Manuscript Details

Manuscript number	EARTH_2018_636
Title	Late Quaternary glacial phases in the Iberian Peninsula
Article type	Review Article

Abstract

The only glaciers existing now in the Iberian Peninsula are small features located in the Pyrenees, though their number and extension has undergone significant changes over the Late Quaternary. The wide range of glacial landforms and deposits distributed across different Iberian ranges suggests the occurrence of several past stages with larger glacial systems. The objective of this research is to summarize the current knowledge on the spatial and temporal patterns of glacial activity in the Iberian mountains during the Late Quaternary. To this purpose, the chronological framework was divided in six periods: glaciations prior to the Last Glacial Cycle (Middle Pleistocene), Last Glacial Cycle (Late Pleistocene), Termination-1, Holocene, Little Ice Age (LIA) and present-day. The data were geographically divided considering the mountain systems where glacial evidence exists: Pyrenees, Cantabrian Range, NW ranges, Central Range, Iberian Range and Sierra Nevada. During cold Quaternary stages, ice accumulated in the head valleys of these mountain ranges and glaciers flowed down-valleys. In all cases, glaciers remained confined within the mountain systems and did not reach the surrounding lowlands. Depending on the combination of temperatures and moisture conditions, more or less ice was stored. In some ranges, there is evidence of Middle Pleistocene glaciations, one potentially correlating with marine isotope stage (MIS) 12 and another correlating with MIS 6 with glaciation dated to ca. 130-170 ka. However, most of the glacial records correspond to the Last Glacial Cycle and subsequent Termination. The maximum glacial expansion of this last Pleistocene glaciation stage occurred well before the global Last Glacial Maximum (LGM) between 30 and 60 ka in the Cantabrian Mountains and Pyrenees, at ca. 30 ka in Sierra Nevada and NW ranges, and (almost) synchronously to the LGM in the Central Range and Iberian Range. A massive glacial retreat occurred in all ranges at 19-20 ka, but the long-term deglaciation process was interrupted by cold stages, such as the Oldest and Younger Dryas, which favoured glacial expansion in the highest mountains. Temperature increase recorded during the Holocene conditioned the melting of glaciers, which only reappeared in the highest massifs during the coldest stages, such as the LIA. However, post-LIA warming led to glacier disappearance in the Cantabrian Mountains, Sierra Nevada and most massifs of the Pyrenees, together with an accelerated shrinking of the small glaciers still existing in this range at elevations near 3000 m.

Keywords	Iberian Peninsula, glaciation, Last Glacial Maximum, Termination-1, Holocene, Little Ice Age.

Corresponding Author	Marc Oliva
Corresponding Author's Institution	Department of Geography, University of Barcelona, Spain
Order of Authors	Marc Oliva, palacios david, José M. Fernández-Fernández, Laura Rodríguez-Rodríguez, Jose-Maria Garcia Ruiz, Nuria Andrés, Rosa M. Carrasco, Javier Pedraza, Augusto Perez Alberti, Marcos Valcarcel, Philip. Hughes
Suggested reviewers	Jesus Ruiz-Fernández, Susan Ivy-Ochs, Jamie Woodward, Mauro Guglielmin

Submission Files Included in this PDF

File Name [File Type]

Cover letter.pdf [Cover Letter]

Abstract.docx [Abstract]

Manuscript.docx [Manuscript File]

Figure 1.tif [Figure]

Figure 2.tif [Figure]

Figure 3.tif [Figure]

Figure 4.tif [Figure]

Figure 5.tif [Figure]

Figure 6.tif [Figure]

Figure 7.tif [Figure]

Figure 8.jpg [Figure]

Figure 9.tif [Figure]

Figure 10.tif [Figure]

Figure 11.tif [Figure]

Figure 12.tif [Figure]

Figure 13.tif [Figure]

Figure 14.tif [Figure]

Tables.docx [Table]

Submission Files Not Included in this PDF

File Name [File Type]

Supplementary material.kmz [Interactive Map Data (.kml, .kmz)]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

This manuscript contains content innovation file(s).
General instructions for reviewing content innovation files can be found here.

Abstract

The only glaciers existing now in the Iberian Peninsula are small features located in the Pyrenees, though their number and extension has undergone significant changes over the Late Quaternary. The wide range of glacial landforms and deposits distributed across different Iberian ranges suggests the occurrence of several past stages with larger glacial systems. The objective of this research is to summarize the current knowledge on the spatial and temporal patterns of glacial activity in the Iberian mountains during the Late Quaternary. To this purpose, the chronological framework was divided in six periods: glaciations prior to the Last Glacial Cycle (Middle Pleistocene), Last Glacial Cycle (Late Pleistocene), Termination-1, Holocene, Little Ice Age (LIA) and present-day. The data were geographically divided considering the mountain systems where glacial evidence exists: Pyrenees, Cantabrian Range, NW ranges, Central Range, Iberian Range and Sierra Nevada. During cold Quaternary stages, ice accumulated in the head valleys of these mountain ranges and glaciers flowed down-valleys. In all cases, glaciers remained confined within the mountain systems and did not reach the surrounding lowlands. Depending on the combination of temperatures and moisture conditions, more or less ice was stored. In some ranges, there is evidence of Middle Pleistocene glaciations, one potentially correlating with marine isotope stage (MIS) 12 and another correlating with MIS 6 with glaciation dated to ca. 130-170 ka. However, most of the glacial records correspond to the Last Glacial Cycle and subsequent Termination. The maximum glacial expansion of this last Pleistocene glaciation stage occurred well before the global Last Glacial Maximum (LGM) between 30 and 60 ka in the Cantabrian Mountains and Pyrenees, at ca. 30 ka in Sierra Nevada and NW ranges, and (almost) synchronously to the LGM in the Central Range and Iberian Range. A massive glacial retreat occurred in all ranges at 19-20 ka, but the long-term deglaciation process was interrupted by cold stages, such as the Oldest and Younger Dryas, which favoured glacial expansion in the highest mountains. Temperature increase recorded during the Holocene conditioned the melting of glaciers, which only reappeared in the highest massifs during the coldest stages, such as the LIA. However, post-LIA warming led to glacier disappearance in the Cantabrian Mountains, Sierra Nevada and most massifs of the Pyrenees, together with an accelerated shrinking of the small glaciers still existing in this range at elevations near 3000 m.

Key words: Iberian Peninsula, glaciation, Last Glacial Maximum, Termination-1, Holocene, Little Ice Age.

