentration around the main direction of the deposit - are very low (around 0.5, Table 2), except in the unit vii (rock fall screens, S1: 0.70) and one depression in the upper rock glacier (S1: 0.72). This low concentration of V1 is observed in the fabric shape (Fig. 6), where the stereograms display concentration contours <5%, except in the talus slope at the front of the lower sector of the rock glacier, where they reach 12%. So, the majority of the samples show girdle shapes, the talus slopes being the exception, displaying a cluster shape.

The mean block size exceeds 45 cm major axis in all units (Fig. 7). The highest mean block size occurs in the southern rock glacier, in the debris avalanche deposits and the lower sector of the lower rock glacier (Fig. 7).

4.3. Schmidt-hammer dating

SH-R results show similar mean R-values across the 102 studied boulders, ranging from 73 to 79.9 (Fig. 8; Table 3). At each site, mean differences of 5.8 points (between 2.1 and 10.4) occurred between the maximum and minimum R- values of the six sampled boulders, while these differences accounted for 8.3 points at each single boulder.

The highest mean R-value found was 79.9 (Fig. 8), in the rock fall screens. Five boulders of this deposit show values over 79.5 and are in the nine higher values. The second higher value was obtained in the internal ridge of the lower section of the rock glacier, with R of 77.2. The results in the rest of the units show very similar mean R-values ranging from 76.8 to 75.0 (Table 3), except for the rock avalanche deposits (74.2) and one sample in the debris avalanche (73.0), which display slightly lower values.

4.4. CRE ages chronology

Three sampled boulders (MUX-4, MUX-5 and MUX-6) in the right (southern) margin of the lower sector of the rock glacier yielded exposure ages of 12.4 ± 0.9, 14.9 ± 1.0, and 14.2 ± 2.5 ka. Exposure ages from two adjacent ridges in the upper sector of the rock glacier, yielded slightly younger exposure ages of 13.3 ± 0.9, 13.9 ± 0.8 and 13.4 ± 0.8 ka respectively (samples MUX-1, MUX-2 and MUX-3; Table 4, total uncertainty), indicative of the stabilization of the highest—and hence youngest—generation of the rock glacier. The chi-2 test (according to
Ward and Wilson, 1978) showed that the three exposure ages within each geomorphological unit are consistent with each other and thus, no potential outliers were detected.

Finally, the three sampled boulders at the distal part of the debris avalanche yielded exposure ages of 13.5 ± 0.8, 14.0 ± 1.0, 14.4 ± 0.9 ka and 19.7 ± 1.7 ka (samples MUX-7, MUX-8, MUX-10 and MUX-9; Table 4). The chi-2 test identified the sample MUX-9 as a potential outlier. No spatial pattern has been detected from the CRE ages at this site.

5. Analysis of results and discussion

5.1. Geomorphological evolution of the eastern slope of the Muxivén Cirque

5.1.1. Geomorphological interpretation

Our results allow us to proposed a reconstruction the geomorphological sequence occurred in the Muxivén Cirque during the final deglaciation of the Lumajo Valley:

(i) Small glaciers occupied the bottom of the cirque at the end of deglaciation, as evidenced by the moraine that closes the base of the cirque. The alignment of the moraine and its lithological composition indicate that the glacier flowed from the cirque, and not from the main Lumajo valley. In addition, the absence of large boulders and a clear single ridge indicates that it corresponded to a debris-free glacier.

(ii) Subsequently, as glaciers retreated, large rock avalanches occurred on the cirque wall, whose scar is still well-preserved. In fact, many valleys and cirque floors of the River Sil basin are affected by different types of landslides and avalanches, indicating intense paraglacial dynamics (Santos-González et al., 2018), as it usually occurs in many deglaciated valleys (Ballantyne, 2002; Linge et al., 2020). The rock avalanche deposits, including many boulders exceeding 4 m of longest axis, covered the upper part of the aforementioned moraine. The rock avalanche deposits show a spatial connection with the margins of the rock glaciers.

