

Glacial and periglacial dynamics during the last deglaciation in the Bonabé Valley (Marimanha Massif), central southern Pyrenees

Josep Ventura^{a,*}, Marc Oliva^a, José M. Fernández-Fernández^b, Marcelo Fernandes^c, David Palacios^b, Tancrede Leger^d, Vincent Jomelli^e, Oriol Grau^f, A.S.T.E.R. TEAM^e

^a Department of Geography, Universitat de Barcelona, Montalegre 6, 08001 Barcelona, Catalonia, Spain

^b Department of Geography, Universidad Complutense de Madrid, Calle del Profesor Aranguren, s/n., Facultad de Geografía e Historia, Ciudad Universitaria 28040, Madrid, Spain

^c Centre of Geographical Studies, Institute of Geography and Spatial Planning, Universidade de Lisboa, Rua Branca Edmée Marques, 1600-276 Lisboa, Portugal

^d Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland

^e CEREGE, UMR 34 Aix-Marseille University-CNRS-IRD-Coll. France-INRAE, 13545 Aix-en-Provence, France

^f Alt Pirineu Natural Park, Catalonia, Spain

ARTICLE INFO

Keywords:

Deglaciation
Moraines
Rock glaciers
Cosmic-ray exposure dating
Central Pyrenees

ABSTRACT

In this study we reconstruct the deglaciation of the Bonabé valley in the Marimanha massif (upper Noguera Pallaresa valley, central southern Pyrenees) by combining geomorphological mapping and cosmic-ray exposure dating methods applied to a set of 17 samples from moraines, rock glacier boulders and glacially-polished surfaces. This valley includes eight moraine systems and two rock glaciers, and the geochronological results reveal one of the most complete sequences of glacial and periglacial phases documented in the Pyrenees, from the Heinrich Stadial 1, Bølling-Allerød and Younger Dryas events to the onset of the Holocene. The cooling recorded during the Heinrich Stadial 1 generated three phases of glacier advance/still stands between 17.3 and 15.3 ka, with the development of 2–4 km long alpine glaciers. The Bølling-Allerød interstadial entailed a rapid process of valley and cirque deglaciation around 15–13 ka, and the replacement of glacial processes by periglacial dynamics characterised by the formation of polygenetic rock glaciers. The Younger Dryas favoured both the development of the upper ridges of a rock glacier that stabilised around 12.3 ka, and the formation of new small cirque glaciers that built moraines which stabilised around 11 ka.

1. Introduction

Knowledge of the last deglaciation in the Pyrenees has advanced considerably in the last decade with the publication of several articles and doctoral theses (Delmas, 2009; Oliva et al., 2019; Oliva et al., 2022; Reixach (2022); Vidaller, 2025), and in particular with the incorporation of paleoglacial reconstruction modelling approaches and the use of terrestrial cosmogenic nuclide exposure dating (CRE dating). These recent studies have improved the knowledge of the deglaciation chronology (see synthesis in Delmas et al., 2023a, 2023b, 2023c), and in particular glacier activity during the last global glacial termination (Termination-1; T-1), its extent, paleoclimatic inferences, interaction with periglacial and paraglacial processes, etc.

Unlike the last glacial cycle in the Pyrenees, where the regional LGM does not coincide with the globale LGM (Oliva et al., 2019), the sequence of the Pyrenean deglaciation is consistent with the evolution of

glacier oscillations in Europe and the North Atlantic (Clark et al., 2012; Naughton et al., 2023a, 2023b). In this study, we divide the deglaciation period into sub-events following the Greenland chronostratigraphy proposed by Rasmussen et al. (2014) based on ice core records: a) Heinrich Stadial 1 (Naughton et al., 2023a, 2023b), (HS-1; ~18–14.6 ka; GS-2 1a); b) Bølling–Allerød (B-A; 14.6–12.9 ka; GI-1); c) Younger Dryas (YD, 12.9–11.7 ka; GS-1); and d) Holocene (11.7 ka–present day).

Following the LGM (~29–19 ka; Clark et al., 2009; Hughes, 2022), the Pyrenees experienced a sharp glacial retreat. Subsequently, during the HS1, new phases of glacial growth were detected, always with a much smaller extent than that reached during the LGM (Delmas, 2015; Oliva et al., 2019; Delmas et al., 2023a, 2023b, 2023c). HS1 includes valley glaciers ranging from 15 to 27.5 km long in the most extensive and highest basins, such as the Ariège (Reixach et al., 2021), the Garonne or the Gállego (Palacios et al., 2015a), to glaciers of smaller extent (2–6.5 km) in less extensive catchments or in less elevated massifs and

* Corresponding author.

<https://doi.org/10.1016/j.geomorph.2025.109801>

Received 27 January 2025; Received in revised form 24 April 2025; Accepted 24 April 2025

Available online 25 April 2025

0169-555X/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

south-exposed valleys (Pallàs et al., 2010; Palacios et al., 2015b). In the above-mentioned studies on HS1, they place the Equilibrium Line Altitudes (ELA) between 2100 and 2400 m a.s.l., depending on the configuration of the accumulation zones and the geographical situation of the massifs.

During the late HS-1 and the B-A interstadial, and especially around 15–14 ka (Delmas et al., 2023b), extensive and rapid glacial retreat occurred in response to a 3–5 °C temperature increase in western Europe relative to HS-1 at that time (Clark et al., 2012). This warming led to the disappearance of glaciers in many Pyrenean massifs where the regional ELAs was between 2400 and 2500 m asl. The reduction and subsequent disappearance of glaciers implied the replacement of glacial dynamics by periglacial and paraglacial processes in the cirques (Palacios et al., 2017). As a consequence, rock walls, cirque slopes and valley headwaters were strongly affected, leading to the formation of rock glaciers in many of them (Jomelli et al., 2020; Reixach et al., 2021; Oliva et al., 2021; Fernandes et al., 2023). Two minor phases of glacier stagnation or advance have been argued to have occurred around the Older Dryas (GI-1d, 14 ka) and the intra-Allerød cold period (13.3 ka) (Fernandes et al., 2021), which were not detected in all the few basins studied in the Pyrenees (Delmas et al., 2008; Pallàs et al., 2010; Palacios et al., 2017; Jomelli et al., 2020; Reixach et al., 2021) and are difficult to chronologically fix due to the uncertainty ranges associated with CRE dating. From a regional point of view, a divergent geomorphological evolution between the Northern or Southern slopes of the Pyrenees range, and between the cirques below peaks between 2500 and 2600 m asl and those above 2800–3000 m asl, began from the B-A interstadial (Oliva et al., 2021). In the highest massifs of the central Pyrenees (e.g. Maladeta, 3404 m asl; Monte Perdido, 3348 m asl; Picos del Infierno, 3080 m asl, etc.), the cirques hosted glaciers from the beginning of T-1 until well into the Holocene, whereas in the rest of the massifs, deglaciation was practically complete during the B-A interstadial.

During the YD, an abrupt cooling of 2–4 °C relative to B-A was recorded in southern Europe, including the Pyrenees (García Ruíz et al., 2016; Delmas et al., 2023a, 2023b, 2023c). In this mountain range, previous studies suggest the ELAs to have been located around 2450–2550 m asl during this event (Moreno et al., 2014; Jomelli et al., 2020; Fernandes et al., 2021; Oliva et al., 2021), which favoured glacier expansion in the highest massifs (small glaciers; 2–3 km long) and the formation of a new generation of rock glaciers at higher altitudes (with fronts at 2350–2500 m asl) on North-oriented slopes. These glaciers and rock glaciers remained active well into the early Holocene, when the latter YD landforms finally stabilised before the Holocene Thermal Maximum (11–5 ka BP; Renssen et al., 2009, 2012). This warm phase was followed by Neoglaciation (Porter, 2000), associated with a cooling trend that started at ca. 5–4 ka, which allowed the formation of new glaciers and the expansion of existing ones. In the Pyrenees, evidence of neoglaciation activity before the Little Ice Age (LIA) is very scarce and limited to three sites in the central Pyrenees: the Troumouse and Marboré cirques (Monte Perdido massif) and the Ibón de Tendeñera cirque (Sierra de Tendeñera; Gellatly et al., 1992; García-Ruiz et al., 2014, 2020b). In addition, the long-term cooling that occurred during Neoglaciation is argued to have favoured the formation of some of the most extensive active rock glaciers, such as Gemelos (Posets massif), Argualas (Picos del Infierno) and Besiberri NW (Besiberri) (Serrano and Agudo, 2004).

To date, of the 30 Pyrenean basins that were glaciated during the last glacial cycle, information on the last deglaciation is available for 10 of them: three in the eastern Pyrenees (Têt, Segre and Ariège), five in the central Pyrenees (Ésera, Noguera Ribagorçana, Cinca, Gave de Pau and Garona) and two in the western Pyrenees (Gállego and Gave d'Ossau). In total, there are 33 sites with partial or complete CRE-derived chronologies for T-1 stadials and interstadials (Delmas et al., 2023a, 2023b, 2023c). So far, the Gállego (Palacios et al., 2015a, 2017), Garonne (Fernandes et al., 2021; Fernandes, 2023; Oliva et al., 2021) and Ariège (Crest et al., 2017; Jomelli et al., 2020; Reixach et al., 2021) basins are

those displaying the most amount of information.

Despite the information provided by recent studies, knowledge of the last deglaciation in the Pyrenees is still limited. In fact, for many large basins and massifs, data are still scarce, and information is fragmentary. Therefore, the aim of this work is to provide new data on the environmental evolution and chronology of the deglaciation of the Noguera Pallaresa basin, one of the largest basins on the southern slopes of the Pyrenees where glacial history is still unknown, particularly the transition from glacial to periglacial or paraglacial dynamics. The objectives of this work are:

- To characterise the main glacial and periglacial features and reconstruct the last deglaciation, with particular emphasis on the age, origin and evolution of rock glaciers and the subsequent formation of new glaciers at higher elevations.
- To provide a first chronological record of deglaciation in the Noguera Pallaresa basin.
- To integrate the results obtained in the Pyrenees in the wider context of the Central European and Mediterranean mountain ranges.

2. Study area

The Marimánha massif (123 km²; Pic de Moredo, 42° 43' 08"N, 1° 02' 59"E; 2766 m asl) is located in the central Pyrenees and separates the catchments of the Garonne river (Atlantic drainage) and Noguera Pallaresa river (Mediterranean drainage) (Fig. 1A). The course of the Noguera Pallaresa river runs along the Western, Northern, and Eastern peripheries of the massif, receiving contributions from different tributary valleys that descend radially from the centre of the massif. This study focuses on the Llançanes or Ras de Bonabé valley and its source, the cirque of the Clot del Ras (hereafter referred to as the Bonabé cirque

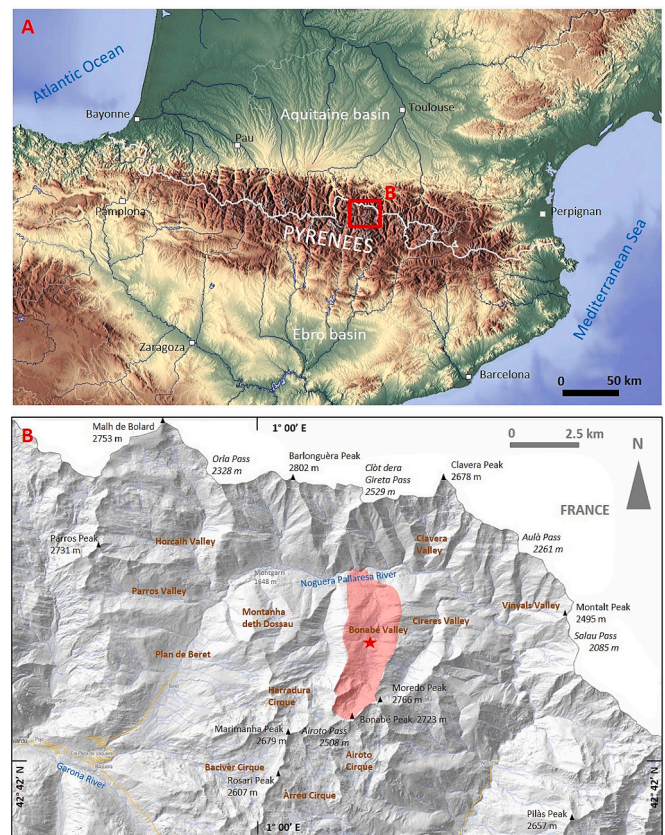


Fig. 1. Map of the study area. (A) Location of the Marimánha massif in the context of the Pyrenees (Spain-France); (B) The Bonabé valley in the Marimánha massif (central Pyrenees).

or valley), located on the Northern face of the Tuc de Bonabé (42°42' 47" N, 1° 02'17" E; 2723 m asl) (Fig. 1B). The cirque and the valley, oriented towards the Northeast and North respectively, cover an area of 6.7 km² and a length of 5.3 km from the peaks to the confluence with the Noguera Pallaresa, at 1540 m asl. A large part of the Marimanha massif is included in the Alt Pirineu Natural Park.

The Marimanha massif is part of the structural unit of the lower South Pyrenean mantle (thrust mantle, south-trending and alpine age), which contains only Paleozoic lithologies (Muñoz, 1992). The lithology of the Bonabé cirque is composed of biotitic granodiorite and biotitic heterogranular granite belonging to the Marimanha batholith of Carboniferous-Permian age (Losantos et al., 1986; Palau, 1997; ICGC, 2007). At the threshold of the cirque and towards the upper parts of the valley, the bedrock consists of Devonian materials affected by contact metamorphism, mainly marbles, shales and quartzites. In the rest of the valley, Silurian grey limestones and dark shales with Devonian limestone intercalations occur in West-East bands.

The Bonabé valley and the entire Marimanha massif were occupied and eroded by Quaternary glaciers, forming one of the largest glacial accumulation areas (ice thickness over 700 m) of the Noguera Pallaresa paleoglaciar, the most extensive in the southern Pyrenees, with a length of 63 km (Ventura and Turu, 2022). Deposits from the last two glacial cycles have also been found in the valley (Turu et al., 2023), with remnants of ancient preglacial erosion surfaces in the water divides (Zandvliet, 1960; Kleinsmiede, 1960; Ortuño and Vilaplana-Muzas, 2018).