Abstract

The only glaciers existing now in the Iberian Peninsula are small features located in the Pyrenees, though their number and extension has undergone significant changes over the Late Quaternary. The wide range of glacial landforms and deposits distributed across different Iberian ranges suggests the occurrence of several past stages with larger glacial systems. The objective of this research is to summarize the current knowledge on the spatial and temporal patterns of glacial activity in the Iberian mountains during the Late Quaternary. To this purpose, the chronological framework was divided in six periods: glaciations prior to the Last Glacial Cycle (Middle Pleistocene), Last Glacial Cycle (Late Pleistocene), Termination-1, Holocene, Little Ice Age (LIA) and present-day. The data were geographically divided considering the mountain systems where glacial evidence exists: Pyrenees, Cantabrian Range, NW ranges, Central Range, Iberian Range and Sierra Nevada. During cold Quaternary stages, ice accumulated in the head valleys of these mountain ranges and glaciers flowed down-valleys. In all cases, glaciers remained confined within the mountain systems and did not reach the surrounding lowlands. Depending on the combination of temperatures and moisture conditions, more or less ice was stored. In some ranges, there is evidence of Middle Pleistocene glaciations, one potentially correlating with marine isotope stage (MIS) 12 and another correlating with MIS 6 with glaciation dated to ca. 130-170 ka. However, most of the glacial records correspond to the Last Glacial Cycle and subsequent Termination. The maximum glacial expansion of this last Pleistocene glaciation stage occurred well before the global Last Glacial Maximum (LGM) between 30 and 60 ka in the Cantabrian Mountains and Pyrenees, at ca. 30 ka in Sierra Nevada and NW ranges, and (almost) synchronously to the LGM in the Central Range and Iberian Range. A massive glacial retreat occurred in all ranges at 19-20 ka, but the long-term deglaciation process was interrupted by cold stages, such as the Oldest and Younger Dryas, which favoured glacial expansion in the highest mountains. Temperature increase recorded during the Holocene conditioned the melting of glaciers, which only reappeared in the highest massifs during the coldest stages, such as the LIA. However, post-LIA warming led to glacier disappearance in the Cantabrian Mountains, Sierra Nevada and most massifs of the Pyrenees, together with an accelerated shrinking of the small glaciers still existing in this range at elevations near 3000 m.

Key words: Iberian Peninsula, glaciation, Last Glacial Maximum, Termination-1, Holocene, Little Ice Age.

1- Introduction

The landscape of the highest Iberian mountain ranges has been intensely shaped by both Quaternary glaciations and postglacial periglacial processes prevailing during interglacial periods (Oliva et al., 2016). Until the mid-19th century, the biblical Great Flood theory was widely accepted to explain the existence of glacial deposits and landforms in mountain areas around the world (Ehlers et al., 2016). The first notes including a scientific perspective were carried out in the Alps by Agassiz (1840), who described the impact on Alpine landscapes of large glaciers flowing down-valleys during ancient ice ages. Taking into account these observations, early scientists from Central Europe (biologists, geologists, geographers, etc.) – who had previously conducted research in the Alps – exported their knowledge to southern European ranges, such as Iberian mountains (i.e. Boissier, 1839), describing similar geomorphological features and processes to those observed in their home countries (Gómez-Ortiz et al., 2018). The visits of Albrecht Penck – a geomorphologist with a long previous field experience on the study of glacial features in the Alps –, to various Iberian ranges allowed the identification of the size and distribution of past glaciers, for the very first time, as well as the existence of geomorphic features of several glacial cycles (see, for example, Penck, 1883). In a parallel way, the Quaternary scientist Hugo Obermaier (1877-1946) promoted the study of Iberian glaciations from the beginning of the 20th century.

In the Iberian Peninsula, early reports on the role of glaciers shaping the high lands focused on the still glaciated massifs at the end of the Little Ice Age (LIA), namely the Pyrenees (see González-Trueba et al., 2008), Cantabrian Mountains (see González-Trueba, 2006, 2007) and Sierra Nevada (see Gómez-Ortiz et al., 2006, 2009). The first texts were accompanied by geographical sketches, paintings and photographs of those glaciers (e.g. Bide, 1893; Schrader, 1895; Briet, 1902), together with accurate descriptions of their topographical characteristics, elevations and dimensions. Although some researchers described cold-climate geomorphological features in the main massifs over the first half of the 20th century (Panzer, 1926; García-Sainz, 1935; Dresch, 1937; Nussbaum, 1956), the turning point for glacial and periglacial research in the Iberian Peninsula was the organization of the International Union for Quaternary Research (INQUA) meeting in Barcelona-Madrid in 1957 (Gómez-Ortiz and Palacios, 1995; Gómez-Ortiz and Vieira, 2006). This conference was a major boost for research on past and present glacial and periglacial processes, favouring networking and promoting internationalization, which resulted in the publication of key studies over the next decades (Barrère, 1963; Messerli, 1967; Serrat, 1977; García-Ruiz, 1979; Pérez-Alberti, 1979; Gómez-Ortiz, 1980; Vilaplana, 1983; Bru, 1985; Ortigosa, 1986). Most of these works included new advances on the monitoring of geomorphic processes, sedimentological analysis of glacial and periglacial deposits as well as new observations in unexplored areas that opened new perspectives on the impact of Quaternary climate variability on Iberian mountain landscapes. For some ranges, some authors even proposed the existence several glacial stages based on the existence of landforms and processes left by past glaciers, such as in the Pyrenees where three glacial cycles were described (Penck, 1883).