(iii) We assume that these rock avalanches contributed to the formation of the rock glaciers. The precedence of the rock glacier debris is supported by the sedimentological analysis: the debris sizes at the lower sector of the northern rock glacier and the southern rock glacier are very similar to the rock avalanche deposits, both including boulders over 4 m of longest axis (Fig. 7), unlike the talus slopes that covered the cirque. In addition, the roots of the rock glaciers - except the upper sector of the northern one, as discussed later - are topographically connected with the rock avalanche deposits. The large size of the boulders is a common characteristic of the “paraglacial rock glaciers”, where debris was supplied by rock avalanches and the subsurface ice originated from a retreating glacier; therefore, they are interpreted as “glacier-derived rock glaciers” (Knight et al., 2019). This process has been identified in many mountain areas where paraglacial processes where dominant (Johnson, 1984; Berthling, 2011; Janke et al., 2015; Hartvich et al., 2017; Monnier and Kinnard, 2017; Anderson et al., 2018; Knight et al., 2019; Etzelmüller et al., 2020; Fernández-Fernández et al., 2020; Linge et al., 2020; Charton et al., 2021; Palacios et al., 2021; RGIK, 2021; Tanarro et al., 2021).

The lower altitudinal limits of the Muxivén rock glaciers are similar to other rock glaciers existing in this range (Gómez-Villar et al., 2011), which could be indicative of the lower limit of discontinuous permafrost in the past (Kerschner, 1978; Giraudi Fig. 6. Representative fabric shape of selected samples distributed across the different landforms.

and Frezzotti, 1997; Hughes et al., 2003). Nevertheless, rock glacier distribution in the Cantabrian Mountains (Gómez-Villar et al., 2011) is restricted to glacial cirques (Santos-González et al., 2018), which show a limited altitudinal range (Gómez-Villar et al., 2015). In the case of Muxivén rock glaciers, its location is conditioned by the presence of steep glacial escarpments that facilitate rock avalanches.

(iv) Rock glaciers expanded, particularly the northern one, while the southern developed a less defined morphology, probably due to a less lasting activity. The northern rock glacier, with its headwaters at a higher altitude and a larger and more favourable feeding area, evolved towards a more mature rock glacier morphology and subdivided in two sectors; the upper one was fed only by rock fall screes (including smaller clast size; Fig. 7) and overlapped the lower one, as previously noticed by Rodríguez et al. (2020). This sector also shows a clearer transversal ridge and furrow morphology with fewer collapses. So this sector is considered a talus-derived rock glacier.

(v) At the southern margin of the northern rock glacier, a high-energy debris avalanche occurred, which descended to the valley

Fig. 7. Distribution of the large boulders >4 m of major axis size together with the grain size data (mean size of the main axis in brackets) of the main deposits in the study area.

Fig. 8. Schmidt-hammer rebound (R-) values in the different landforms, including the distribution of the samples obtained for CRE dating.
The sedimentological analysis showed that the sampled deposits are associated with the deglaciation of this cirque (and not with the main Lumajo Valley). Macrofabric analysis do not show a clear difference on the origin of each of the deposits, as they near all of them come from massive flows, although with different types of transport (rock glaciers, rock movements). Due to that, fabrics are girdle and S1 values are low, as usually occur in relict rock glaciers and landslides (González-Gutiérrez et al., 2019). The talus slopes derived either from rock falls on the highest talus slopes from the headwall, with creep talus in favourable areas. The rock falls still persist today in the highest areas.

Subsequently, the cirque probably underwent a phase of geomorphic stability, except for rock falls on the highest talus slopes. Due to that, fabrics are girdle and S1 values are low, as usually occur in relict rock glaciers and landslides (González-Gutiérrez et al., 2019). The talus slopes derived either from rock falls from the rock glacier front or the wall are the only features showing a cluster fabric.