Climatically, the study area is today characterised by a mean annual air temperature of 2.8 °C and an average annual rainfall of 1187 mm at Port de la Bonaigua weather station (2266 m asl). The snow cover lasts from November to early June, with a maximum thickness of 2 m, which is reached between late winter and early spring. In the central Pyrenees, the regional 0 °C isotherm is located at about 2950 m asl (López-Moreno et al., 2018).

The first geomorphological descriptions of the Marimanha massif were made by García Sainz (1935) and Nussbaum (1956), although they were limited to the valley floor, the Pla de Beret and the course of the Noguera Pallaresa (Fig. 1). Zandvliet (1960) commented on the preglacial relief of the massif, with remnants of erosion surfaces later modelled by glaciers, the extensive moraine deposits of the Ras de Bonabé and the presence of moraines above 2100 m asl, close to the cirque walls. Serrat et al. (1994), in their synthesis map of glaciers in the central Pyrenees at 1:50,000 scale, included a general mapping of the glacial landforms in the Marimanha massif. In the geomorphological map of National Topographic Map (1:50,000 scale, MTN50 series, Isil; IGME, 2013), rock glaciers were not distinguished as such, but were included in the set of glacial deposits. Later, Parera-Portell (2016) presented a first approach to the rock glaciers of the massif. Finally, Oliva et al. (2021) provided the first set of CRE datings for the massif, reconstructing the deglaciation of the Bacivèr Cirque, on the Atlantic slope of the Marimanha massif, with distinct phases: (i) rapid deglaciation of the cirque during the B-A (14.6–12.9 ka); (ii) glacier formation during the transition from the B-A to the YD (12.9–11.7 ka), and (iii) paraglacial readjustment after the YD, with the formation of new rock and debris-covered glaciers.

3. Methodology

3.1. Geomorphological mapping

A geomorphological map at a scale of 1:10,000 was generated using orthophotomaps digitised following ground-truthing in the field during the summer seasons of 2018 and 2021. The production of the map was carried out through the stereoscopic visualisation and interpretation of photograms from different analogue and digital photogrammetric flights provided by the Institut Cartogràfic i Geològic de Catalunya (ICGC), combined with the use of other cartographic resources, such as high-

resolution (25 cm/pixel) RGB and IR digital orthophotos, displayed in semi-transparency at 1:5000 in the Vissir3 cartographic viewer (<http://srv.icgc.cat/vissir3/>), using the Google Earth Pro browser and interpreting digital terrain models with a regular 2 × 2 m grid (LIDAR data (2 × 2 (MET-2) v1.0, 2016, <https://www.icgc.cat/en/Downloads>), viewed as a hillshade. The geomorphological legend followed the proposal of the Université de Lausanne-UNIL (Lambiel et al., 2013, 2016) with minor adaptations (Fig. 2).

3.2. Sampling strategy

Based on the geomorphological mapping, the most suitable features were selected for sampling and CRE dating. Due to the granitic nature of the study area and the high quartz content of the lithology present, ¹⁰Be (associated with lower measurement and production-rate uncertainties relative to other cosmogenic nuclides) was used (Dunai, 2010). During the fieldwork in summer 2021, 17 samples from moraine boulders (8), rock glacier boulders (4), glacially polished bedrock surfaces (4) and erratic boulders located on the bedrock (1) were collected, both in the valley and in the cirque, at altitudes between 2097 and 2515 m asl (Table 1). The upper surface of the boulders (thickness: 2–5.5 cm, weight: ~1 kg) was extracted using standard procedures (Gosse and Phillips, 2001), using a hammer and chisel, in horizontal or sub-horizontal planes, to optimise the reception of the cosmic-ray flux. The location and characteristics of the sampled features are summarised in Table 1.

The sampling of moraine boulders focused on the highest and most stable sections of the moraine ridges, where the boulders are relatively well anchored and far from the flanks, in order to minimise possible post-glacial disturbance processes (burial, overturning, etc.) that could affect the exposure ages obtained. In the case of the rock outcrops, selected sites protrude several metres from their immediate

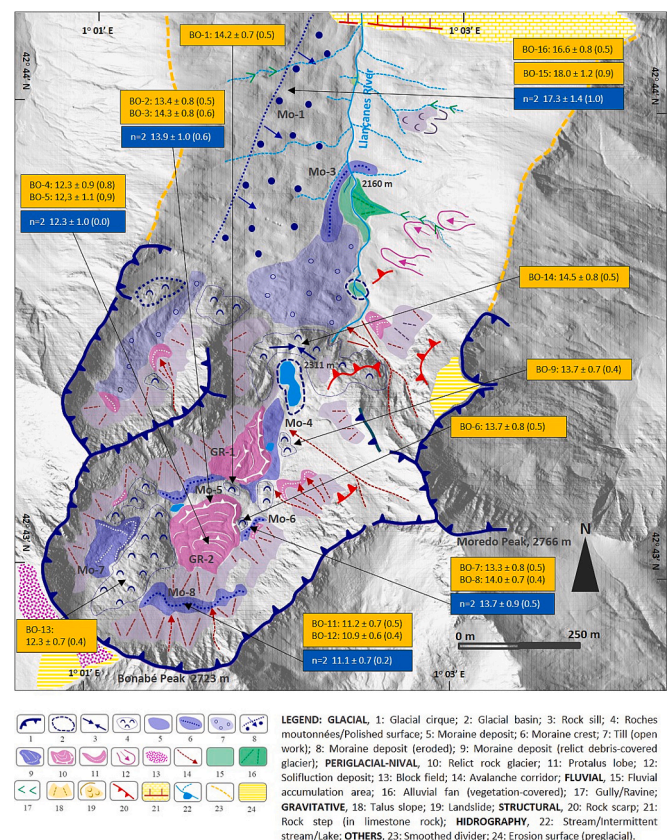


Fig. 2. Geomorphological map of the study area, including the Estany del Ras cirque and the upper Bonabé valley.

Table 1
Geographical location of samples, topographic shielding factor and sample thickness.

Sample name	Landform		Latitude (DD)	Longitude (DD)	Elevation (m a.s.l.)*	Topographic shielding factor	Thickness (cm)	Size of the boulders largest axis (m)
<i>Valley moraines</i>								
BO-16	Mo-1	Moraine boulder	42.7332	1.0415	2231	0.9961	3.0	3.5
BO-15	Mo-1	Moraine boulder	42.7331	1.0419	2222	0.9939	5.5	2
BO-18	Mo-2	Moraine boulder	42.7404	1.0454	2094	0.9966	2.5	4
BO-17	Mo-2	Moraine boulder	42.7401	1.0455	2097	0.9945	3.5	4
<i>Cirque erratic boulder</i>								
BO-14		Erratic boulder	42.7250	1.0422	2313	0.9803	5.5	3
<i>Cirque polished surfaces</i>								
BO-9		Polished surface	42.7214	1.0423	2334	0.9564	2.0	
BO-1		Polished surface	42.7198	1.0400	2355	0.9592	5.4	
BO-6		Polished surface	42.7186	1.0404	2388	0.9585	4.0	
BO-13		Polished surface	42.7161	1.0349	2498	0.9760	5.0	
<i>Cirque bottom moraines</i>								
BO-7	Mo-6	Moraine boulder	42.7186	1.0404	2385	0.9596	3.5	2
BO-8	Mo-6	Moraine boulder	42.7186	1.0404	2385	0.9594	4.5	1
<i>Cirque rock glacier</i>								
BO-2	GR-2 lower unit	Rock glacier boulder	42.7192	1.0397	2380	0.9656	4.0	2
BO-3	GR-2 lower unit	Rock glacier boulder	42.7192	1.0400	2377	0.9628	4.5	1
BO-4	GR-2 upper unit	Rock glacier boulder	42.7182	1.0397	2391	0.9581	3.5	1.5
BO-5	GR-2 upper unit	Rock glacier boulder	42.7181	1.0399	2391	0.9511	3.5	0.6
<i>Cirque highest moraines</i>								
BO-11	Mo-8	Moraine boulder	42.7159	1.0361	2515	0.9727	4.4	4
BO-12	Mo-8	Moraine boulder	42.7159	1.0361	2515	0.9729	4.6	4.5

* Elevations are derived from topographic map 1:5.000 (map viewer Vissir3.35) from Institut Cartogràfic i Geològic de Catalunya (ICGC).

surroundings and, where possible, include the presence of striations and evidence of glacial polishing. Field data were also collected on the samples, related to the location, type of substrate, geomorphological unit, dimensions of the blocks, thickness of the sample and orientation and inclination of the surface analysed.

3.3. Laboratory procedures and calculation of exposure ages

Physical and chemical treatment of the samples was performed at the Laboratoire National des Nucléides Cosmogéniques (LN₂ C) of the Centre Européen de Recherche et d'Enseignement des Geosciences de l'Environnement (CEREGE; Aix-en-Provence, France).

Physical processing began with crushing and sieving of the samples to the 250–500 µm fraction, and continued with the removal of magnetic minerals using the Frantz LB-1 magnetic separator. Chemical processing then began with the removal of the remaining minerals other than quartz (e.g. feldspar and many other minerals) through several successive leachings with a concentrated 1:2 mixture of hydrochloric acid (HCl) and hexafluorosilicic acid (H₂SiF₆). The remaining minerals were subjected to 4–5 partial dissolutions with hydrofluoric acid (HF) in order to remove atmospheric ¹⁰Be and other impurities from the quartz. To ensure the purity of the sample, remaining quartz grains were examined

using a binocular microscope. Between 16.2 and 25.3 g of pure quartz were obtained per sample. Next, 450 µL of the in-house manufactured ⁹Be carrier solution (spike, 997 ± 9 µg g⁻¹; obtained from a phenakite crystal) was added (Merchel et al., 2008). Finally, the quartz was dissolved in hydrofluoric acid (HF). Beryllium was separated from other elements in resin exchange columns: first, through an anion exchange column (Dowex 1 × 8) to remove Fe, Mn and Ti, and then, through a cation exchange column (Dowex 50Wx8) to discard B and separate Be from other elements (Merchel and Herpers, 1999). The eluted Be was then precipitated back to beryllium hydroxide (Be (OH)₂), which was oxidised at 700 °C to BeO. BeO targets were mixed with niobium powder and loaded into copper cathodes.

The measurement of the ¹⁰Be/⁹Be ratios was performed at the 'Accélérateur pour les Sciences de la Terre, Environnement et Risques' (ASTER) of CEREGE, in February 2023. The measurements were calibrated with the internal standard STD- 11, with an assigned ¹⁰Be/⁹Be ratio of 1.191 (±0.013) × 10⁻¹¹ (Braucher et al., 2015) and a ¹⁰Be half-life of 1.387 ± 0.0012 × 10⁶ years (Chmeleff et al., 2010; Korschineck et al., 2010). The AMS measurements are presented with their full uncertainties, including the analytical AMS uncertainty (in brackets) and the production rate uncertainty (Table 2).

Partial shielding by the surrounding mountains and hills was taken

Table 2

AMS analytical data and exposure ages. $^{10}\text{Be}/^{9}\text{Be}$ ratios were derived from measurements at the ASTER AMS facility. Individual ages are given with their full uncertainties (including AMS analytical uncertainty and production rate uncertainty) and analytical uncertainty only within brackets. Arithmetic mean ages are given with full uncertainties and standard deviations in brackets.

Sample name	Landform	Quartz weigth (g)	Mass of carrier (⁹ Be mg)	ASTER TEAM cathode number	¹⁰ Be/ ⁹ Be (10 ⁻¹⁴)	Blank correction (%)	[¹⁰ Be] (10 ⁴ atoms g ⁻¹)	Age (ka)	Mean age (ka)
Valley moraines									
BO-16	Mo-1	18.6176	0.564	CLVC	18.349 ± 0.570	1.46	36.61 ± 1.16	16.6 ± 0.8 (0.5)	17.3 ± 1.4 (1.0)
BO-15	Mo-1	21.8306	0.462	CLVB	27.689 ± 1.493	1.18	38.67 ± 2.11	18.0 ± 1.2 (0.9)	
BO-18	Mo-2	20.3586	0.466	CLVE	19.981 ± 0.642	1.63	30.07 ± 0.99	15.0 ± 0.8 (0.5)	15.3 ± 0.9 (0.4)
BO-17	Mo-2	22.9985	0.468	CLVD	23.013 ± 0.733	1.41	30.83 ± 1.00	15.5 ± 0.8 (0.5)	
Cirque erratic boulder									
BO-14		20.2359	0.465	CLVA	21.609 ± 0.740	1.51	32.66 ± 1.14	14.5 ± 0.8 (0.5)	
Cirque polished surfaces									
BO-9		25.3687	0.464	CLUW	25.956 ± 0.806	1.26	31.34 ± 0.99	13.7 ± 0.7 (0.4)	
BO-1		22.6820	0.457	CLUO	23.990 ± 0.806	1.38	31.88 ± 1.09	14.2 ± 0.7 (0.5)	
BO-6		20.6659	0.464	CLUT	21.646 ± 0.813	1.51	31.95 ± 1.22	13.7 ± 0.8 (0.5)	
BO-13		21.1967	0.466	CLUZ	21.795 ± 0.741	1.49	31.51 ± 1.09	12.3 ± 0.7 (0.4)	
Cirque bottom moraines									
BO-7	Mo-6	24.8561	0.463	CLUU	25.331 ± 1.010	1.29	31.14 ± 1.26	13.3 ± 0.8 (0.5)	13.7 ± 0.9 (0.5)
BO-8	Mo-6	18.9815	0.466	CLUV	20.154 ± 0.631	1.61	32.52 ± 1.04	14.0 ± 0.7 (0.4)	
Cirque rock glacier									
BO-2	GR-2 lower unit	20.3428	0.460	CLUP	21.081 ± 0.808	1.56	31.34 ± 1.22	13.4 ± 0.8 (0.5)	13.9 ± 1.0 (0.6)
BO-3	GR-2 lower unit	20.6532	0.459	CLUQ	22.731 ± 0.903	1.45	33.26 ± 1.34	14.3 ± 0.8 (0.6)	
BO-4	GR-2 upper unit	18.9565	0.459	CLUR	18.212 ± 1.117	1.81	28.94 ± 1.81	12.3 ± 0.9 (0.8)	
BO-5	GR-2 upper unit	16.2221	0.464	CLUS	15.380 ± 1.173	2.12	28.76 ± 2.24	12.3 ± 1.1 (0.9)	
Cirque highest moraines									
BO-11	Mo-8	19.5248	0.466	CLUX	18.428 ± 0.793	1.76	28.87 ± 1.27	11.2 ± 0.7 (0.5)	11.1 ± 0.7 (0.2)
BO-12	Mo-8	24.4681	0.539	CLUY	19.380 ± 0.617	1.45	28.11 ± 0.91	10.9 ± 0.6 (0.4)	

into account by implementing the topographic shielding factor; it was calculated for all sampling sites using the ArcGIS toolbox programmed by Li (2018), which implements the routines described in Dunne et al. (1999). It requires a point shapefile of the sampling sites (including strike and dip of the sampling surfaces) and a DEM with a cell size of 25 m, provided by the Spanish National Centre of Geographic Information.