The relative chronological reconstruction of glacial stages proposed in some of these studies was progressively complemented with the implementation of absolute dating techniques – namely radiocarbon dating – that allowed placing in time environmental events, and therefore providing ages for past glacial activity. The first works including radiocarbon ages were based on organic remnants trapped within glacial sediments that provided evidence on glacial advances occurred during the Last Glacial Cycle (Late Pleistocene) until ca. 40 ka cal BP. This technique was subsequently complemented with the use of Optically Stimulated Luminescence (OSL) dating on fluvio-glacial sediments in the late 1990s and early 2000s, which allowed expanding the chronology until ca. 80-90 ka BP (García-Ruiz et al., 2010). However, the use of these two dating methods generated a deep discussion on the chronology of the local Maximum Ice Extent (MIE) of the Last Glacial Cycle in the Iberian mountains (Pérez-Alberti et al., 2004; Hughes et al., 2006a; Hughes and Woodward, 2008; García-Ruiz et al., 2010), which was even more intense when the use of surface exposure dating using Cosmic-Ray Exposure (CRE) dating became widespread (Pallàs et al., 2006; García-Ruiz et al., 2010; Palacios et al., 2011, 2018). The global Last Glacial Maximum is defined as the interval 26.5-20/19 ka (Clark et al., 2009) or 27.5-23.3 ka (Hughes and Gibbard, 2015), with both these overlapping definitions falling within marine isoptope stage (MIS) 2. Whereas chronologies based on ^{14}C and OSL suggested a local MIE predating the global LGM in most ranges (García-Ruiz et al., 2003, 2012; Lewis et al., 2009; Ruiz-Fernández et al., 2016; Serrano et al., 2013, 2015, 2017), CRE dates approached the age of the MIE in the Pyrenees and Central Range mountains closer to the LGM timing (Pallàs et al., 2006; Palacios et al., 2011, 2012a,b, 2015; Domínguez-Villar et al., 2013) but confirmed a MIE older than the LGM in the NW ranges (Rodríguez-Rodríguez et al., 2011, 2014), Cantabrian Mountains (Rodríguez-Rodríguez et al., 2015, 2016) and Sierra Nevada (Gómez-Ortiz et al., 2012a, 2015; Palacios et al., 2016). Recent advances on surface exposure dating have also favoured the chronological reconstruction of older and younger glaciations in some mountain ranges (García-Ruiz et al., 2014, 2016; Palacios et al., 2017a, b, 2018), which is crucial to better understand Quaternary climate variability in southern Europe.

With this large increase in the number of studies focusing on past glaciations in the Iberian Peninsula, the objective of this work is to review the different glacial stages occurred in the Iberian mountains from a spatio-temporal perspective. We have reviewed all available dates (^{14}C, OSL, U-Th series, ^{210}Pb, and historical sources), as well as unified the criteria used from several authors in different massifs including the last advances on the production rate of CRE (namely ^{10}Be, ^{36}Cl and ^{21}Ne) with the purpose of giving answer to the following questions:

- What sort of geomorphic evidence is there from glaciations occurred prior to the Last Glacial Cycle in the Iberian Peninsula?
- What is the exact timing of the local MIE in the different Iberian mountain ranges?
- What do we know about the chronology and the impact of glacial stages following the post-LGM massive deglaciation on the current landscape of these massifs?
- Are these glacial advances and retreats synchronous to patterns occurred in other high mountain ranges from Europe and northern Africa?
- What is the main factor (temperature vs moisture) controlling the major glacial expansion and subsequent advances and retreats in the Iberian Peninsula?
- Are results from the different dating methods used until now comparable?
- What are the temporal and spatial gaps on our current understanding of Late Quaternary glacial processes in the Iberian Peninsula?

2- Study area

Extending over an area of 582,925 km², the Iberian Peninsula is located in the SW corner of Europe between latitude 43° 47′ N and 36° 01′ N and longitude 9º 30’ W and 3º 19’. Mountain ranges in the Iberian Peninsula are generally aligned W-E and distributed in the periphery, separating the relatively flat areas of the central part of the peninsula from the surrounding coastal fringes. This rough topography, together with the differing influences affecting the Iberian Peninsula, such as the maritime (Atlantic/Mediterranean), climatic (subtropical high pressure belt/mid-latitude westerlies) and biomes (Europe/Africa), result in the variety of landscapes existing across Iberia (Oliva et al., 2018).

The Iberian Peninsula includes six mountain ranges with peaks above 2000 m a.s.l.: the Pyrenees, the Cantabrian Mountains, the NW ranges, the Central Range, the Iberian Range and the Betic Range. Glacial landscape features are widespread in these mountains, though evidence of Quaternary glacial activity is also found in other mountains at lower altitudes, particularly in the NW corner (Figure 1).

Figure 1

Iberian climate is highly variable and affected by continental and maritime air masses from distinct origins. The complex terrain determines the existence of a wide range of microclimatic regimes across the Iberian Peninsula and within the individual mountain systems. Whereas precipitation is mostly concentrated between October and May brought by the mid-latitude cyclones associated to the prevailing zonal circulation, the summer is generally a dry season due to the influence of the Azores anticyclone (Trigo et al., 2004). Consequently, precipitation in the Iberian Peninsula decreases generally from N to S and from W to E, with values over 2000-2500 mm in Atlantic-influenced ranges and minima of 600-900 mm in the Sierra Nevada. Mean annual air temperatures (MAAT) follow an opposite pattern, increasing towards the S and the E. The regional 0 °C isotherm is placed at ca. 2400-2500 m in the Cantabrian Mountains (Muñoz, 1982), ca. 2950 m in the Pyrenees (Chueca et al., 2005) and at 3400 m in the Sierra Nevada (Oliva et al., 2016b).

The highest lands of these mountain ranges have been intensely shaped by glacial processes during the Quaternary, as well as by postglacial environmental dynamics, namely by periglacial, slope and alluvial processes and shallow- and deep-seated landslides (Oliva et al., 2016a). Quaternary cold stages (glacial) favoured the development of glaciers filling the valley heads and flowing down-slope. The combination of temperatures and moisture conditions controlled the elevation shifts of the Equilibrium Line Altitude (ELA), and therefore the ice volume stored in the Iberian mountains and the length of the glaciers. Apart from climate conditions prevailing in the North Atlantic region, the latitude as well as the geographical influence of sea surface water temperatures (cool Atlantic Ocean vs warm Mediterranean Sea) determined the spatial distribution of the glaciated domain in the Iberian ranges during Quaternary glacial stages, generally increasing towards the S and E (Pérez-Alberti et al., 2004). Ice-free areas located above the ELA and below the glaciated environments were affected by very active periglacial processes, with the formation of permafrost landforms and seasonal frost features that are inactive under present-day climate regime (Oliva et al., 2016a). Quaternary warm periods (interglacial) promoted the migration of the periglacial belt to higher areas, and cryonival dynamics reshaped the formerly glaciated environments. This is what is occurred in the present-day interglacial, the Holocene, and very small remnants of Quaternary glaciers currently exist only in the Pyrenees and the highest massifs are affected by periglacial activity.

3- Methodology

This paper presents a thorough review of all existing scientific literature on glacial processes in the Iberian mountains, including research papers published in international peer-reviewed journals, book chapters and conference proceedings, theses and books as well as other regional publications published in local languages.