5.1.2 Chronological reconstruction based on $^{10}$Be CRE and SH-R

CRE results are limited to the two sectors of the northern rock glacier and the debris avalanche. Only the results of one sample that yielded $19.7 \pm 1.7$ ka (MUX-9) do not follow the logical chronostratigraphical sequence, as it is much older than samples located around and above it. In addition to this, the chi-2 test gives ground to consider this sample as an outlier. The interpretation of this exposure age is not straightforward, and we hypothesize on two plausible scenarios as it could be either (i) a moraine boulder fallen from the upper part of the slope, thus leading to an anomalously old exposure age; or (ii) a boulder directly fallen from the cirque wall, inefficiently eroded during its displacement, and thus retaining an inherited $^{10}$Be inventory whose corresponding apparent exposure age does not indicate to the deposition of the boulder (Çiner et al., 2017). The latter hypothesis seems less plausible, since the SH-R data also show clearly lower value than the other samples. The rest of the three boulders at the debris avalanche front gave very similar exposure ages, with an arithmetic mean of $14.0 \pm 0.9$ ka. Two of the three boulders sampled in the lower sector of the northern rock glacier gave very similar ages, averaging $14.5 \pm 1.5$ ka, while the third one is younger, $12.4 \pm 0.9$ ka, and may indicate a subsequent mobilization driven by the degradation of this landform. The three blocks sampled in the upper sector of the northern rock glacier gave identical ages, with an average of $13.5 \pm 0.8$ ka, which may indicate a later stabilization at higher elevations.

Plotting $^{10}$Be exposure ages against SH-R values (Fig. 9A) yielded a coefficient of determination $R^2 = 0.65$, i.e. a moderate correlation. Correlations and line tendency using maximum SH-R value instead of the mean value show very similar results ($R^2 = 0.60$). Nine of the boulders showed quite similar medium SH-R values ($74.8$ to $78.6$). The only external value is obtained in the outlier MUX-9 that show SH-R value of $72.5$, coinciding with the different value in $^{10}$Be data ($19.7$ ka) (Fig. 9A). If this sample is not considered (Fig. 9B), the trendline is