Exposure ages were calculated in the CREP online calculator (Martin et al., 2017). To allow comparison of our results with the updated glacial chronology in the Iberian mountains (Oliva et al., 2022), the following settings were defined: (i) Lifton-Sato-Dunai (LSDn) elevation/latitude scaling scheme (Lifton et al., 2014); (ii) ERA40 atmospheric model (Uppala and 45 others, 2005); and (iii) geomagnetic database based on the LSDn model (Lifton et al., 2014). These fits derive a global average production rate of 3.98 ± 0.22 atoms per ^{10}Be g^{-1} year $^{-1}$ at high latitudes and at sea level (Martin et al., 2017) to enable full intercomparison with the updated glacial chronology in the Iberian mountains (Oliva et al., 2022).

The exposure ages of the samples with both their 1σ full and analytical uncertainties are given in Table 2. Uncertainties discussed in the text include both analytical and production rate errors, unless otherwise noted.

In addition, postglacial erosion was corrected with a conservative rate of 1 mm ka^{-1} , representative of the biotite-rich crystalline rock type (André, 2002) and the context of the area (mid-latitudes, climate and altitude). The effect of snow cover was also considered (Table 3), with a snow thickness of 1 m, a density of 0.2 g cm^{-3} and a duration of 7 months at 2200–2300 m asl, according to data from the Bonaigua weather

station (Servei Meteorològic de Catalunya, 1997–2021; Oliva et al., 2021). The snow shielding factor was calculated using eq. 3.76 in Gosse and Phillips (2001). The effect of both corrections resulted in $\sim 8.6\%$ higher ages ($\sim 1.3\%$ $\sim 7.1\%$ due to erosion correction and snow shielding, respectively; see Table 3). It should be borne in mind that the duration and thickness of the snow cover is likely to have varied considerably over time as a function of alternating cold and warm periods, together with oscillations in annual precipitation or changes in mean seasonal temperatures. However, to facilitate comparison with published results from other areas, uncorrected ages are presented and discussed in the text.

Finally, the chi-squared test according to Ward and Wilson (1978) was applied to the samples belonging to each geomorphological unit to detect possible outliers of exposure age (i.e., "too old" or "too young"; Heyman et al., 2011). No statistically-significant outliers were found (Table 2).

3.4. Glacier reconstruction and Equilibrium-line altitude calculation

The Bonabé paleoglacier was reconstructed in 3D for the different glacial phases for which numerical dates are available using the "PaleoIce" ArcGIS toolbox programmed by Li (2023). This tool requires the glacier flow lines, the approximate geometry of the paleoglacier (derived from the frontal and lateral moraines and other mapped geomorphological features) and a digital elevation model. A shear stress of 100 kPa was applied along the flowline to estimate the former ice thickness for each glacial phase, assuming perfect plasticity (Benn and

Table 3

Exposure ages according to erosion and snow cover corrections.

Sample name	Landform	Exposure ages (ka)			
		No correction	Erosion correction	Snow correction	Erosion+ snow correction
<i>Valley moraines</i>					
BO-16	Mo-1	16.6 ± 0.8 (0.5)	16.8 ± 0.9 (0.5)	17.8 ± 0.9 (0.5)	18.1 ± 0.9 (0.5)
BO-15	Mo-1	18.0 ± 1.2 (0.9)	18.3 ± 1.2 (0.9)	19.2 ± 1.2 (1.0)	19.6 ± 1.2 (1.0)
BO-18	Mo-2	15.0 ± 0.8 (0.5)	15.3 ± 0.8 (0.5)	16.1 ± 0.8 (0.5)	16.4 ± 0.9 (0.5)
BO-17	Mo-2	15.5 ± 0.8 (0.5)	15.8 ± 0.8 (0.5)	16.6 ± 0.9 (0.5)	16.9 ± 0.9 (0.5)
<i>Cirque erratic boulder</i>					
BO-14		14.5 ± 0.8 (0.5)	14.7 ± 0.8 (0.5)	15.6 ± 0.8 (0.5)	15.8 ± 0.8 (0.5)
<i>Cirque polished surfaces</i>					
BO-9		13.7 ± 0.7 (0.4)	13.9 ± 0.7 (0.4)	14.7 ± 0.7 (0.4)	14.9 ± 0.8 (0.4)
BO-1		14.2 ± 0.7 (0.5)	14.3 ± 0.7 (0.5)	15.1 ± 0.8 (0.5)	15.3 ± 0.8 (0.5)
BO-6		13.7 ± 0.8 (0.5)	13.8 ± 0.8 (0.5)	14.6 ± 0.8 (0.5)	14.8 ± 0.8 (0.5)
BO-13		12.3 ± 0.7 (0.4)	12.5 ± 0.7 (0.4)	13.2 ± 0.7 (0.5)	13.4 ± 0.7 (0.5)
<i>Cirque bottom moraines</i>					
BO-7	Mo-6	13.3 ± 0.8 (0.5)	13.4 ± 0.8 (0.5)	14.2 ± 0.8 (0.6)	14.4 ± 0.8 (0.6)
BO-8	Mo-6	14.0 ± 0.7 (0.4)	14.1 ± 0.7 (0.4)	14.9 ± 0.8 (0.5)	15.1 ± 0.8 (0.5)
<i>Cirque rock glacier</i>					
BO-2	GR-2 lower unit	13.4 ± 0.8 (0.5)	13.5 ± 0.8 (0.5)	14.3 ± 0.8 (0.5)	14.5 ± 0.8 (0.5)
BO-3	GR-2 lower unit	14.3 ± 0.8 (0.6)	14.5 ± 0.8 (0.6)	15.3 ± 0.9 (0.6)	15.5 ± 0.9 (0.6)
BO-4	GR-2 upper unit	12.3 ± 0.9 (0.8)	12.5 ± 0.9 (0.8)	13.2 ± 1.0 (0.8)	13.4 ± 1.0 (0.8)
BO-5	GR-2 upper unit	12.3 ± 1.1 (0.9)	12.5 ± 1.1 (1.0)	13.2 ± 1.1 (1.0)	13.4 ± 1.2 (1.0)
<i>Cirque highest moraines</i>					
BO-11	Mo-8	11.2 ± 0.7 (0.5)	11.3 ± 0.7 (0.5)	12.0 ± 0.7 (0.5)	12.1 ± 0.7 (0.5)
BO-12	Mo-8	10.9 ± 0.6 (0.4)	11.0 ± 0.6 (0.4)	11.7 ± 0.6 (0.4)	11.8 ± 0.6 (0.4)

Hulton, 2010). Equilibrium line altitudes (ELAs) were calculated from the paleoglacier DEMs using the ELA toolbox included in the PaleoIce toolbox, taking into account the AABR (BR = 1.75; Rea, 2009) and AAR (AAR = 0.6; Porter, 1975) methods. The estimated ELA values allow comparisons for other studies in the region focusing on past glacial oscillations (Oliva et al., 2019), and should be interpreted as approximate paleotemperature fluctuations.

4. Results

4.1. Geomorphological evidence

The study area comprises two main geomorphological units (Figs. 2, 3 and 4): A composite glacial cirque with two adjacent cirques and the glacial valley that runs towards the Noguera Pallaresa.

The highest part of the valley (Ras de Bonabé) is wide, gently sloping and bounded by interfluvies smoothed by past glacial erosion. The valley floor is covered by erratic boulders, till deposits and three moraine ridges (one terminal moraine and two lateral moraines) between 1890 and 2300 m asl. These glacial deposits are interrupted by two exposed limestone outcrops (2125 and 2035 m asl), perpendicular to the valley direction. The upper outcrop shows traces of glacial abrasion and sectors of degraded karst morphology (exposed solution channels). Further north, in the wooded area, the valley narrows to form a small subglacial gorge and hangs about 500 m above the main valley of the Noguera Pallaresa. The main glacial sedimentary landforms of this unit are:

- In the lower part of the Ras de Bonabé, the Llançanes River and another small stream delimit the 350 m long outermost moraine ridge (Mo-2), between 2115 and 2060 m asl (Fig. 3E). Two large granite boulders from this moraine ridge were sampled for CRE dating purposes (BO-17 and BO-18).
- Erratic boulders scattered at 2200–2225 m asl and located on the divide with the Marimánha valley (Fig. 3B). These are associated

with the wide transfluvial cols between Bonabé and the adjacent Marimánha and Cireres valleys during glacial expansion phases.

- Remains of a moraine ridge (Mo-1) are located on the true-left side of the valley, between 130 and 85 m above the valley floor. These aligned granitic boulders rest on a schist substrate (Fig. 3C). Samples BO-15 and BO-16 were taken from two large and well-anchored boulders from the moraine ridge.
- The latero-frontal moraine Mo-3 developed between 2175 and 2160 m asl on the left margin of the valley (Fig. 3A) that starts from a chaotic till accumulation dominated by large boulders, located below the cirque margin.

Upstream, the headwaters of the valley are formed by two simple cirques: the Bonabé cirque, which faces Northeast, and a second, smaller cirque to the west of the first, which also faces Northeast and contains moraine boulders, polished bedrock surfaces and a protalus lobe on its northern slope. The main cirque forms an amphitheatre with elongated ridges (average elevation 2630 m asl) and steep walls with slopes of 200–300 m. Inside the cirque (2310–2360 m asl) there is an overdeepened basin occupied by the Estany del Ras and moraines very close to the cirque walls, a set of two rock glaciers and moraines formed by a debris-covered glacier (Fig. 4A). Inside the cirque, between 2320 and 2475 m asl, several escarpments with evidence of glacial abrasion can be distinguished. The main deposits are:

- The cirque floor is covered by scattered till and a small moraine (Mo-4), partly covered by the front of a rock glacier. This is a lobate rock glacier (GR-1; mean elevation of 2349 m asl, Southeast exposed and 3.5 ha in areal extent), is located on the East slope of the cirque and rooted in a talus slope. This talus-rock glacier consists of two large deposits separated by a 13 m high inner front (Fig. 2). Between the two units there is an accumulation of large angular boulders (major axis between 5 and 8 m). Vegetation is sparse and confined to small areas only on the distal flanks of the outer slopes of the frontal arcs.

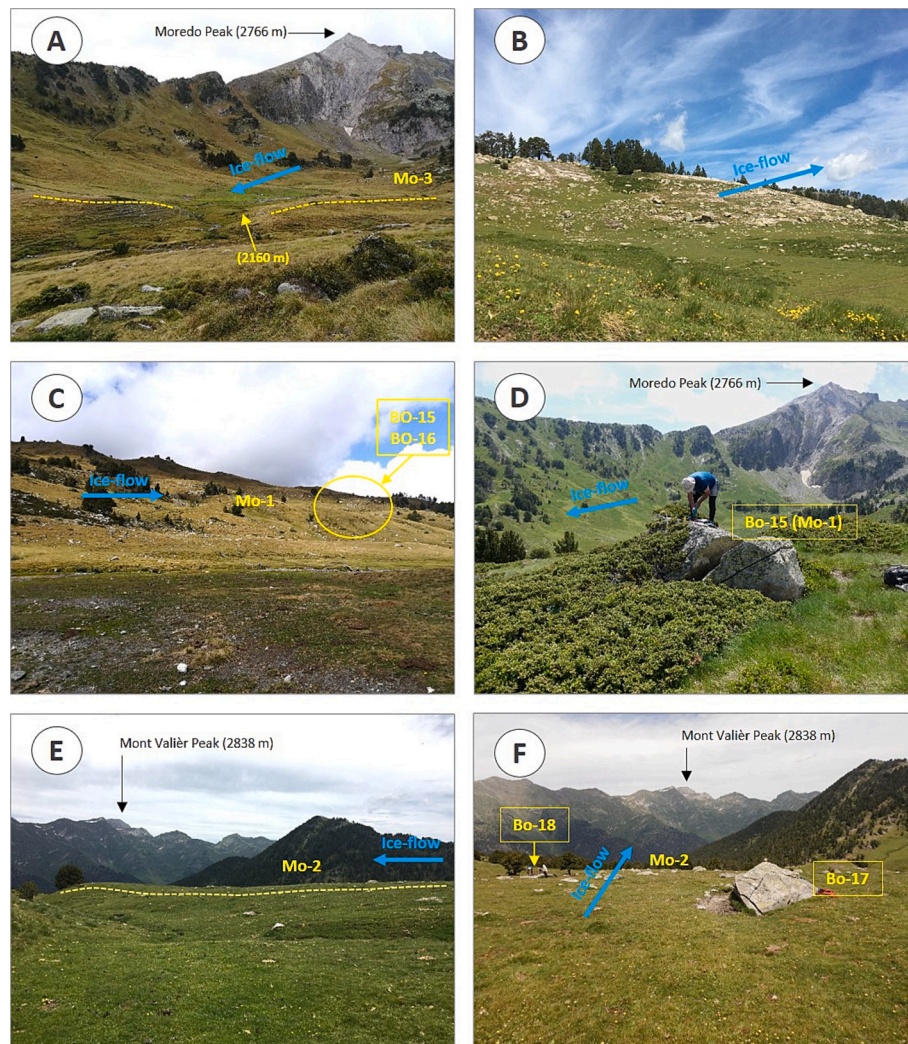


Fig. 3. Examples of the main geomorphological units in the Bonabé valley, including the location of the dated samples: (A) moraine Mo-3 located at the bottom of the valley; (B) polished bedrock (limestone) with erratic boulders on the surface near the W divide of the valley; (C) eroded moraine Mo-1, with the location of samples BO-15 and BO-16; (D) sample BO-15 from Mo-1; (E) moraine Mo-2; (F) samples BO-17 and BO-18 (granitic boulders) from Mo-2.