With the purpose of better understanding the spatial and temporal patterns of glacial activity in the Iberian Peninsula, chronological and geomorphological data were compiled and divided considering the different mountain ranges: Pyrenees, Cantabrian Mountains, NW ranges, Central Range, Iberian Range and Betic Range (i.e. Sierra Nevada). In addition, for each study area, data are organized based on six main periods: glaciations prior to the Last Glacial Cycle (Middle Pleistocene), Last Glacial Cycle (Late Pleistocene), Termination-1, Holocene, LIA and present-day. In this paper these intervals are informally defined and are not intended to indicate or replace any existing formal stratigraphical basis, as the intervals sometimes represent transitions between major climatic changes.

Several definitions can be used to define the Last Glacial Cycle (Hughes and Gibbard, 2018). In this paper, the Last Glacial Cycle is defined by the marine isotopic stage boundaries and includes MIS 5d-2 starting at the end of Eemian period, at 115 ka (Dahl-Jensen et al., 2013). The onset of global climate changes leading to Termination-1 (which marks the boundary between the Late Pleistocene and the Holocene; Hughes and Gibbard, 2018) started at 19-20 ka when a widespread glacial retreat is detected across the Northern Hemisphere (Clark et al., 2009). This includes several cold and warm stages until the Holocene, namely: the Oldest Dryas (OD; 17.5-14.7 ka, stadial GS-2.1a), Bølling-Allerød (BA; 14.7-12.9 ka, interstadial GI-1) and

Younger Dryas (YD; 12.9-11.7 ka, stadial GS1). All of these intervals correspond to the classical Late-glacial in northwest Europe (Mangerud, 1974). Following Walker et al. (2012), the Holocene is subdivided in the Early (11.7-8.2 ka BP), Middle (8.2-4.2 ka) and Late Holocene (since 4.2 ka BP), which includes the LIA that in the Iberian Peninsula extends from 1300 to 1850 (Oliva et al., 2018). Finally, we also include a description on present-day geomorphological processes to better frame post-LIA environmental dynamics.

Table 1

Figure 2

The different glacial phases have been inferred using different dating methods, including 351 (^{36}Cl, ^{10}Be and ^{21}Ne) CRE dates, 68 ^{14}C, 43 OSL and 9 other (such as U-Th series, ^{210}Pb, and historical sources). Their distribution considering the diverse time periods and mountain ranges is summarized in Table 1 and Figure 2. All ^{14}C radiocarbon dates have been calibrated using the CALIB 7.1 program. Also, in this study, CRE ages have been re-calculated for those samples from which enough information is available so that a new re-assessment can be done. In the cases where required data is not available for recalculation, the original published age is indicated (Supplementary material). The ^{36}Cl CRE ages have been recalculated applying the same parameters aiming to achieve comparable results, so the following ^{36}Cl production rates have been implemented: 42.2 ± 4.8 atoms ^{36}Cl (g Ca)$^{-1}$ yr^{-1} from Ca spallation (Schimmelpfennig et al., 2011), 148.1 ± 7.8 atoms ^{36}Cl (g K)$^{-1}$ yr^{-1} from K spallation (Schimmelpfennig et al., 2014), 13 ± 3 atoms ^{36}Cl (g Ti)$^{-1}$ yr^{-1} from Ti spallation (Fink et al., 2002) and 1.9 atoms ^{36}Cl (g Fe)$^{-1}$ yr^{-1} from Fe spallation (Stone et al., 2005). A value of 696 ± 185 neutrons (g air)$^{-1}$ yr^{-1} was applied as the production rate of the epithermal neutrons from fast neutrons in the land/atmosphere interface (Marrero et al., 2016). Scaling factors for nucleonic and mounic production were recalculated following the formulae in Stone (2000). On the other hand, ^{10}Be CRE ages have been recalculated by using the "CREp" (Cosmic Ray Exposure Program) online calculator (Martin et al., 2017; http://crep.crpg.cnrs-nancy.fr/#/). With the aim of unify the exposure age calculation for all samples, we have applied the LSD (Lifton-Dunai-Sato) scaling scheme (Lifton et al., 2014), the ERA40 atmospheric model (Uppala et al., 2005) and the geomagnetic database based on the LSD Framework (Lifton et al., 2014). Applying the aforementioned parameters implies, in turn, a SLHL (Sea-Level High-Latitude) ^{10}Be production rate from Be spallation of 3.99 ± 0.22 atoms g^{-1} yr^{-1}.

Topographic shielding factor of each ^{10}Be/^{36}Cl sampling site has been re-calculated through the Topographic Shielding Factor through the "Topographic Shielding Calculator v.2" belonging to the "CRONUSCalc" Program (Marrero et al., 2016). However, for those samples whose field measurements for topographic shielding factor calculation are unreliable or unavailable, it has been obtained from the "Point-based Shielding Model" GIS-tool devised by Li (2018), which implements the method proposed by Balco et al. (2008). It only requires a Digital Elevation Model, a point shapefile with the location of the samples and the dipping and strike data stored in two separate fields.

For each mountain range, all the data were summarized in a table including available chronology (if existing), geomorphic evidence (environments, landforms and processes), main references as well as a figure with features representative of each of the stages. The different time periods were mapped in GIS environment to better represent the spatio-temporal patterns of glacial activity in each mountain range.

4- Results

The study of glacial processes in the Iberian Peninsula has been solely focused on mountain ranges, where the impact of cold-climate geomorphological processes on the landscape is widespread as shown by the existence of a wide range of landforms and deposits described below.