<table>
<thead>
<tr>
<th>Samples</th>
<th>Number of boulders sampled</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Boulder maximum mean</th>
<th>Boulder minimum mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock fall scree</td>
<td>6</td>
<td>79.9</td>
<td>2.78</td>
<td>83.4</td>
<td>77.2</td>
</tr>
<tr>
<td>Relict creep talus</td>
<td>6</td>
<td>76.8</td>
<td>4.41</td>
<td>81.0</td>
<td>74.0</td>
</tr>
<tr>
<td>Upper northern rock glacier</td>
<td>Upper part</td>
<td>6</td>
<td>75.5</td>
<td>76.6</td>
<td>74.1</td>
</tr>
<tr>
<td></td>
<td>Ridge</td>
<td>6</td>
<td>75.5</td>
<td>78.2</td>
<td>71.7</td>
</tr>
<tr>
<td>Rock avalanche</td>
<td>6</td>
<td>74.2</td>
<td>3.86</td>
<td>79.2</td>
<td>71.5</td>
</tr>
<tr>
<td>Southern rock glacier</td>
<td>Ridge</td>
<td>6</td>
<td>76.3</td>
<td>79.7</td>
<td>73.5</td>
</tr>
<tr>
<td>Lower northern rock glacier</td>
<td>Internal ridge</td>
<td>6</td>
<td>75.2</td>
<td>78.9</td>
<td>71.0</td>
</tr>
<tr>
<td></td>
<td>Lateral ridge</td>
<td>6</td>
<td>75.6</td>
<td>77.3</td>
<td>71.0</td>
</tr>
<tr>
<td>Talus slope</td>
<td>6</td>
<td>77.2</td>
<td>4.00</td>
<td>81.2</td>
<td>70.8</td>
</tr>
<tr>
<td>Debris avalanche</td>
<td>Middle</td>
<td>6</td>
<td>75.7</td>
<td>77.5</td>
<td>74.0</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>6</td>
<td>73.0</td>
<td>76.3</td>
<td>69.2</td>
</tr>
<tr>
<td></td>
<td>Opposite slope</td>
<td>6</td>
<td>76.1</td>
<td>78.6</td>
<td>72.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Quartz weight (g)</th>
<th>Mass of carrier ($^{10}$Be mg)</th>
<th>$^{10}$Be/$^{9}$Be ($10^{-14}$)</th>
<th>Blank correction (%)</th>
<th>$^{10}$Be ($10^4$ atoms g$^{-1}$)</th>
<th>$^{10}$Be exposure ages (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper northern rock glacier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX-1</td>
<td>14.8012</td>
<td>0.4831</td>
<td>8.508 ± 0.395</td>
<td>1.28</td>
<td>18.310 ± 0.866</td>
<td>13.3 ± 0.9 (0.6)</td>
</tr>
<tr>
<td>MUX-2</td>
<td>19.1102</td>
<td>0.4801</td>
<td>11.426 ± 0.400</td>
<td>0.96</td>
<td>18.091 ± 0.675</td>
<td>13.9 ± 0.8 (0.5)</td>
</tr>
<tr>
<td>MUX-3</td>
<td>17.4239</td>
<td>0.4746</td>
<td>10.091 ± 0.391</td>
<td>1.10</td>
<td>18.162 ± 0.715</td>
<td>13.4 ± 0.8 (0.5)</td>
</tr>
<tr>
<td>Lower northern rock glacier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX-4</td>
<td>15.8336</td>
<td>0.4752</td>
<td>8.369 ± 0.511</td>
<td>2.28</td>
<td>16.401 ± 1.034</td>
<td>12.4 ± 0.9 (0.8)</td>
</tr>
<tr>
<td>MUX-5</td>
<td>8.4065</td>
<td>0.4783</td>
<td>5.418 ± 0.305</td>
<td>3.49</td>
<td>19.870 ± 1.184</td>
<td>14.9 ± 1.0 (0.8)</td>
</tr>
<tr>
<td>MUX-6</td>
<td>15.7994</td>
<td>0.4822</td>
<td>9.395 ± 1.715</td>
<td>1.96</td>
<td>19.178 ± 3.501</td>
<td>14.2 ± 2.5 (2.4)</td>
</tr>
<tr>
<td>Debris avalanche</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX-7</td>
<td>18.8113</td>
<td>0.4804</td>
<td>9.563 ± 0.334</td>
<td>1.97</td>
<td>15.992 ± 0.582</td>
<td>13.5 ± 0.8 (0.5)</td>
</tr>
<tr>
<td>MUX-8</td>
<td>13.0661</td>
<td>0.4731</td>
<td>6.962 ± 0.386</td>
<td>2.75</td>
<td>16.383 ± 0.948</td>
<td>14.0 ± 1.0 (0.8)</td>
</tr>
<tr>
<td>MUX-9</td>
<td>19.5324</td>
<td>0.4677</td>
<td>14.321 ± 1.172</td>
<td>0.79</td>
<td>22.731 ± 1.877</td>
<td>19.7 ± 1.7 (1.5)</td>
</tr>
<tr>
<td>MUX-10</td>
<td>15.3757</td>
<td>0.4547</td>
<td>8.469 ± 0.391</td>
<td>1.27</td>
<td>16.511 ± 0.776</td>
<td>14.4 ± 0.9 (0.6)</td>
</tr>
</tbody>
</table>

Chemistry blank data

<table>
<thead>
<tr>
<th>Blank name</th>
<th>Processed with</th>
<th>Mass of carrier ($^{10}$Be mg)</th>
<th>$^{10}$Be/$^{9}$Be ($10^{-14}$)</th>
<th>$^{10}$Be ($10^4$ atoms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK-15</td>
<td>MUX-4, 5, 6, 7, 8</td>
<td>0.4731</td>
<td>0.191 ± 0.063</td>
<td>6.051 ± 1.984</td>
</tr>
<tr>
<td>BK-16</td>
<td>MUX-1, 2, 3, 9, 10</td>
<td>0.4665</td>
<td>0.113 ± 0.029</td>
<td>3.526 ± 0.903</td>
</tr>
</tbody>
</table>
very similar but correlation is very low ($R^2 = 0.19$). Anyway, age differences are also very negligible. Probably because these low age differences in Muxivén samples, correlations between SH-R and CRE are lower than previous works (e.g. Tomkins et al., 2016). In any case, the degree of uncertainty of the SH-R results only allows us to determine that debris avalanche and rock glacier boulders show very similar SH-R values, so it is reasonable to hypothesize on both having a similar age. The SH-R values also indicate that the rock avalanche deposits is slightly older or very similar in age, and that boulders from the rock fall scree are clearly younger than the rest of the analysed deposits. In addition, the similarity of CRE ages in each sampled site of the northern rock glacier and the debris avalanche (Fig. 10) does allow us to establish a chronology in good agreement with the previously determined geomorphological phases:

(i) Although the moraine could not be dated due to the absence of suitable boulders, it must have been formed during the deglaciation of the main valley, when the glacier was restricted to the cirque, likely at 16 cal ka BP (Jalut et al., 2010).

(ii) The probably polygenic rock avalanches must have occurred slightly before and during the formation of rock glaciers, as proposed by the SH-R results and the geomorphological reconstructions, in any case between 16 and 14.5 ka.

(iii) The rock glacier expanded, but the lower sector of the northern

---

**Fig. 9.** Correlation between mean SH-R values and $^{10}$Be CRE ages. A: all samples included. B: all samples except MUX-9 included.
rock glacier definitively stabilized at 14.5 ± 1.5 ka. However, the upper sector remained active slightly longer given its higher elevation and the more dynamic feeding area (rock fall screes), stabilising at 13.5 ± 0.8 ka.

(iv) The younger debris avalanche occurred concurrently with the stabilization of the lower northern rock glacier front at 14.0 ± 0.9 ka.

(v) The rock fall screes showed limited activity at present, being more dynamic in the highest areas.

Although nuclide inheritance may be common in some rock glaciers (Giner et al., 2017), the fact that the boulder exposure ages of the Muxivén rock glaciers are either fully coincident or somewhat younger than those closer to the headwall, may rule out this scenario. In fact, nuclide inheritance has been also discarded in the dating of boulders of many other small rock glaciers in Iberia (Palacios et al., 2016, 2017, 2020; Rodríguez-Rodríguez et al., 2017; Andrés et al., 2018; García-Ruiz et al., 2020; Oliva et al., 2021). However, the sample MUX-9, collected from the debris avalanche, is considered to retain nuclide inheritance, not removed during the avalanche event, which is very common in this type of mass movements (Hughes et al., 2014).

5.2. The Bølling-Allerød interstadial in the Iberian Peninsula and its role on the rock glacier development

The results obtained from the Muxivén rock glaciers show ages (14.0 ± 0.9 ka and 13.5 ± 0.8 ka) close to that of the two other rock glaciers dated so far in the Cantabrian Mountains: at Porma River (Requejines cirque), at the southern slope of the mountains (15.7 ± 0.8 ka: Rodríguez-Rodríguez et al., 2016) and in the headwaters of the Monasterio River at the northern slope of the mountains (13.0 ± 0.5 ka), the latter being located upslope a moraine with an age of 14.0 ± 0.6 ka (Rodríguez-Rodríguez et al., 2017). Similar geomorphological sequences, with small moraines and rock glaciers in the cirques are common in many sectors of the Cantabrian Mountains, although their minimum ages are only poorly defined through radiocarbon dating applied to lacustrine sediments or peat bogs, but they do confirm that they formed around 15 ka (Pellitero, 2021; Santos-González et al., 2021). Similar landforms have been found in the Central (Catíarías, Piniecho and Brazato cirques in the Gállego catchment; Palacios et al., 2017) and Eastern (Malniu and Perafita cirques; Andrés et al., 2018) Pyrenees, also with ages ranging from 16 ka for the moraines to 15–14 ka for the rock glacier fronts. In the Iberian Range, to the south-east of the study area, a date from a rock glacier in Peña Negra (Sierra Cellobiera) reported its definitive stabilization at 15–14 ka, following the glacier withdrawal from the moraine at 16 ka (García-Ruiz et al., 2020).