Sample BO-14 was taken from an erratic boulder located at the top of the rock outcrop that closes the cirque, and sample BO-9 was collected from the upper surface of a glacially-polished escarpment near Mo-4 and in front of GR-1.

- Close to the highest peaks, the cirque floor is occupied by a rock glacier (GR-2; 2388 m asl average elevation, North-facing and 6.2 ha in areal extent) in the form of a tongue with a frontal arch (25 m high), steep sides and a sequence of transverse ridges and furrows (Fig. 4B). The source area of the landform is constituted by debris from moraines situated above it, as well as by the considerable volume and surface area of the landform. These factors suggest that the landform originated as a debris-rock glacier. In accordance with the nomenclature proposed by [RGIK \(2023\)](#), this rock glacier system is constituted by two superimposed generations. The lower unit is situated at an elevation of 2360–2388 m asl, while the upper is located at 2388–2412 m asl. The upper deposit forms a 8 m high frontal ridge, which overlaps the body of the lower unit, which is formed by ridges and furrows with an elevation of 1–2 m. Samples BO-1 and BO-6 were obtained from two glacially-polished rock surfaces situated in close proximity to the base of the external talus of GR-2. Samples were obtained from well-anchored boulders located on the crest of the external ridge of GR-2 (samples BO-2 and BO-3) and from the front of the upper unit of GR-2 (samples BO-4 and BO-5).

- Two frontal moraine arcs (Mo-5 and Mo-6) built by small glaciers are situated towards the base of the lateral cirque walls. The Mo-6 ridge (2385 m asl) is situated in close proximity to the GR-2, which traverses the interior of the cirque. A 15 m-deep hollow is present between the moraine and the slope, which is occupied by a small protalus lobe. Between Mo-5, the left side of the rock glacier (GR-2) and the rocky cliffs, there is a depression (2360 m) occupied by a seasonal lake and snowfields. Two boulders of the Mo-6 ridge were sampled for CRE dating (BO-7 and BO-8).
- At the western margin of the cirque there is a substantial accumulation of moraine boulders with an open work structure (Mo-7; 2495–2420 m asl). These boulders delineate a series of depressions and three moraine ridges, which are indicative of the retreat process of a small glacier and its gradual transformation into a debris-covered glacier.
- The moraine Mo-8 is located at an altitude of 2460–2525 m asl at the base of the northern face of the Tuc de Bonabé (Fig. 4E). The deposit is composed of angular boulders with minimal matrix and forms an abrupt external front with three laterally connected arcs (10–15 m high). These arcs are situated on polished rock surfaces that are partially covered by moraine deposits. A minor depression is present between the moraine and the cirque wall, currently occupied by a late-lasting snow patch surrounded by boulders with minimal lichen



Fig. 4. Examples of the main geomorphological units in the Bonabé cirque, including the location of the dated samples: (A) oblique aerial view of the interior of the Bonabé cirque showing the location of the main landforms; (B) front of the rock glacier (GR-2) and location of samples BO-2 and BO-3; (C) detail of sample BO-5 in the upper unit of the rock glacier (GR-2); (D) polished bedrock near the cirque walls and location of sample BO-13; (E) detail of sample BO-11 in the highest moraine (Mo-8) near the cirque walls.

growth. Two samples (BO-11 and BO-12) were obtained from stable boulders situated on the eastern sector of the Mo-8 ridge. The sample BO-13 was taken from a glacially polished rock surface located at 2498 m asl, which separates the moraine deposits of Mo-7 and Mo-8.

- Four protalus lobes are located at the foot of the side walls of the cirque (both in a southeast and northwest orientation), between 2365 and 2461 m asl, at a higher altitude than the rest of the others deposits (except Mo-7 and Mo-8).

4.2. Geochronological data

The 17 CRE ages obtained were found to be consistent, with no outliers detected following the application of the χ^2 -test to the different groups of samples (Ward and Wilson, 1978). It can therefore be concluded that the geochronological values obtained present limited scatter and represent minimum ages. The exposure ages range from 18.0 ± 1.2 ka to 10.9 ± 0.6 ka (without the snow and erosion correction), indicating a period spanning from the onset of the last deglaciation to the Early Holocene (Fig. 5). Sample ages exhibit a gradient of decreasing exposure ages from the valley to the cirque and from the cirque to the summit. Fig. 6 shows the ages of the different types of samples in relation to their altitude and distance from the cirque wall.

The oldest samples are those corresponding to the valley moraines. The Mo-1 samples (18.0 ± 1.2 and 16.6 ± 0.8 ka) yielded a mean age of 17.3 ± 1.4 ka, while the Mo-2 samples (15.5 ± 0.8 and 15.0 ± 0.8 ka) resulted in a mean age of 15.3 ± 0.9 ka.

The four samples collected at the base of the main cirque also show consistent values for the deglaciation process, both from the polished bedrock surface (13.7 ± 0.7 ka; 14.2 ± 0.7 ka; and 13.7 ± 0.8 ka) and from the erratic boulders at the cirque margin (14.5 ± 0.8 ka).

The samples from the cirque floor corresponding to the rock glacier (GR-2) and the Mo-6 moraine boulders. The ages of the Mo-6 boulders (13.3 ± 0.8 ka and 14.0 ± 0.7 ka) suggest a mean age of 13.7 ± 0.9 ka. The ages obtained from boulders of the outer front of the GR-2 rock glacier (13.4 ± 0.8 ka and 14.3 ± 0.8 ka), yielded a mean age of 13.9 ± 1.0 ka. The samples collected from the upper unit of the rock glacier (12.3 ± 0.9 ka and 12.3 ± 1.1 ka) gave an average age of 12.3 ± 1.0 ka.

In the uppermost zone of the cirque, the age of the samples collected from the glacially polished rock surface was 12.3 ± 0.7 ka. The Mo-8 boulders yielded ages of 11.2 ± 0.7 ka and 10.9 ± 0.6 ka, resulting in a mean age of 11.1 ± 0.7 ka.

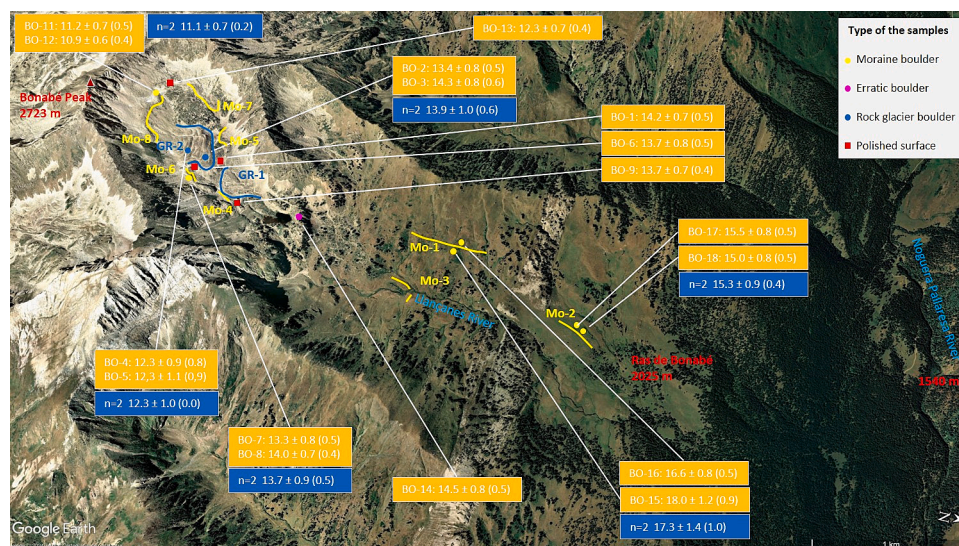


Fig. 5. 3D view (Google Earth) of the study area showing the location of key features and samples. Ages in the image (orange rectangle) reported for the 'no correction' scenario. The mean age of each formation is indicated by a blue rectangle.

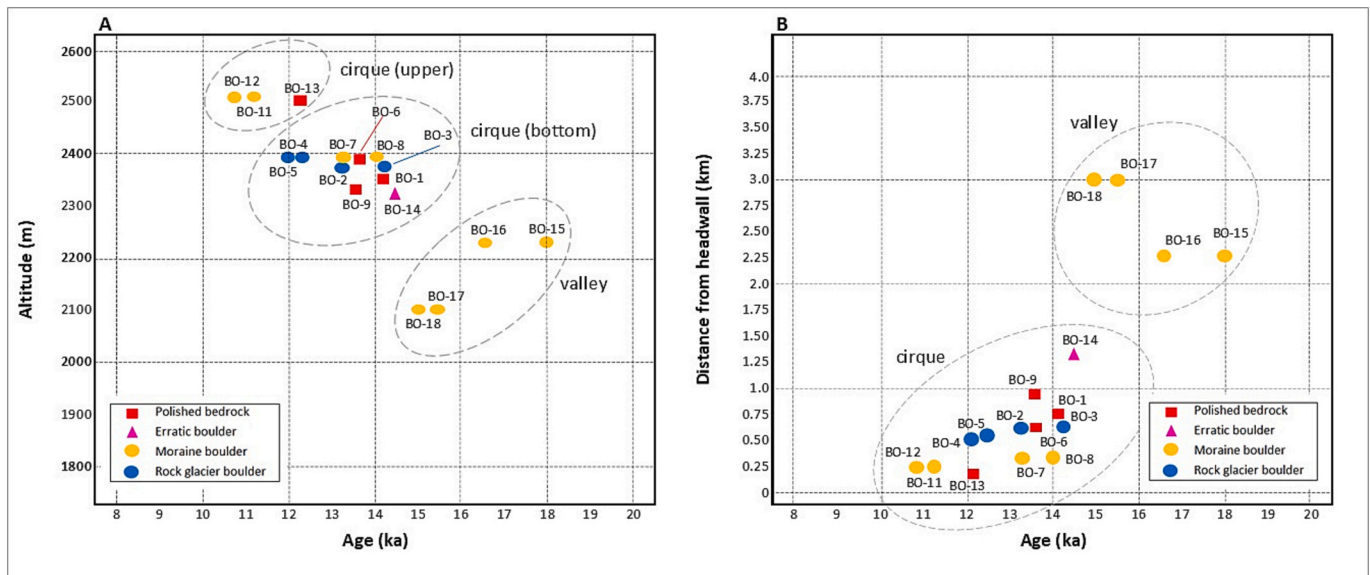


Fig. 6. (A) ^{10}Be CRE ages, sample type, and sample location in relation to elevation; (B) ^{10}Be CRE ages, sample type, and sample location in relation to distance from the cirque headwall. CRE ages are reported as "No correction".

4.3. Reconstruction of ELAs

The geomorphological and chronological data obtained from the dated moraine samples in the Bonabé area have enabled the identification of three main glacial phases. A spatial reconstruction of the paleoglaciers was performed for each of the identified phases, along with the calculation of the corresponding approximate ELAs: (i) in the oldest phase, dated at 17.3 ± 1.4 ka (mean age), with a glacier 3.8 km long (and 155 m maximum thickness), the ELA is here estimated at 2258 m asl; (ii) in the next phase, dated at 15.3 ± 0.9 ka, the glacier was 2.9 km long (and 147 m maximum thickness) and its ELA is estimated at 2321 m asl; (iii) finally, in the last phase, dated at 11.1 ± 0.7 ka, the paleoglacier was reduced to a small cirque glacier, with a length of ~ 300 m, a maximum thickness of ~ 18 m and an estimated ELA of 2537 m asl (Fig. 7). The paleoglaciers at Bonabé represent between 4.6 and 6 % of the total glacier length of the Noguera Pallaresa (63 km) during HS-1, with a further reduction during the YD-Holocene transition (0.5 %).

5. Discussion

5.1. Chronology of deglaciation in the Bonabé valley

The undated erratic boulders located on the divide with the Marimanha valley (2200–2225 m asl) are likely to be the oldest glacial deposits in the study area (Fig. 3B), thus potentially associated with the Local Last Glacial Maximum (LLGM). During this phase, the majority of the northern slope of the massif was occupied by glaciers, with the ice crossing the preglacial divides of the high tributary valleys of Marimanha, Llançanes and Cireres. This resulted in the formation of an ice field that was connected to the main source area, the Noguera Pallaresa paleoglacier (Ventura and Turu, 2022). The location of erratic boulders in the transfluence and difffluence cols and juxtaglacial deposits at high elevations in lateral ravines (Ventura and Turu, 2022) suggest a maximum ice thickness of 540–730 m in the main axis of the paleoglacier, as also confirmed in the Plan de Beret area (Oliva et al., 2021).