4.1. The Pyrenees

Quaternary glaciations left a deep imprint on the relief of the Pyrenees because of the large extent of glaciers, with ice tongues exceeding 30–50 km long and 400 m thick, and even reaching up to 800 m in the overdeepened basin of Benasque in the Ésera valley (Bordonau, 1992) as well as in the upper Garonne valley (Fernandes et al., 2017). Altitude and latitude played a major role to explain the size and geomorphological features of glaciers in the Pyrenees: Thus, altitude exceeds 2500 m in the main divides from the headwater of the Ansó valley eastwards, and frequently surpasses 3000 m between the headwaters of the Gállego valley and the Noguera Ribagorçana valley (Aneto, 3404 m; Posets, 3375 m; Monte Perdido: 3355 m). Besides, The Pyrenees are, together with the Cantabrian Mountains and the NW ranges, those located at higher latitudes in the Iberian Peninsula, resulting in a relatively low position of the 0 ºC isotherm and the ELA during the coldest periods. Here, more than in any other Mediterranean mountains, a large variety of well-developed landforms and deposits can be found: glacial cirques, U-shaped valleys (like, for instance, those of the Aragón Subordán, Estarrún, Aragón, Gállego, Ara, Cinca, Cinqueta, Ésera, Noguera Ribagorçana and Noguera Pallaresa valleys), *verrous* or rocky thresholds, hanging-tributary valleys (like the Ip valley, a tributary of the Aragón valley; the Arazas valley, a tributary of the Ara valley; and most of glacial tributaries of the Ésera paleoglacier), glacio-lacustrine deposits in ice/moraine-dammed lakes (many examples, particularly the Linás de Broto paleolake dammed by a lateral moraine of the Ara glacier; Sancho et al., 2018), glacial transfluences, erratic blocks, glacial-origin lakes, *roches moutonnées* and proglacial plains (e.g. that located at the front of the Senegüé moraine, in the Gállego valley), as well as lateral and frontal moraines (like those of the Villanúa-Castiello de Jaca basin in the Aragón valley, the Senegüé moraine in the Gállego valley, the Sant Antoni moraine in the Noguera Ribagorçana valley, and the Puigcerdá complex at the Cerdanya plain), and flute moraines caused by surging glaciers (e.g. in the Marboré cirque, Monte Perdido massif: Serrano and Martín-Moreno, 2018). Most of the main glaciers started from cirques shaped in the paleozoic axis of the Pyrenees (granite, quartzite and limestone), although relatively big glaciers also started in the Inner Sierras, composed of Mesozoic and Cenozoic limestone and sandstone (García-Ruiz et al., 2000), affected by the Alpine tectonics. Their thickness decreased relatively rapid as clearly represented by the declining height of the lateral moraines near their terminal basins. The outermost moraines are located at approximately 800–900 m, and even less in valleys descending to the northern slope of the range (i.e. Garone valley glacier) and in some southern valleys (i.e. Gállego valley glacier).

The Pyrenees include deposits from various glacial cycles. Studies on Pyrenean Quaternary glaciers account for a long tradition since the last decades of the 19th century, thanks to prestigious foreigner geomorphologists. This was the case of Penck (1883) and Panzer (1926). The first one visited the Aragón, Gállego and Ara valleys and raised the question of how many glaciations are represented in the morainic deposits of the Pyrenees; the second one recognized two glacial cycles in the terminal glacial basin of Castiello de Jaca-Villanúa, Aragón River valley, which were then attributed to Riss and Würm – following the Alpine terminology proposed by Penck (1883) – according to the connections between the main moraines and the 60 and 20 m fluvial terraces. The pioneer works of both geomorphologists were the basis for posterior studies focused for decades on: (i) examining the maximum extent recorded by the main Pyrenean glaciers; and (ii) discussing, in absence of direct dates, if the morainic deposits corresponded to one or more glacial cycles. Among such studies, the works of Obermaier (1921), Solé Sabarís (1941, 1951), Llopis-Lladó (1947), Nussbaum (1949), Barrère (1963), Gómez-Ortiz (1987), Bordonau (1992), Serrat et al. (1994), Martí-Bono and García-Ruiz (1994), Chueca et al. (1998) and Serrano (1998) described the position of the main glacial deposits and tried to establish a sequence of glacial periods based on the fabric characteristics and location of the deposits, e.g. Glacial Maximum, Intermediate Stable Stage, Disjunctive Stage and Finiglacial Stage (Martínez de Pisón, 1989). Recent studies carried out during the last two decades have decisively contributed to answer such questions and to pose new ones related with the age of the maximum extent of Pyrenean glaciers and of the distinct stages during deglaciation processes. Currently, the main features of the Late Pleistocene Pyrenean glacial cycle are relatively well known, although new chronological data are needed to establish better correlations between Pyrenean valleys with the glacial sequences identified in other Iberian and European ranges.

Table 2

Figure 3

Glaciations prior to the Last Glacial Cycle

The identification of distinct glacial stages in the Spanish Pyrenees was a major objective for many geomorphologists, although it was a difficult task because of the absence of chronological information. The best site to discuss this problem was at the end glacial basin of Castiello de Jaca-Villanúa, in the Aragón valley (Figure 3a). There, Panzer (1926) identified six frontal moraines that were subsequently named by Llopis-Lladó (1947) as M1, M2 (the main moraines) and m1, m2, m3 and m4 (the minor moraines) within a distance of 3 km (Figure 4). The end glacial basin of the Aragón valley is flanked by lateral moraines that show a progressive decline in height that corresponds to the thinning of the ice tongue. Three lateral moraines appear in the western margin of the valley and two in the eastern one. Panzer (1926) identified two glacial stages – that were attributed to the Riss and Würm – based on the apparent connection between the two main moraines and two terrace levels at 60 and 20 m above the present-day stream bed. However, Barrère (1963) concluded that only one glacial stage is represented in the terminal basin of the Aragón River stating that the outermost moraine is not really connected with the 60 m terrace, but leans against the terrace, thus rejecting the link between the two sedimentary bodies. Therefore, all the moraines would correspond to the same glacial stage.

Nevertheless, the dating of M1 and m2 moraines and the 20 and 60 m terraces using OSL techniques provided a new perspective (Figure 4): (i) Moraine M1 (i.e. the outermost ridge) apparently connects with the 60 m terrace, giving the impression that they correspond to the same cycle. However, OSL dates indicate that the terrace is the oldest geomorphological element present in the terminal basin, with an age of 263 ± 21 ka; (ii) M1 yielded an OSL age of 171 ± 22 ka (García-Ruiz et al., 2013), confirming, as suggested by Barrère (1963), that the moraine M1 struck against the pre-existent terrace; (iii) It is noteworthy that the 60 m terrace can also be associated with a glacial cycle: from the bottom to the uppermost part of the terrace, the sediment clearly changes from fluvial (28 cm for the median size of the gravels) to fluvio-glacial (median size: 75 cm), suggesting that initially the glacier front was located some kilometres upstream and advanced progressively towards the south, causing the increase in the median size of gravels (Höllermann, 1971; Martí-Bono, 1973).