Such a relatively frequent chronological sequence in the cirques is well known in the Iberian mountains and is summarized in four main stages: (i) moraines deposited in a previous glacial advance at ~16 ka (GS-2.1a, following Rasmussen et al., 2014); (ii) a rapid glacial retreat at ~15 ka (GS-2.1a); (iii) the formation of rock glaciers when paraglacial processes, as rock avalanches, cover the retreating glaciers; and (iv) a rapid stabilization of the rock glacier fronts at 15–14 ka (GI-1e, GI-1d). This sequence is fully coherent with the well-studied climatic evolution in the Iberian Peninsula, which underwent one of the most abrupt climatic changes of the Late Pleistocene at the end of the very cold Heinrich Stadial-1 (HS-1) (Cacho, 2021). Its effects on the Iberian climate ended at 15.7–15.2 cal ka BP, according to different terrestrial (Camuera et al., 2021) and marine (Martrat et al., 2014; Ausín et al., 2020) proxies. Around 15 cal ka BP, the sea surface temperature increased 4 °C on average around the Iberian Peninsula (Cacho et al., 2001; Rodrigo-Gamiz et al., 2014) and warm air temperatures similar to the present-day values, prevailed during most of the B-A interstadial (Fletcher et al., 2010b). Precipitation increased to near current levels, as reflected in the speleothems (Moreno et al., 2010). The vegetation changed drastically towards a temperate Mediterranean forest throughout the peninsula (Fletcher and Sánchez-Góñi, 2008; Fletcher et al., 2010b; García-Alix et al., 2014; Martrat et al., 2014; Naughton et al., 2016; González-Sampériz et al., 2017; Ausín et al., 2020; López-Sáez et al., 2020; Camuera et al., 2021). The effects of the major changes occurring in the North Atlantic were amplified in the Iberian Peninsula at that time (Cacho, 2021), from the strengthening of the Atlantic Meridional Overturning Circulation (McManus et al., 2004), the sharp decline in the sea ice extent (Denton et al., 2005) and the general warming in the Northern Hemisphere reflected in the Greenland ice-core records (Clark et al., 2012; Rasmussen et al., 2014).

The recent geomorphological information available from the Iberian Peninsula allows us to know the immediate reaction of the glaciers to past warm phases such as the B-A, in the form of a rapid retreat and even their total disappearance (Oliva et al., 2019). In the Cantabrian Mountains (Jiménez-Sánchez et al., 2021; Ruiz-Fernández et al., 2021a,b; Serrano et al., 2020a,b) and Northwestern Mountains of Iberia (Rodríguez-Rodríguez et al., 2021; Pérez-Alberti and Valcárcel, 2021), the valleys were deglaciated by 15–14.5 ka. In the Central Pyrenees, for example, a recent study at Bacièr cirque evidences a rapid deglaciation underway at 15–14 ka (Oliva et al., 2021). In the Iberian Range, most glaciers must have disappeared around 14 ka, except some debris-covered glaciers (García-Ruiz, 2021). In the Central Range, the glaciers retreated from 15.5 ka, and by 14.6 ka they were already confined to the cirques or even had disappeared (Carrasco et al., 2021b,a). In the Sierra Nevada, glaciers started to retreat at an average date of 14.6 ± 1.5 ka, but most of the glaciers of the range had already melted away by 14 ka (Palacios et al., 2016, 2020).

The warm and humid B-A interstadial was interrupted in the Iberian Peninsula by two short cold and dry periods at 14.0 and 13.3 ka, in phase with the cold events detected in the Greenland ice-cores, i.e. the GI-1d (Older Dryas) and GI-1b (Intra-Allerød Cold Period).
Due to the range of uncertainty in the dating methods, it is very difficult to determine the impact of these cold events on the Iberian glaciers and rock glaciers, although in some cases the existence of intra-B-A moraines has been pointed out (Oliva et al., 2021).