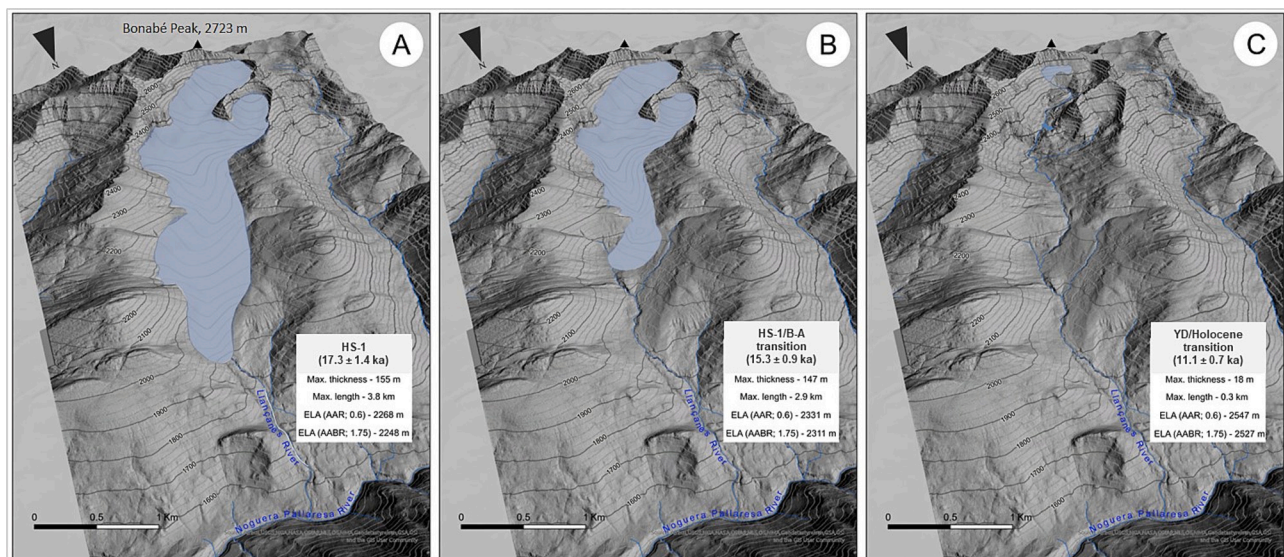


Fig. 7. Paleoglacier reconstruction of the different stages: (A) glacier extent during the HS-1; (B) glacier extent during the HS-1/B-A transition; and (C) small glaciers during the YD/Holocene transition.

The distribution of geomorphological features thus indicates an extensive glacial occupation during the local LGM, which contrasts with the general landscape of the upper Noguera Pallaresa valley where a fluvial morphology is preserved, with stretches of fluvial gorge and rocky erosion terraces (Nussbaum, 1956). The rapid retreat of the glacier after the ILGM resulted in the disappearance of the main glacier in the Noguera Pallaresa valley and the disconnection and isolation of the tributary glaciers at high altitudes, with almost no associated deposits (Ventura and Turu, 2022). The subsequent group of moraines, including those studied in the Bonabé area, is located in valleys and cirques above altitude of 1800–1900 m asl. This is associated with phases of glacier expansion or stabilisation within the last deglaciation.

In the Bonabé valley, the oldest dated deposits correspond to the Mo-1 and Mo-2 moraines, which were formed by a valley glacier with fronts above 1850 m asl. The Mo-1 moraines indicate the position of a valley glacier around 17.3 ± 1.4 ka (early HS-1). The Mo-1 formation is identified as the remains of the left lateral moraine of the glacier. No glacial deposits are observed between the moraine and the divide over a distance of approximately 330 m. Beyond the northern limit of the Mo-1 moraine, the elevation of the divide declines, and erratic boulders become increasingly widespread. Mo-2, situated on the broad valley floor, provides a mean CRE age of 15.3 ± 0.9 ka (end of HS-1) for a glacier measuring 2.9 km in length. Mo-3 (undated) is 1 km upstream of Mo-2 with a moraine terminus at 2160 m for a 2.0 km long glacier. Its stabilisation must have occurred between 15.3 ± 0.9 ka (Mo-2) and 14.5 ± 0.8 ka (cirque edge), thus between late HS-1 and early interstadial B-A.

The HS-1 glaciers on the northern slope of the Marimánha massif were already small valley glaciers with fronts at 1875–2025 m, and were disconnected from each other and from the main paleoglacier in the Noguera Pallaresa valley. The rapid ascent of the ELA (~200–300 m) during the onset of T-1 and the relatively low elevations of the summit line (2535 m asl) likely favoured the disappearance of the Bonabé glacier, as well as glacial retreat and fragmentation in the upper basin of the Noguera Pallaresa (Ventura and Turu, 2022). The glacial retreat and rapid fragmentation observed in the Bonabé area are comparable to those seen on the high plateaus formerly occupied by ice in the south-eastern sector of the Carlit Massif, in the eastern Pyrenees (Delmas et al., 2008).

The deglaciation of the cirque during the B-A favoured the ice-free exposure of rock surfaces within the cirque, as evidenced by CRE ages ranging from 14.2 ± 0.7 to 13.7 ± 0.7 ka (obtained in glacially-polished surfaces). This indicated a rapid and complete deglaciation of the upper valley and the interior of the cirque, where the ice disappeared.

The presence of frontal moraines on both sides of the cirque (Mo-5 and Mo-6) likely indicates the formation of small glaciers along the cirque walls during short cold pulses within the B-A (with a mean age of 13.7 ± 0.9 ka for Mo-6). Following glacial retreat, we hypothesise these moraines were partially covered by the development, on the slopes of the cirque (due to an intensification of periglacial and paraglacial activity), of protalus lobes and by GR-2. The proximity and temporal overlap of these age groups, together with the partial overlap of the uncertainty ranges associated with the CRE dating, do not allow us to unambiguously associate either the culmination of Mo-6 or that of the GR-2 front with the short-lived cold episodes that occurred during the second half of the B-A. These phases have been identified in nearby areas of the central Pyrenees, such as in the Saboredo cirque-Ruda valley (Fernandes et al., 2021) with two groups of moraines at 2080 m asl (13.5 ± 0.9 ka) and 2190 m asl (13.0 ± 0.8 ka) and in the Locampo cirque (Fernandes et al., 2023) with a frontal moraine at 2220 m asl (13.2 ± 1.1 ka).

Glacial retreat led to the replacement of glaciers by periglacial and paraglacial dynamics, which affected ice-free ridges, rock walls and cirque slopes. One of the most notable effects of this change was the rapid formation and stabilisation of rock glaciers (GR-1 and GR-2) and protalus lobes (Fig. 2). The transition between deglaciation and the

subsequent formation of rock glaciers was rapid, as evidenced by the available CRE dates. The deglaciation age of the rock outcrops located at the base of GR-2 (Fig. 2) is 14.0 ± 0.8 ka, which is close to the 13.9 ± 1.0 ka (within B-A) average age of stabilisation of the lower unit of GR-2. This rock glacier was originating from the talus slopes and by moraines formed by a receding small glacier at the foot of the Bonabé Peak (2733 m asl). GR-2 is thus the result of the final disappearance of a glacier and its rapid transformation into a rock glacier. Both GR-1 and GR-2 are currently situated below the lower limit of active rock glaciers in the Pyrenees, which is established at 2650 m asl (Serrano et al., 2011).

The colder conditions that prevailed during the YD period gave rise to the formation of new glacial and periglacial landforms in the higher parts of the cirques. In the Bonabé area, the impact of the YD is reflected in the formation of a cirque glacier on the north face of the Tuc de Bonabé (>2450 m asl), which persisted throughout the YD. The onset of glacial retreat at approximately 12.3 ± 0.7 ka resulted in the exposure of an ice-free bedrock surface to the west of the cirque, close to the less elevated and steeper section of the ridge at ca. 2585–2655 m asl. The moraine produced by the debris-covered glacier (Mo-7) was probably also stabilised during this episode. The small glacier remained active longer, likely protected by the higher peaks (2650–2723 m asl) with steeper walls. Our results suggest the frontal moraines of the glacier (Mo-8, 2460–2525 m asl) stabilised at around 11.1 ± 0.7 ka, at the transition between the YD and the Early Holocene, when conditions were still favourable for the maintenance of small glaciers on the northern slopes under the highest peaks of the Pyrenees. YD glaciers have also been found in nearby cirques with similar geomorphological settings, with moraines at the base of the cirque walls. For example, moraines at 2470 m asl below Tuc de Sendrosa (2702 m asl) in the Ruda valley have CRE stabilisation ages of 12.6 ± 1.3 ka (Fernandes et al., 2021) or those located at 2431 m asl near Pic de Rosari (2607 m asl) in the Baciver cirque (Marimánha) with ages of 12.8 ± 0.5 ka (Oliva et al., 2021). The cooling of the YD also favoured the formation or reactivation of the upper unit of GR-2, whose stabilisation occurred around 12.3 ± 1.0 ka. However, the range of uncertainties associated with the CRE ages makes it challenging to discern whether some features were stabilised under colder/warmer conditions, particularly at the HS-1/B-A and B-A/YD boundaries.

The highest moraine ridge (Mo-8) is indicative of the last phase, with the presence of glaciers in Bonabé to the present day. However, in other high massifs of the mountain range (> 2800 m asl) including parts of the Noguera Pallaresa basin, moraines at 2550–2800 m asl may have developed during colder phases of the Holocene (e.g. Neoglacial, LIA; Ventura and Turu, 2022).

By comparing the data from the three palaeo-ELAs identified at Bonabé with the current climatic ELA in the Pyrenees—located at 3100 m a.s.l. (René, 2011; Jomelli et al., 2020)—we can estimate the variation or depression of the ELA (Δ ELA). To infer corresponding summer temperature reductions, a thermal lapse rate of 0.65°C per 100 m was applied, under the assumption that past precipitation patterns were similar to those of the present. The results compared to the present climate data are as follows: i) HS-1 (Δ ELA = 842 m), 5.5°C ; ii) HS-1-B-A transition (Δ ELA = 779 m), 5.0°C ; iii) YD-Holocene transition (Δ ELA = 563 m), 3.6°C . These estimated values inferred from Bonabé valley are consistent with those obtained in the nearby Pyrenean massifs of the central Pyrenees (Jomelli et al., 2020; Fernandes et al., 2021; Oliva et al., 2021). In the same Marimánha massif, in the Baciver cirque (2679 m), Oliva et al. (2021) determined a temperature reduction of 3.4°C for the YD and Fernandes et al. (2021) a reduction between 3.9 and 3.0°C , also for the YD in the Saboredo cirque (Aran valley). Jomelli et al. (2020), using the mass balance method, estimated a temperature reduction of 5.1°C (for HS-1) and 3.9°C (transition Late Glacial-YD) in the Medacorba massif (2915 m).

5.2. Chronology of deglaciation in the central Pyrenees in the context of Southern Europe

Glacial expansion of HS-1 has been detected in several valleys in the Pyrenees, both in large glacial basins, with 7–27 km long alpine glaciers in the Ariège (Delmas et al., 2011; Reixach et al., 2021; Reixach, 2022), the Noguera Ribagorçana (Pallàs et al., 2006), the Gállego (Palacios et al., 2015a), as well as in smaller headwaters or in southern orientations, with shorter glaciers (2–5 km), such as those of Arànsér (Andrés et al., 2018; Palacios et al., 2015b), Têt (Delmas et al., 2008; Tomkins et al., 2018) or Malniu (Andrés et al., 2018; Palacios et al., 2015b; Pallàs et al., 2010) in the eastern Pyrenees.

To date, there is only one numerical date related to HS-1 in the Noguera Pallaresa basin. Organic remains within a subglacial till at the base of the glaciolacustrine complex of Burg Lake (1821 m asl) - part of a 2 km long glacier to the west of Pic de la Màniga (2517 m asl) - were radiocarbon dated to 17 ka cal BP (Vizcaino et al., 2011; Vizcaino and Pèlachs, 2019). Although several moraine systems have been identified in the Noguera Pallaresa basin that could be associated with HS-1 based on their morphostratigraphic position relative to other earlier deposits, the lack of absolute or numerical ages makes it difficult to constrain their timing. These include the fluvio-glacial deposits at 1400 m asl in the headwaters of the Valferrera and Tavascan valleys (Bru, 1985), which formed glaciers with tongues of 11 km and 7 km respectively, and moraines located between 1500 and 2000 m asl in lateral valleys with peaks at 2700–2900 m asl (Ventura and Turu, 2022). Based on geomorphological criteria and paleoglacial reconstructions, Fernandes et al. (2017) also proposed an HS-1 age for the Plan de Beret moraine complex (1860–1915 m asl), formed by ice transfluence from the Garonne glacier.

Glacial advance during HS-1 has also been reported by CRE dating in other Iberian mountain ranges. In the Iberian Range, on the northern slope of Peña Negra (2023 m asl), García-Ruiz et al. (2020a) dated the internal moraines of a small glacier (0.9 km long) with an average age of 16.8 ± 1.0 ka. In the Monasterio valley (North orientation; maximum altitude, 2019 m asl), Cantabrian Mountains, Rodríguez-Rodríguez et al. (2017) also dated internal moraines (of a 2.5 km long glacier) with an average age of 16.7 ± 0.4 ka. In the San Juan valley, Sierra Nevada, glaciers were still extensive during the last stages of HS-1, as evidenced by several polished surfaces (at 2331–2350 m asl) under summits of 3100 m asl, which reported deglaciation ages of 15.0 ± 1.2 ka for 3 km long paleoglaciers (Palacios et al., 2016).

Evidence of glacial activity during Heinrich Stadial 1 (HS-1) has also been identified in other European mountain ranges. In the Alps, deposits from this phase are characterised by frontal and lateral moraine complexes situated between 800 and 1700 m a.s.l. in both tributary valleys and the upper sections of main valleys. Notable examples include the Clarée Valley in the Western Alps (Cossart et al., 2012), the Gschnitz Valley in the Eastern Alps (Ivy-Ochs, 2015), and the Dolomites Massif in the Southern Alps (Ghini and Soldati, 2017). This phase corresponds to the so-called 'Gschnitz' stage, which has been dated using CRE to approximately 17–16 ka (Ivy-Ochs et al., 2023a). The extent of the glaciers varied, as in the central Pyrenees, depending on the altitude of the peaks and the extent of the basins; some glaciers during HS-1 reached 20–30 km in length, as in the Haslital valley in the Bernese Oberland (Wirsig et al., 2016) or 13.5 km in the Gesso basin in the Maritime Alps (Federici et al., 2016). Glaciers during HS-1 in less elevated alpine massifs had a much smaller extent, such as in the Reisseck Group (2558 m asl), where 3–3.8 km long ice tongues flowed with fronts located at 1300 m (North) and 1700 m asl (South). At the end of HS-1, these retreating glaciers were overrun by rock glaciers formed on the valley slopes (Steinemann et al., 2020). In the Gran Sasso (2912 m asl), central Apennine massif, based on radiocarbon dating and tephrochronology in lacustrine sediments, three glacial stages have been differentiated within HS-1, with small glaciers 1–1.8 km long, fronts at 1650–2000 m asl and an estimated ELA at 1750–2150 m asl (Ribolini et al., 2023b). CRE dating in the eastern and southern Carpathians in Romania

(summits at 2300–2540 m asl), identified HS-1 moraines with ages between 18.4 and 15.8 ka belonging to 4–8 km long glaciers and fronts located at 1116–1450 m asl (ELA at 1680–1950 m asl); at the end of this period, rock glaciers developed at altitudes of 1730–1860 m asl (Urdeu et al., 2023).