Figure 4

There are other evidences of past glacial cycles, although no dates have been obtained. For instance, in the La Sía valley (a tributary of the Gállego valley), Fontboté (1948), Martí-Bono (1978) and Serrano (1992) found erratic granitic blocks located far away from the main valley (approximately, between 6 and 8 km). In the Noguera Ribagorçana valley, Vilaplana (1983) described a 180 m fluvio-glacial terrace, which cannot correspond to the last glacial cycle. Besides the dating of high fluvial terraces in the Gállego and Cinca rivers informs on terrace development at 178 ± 21 OSL ka (Lewis et al., 2009), coinciding with the formation of moraine M1 in the Aragón valley. Evidence of possible older glaciations predating the Last Glacial Cycle have been also described in valleys of the northern slope of the Pyrenees, such as in the Garonne valley (Andrieu, 1991; Fernandes et al., 2017).

Last Glacial Cycle

An increasing number of dates have been obtained for the Last Glacial Cycle from distinct dating techniques (^{14}C, OSL, ^{10}Be and ^{36}Cl surface exposure ages), suggesting the occurrence of various remarkable glacial fluctuations (Table 2). Figure 3a shows that the terminal glacial basin of Villanúa-Castiello de Jaca in the Aragón valley includes the m2 moraine, dated at 51 ± 4.5 OSL ka, and the 20 m fluvial terrace that connects with moraine M1, dated at 68 ± 7 OSL ka (García-Ruiz et al., 2013).

On the right margin of the Gállego valley, the Tramacastilla Lake occupies an over-excavation performed by the Escarra glacier in a divide that was a diffluence pass towards the Lana Mayor valley glacier. Once the glacier retreated, the basin was occupied by the lake and sediments started accumulating. This glacio-lacustrine sequence was studied by Montserrat (1992), who dated the organic matter incorporated into the sediment at 29,400 ± 600 ^{14}C cal yr BP. This led to deduce for the first time in the Spanish Pyrenees that the MIE must have occurred before the LGM. This asynchroneity more or less coincided with other dates obtained in the glacio-lacustrine sequence of Biscaye, close to Lourdes, French Pyrenees, dated at before 38,000 ^{14}C cal yr BP (Mardonès and Jalut, 1983), similarly to the timing inferred in other places in the Northern Pyrenees (Andrieu et al., 1988). Interestingly, two lateral moraines are located at least 100 m above the Tramacastilla Lake (García-Ruiz et al., 2003), thus suggesting that the MIE in the Gállego valley occurred much earlier than the LGM. The paper from García-Ruiz et al. (2003) also recognized the presence of laminated lacustrine clays in a small lake located just at the north of the Tramacastilla Lake, and it was dated at 20,600 ± 170 ^{14}C cal yr BP, suggesting that the glacier front was located farther upstream. A confirmation of this research was made by González-Sampériz (2006) in the El Portalet peatbog sequence, Gállego valley, just close to the Spanish-French border, at 1802 m. The base of the sedimentary sequence was dated at 32,183–33,773 ^{14}C cal yr BP and 30 cm above at 28,717–29,559 ^{14}C cal yr BP, announcing that the Gállego valley was deglaciated even at the headwater, approximately 10,000 years before the LGM. Curiously, the sequence shows a hiatus during the LGM, suggesting that the glacier was temporarily reconstructed during the coldest period of the LGM.

A stronger evidence of an earlier MIE in the Pyrenees was presented by Lewis et al. (2009) for the Gállego and Cinca valleys. In the terminal basin of the Gállego valley (Senegüé-Sabiñánigo basin), the outermost moraine (Aurín) was dated at 85 ± 5 OSL ka, and the big moraine of Senegüé, located 1 km upstream, at 36 ± 3 OSL ka, although this latter date has been recently questioned and considered as a minimum date, probably of approximately 51 ka (Guerrero et al., 2018). Such landslide-dam paleolakes imply that the age of the Senegüé moraine must be older than the paleolakes. In any case, the Gállego glacier shows the presence of well-developed lateral moraines that indicate the occurrence of three distinct stages around the maximum, like in other Pyrenean valleys, particularly the Aragón and the Ésera valleys (Martínez de Pisón, 1989; Serrano, 1991; García-Ruiz et al., 1992, 2013), although no deposits from the LGM have been found yet. A confirmation of an early deglaciation in the Upper Gállego valley was the development of lakes upstream landslides that occurred as early as 41.5 ± 3.9 OSL ka, whereas other glacial branches in the headwater of the Gállego glacier were still active (Aguas Limpias and Caldarés valleys) due to the much higher height of divides and cirques (Guerrero et al., 2018).

In the Cinca valley, Lewis et al. (2009) obtained three dates from glacial deposits in the terminal area of the valley, with a weighted mean age of 64 ± 11 OSL ka, which is similar to the age of a correlated fluvial terrace (61 ± 4 OSL ka), interpreted as a glacial outwash. Other sample reported a date of 46 ± 4 OSL ka, which was interpreted as pertaining to a later glacial fluctuation. Other fluvial terraces of the Cinca River were dated at approximately 47 ± 4 and 45 ± 3 OSL ka.

Between the Gállego and the Cinca rivers, some glacial-related deposits from the Ara valley were also dated, particularly the main lateral moraine and the associated 55 m thick glacio-lacustrine deposit in the tributary valley of Sorrosal. Sancho et al. (2018) dated the lateral moraine of the Ara valley at 49 ± 8 OSL ka, whereas sediments of the paleolake provided ages at 55 ± 9 and 49 ± 11 OSL ka for the middle and upper parts, respectively. The glacio-lacustrine deposit in the Sorrosal valley (also called the Linás de Broto deposit) is the largest one in the Pyrenees, and shows the occurrence of a variety of sedimentary processes with significant fluctuations of the water depth, causing dramatic changes in the sedimentary facies (Serrat et al., 1983; Sancho et al., 2018).

The occurrence of a cold period in the Central-Western Pyrenees during the global LGM has been indirectly detected. For instance, loess deposits and stratified screes in the Cinca valley at approximately 20 ± 3 OSL ka

(Lewis et al., 2009) and 22,800 ± 200 ^{14}C cal yr BP (García-Ruiz et al., 2001a), respectively, indicate extremely cold conditions during the global LGM. Also, García-Ruiz et al. (2001b, 2003) and García-Ruiz and Martí-Bono (2011) interpreted a glacial re-advance represented in lateral moraines in the Escarra valley (Gállego valley) and Aragón Subordán valley, located some kilometres upstream of the MIE. Unfortunately, such lateral moraines have not been yet dated.