The rapid deglaciation of the Iberian mountain cirques triggered the acceleration of paraglacial processes on their walls (Oliva et al., 2019). The origin of many of the Iberian rock glaciers that formed just before or during B-A has been related to the effects of these paraglacial processes on the retreating glaciers (Palacios et al., 2016, 2017, 2020; Andrés et al., 2018; García-Ruiz et al., 2020; Oliva et al., 2021). Thus, this generation of rock glaciers may therefore be related to the coupling between the climate warming, retreat of the glaciers and onset of the paraglacial processes, whose deposits eventually cover and insulate the glaciers, protecting the ice from melting.

The collapse of the rock glaciers at Muxivén represented the definitive disappearance of ice in the cirque. Although small glaciers did exceptionally form on some Iberian mountains during the YD, those only developed at the foot of the highest peaks of the major mountain ranges, but not in mid-altitude mountains such as in the Muxivén area (García-Ruiz et al., 2016).

5.3. The palaeoclimatic significance of rock glaciers and the paraglacial influence

The rock glaciers of the Muxivén Cirque may constitute examples for a model explaining the generation of Iberian rock glaciers closely related to the effects of the B-A warming. Their origin is related to shrinking glaciers which triggered paraglacial processes as their surrounding walls remained ice-free, subsequently increasing their self-weight shear stress (Ballantyne, 2002), which supplied great volumes of debris that favoured the partial insulation of the ice from the air temperature fluctuations and the solar radiation (Humlum, 2000), and hence, the rock glacier development. In fact, the Muxivén rock glaciers originated from paraglacial rock avalanches. Different types of large paraglacial avalanches and landslides are relatively frequent in the area (Santos-González et al., 2018). The generation of rock glaciers by secondary creep from rock avalanches in permafrost environments has been previously addressed (Knight et al., 2019; Ettelmüller et al., 2020; RGK, 2021), suggesting the possible polygenetic nature of some boulder-dominated depositional landforms (Wilson et al., 2020). The transformation of retreating glaciers into rock glaciers due to the paraglacial processes may occur within only a few hundred years, when paraglacial debris supply buried the residual ice during and soon after deglaciation (Linge et al., 2020). This process is what our data seem to indicate happened in Muxiven, as well as in many Iberian rock glaciers.

The insulating potential of ice by the debris layer of the rock glaciers is limited in a climatic context of strong warming. Probably for this reason, the Muxivén rock glaciers stabilized shortly after it developed, as it has also been observed in other cases of the same generation of Iberian rock glaciers (Palacios et al., 2016, 2017, 2020; Rodríguez-Rodríguez et al., 2017; Andrés et al., 2018; García-Ruiz et al., 2020; Oliva et al., 2021) and in many other areas (Humlum, 2000; Hippolyte et al., 2009; Janke et al., 2015; Monnier and Kinnard, 2015; Moran et al., 2016; Dedé et al., 2017; Winkler and Lambiel, 2018; Linge et al., 2020). Therefore, the rock glacier remains active and flows long enough to acquire its characteristic morphology of furrows and ridges, transverse to the flow and to form a steep front (Berthling, 2011; Janke et al., 2013, 2015). Muxivén rock glacier history confirms how some rock glaciers can form and deactivate rapidly as a result of a warming climate change, not from a cooling one (Knight et al., 2019; Linge et al., 2020). In this sense, the dichotomy between glacier derived rock glaciers versus talus derived rock glaciers is incomplete (Linge et al., 2020), as it does not include many of the (paraglacial) rock glaciers, whose ice comes from a glacier and its debris from rock avalanches, reactivated precisely when the upper part of the headwalls are freed from the receding glacier (Knight et al., 2019).

Our exposure age results from the termini of the two rock glaciers generation at Muxivén lead us to hypothesize that the melting of the rock glacier margins, especially when it is on a steep slope, may be responsible of its collapse. Thus, just as the lower sector of the rock glacier was stabilising, a large debris avalanche occurred. This fact could explain why the age of stabilization of the lower sector of the rock glacier (14.5 ± 1.5 ka) and that of the debris avalanche at its front (14.0 ± 0.9 ka) is very close. The influence of a warming climate in rock glaciers destabilization has been observed recently in the Alps (Marcer et al., 2021).