The process of intense deglaciation detected in Bonabé between 15 and 13 ka is also recorded in other valleys in the Pyrenees, including some close to the study area. In the Marimánha massif, it has been identified in the Bacivèr cirque (Oliva et al., 2021), and also in the nearby Locampo (Fernandes et al., 2023) and Saboredo (Fernandes et al., 2021) cirques. Cirques with lower peaks of 2500–2600 m asl were completely deglaciated during the B-A (Oliva et al., 2021), especially in the eastern Pyrenees. This rapid deglaciation of the cirques generated a large volume of debris by periglacial and paraglacial processes, which favoured the development of debris-covered glaciers and rock glaciers in the Pyrenees and other mountain ranges. Although the rock glaciers located at lower altitudes would have formed during HS-1 and stabilised at the beginning of the B-A, it is during this interstadial that a large number of rock glaciers are generated (Andrés et al., 2017; Andrés et al., 2018). In any case, the formation of rock glaciers has continued in later glacial stages (YD).

The rock glaciers of the Pyrenees are therefore not linked to a single stadial or interstadial, but are more likely to form due to the particular dynamics of the deglaciation of each massif. For example, in the Panticosa massif, central Pyrenees, rock glaciers with fronts at 2200–2300 m asl, formed in the B-A and stabilised towards the end of the same interstadial and the beginning of the YD, whilst higher rock glaciers (fronts at 2400 m asl) formed during the YD or at the beginning of the Holocene, and remained active until the middle Holocene (Andrés et al., 2017). Other cirques in the Pyrenees with evidence of B-A glacial retreat have been identified in the eastern (Ariège valley; Delmas et al., 2011), central (Ésèra valley; Crest et al., 2017; Vidaller, 2025) and in the western Pyrenees (Gállego valley; Palacios et al., 2015a).

Glacial retreat during the B-A has been also detected in other Iberian massifs such as the Sierra Nevada (Palacios et al., 2016), the Iberian Range (García-Ruiz et al., 2020a) and the Cantabrian Mountains (Rodríguez-Rodríguez et al., 2017), as well as in other European and Mediterranean mountain ranges, including the Alps (Ivy-Ochs, 2015), Taurus (Çiner and Sarikaya, 2017) to the Tatra Mountains in the Carpathians (Zasadni et al., 2020). In these mountain ranges, deglaciation also favoured the development of rock glaciers, which stabilised at similar times as in the Pyrenees. In the Tatra Mountains, eight rock glaciers with fronts between 1404 and 1856 m asl have been dated between the HS-1 and the Early Holocene (Dlabackova et al., 2023). In the Italian Apennines, Ribolini and Giraudo (2023) identified five distinct generations of rock glaciers dated between 17 and 1 ka with fronts at 1500–1600, 1700–1800, 1900, 2000, and > 2300 m asl.

In contrast to the eastern Pyrenees, where evidence is scarce (Çiner et al., 2024), evidence of glacier expansion during the YD is widespread in the cirques of the central Pyrenees. Ice masses during the YD were always limited to high massifs (summits >2600 m asl) and mostly in favourable aspects (North), with small cirque glaciers with tongues of 2 to 3.5 km maximum length and the generation of new rock glaciers (García Ruíz et al., 2016; Oliva et al., 2019). Some examples can be found in the Ibones Azules and Piniecho cirques in the Panticosa massif (Serrano and Agudo, 1988; Palacios et al., 2015a), the Mulleres valley in the Noguera Ribagorçana (Pallàs et al., 2006), Renclusa in the Maladeta massif (Crest et al., 2017) or the Medacorba cirque in the Soulcem valley in Ariège (Jomelli et al., 2020), among others (see synthesis in Delmas et al., 2023c).

The existence of glaciers during the YD has also been inferred in other mountains of the Iberian Peninsula (Oliva et al., 2023). In the Sierra Nevada, cirque glaciers with tongues <2 km long were located under peaks >3000 m asl in the valleys of San Juan, Lanjarón and Hoya de la Mora (Palacios et al., 2016). In other ice-free cirques, such as in Rio Seco and Dílar, rock glaciers are argued to have formed and stabilised at

11.4 ka, while the upper ridges remained active until the Mid Holocene (Gómez-Ortiz et al., 2012, 2021). In other mountain ranges, such as the Central System and the Iberian Range, evidence for YD glaciation is much more limited. In the former range, the highest moraines (2120 m asl) formed by the paleoglacier of the Cuerpo del Hombre, Sierra de Béjar, have been dated to 11.1 ka (Carrasco et al., 2015, 2021). In the Iberian Range, there is no chronological evidence for the YD, although there are deposits supporting a possible YD glacial advance in the Revinuesa and Mencilla cirques (García-Ruiz, 2021); in the Sierra de la Demanda, a CRE-dated debris-covered glacier stabilised shortly after the YD-Holocene transition (Fernández-Fernández et al., 2017). The YD stadial has been reconstructed detected in many massifs of the Cantabrian Mountains, especially in those with peaks >2000 m asl, with cirque-hosted moraines, based on relative dating approaches. In the Alto Carrión, moraines at 2100–2200 m asl and rock glaciers with fronts at 1800–2000 m asl, have been associated with the YD (Pellitero, 2021). In the Picos de Europa massif (2649 m asl), 70 small glaciers 0–5–1 km long with moraines at 1800–2000 m asl have been associated with the YD, together with some rock glaciers in this limestone massif (Ruiz-Fernández et al., 2021). Their attribution to the YD is only supported by radiocarbon ages from lake sediments in the Áliva and Enol lake areas, which yielded ages of 13.5–11.6 cal ka BP (Moreno et al., 2011; Serrano et al., 2012).

In other European mountains, widespread YD glacial advances have been identified and dated in 35 valleys in the Alps, with an average moraine elevation of 1665 m asl and an ELA of 2370 m asl (see synthesis in Ivy-Ochs et al., 2023b). In the Val Viola (Rhaetian Alps, Switzerland), YD frontal moraines located at 2100 m asl (from 5.5 km long glaciers) were CRE dated to 12.3 ka, and rock glaciers of the same age placed their fronts at 2400 m asl (Scotti et al., 2017). In the Clarée valley (Western Alps), frontal moraines of YD glaciers (up to 8 km long) are located at 1900 m asl and yielded CRE ages of 12.8 ka (Cossart et al., 2012). YD glaciation has also been studied in several massifs of the Carpathians, such as in Mt. Krivan (2494 m asl), where rock glaciers with fronts at 1675–2220 m asl stabilised at 11.1 ka (Zasadni et al., 2020). In the Rodna Mountains, László et al. (2013), based on paleoglacial reconstructions and paleoELAs calculations attribute, by comparison with other nearby massifs, to the YD a series of moraines located at 1750–1950 m asl and rock glaciers with fronts at 1770 m asl. In the central Apennines, moraines formed by small glaciers at 2240 m asl and rock glaciers with fronts at 1800 m asl have been attributed to the YD (Ribolini et al., 2023a). Evidence for YD glaciation has also been reported in various massifs in Greece and Anatolia, based on CRE dating of glacial features. In the Megalakazania cirque on Mt. Olympus (2918 m asl), moraines at 2245 m asl from a small 0.8 km long glacier were dated to 12.0 ka (Styllas et al., 2018), and in the Dedegol Mountains (Western Taurus), a lateral moraine of the Kisbe paleoglacier (length 4 km; front at 1690 m asl), was dated to 11.5 ka (Akçar, 2023). A frontal moraine (at 2900 m asl) of the ancient Kavron valley glacier (2.3 km long) in the Eastern Black Sea Mountains also developed at 12.8 ka (Akçar et al., 2007).

Overall, the data from the Bonabé Valley suggest that deglaciation followed consistent climatic patterns across Europe, with only minor variations due to local topoclimatic factors. Data also confirm that the period from HS-1 to the Early Holocene significantly altered the mountainous landscape of the Pyrenees, favouring the development of the wide range of glacial and periglacial landforms that exist today in the high mountains of this range.

6. Conclusions

In this study we have investigated the deglaciation timing during the Pleistocene-Holocene transition in the Bonabé valley (Marimánha massif) in the southern central Pyrenees. This is the first study in the Noguera Pallaresa basin to combine geomorphological work with numerical dating using Terrestrial cosmogenic nuclide exposure dating

(CRE dating). A total of 17 samples collected along the Bonabé valley were (^{10}Be) CRE dated, and provided chronological information on the last deglaciation. The CRE dates obtained are well clustered and thus allow us to distinguish several glacial phases. Our results thus suggest that:

1. Glaciers developed in the valley during, at least, three phases within the Heinrich Stadial 1 (HS-1; ~18.0 - 14.6 ka), with lengths of 3.8, 2.9 and 2.0 km from headwall, respectively. The two oldest phases have been dated to 17.3 ± 1.4 ka and 15.3 ± 0.9 ka, respectively.
2. Rapid glacial retreat occurred during the Bølling-Allerød (B-A; 14.6–12.9 ka) interstadial, leaving the cirque almost ice-free between 15 and 13 ka. This phase was followed by increased periglacial and paraglacial activity, which favoured the development of two generations of rock glaciers. The lower unit stabilised soon after its formation (mean age 13.9 ± 1.0 ka). Within a short cold pulse during B-A, when rock glaciers were still active, new small glaciers developed in the cirque slopes, forming moraines that stabilised at 13.7 ± 0.9 ka.
3. A new glacial expansion occurred during the Younger Dryas (YD; 12.9–11.7 ka), with the development of a small glacier below the highest peaks, which deposited moraines at 2460 m asl, abandoned by the ice during the Early Holocene at 11.1 ± 0.7 ka. In parallel, the upper ridges of the rock glacier remained active during the YD and stabilised around 12.3 ± 1.0 ka.
4. Landforms related to Holocene glaciations are not recorded in the area.
5. Our new chronology has very little scatter and is broadly consistent in the timing of major glacial events with many other sites and glacial reconstructions in the Pyrenees and southern Europe. It reinforces the hypothesis that paleoglacial oscillations in this understudied region of the Pyrenees are good indicators of paleoclimatic events.

CRedit authorship contribution statement

Josep Ventura: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Marc Oliva:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **José M. Fernández-Fernández:** Writing – review & editing, Software, Methodology, Investigation. **Marcelo Fernandes:** Writing – review & editing, Methodology, Investigation. **David Palacios:** Writing – review & editing, Methodology, Investigation. **Tancrède Leger:** Writing – review & editing, Software, Data curation. **Vincent Jomelli:** Supervision, Software, Methodology. **Oriol Grau:** Methodology, Investigation.

Declaration of competing interest

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

Acknowledgements

This research article has been supported by the CRIOPIRINEUS project (Alt Pirineu Natural Park, Government of Catalonia) and by the ANTALP research group (Antarctic, Arctic, Alpine Environments; 2021-SGR-00269) funded by the Government of Catalonia. The ^{10}Be measurements were carried out at the ASTER AMS National Facility (CEREGE, Aix-en-Provence), supported by the INSU/CNRS and the ANR through the "Projets thématiques d'excellence" programme for the "Équipements d'excellence" ASTER-CEREGE action and the IRD. We would also like to thank Jordi Nofre and Jordi Martín for their assistance in the field.

Data availability

Data will be made available on request.