In the Central-Eastern Pyrenees, studies based on ^{10}Be exposure ages have contributed to very much improve the knowledge on the global and local maximum ice extent. Pallás et al. (2006) and Rodés et al. (2008) indicated that the MIE in the Upper Noguera Ribagorçana valley coincided with the global LGM, i.e. ca. 21 ± 4.4 ^{10}Be ka, and a similar sequence was found at La Cerdanya by Palacios et al. (2015a). This date coincided with that obtained by Delmas et al. (2008) from the Têt valley in the Eastern French Pyrenees, confirming a LGM (Marine Isotope Stage; MIS-2) re-advance between 21.4 ± 3.7 and 24.9 ± 4.4 ^{10}Be ka, although the MIE occurred during MIS-3 between 51.1 ± 5.0 and 42.6 ± 4.1 ^{10}Be ka (Tomkins et al., 2018). In the same way, Pallàs et al. (2010) dated the occurrence of a MIE at a minimum of 49.2 ± 1.3 ^{10}Be ka and an almost similar advance during the global LGM at 21.3 ± 0.6 ^{10}Be ka in the small Malniu basin, located in the Querol valley. It is noteworthy that Andrés et al. (2018) dated 8 new ^{36}Cl samples from the Malniu-Guils complex and recalculated the dates obtained from three nearby valleys (Arànser, La Llosa and Duran). The results obtained did not lead to consistent conclusions in relation to the age of the MIE in the Eastern Pyrenees, with ages of the main lateral moraines reporting approximately 20–21 ^{36}Cl ka. By contrast, Delmas et al. (2011) and Delmas (2015) concluded that the MIE occurred in the Ariège valley (French Eastern Pyrenees) much earlier than the global LGM, with ice advances at 79.9 ± 14.3 and 35.3 ± 8.6 ^{10}Be ka, whereas moraines of the global LGM, dated at 22.8 ^{10}Be ka are located less than 100 m upstream the MIE. Turu et al. (2016) obtained similar dates in an ice-dammed paleolake of Andorra.

The recent effort made to date distinct glacial-related deposits (glacio-lacustrine sediments, fluvial terraces and moraines) as well as moraines, erratic boulders and polished surfaces confirm the complexity of chronologies during the last glacial cycle. It is increasingly accepted that the MIE in the Pyrenees occurred much before the global LGM, like in other mountains in northern Iberian Peninsula, although dating with several other procedures would be necessary in order to establish clear stages. Now, we find various scattered dates that can be grouped with difficulties. The clearest periods of glacial advance occurred (i) between 50 and 70 ka (MIS-4), as suggested by dates in the Aragón, Ara, Cinca and Ariège valleys of the Central Pyrenees and in the Têt valley; (ii) between 30 and 40 ka (MIS-3) in some minor valleys of the Eastern Pyrenees; and (iii) between 22 and 19 ka (MIS-2), coinciding with the global LGM, including many dates in the Eastern Pyrenees, where the MIE and the global LGM almost coincided in extent. Surprisingly, the occurrence of the global LGM in the Central Pyrenees has not been clearly detected, except for some indirect evidence, although a relatively minor advance for the global LGM has been suggested for the Central Pyrenees. The reason for this unbalance is not well known, although the distinct climatic influences that affected both areas of the Pyrenees should be the most logical explanation. Other glacial-related sediments have been ^{14}C and AMS dated at approximately 30 ka (MIS-3), although they can be older given the limitations of radiocarbon techniques to date older deposits.

Termination-1

The glacial history leading up to Termination-1 in the Pyrenees is very well known thanks to recent studies in the Central and Eastern sectors of the range using ^{10}Be and ^{36}Cl surface exposure ages (Pallàs et al., 2010; Palacios et al., 2015a, 2015b, 2016, 2017; Andrés et al., 2018), on both the north- and south-facing slopes of the Central and Eastern Pyrenees, and ^{14}C dating of glacio-lacustrine sequences (González-Sampériz et al., 2006, 2017) in the headwater of the Gállego valley.

Following the global LGM, the deglaciation was very rapid and intense, almost causing the total disappearance of the glaciers at the beginning of a new cold period, the OD (Palacios et al., 2016). In the El Portalet peatbog, the OD has been identified as an arid period, with expansion of cold steppe vegetation (González-Sampériz et al., 2006). Also in the Gállego valley, the glaciers were affected by a relatively remarkable re-advance with ice tongues of several kilometres in length, although the main glacier tongues in the headwater remained disconnected (Palacios et al., 2017a). Their maximum extent occurred at approximately 18.6–16.5 ^{10}Be ka, as dated in a lateral moraine in the Caldarés valley, a main tributary of the Gállego valley, evidencing the development of a glacial tongue exceeding 12 km in length. This was followed by a retreat and new recoveries, with the last occurring by 15.5 ^{36}Cl ka (Palacios et al., 2015b; 2016) in the Piniecho and other neighbouring cirques. In the Maladeta massif – the highest one in the Pyrenees –, the Aigualluts moraines were deposited during the OD (16.2 ± 1.1 and 14.8 ± 1.4 ^{10}Be ka) (Crest et al., 2017). In the Noguera Ribagorçana valley moraines from the OD were identified at a distance of more than 10 km from the headwater (Pallàs et al., 2006). Afterwards, the retreat of the glaciers was very rapid so that they were confined to the cirques and most of them disappeared during the BA interstadial. Crest et al. (2017) noted that at 14.3 ± 0.5 ^{10}Be ka the glaciers from distinct cirques in the Maladeta massif were already disconnected, showing the warming effect at the beginning of the BA interstadial.

In the Eastern Pyrenees, the OD is well represented in the Carlit massif, where some moraines were dated at 15 ^{10}Be ka (Delmas et al., 2008). In the case of La Cerdanya, Pallàs et al. (2010) dated the outermost morainic arcs at 24 ^{10}Be ka and the innermost ones at 15.5 ^{10}Be ka, coinciding with one of the advances recorded during the OD. Palacios et al. (2015a) dated several moraines in La Cerdanya as belonging to the OD (16-17 ka and 15.5 ^{36}Cl ka), at a short distance from the global LGM moraines. Clear re-advances during the OD were also detected by Tomkins et al. (2017) in the Eastern Pyrenees, particularly in the Têt valley with average values at 16.1 ± 0.5 ^{10}Be ka.