The concept of stabilization in a rock glacier is not straightforward. It may relate either to the complete melting of the interstitial ice or, to a stagnant state even when ice is still present. However, CRE dating does not allow differentiating between the such situations when applied to relic formations (Mackay and Marchant, 2016; Crump et al., 2017; Fernández-Fernández et al., 2020; Scherler and Egholm, 2020; Amschwand et al., 2021; Chorton et al., 2021). In Muxivén area, the upper sector of the rock glacier stabilized about a thousand years (13.5 ± 0.8 ka) after the lower sector also did, probably due to a more continue rock fall debris supply from the cirque headwalls, although more samples would be needed to confirm this age difference. In other cases, in the Iberian Peninsula, the Alps and Northern Ireland, it has also been detected that the stabilization process is delayed in the higher altitude sectors of rock glaciers (Palacios et al., 2016, 2017; Andrés et al., 2018; Fernández-Fernández et al., 2020; Steinemann et al., 2020), even until the Mid Holocene (e.g. Palacios et al., 2017).

6. Conclusions

The results obtained for the Muxivén Cirque confirm the major role that the warming recorded during the B-A, which caused the glaciers to retreat on the mountains of the Iberian Peninsula, although the melting of the ice was slowed down by the action of paraglacial processes. These processes were the main causes driving the evolution of some glaciers into rock glaciers. In this work, this was confirmed by a dataset of 9 CRE ages that are in good agreement with high-detailed geomorphological reconstruction, sedimentological analysis and SH-R measurements. The rapid collapse of the rock glaciers is demonstrated by the homogeneity of the exposure ages within the B-A.

The main valley where the Muxivén Cirque is located was most likely deglaciated at 16 ka. Subsequently a small glacier remained inside the cirque and left a moraine, of unknown age. Following the glacier withdrawal from this moraine, important rock avalanches occurred in the cirque, favouring the generation of two rock glaciers. The lower frontal sector of the northern one was stabilized at 14.5 ± 1.5 ka, while at higher altitude the upper sector stabilized at 13.5 ± 0.8 ka. A debris avalanche transferred loose clast supported material towards the valley bottom, crossing the stream and remounting to the opposite hillslope at 14.0 ± 0.9 ka, although we cannot confirm whether the movement of the rock glacier could have contributed to trigger the debris avalanche.

Our findings show the Muxivén Cirque as an illustrative example of many Iberian rock glaciers, which were formed during the B-A interstadial. The exposure age results show that these formations were largely active during short periods of time and whose period of maximum activity at their front usually did not exceed a thousand years.

Their origin was closely related to the glacier retreat at the end of the HS-1, when they remained confined to the cirques and their gradual shrinking favoured the paraglacial readjustment of the cirques to the newly ice-free conditions. Therefore, this work confirms again that most rock glaciers in Iberia did not depend mainly on optimal permafrost conditions but on the existence of retreating glaciers and the intensity of paraglacial processes operating on the cirque headwalls in coincidence with the glacial retreat.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the project LE808G19 (Paleo-environmental significance and relationship with the global change of the Cantabrian Mountains rock glaciers: relative age dating and analysis of the internal structural system using electrical tomography), founded by the Junta de Castilla y León and PR108/20–20 (Santander Bank–UCM Projects). José M. Fernández-Fernández is supported by a postdoctoral grant within the NUNANTAR project, funded by the Fundación para a Ciência e Tecnologia de Portugal (PTDC/CTA-GEI/32002/2017). Marc Oliva is supported by the Ramón y Cajal Program (RYC-2015-17597) and by the Research Group ANIATLP (Antarctic, Arctic, Alpine Environments; 2017-SGR-1102) funded by the Government of Catalonia. Adrián Melón-Nava was supported by the FPU program from the Spanish Ministry of Universidades (FPU201/01220). We thank the comments and suggestions made by Dr. Stefan Winkler and Dr. Philip D. Hughes, which have considerably improved the quality of an earlier version of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2022.108112.

References