References

- Akçar, N., 2023. The Anatolian Mountains: Glacial landforms from the Younger Dryas stadial. In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, pp. 581–586.
- Akçar, N., Yavuz, V., Ivy-Ochs, S., Kubik, P.W., Vardar, M., Schlüchter, C., 2007. Paleoglacial records from Kavron valley, NE Turkey: field and cosmogenic exposure dating evidence. *Quat. Int.* 164–165, 170–183.
- André, M.F., 2002. Rates of postglacial rock weathering on glacially scoured outcrops (Abisko area, 68°N). *Geogr. Ann. Ser. B* 84, 139–150.
- Andrés, N., García-Ruiz, J.M., Campos, N., Palacios, D., 2017. Origen y cronología de los glaciares fósiles del macizo de Panticosa (Pirineo Central). In: Ruiz-Fernández, J., García-Hernández, C., Oliva, M., Rodríguez-Pérez, C., Gallinar, D. (Eds.), *Ambientes periglaciares: avances en su estudio, valoración patrimonial y riesgos asociados*. Servicio de Publicaciones de la Universidad de Oviedo, pp. 105–112.
- Andrés, N., Gómez-Ortiz, A., Fernández-Fernández, J.M., Tanarro, L.M., Salvador-Franch, F., Oliva, M., Palacios, D., 2018. Timing of deglaciation and rock glacier origin in the southeastern Pyrenees: a review and new data. *Boreas* 47, 1050–1071.
- Benn, D.I., Hulton, N.R.J., 2010. An Excel™ spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps. *Comput. Geosci.* 36 (5), 605–610.
- Braucher, R., Guillou, V., Bourlès, D.L., Arnold, M., Aumaitre, G., Keddadouche, K., Nottoli, E., 2015. Preparation of ASTER in-house ¹⁰Be/⁹Be standard solutions. *Nucl. Instrum. Methods Phys. Res., Sect. B* 361, 335–340.
- Bru, J., 1985. Estudi geomorfològic: el modelatge glacial d'un sector del Pirineu Central (Valls Ferrera i de Cardós). Ph D Thesis. Barcelona, Facultat de Geografia i Història, Universitat. 487.
- Carrasco, R.M., Pedraza, J., Domínguez-Villar, D., Willenbring, J.K., Villa, J., 2015. Sequence and chronology of the Cuerpo de Hombre paleoglaciar (Iberian Central System) during the last glacial cycle. *Quat. Sci. Rev.* 129, 163–177.
- Carrasco, R.M., Pedraza, J., Palacios, D., 2021. The glaciers of the Sierra de Gredos. In: Oliva, M., Palacios, D., Fernández-Fernández, J.M. (Eds.), *Iberia, Land of Glaciers*. Elsevier, Amsterdam, pp. 457–483.
- Chmieleff, J., von Blanckenburg, F., Kossert, K., Jakob, D., 2010. Determination of the ¹⁰Be half-life by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B Beam Interactions with Materials and Atoms* 268, 192–199.
- Çiner, A., Sarikaya, M.A., 2017. Cosmogenic ³⁶Cl geochronology of late Quaternary glaciers in the Bolkar Mountains, south Central Turkey. *Geol. Soc. Lond. Spec. Publ.* 433, 271–287.
- Çiner, A., Oliva, M., Ventura, J., Sarikaya, M.A., Candaş, A., Palacios, D., Altınay, O., Binnie, S.A., Castañeda, N., 2024. Last Glacial Maximum and Younger Dryas moraines at unexpected and contrasting altitudes: the Cadí Massif, SE Pyrenees, Spain. *Quat. Sci. Rev.* 345, 1–20.
- Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., et al., 2009. The Last Glacial Maximum. *Science* (New York, N.Y.), vol. 325, pp. 710–714.
- Clark, P.U., Shakun, J.D., Baker, P.A., Bartlein, P.J., Brewer, S., Brook, E., Carlson, A.E., Cheng, H., Kaufman, D.S., Liu, Z., Marchitto, T.M., Mix, A.C., Morrill, C., Otto-Bliesner, B.L., Pahnke, K., Russell, J.M., Whitlock, C., Adkins, J.F., Blois, J.L., Clark, J., Colman, S.M., Curry, W.B., Flower, B.P., He, F., Johnson, T.C., Lynch-Stieglitz, J., Markgraf, V., McManus, J., Mitrovica, J.X., Moreno, P.I., Williams, J.W., 2012. Global climate evolution during the last deglaciation. *Proc. Natl. Acad. Sci.* 109, E1134–E1142.
- Cossart, E., Fort, M., Bourles, D., Braucher, R., Perrier, R., Siame, L., 2012. Deglaciation pattern during the Lateglacial/Holocene transition in the southern French Alps. Chronological data and geographical reconstruction from the Clarée Valley (upper Durance catchment, southeastern France). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 315–316, 109–123.
- Crest, Y., Delmas, M., Braucher, R., Gunnell, Y., Calvet, M., 2017. Cirques have growth spurts during deglacial and interglacial periods: evidence from ¹⁰Be and ²⁶Al nuclide inventories in the central and eastern Pyrenees. *Geomorphology* 278, 60–77.
- Delmas, M., 2009. Chronology et impact géomorphologique des glaciations quaternaires dans l'est des Pyrénées. Ph D Thesis. University of Paris, p. 530.
- Delmas, M., 2015. La última máxima extensión del hielo y posterior deglaciación de los Pirineos: revisión de la investigación reciente. *Cuadernos de Investigación Geográfica* 41, 359–387.
- Delmas, M., Gunnell, Y., Braucher, R., Calvet, M., Bourlès, D.L., 2008. Exposure age chronology of the last glaciation in the eastern Pyrenees. *Quat. Res.* 69, 231–241.
- Delmas, M., Calvet, M., Gunnell, Y., Braucher, R., Bourlès, D., 2011. Paleogeography and ¹⁰Be exposure-age chronology of Middle and late Pleistocene glacier systems in the northern Pyrenees: implications for reconstructing regional paleoclimates. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 305, 109–122.
- Delmas, M., Gunnell, Y., Calvet, M., Reixach, T., Oliva, M., 2023a. The Pyrenees: Environments and landforms in the aftermath of the LGM (18.9–14.6 ka). In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, pp. 185–200.
- Delmas, M., Oliva, M., Gunnell, Y., Fernandes, M., Reixach, T., Fernández-Fernández, J.M., Calvet, M., 2023b. The Pyrenees: Glacial landforms from the Bølling-Allerød Interstadial (14.6–12.9 ka). In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, pp. 361–368.
- Delmas, M., Oliva, M., Gunnell, Y., Reixach, T., Fernandes, M., Fernández-Fernández, J.M., Calvet, M., 2023c. The Pyrenees: Glacial landforms from the Younger Dryas (12.9–11.7 ka). In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, pp. 541–552.
- Dlabáková, T., Engel, Z., Uxa, T., Braucher, R., ASTER Team, 2023. ¹⁰Be exposure ages and paleoenvironmental significance of rock glaciers in the Western Tatra Mts. Western Carpathians. *Quaternary Science Reviews* 312, 108–147.
- Dunai, T.J., 2010. *Cosmogenic Nuclides: Principles, Concepts and Application in the Earth Surface Sciences*. Cambridge University Press, Cambridge, p. 198.
- Dunne, J., Elmore, D., Muzikar, P., 1999. Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth on sloped surfaces. *Geomorphology* 27, 3–11.
- Federici, P.R., Ribolini, A., Spagnolo, M., 2016. Glacial history of the Maritime Alps from the last Glacial Maximum to the Little Ice Age. In: Hughes, P.D., Woodward, J.C. (Eds.), *Quaternary Glaciation in the Mediterranean Mountains*, Geological Society, London, Special Publications, vol. 433, pp. 137–159.
- Fernandes, M., 2023. Deglaciation Chronology and Post-Glacial Environmental Evolution of the Upper Garonne Valley (Central Pyrenees). Ph D Thesis. University of Lisboa, p. 234.
- Fernandes, M., Oliva, M., Palma, P., Ruiz-Fernández, J., Lopes, L., 2017. Glacial stages and post-glacial environmental evolution in the Upper Garonne valley, Central Pyrenees. *Sci. Total Environ.* 584–585, 1282–1299.
- Fernandes, M., Oliva, M., Vieira, G., Palacios, D., Fernández-Fernández, J.M., García-Oteyza, J., Schimmelpfennig, I., ASTER Team, Antoniadis, D., 2021. Glacial oscillations during the Bølling–Allerød Interstadial–Younger Dryas transition in the Ruda Valley, Central Pyrenees. *J. Quat. Sci.* 37, 42–58.
- Fernandes, M., Oliva, M., Fernández-Fernández, J.M., Vieira, G., Palacios, D., García-Oteyza, J., Ventura, J., Schimmelpfennig, I., ASTER-Team, 2023. Geomorphological record of the glacial to periglacial transition from the Bølling–Allerød to the Holocene in the Central Pyrenees: the Locampo cirque in the regional context. *Boreas* 53 (1), 71–87.
- Fernández-Fernández, J.M., Palacios, D., García-Ruiz, J.M., Andrés, N., Schimmelpfennig, I., Gómez-Villar, A., Santos-González, J., Álvarez-Martínez, J., Arnáez, J., Úbeda, J., Léanni, L., ASTER Team, 2017. Chronological and geomorphological investigation of fossil debris-covered glaciers in relation to deglaciation processes: a case study in the Sierra de la Demanda, northern Spain. *Quat. Sci. Rev.* 170, 232–249.
- García Ruiz, J.M., Palacios, D., González-Sampériz, P., de Andrés, N., Moreno, A., Valero-Garcés, B., Gómez-Villar, A., 2016. Mountain glacier evolution in the Iberian Peninsula during the Younger Dryas. *Quat. Sci. Rev.* 138, 16–30.
- García Sainz, L., 1935. Morfología glacial y preglacial de la región de la Noguera. *Boletín la Sociedad Geográfica Nacional* 75, 64–130.
- García-Ruiz, J.M., 2021. The glaciers of the Iberian Range. In: Oliva, M., Palacios, D., Fernández-Fernández, J.M. (Eds.), *Iberia, Land of Glaciers*. Elsevier, Amsterdam, pp. 437–455.
- García-Ruiz, J.M., Palacios, D., de Andrés, N., Valero-Garcés, B.L., López-Moreno, J.I., Sanjuán, Y., 2014. Holocene and little ice age glacial activity in the Marboré cirque, Monte Perdido massif, Central Spanish Pyrenees. *Holocene* 24, 1439–1452.
- García-Ruiz, J.M., Palacios, D., Fernández-Fernández, J.M., Andrés, N., Arnáez, J., Gómez-Villar, A., Santos-González, J., Álvarez-Martínez, J., Lana-Renault, N., Léanni, L., 2020a. Glacial stages in the Peña Negra valley, Iberian Range, northern Iberian Peninsula: assessing the importance of the glacial record in small cirques in a marginal mountain area. *Geomorphology* 362, 107–195.
- García-Ruiz, J.M., Palacios, D., Andrés, N., López-Moreno, J.I., 2020b. Neoglaciation in the Spanish Pyrenees: a multiproxy challenge. *Mediterranean Geoscience Reviews* 2, 21–36.
- Gellatly, A.F., Grove, J.M., Switsur, V.R., 1992. Mid-Holocene glacial activity in the Pyrenees. *The Holocene* 2 (3), 266–270.
- Ghinoi, A., Soldati, M., 2017. Reappraisal of Lateglacial stadials in the eastern Alps: the case study of Valparola (eastern Dolomites, Italy). *Alpine and Mediterranean Quaternary* 30 (1), 51–67.
- Gómez-Ortiz, A., Palacios, D., Palade, B., Vázquez-Selem, L., Salvador-Franch, F., 2012. The deglaciation of the sierra Nevada (southern Spain). *Geomorphology* 159–160, 93–105.
- Gómez-Ortiz, A., Oliva, M., Palacios, D., Salvador, F., 2021. The glaciers of the Sierra Nevada. In: Oliva, M., Palacios, D., Fernández-Fernández, J.M. (Eds.), *Iberia, Land of Glaciers*. Elsevier, Amsterdam, pp. 505–524.
- Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. *Quat. Sci. Rev.* 20, 1475–1560.
- Heyman, J., Stroeven, A.P., Harbor, J.M., Caffee, M.W., 2011. Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. *Earth Planet. Sci. Lett.* 302, 71–80.
- Hughes, P.D., 2022. Concept and global context of the glacial landforms from the last Glacial Maximum. In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: Maximum Extent of Glaciations*. Elsevier, Amsterdam, pp. 355–358.
- Institut Cartogràfic i Geològic de Catalunya, ICGC, 2007. Mapa Geològic Comarcal de Catalunya, 1:50.000. Pallars Sobirà. Barcelona.
- Instituto Geológico y Minero de España, IGME, 2013. Mapa Geológico de España 1: 50.000 (incluye mapa geomorfológico), Hoja 149 (Isl). Madrid.
- Ivy-Ochs, S., 2015. Glacier variations in the European Alps at the end of the last Glaciation. *Cuadernos de Investigación Geográfica* 41 (2), 295–315.
- Ivy-Ochs, S., Monegato, G., Reitner, J.M., 2023a. The Alps: Glacial landforms during the deglaciation (18.9–14.6 ka). In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 175–183.

- Ivy-Ochs, S., Monegato, G., Reitner, J., 2023b. The Alps: Glacial landforms from the Younger Dryas Stadial. In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 525–539.
- Jomelli, V., Chapron, E., Favier, V., Rinterknecht, V., Braucher, R., Tournier, N., Gascoïn, S., Marti, R., Galop, D., Binet, S., Deschamps, C., Tissoux, H., Aumaitre, G., Bourlès, D.L., Keddadouche, K., 2020. Glacier fluctuations during the late glacial and Holocene on the Ariège valley, northern slope of the Pyrenees and reconstructed climatic conditions. *Mediterranean Geoscience Reviews* 2, 37–51.
- Kleinsmiede, W.F.J., 1960. Geology of the Valle de Aran (Central Pyrenees). *Leidse. Geol. Meded.* 25, 129–245.
- Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G., von Gostomski, C.L., Kossert, K., Maiti, M., Poutivtsev, M., Remmert, A., 2010. A new value for the half-life of ^{10}Be by heavy-ion elastic recoil detection and liquid scintillation counting. *Nucl. Instrum. Methods Phys. Res., Sect. B* 268, 187–191.
- Lambiel, C., Maillard, B., Martin, S., Pellitero Ondicol, R., Schoeneich, P., Reynard, E., 2013. Adaptation of the geomorphological mapping system of the University of Lausanne for ArcGIS. 8th International Conference on Geomorphology (IAG), Paris 27–31. Aug. 2013.
- Lambiel, C., Maillard, B., Kummert, M., Reynard, E., 2016. Geomorphology of the Hérens valley (Swiss Alps). *J. Maps* 12 (1), 160–172.
- László, P., Kern, Z., Nagy, B., 2013. Late Pleistocene glaciers in the western Rodna Mountains, Romania. *Quat. Int.* 293, 79–91.
- Li, Y., 2018. Determining topographic shielding from digital elevation models for cosmogenic nuclide analysis: a GIS model for discrete sample sites. *J. Mt. Sci.* 15, 939–947.
- Li, Y., 2023. Paleolce: an automated method to reconstruct paleoglaciers using geomorphic evidence and digital elevation models. *Geomorphology* 421, 108523.
- Lifton, N.A., Sato, T., Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes. *Earth Planet. Sci. Lett.* 386, 149–160.
- López-Moreno, J.I., Alonso-González, E., Monserrat, O., et al., 2018. Ground-based remote-sensing techniques for diagnosis of the current state and recent evolution of the Monte Perdido Glacier, Spanish Pyrenees. *J. Glaciol.* 65, 85–100.
- Losantos, M., Palau, J., Sanz, J., 1986. Considerations about hercynian thrusting in the Marimanya Massif (Central Pyrenees). *Tectonophysics* 129, 71–79.
- Martin, L.C.P., Blard, P.H., Balco, G., Lavé, J., Delunel, R., Lifton, N.A., Laurent, V., 2017. The CREP program and the ICE-D production rate calibration database: a fully parameterizable and updated online tool to compute cosmic-ray exposure ages. *Quat. Geochronol.* 38, 25–49.
- Merchel, S., Herpers, U., 1999. An update on radiochemical separation techniques for the determination of long-lived radio-nuclides via accelerator mass spectrometry. *Radiochim. Acta* 84, 215–219.
- Merchel, S., Arnold, M., Aumaitre, G., et al., 2008. Towards more precise ^{10}Be and ^{36}Cl data from measurements at the 10–14 level: Influence of sample preparation. *Nucl. Instrum. Methods Phys. Res., Sect. B* 266, 4921–4926.
- Moreno, A., López-Merino, L., Leira, M., Marco-Barba, J., González-Sampériz, P., Valero-Garcés, B.L., López-Sáez, J.A., Santos, L., Mata, P., Ito, E., 2011. Revealing the last 13,500 years of environmental history from the multiproxy record of a mountain lake (Lago Enol, northern Iberian Peninsula). *J. Paleolimnol.* 46 (3), 327–349.
- Moreno, A., Svensson, A., Brooks, S.J., Connor, S., Engels, S., Fletcher, W., et al., 2014. A compilation of Western European terrestrial records 60–8 ka BP: towards an understanding of latitudinal climatic gradients. *Quat. Sci. Rev.* 106, 167–185.
- Muñoz, J.A., 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: Mcclay, K.R. (Ed.), *Thrust Tectonics*. Springer-Science, London, pp. 235–246.
- Naughton, F., Sánchez-Goni, M.F., Landais, A., Rodrigues, T., Vazquez Riveiros, N., Toucanne, S., 2023a. Introduction to the last Deglaciation climate. In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 33–36.
- Naughton, F., Toucanne, S., Landais, A., Rodrigues, T., Vazquez Riveiros, N., Sánchez-Goni, M.F., 2023b. Heinrich Stadial 1. In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 37–44.
- Nussbaum, F., 1956. Observations morphologiques dans la région de la Noguera Pallaresa. *Pirineos* 39, 57–95.
- Oliva, M., Palacios, D., Fernández-Fernández, J.M., Rodríguez-Rodríguez, L., García-Ruiz, J.M., Andrés, N., Carrasco, R.M., Pedraza, J., Pérez-Alberti, A., Valcárcel, M., Hughes, P.D., 2019. Late Quaternary glacial phases in the Iberian Peninsula. *Earth Sci. Rev.* 192, 564–600.
- Oliva, M., Fernandes, M., Palacios, D., Fernández-Fernández, J.M., Schimmelpenninck, I., ASTER Team, Antoniadis, D., 2021. Rapid deglaciation during the Bølling-Allerød interstadial in the Central Pyrenees and associated glacial and periglacial landforms. *Geomorphology* 385, 107735.
- Oliva, M., Palacios, D., Fernández-Fernández, J.M. (Eds.), 2022. *Iberia, Land of Glaciers: How the Mountains Were Shaped by Glaciers*. Elsevier, Amsterdam, p. 618.
- Oliva, M., Andrés, N., Fernández-Fernández, J.M., Palacios, D., 2023. The evolution of glacial landforms in the Iberian Mountains during the Younger Dryas Stadial. In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 553–562.
- Ortuño, M., Vilaplana-Muñoz, M., 2018. Active fault control in the distribution of Elevated Low Relief Topography in the Central-Western Pyrenees. *Geol. Acta* 16 (4), 499–518.
- Palacios, D., de Andrés, N., López-Moreno, J.I., García-Ruiz, J.M., 2015a. Late Pleistocene deglaciation in the upper Gállego Valley, Central Pyrenees. *Quat. Res.* 83 (3), 397–414.
- Palacios, D., Gómez-Ortiz, A., Andrés, N., Vázquez-Selem, L., Salvador-Franch, F., Oliva, M., 2015b. Maximum extent of late Pleistocene glaciers and last deglaciation of La Cerdanya mountains, southeastern Pyrenees. *Geomorphology* 231, 116–129.
- Palacios, D., Gómez-Ortiz, A., Andrés, N., Salvador-Franch, F., Oliva, M., 2016. Timing and new geomorphologic evidence of the last deglaciation stages in Sierra Nevada (southern Spain). *Quat. Sci. Rev.* 150, 110–129.
- Palacios, D., García-Ruiz, J.M., de Andrés, N., Schimmelpenninck, I., Campos, N., Léanni, L., ASTER Team, 2017. Deglaciation in the Central Pyrenees during the Pleistocene-Holocene transition: timing and geomorphological significance. *Quat. Sci. Rev.* 162, 111–127.
- Palau, J., 1997. El plutó de Marimanya i el seu encaixant. Ph D Thesis. Universitat de Barcelona, p. 436.
- Pallàs, R., Rodés, A., Braucher, R., Carcaillet, J., Ortuño, M., Bordonau, J., Bourlès, D., Vilaplana, J.M., Masana, E., Santanach, P., 2006. Late Pleistocene and Holocene glaciation in the Pyrenees: a critical review and new evidence from ^{10}Be exposure ages, South-Central Pyrenees. *Quat. Sci. Rev.* 25, 2937–2963.
- Pallàs, R., Rodés, A., Braucher, R., Bourlès, D., Delmas, M., Calvet, M., Gunnell, Y., 2010. Small, isolated glacial catchments as priority targets for cosmogenic surface exposure dating of Pleistocene climate fluctuations, southeastern Pyrenees. *Geology* 38, 891–894.
- Parera-Portell, J.A., 2016. Les glaceres rocalloses del Massís de Marimanya (Pirineu Central). Universitat de Barcelona, TFG, p. 46.
- Pellitero, R., 2021. The glaciers of the Montaña Palentina. In: Oliva, M., Palacios, D., Fernández-Fernández, J.M. (Eds.), *Iberia, Land of Glaciers*. Elsevier, Amsterdam, pp. 179–199.
- Porter, S.C., 1975. Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps. *New Zealand. Quaternary Research* 5 (1), 27–47.
- Porter, S.C., 2000. Onset of Neoglaciation in the Southern Hemisphere. *J. Quat. Sci.* 15 (4), 395–408.
- Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W.Z., Lowe, J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallenga, P., Vinther, B.M., Walker, M., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the last glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.* 106, 14–28.
- Rea, B.R., 2009. Defining modern day Area-Altitude Balance Ratios (AABRs) and their use in glacier-climate reconstructions. *Quat. Sci. Rev.* 28 (3–4), 237–248.
- Reixach, T., 2022. Chronologie des fluctuations glaciaires dans les Pyrénées au cours du Pléistocène supérieur. Implications paléoclimatiques. Ph D thesis. Université de Perpignan (UPVD), p. 383.
- Reixach, T., Delmas, M., Calvet, M., 2021. Climatic conditions between 19 and 12 ka in the eastern Pyrenees, and wider implications for atmospheric circulation patterns in Europe. *Quat. Sci. Rev.* 260, 106923.
- René, P., 2011. Régression des glaciers pyrénéens et transformation du paysage depuis le Petit Âge Glaciaire. *Sud-Ouest Européen* 32, 5–19.
- Renssen, H., Seppä, H., Heiri, O., Roche, D.M., Goosse, H., Fichet, T., 2009. The spatial and temporal complexity of the holocene thermal maximum. *Nat. Geosci.* 2, 411–414.
- Renssen, H., Seppä, H., Crosta, X., Goosse, H., Roche, D.M., 2012. Global characterization of the Holocene thermal maximum. *Quat. Sci. Rev.* 48, 7–19.
- RGIK, 2023. Guidelines for inventorying rock glaciers: baseline and practical concepts (version 1.0). IPA Action Group Rock glaciers inventories and kinematics 25.
- Ribolini, A., Giraudo, C., 2023. The Italian Peninsula. In: Oliva, M., Nyvlt, D., Fernandez-Fernandez, J. (Eds.), *Periglacial Landscapes of Europe*. Springer, pp. 69–88.
- Ribolini, A., Spagnolo, M., Giraudo, C., 2023a. The Italian Mountains: Glacial landforms from the Younger Dryas Stadial (12.9–11.7 ka). In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 563–570.
- Ribolini, A., Matteo Spagnolo, N., Giraudo, C., 2023b. The Italian Mountains: Glacial landforms during deglaciation (18.9–14.6 ka). In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 209–220.
- Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J., Rinterknecht, V., Pallàs, R., 2017. Timing of last deglaciation in the Cantabrian Mountains (Iberian Peninsula; North Atlantic Region) based on in situ-produced ^{10}Be exposure dating. *Quat. Sci. Rev.* 171, 166–181.
- Ruiz-Fernández, J., García-Hernández, C., Gallinar-Cañedo, D., 2021. The glaciers of the Picos de Europa. In: Oliva, M., Palacios, D., Fernández-Fernández, J.M. (Eds.), *Iberia, Land of Glaciers*. Elsevier, Amsterdam, pp. 237–263.
- Scotti, R., Brardinoni, F., Crosta, G.B., Cola, G., Mair, V., 2017. Time constraints for post-LGM landscape response to deglaciation in Val Viola, Central Italian Alps. *Quat. Sci. Rev.* 177, 10–33.
- Serrano, E., Agudo, C., 1988. La deglaciation del Valle de los Ibones Azules. Estudio glaciomorfológico. *Cuaternario y Geomorfología* 2 (1–4), 115–123.
- Serrano, E., Agudo, C., 2004. Glaciares rocosos y deglaciation en la alta montaña de los Pirineos aragoneses (España). *Boletín Real Sociedad Española Historia Natural (Sección Geología)* 99 (1–4), 159–172.
- Serrano, E., González Trueba, J.J., San José, J.J., 2011. Dinámica, evolución y estructura de los glaciares rocosos de los Pirineos. *Cuadernos de Investigación Geográfica* 37, 145–170.

- Serrano, E., González-Trueba, J.J., González-García, M., 2012. Mountain glaciation and paleoclimate reconstruction in the Picos de Europa (Iberian Peninsula, SW Europe). *Quat. Res.* 78 (2), 303–314.
- Serrat, D., Bordonau, J., Bru, J., Furdada, G., Gomez, A., Marti, J., Martí, M., Salvador, F., Ventura, J., Vilaplana, J.M., 1994. Síntesis cartográfica del glaciario surpirenaico oriental. In: Bono, C.M., García-Ruiz, J.M. (Eds.), *El Glaciario Surpirenaico: Nuevas Aportaciones*. Geoforma, Logroño, pp. 9–15.
- Steinemann, O., Reitner, J.M., Ivy-Ochs, S., Christl, M., Synal, H.A., 2020. Tracking rock-glacier evolution in the Eastern Alps from the Lateglacial to the early Holocene. *Quat. Sci. Rev.* 241, 106424.
- Styllas, M.N., Schimmelpennig, I., Benedetti, L., Ghilardi, M., Aumaitre, G., Bourle's, D., et al., 2018. Late-glacial and Holocene history of the Northeast Mediterranean mountain glaciers. New insights from in situ-produced ^{36}Cl -based cosmic ray exposure dating of paleo-glacier deposits on Mount Olympus, Greece. *Quaternary Science Reviews* 193, 244–265.
- Tomkins, M.D., Dortch, J.M., Hughes, P., et al., 2018. Rapid age assessment of glacial landforms in the Pyrenees using Schmidt hammer exposure dating (SHED). *Quat. Res.* 90, 26–37.
- Turu, V., Peña-Monné, J.L., Cunha, P.P., Jalut, G., Buylaert, J.P., Murray, A.S., Bridgland, D., Faurschou-Knudsen, M., Oliva, M., Carrasco, R., Ros, X., Turu-Font, L., Ventura, J., 2023. Glacial–interglacial cycles in the south-central and southeastern Pyrenees since ~180 ka (NE Spain–Andorra–S France). *Quat. Res.* 2023 (113), 1–28.
- Uppala, S.M., et al., 2005. The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.* 131, 2961–3012.
- Urdea, P., Ardelean, F., Ardelean, M., Onaca, A., 2023. The Romanian Carpathians: Glacial landforms during deglaciation (18.9–14.6 ka) (chapter 19). In: Palacios, D., Hughes, P., García-Ruiz, J.M., Andrés, A. (Eds.), *European Glacial Landscapes: The Last Deglaciation*. Elsevier, Amsterdam, pp. 165–173.
- Ventura, J., Turu, V., 2022. The glaciers of the Central-Eastern Pyrenees. In: Oliva, M., Palacios, D., Fernández-Fernández, J.M. (Eds.), *Iberia, Land of Glaciers*. Elsevier, Amsterdam, pp. 87–121.
- Vidaller, I., 2025. Past, Present and Future of the Ésera Glacier. *Paleoenvironmental Evolution and Recent Deglaciation*. Ph D Thesis. University of Zaragoza, p. 397.
- Vizcaino, A., Pélachs, A., 2019. L'evolució glacial a la Coma de Burg (Pallars Sobirà). *Ripacurtia* 2 (1), 177–210.
- Vizcaino, A., Pélachs, A., Turu, V., Soriano, J.M., 2011. Geomorfologia glacial de la Coma de Burg (Vall Ferrera, Pallars Sobirà). In: Turu, V., Constante, A. (Eds.), *Simposio de Glaciario. El Cuaternario En España y Áreas Afines*, pp. 45–48.
- Ward, G.K., Wilson, S.R., 1978. Procedures for comparing and combining radiocarbon age determination: a critique. *Archaeometry* 20, 19–31.
- Wirsig, C., Zasadni, J., Ivy-Ochs, S., Christl, M., Kober, F., Schlüchter, C., 2016. A deglaciation model of the Oberhasli, Switzerland. *J. Quat. Sci.* 31, 46–59.
- Zandvliet, J., 1960. The geology of the upper Salat and Pallaresa valleys, Central Pyrenees, France/Spain. *Leidse. Geol. Meded.* 25, 1–127.
- Zasadni, J., Klapýta, P., Brós, E., Ivy-Ochs, S., Swiader, A., Christl, M., Balázovicová, L., 2020. Latest Pleistocene glacier advances and post-Younger Dryas rock glacier stabilization in the Mt. Kriván group, High Tatra Mountains, Slovakia. *Geomorphology* 358, 107093.