Remarkably, many rock glaciers developed in the Central Pyrenees at the end of the OD, coinciding with the moment at which the cirque walls were deglaciated and affected by frequent rockfalls. The fronts of these rock glaciers were already inactive by approximately 14 ka, although their main bodies conserved internal ice and remained active until the Early to Mid-Holocene (Palacios et al., 2016), as also observed in some rock glaciers of La Cerdanya in the Eastern Pyrenees (Palacios et al., 2015a).

The BA interstadial finished abruptly with a rapid and intense cooling during the YD. This cooling coincided with a strongly arid period, such that glacier expansion was possible although very limited in extent. For this reason, glaciers during the YD were restricted to the cirques, with the exception of the highest mountains, where it was possible the development of short glacial tongues of more than 3 km in length (García-Ruiz et al., 2016a, 2016b). This was the case for the Azules Lakes valley, in the Panticosa massif (Serrano and Agudo, 1988). Also, several moraines in the Mulleres valley (a tributary of the Noguera Ribagorçana valley) have been dated at between 10.4 ± 1.0 and 10.1 ± 0.1 ^{10}Be ka, indicating the occurrence of a 3.5 km ice tongue (Pallàs et al., 2006; Delmas, 2015). Various glacial deposits in the Piniecho cirque, Panticosa massif, have been dated between 13.5 ± 1.9 and 11.7 ± 1.7 ^{10}Be ka, confirming the occurrence of distinct glacier fluctuations during the YD (Palacios et al., 2015b). Like in the case of the OD, some permafrost-related landforms, such as rock glaciers and protalus lobes, developed at the end of the YD (Fernandes et al., 2018), as was the case for the Brazato rock glacier, whose activity extended until the Holocene Thermal Optimum at 6.5 ± 0.4 ^{36}Cl ka (Palacios et al., 2017). The presence of several polished bedrocks at the front of the Brazato rock glacier, dated between 13.4 ± 0.8 and 10.4 ± 0.8 ^{36}Cl ka (Palacios et al., 2017; recalculated at 14.5 ± 1.2 and 11.4 ± 0.8 ^{36}Cl ka) confirms the presence of small ice tongues surpassing the limits of the cirque. Also, the Aguas Limpias valley, a major tributary in the headwater of the Gállego valley, shows the presence of many polished rocky thresholds dated at 12.3 ± 1.6, 11.7 ± 1.7, 10.2 ± 0.7 and 8.7 ± 0.6 ^{36}Cl ka (Palacios et al., 2017), revealing the progressive retreat of the glacier front towards the cirque headwalls. These authors include the dating of a high number of polished bedrocks that indicate the regression of the cirque glaciers at the beginning of the Holocene. In the Maladeta massif, one of the lateral moraines of the so-called Renclusa system has been dated at 12.1 ± 0.4 ^{10}Be ka (Crest et al., 2017). In the Eastern Pyrenees, the Querol valley, Eastern Pyrenees, has also a large variety of morainic deposits, some of them dated at 11.8 ± 0.6 ^{10}Be ka, as well as polished bedrocks dated at 11.8 ± 1.2 ^{10}Be ka (Pallàs et al., 2010) and, consequently attributed to the YD. However, no evidence of YD glaciers was found by Andrés et al. (2018) in four areas of the SE Pyrenees.

Holocene

As commented previously, many of the rock glaciers that developed in the Pyrenees at the end of the OD and YD survived until the Early to Mid-Holocene, holding up rests of buried glacial ice and removing the blocks until their definitive emplacement. Outside the LIA moraines, the only place where Holocene glacial deposits have been identified is the Marboré cirque, in the northern face of the Monte Perdido massif, where a moraine has been dated at 5.1 ± 0.1 ^{36}Cl ka (García-Ruiz et al., 2014), recalculated at 6.9 ± 0.8 ^{36}Cl ka, most likely suggesting a final stabilization in the retreat since the YD. The presence of moraines of Mid-Holocene age has been also detected in the northern Pyrenean versant, where moraines of the Troumouse cirque have revealed glacial activity between 5190 ± 90 and 4654 ± 60 ^{14}C cal yr BP (Gellatly et al., 1992). It is also probable that the large moraine parallel to the northern Monte Perdido massif corresponds to the addition of LIA materials to those from the Holocene. It would be the same process that indicated by Crest et al. (2017) for the Maladeta massif. These authors stress that "the absence of moraine accumulations between the innermost Renclusa and the LIA moraines strongly suggests that the historical LIA ice front is indistinguishable from any earlier maximum Holocene ice fronts…The voluminous ablation till deposits contained in the LIA moraine can be ascribed to an unspecified number of Holocene glacial readvances" (p. 70), as also pointed out by Matthews (2013) in the Alps and Norway. Similarly, a large number of surface exposure dates for Neoglacial moraines has been reported for the Alps suggesting the existence of polygenic moraines formed during successive glacial advances (Ivy-Ochs et al., 2009), which could be also the case of the Pyrenees and other Iberian mountains.

Little Ice Age

The LIA has been considered, in general, as the main glacial advance in the Pyrenees since, at least, the beginning of the Holocene (Oliva et al., 2018). Following the warm Medieval Climatic Anomaly, climate conditions started being progressively colder during the 14th and 15th centuries, affecting many cirques (up to 111, according to González-Trueba et al., 2008) where small glaciers began to develop. These new glaciers were, in general, restricted to the cirques and even only to a small part of the cirques, where constructed big moraines, mainly composed of coarse material and identified by the absence of plant cover, the acute crest, and the steep slopes in both versants. The most relevant LIA glaciers in the Pyrenees occurred in those massifs peaking at more than 3000 m (e.g. Infiernos, Monte Perdido, Posets, Perdiguero, Maladeta and Besiberri) in the southern face of the range. Interestingly, some of the LIA glaciers reveal the occurrence of various fluctuations, with the presence of a sequence of moraines, such those in the northern face of the Tendeñera Peak (López-Moreno, 2000), Monte Perdido (García-Ruiz et al., 2014), and the Aneto-Maladeta peaks (González-Trueba et al., 2005). Although there are no direct dates from the LIA moraines, the maximum extent of the glaciers has been traditionally correlated with the Maunder Minimum, during the last decades of the 17th century. A significant glacial expansion is also attributed to the Dalton Minimum, during the first third of the 19th century. In many of the Pyrenean cirques, Serrano and Martín-Moreno (2018) found evidence of the last LIA stage in the Pyrenees, characterized by the development of surging glaciers and flute moraines, particularly in the Marboré cirque. By 1850, the LIA glaciers occupied 2060 ha, including the French versant (René, 2013). After 1850-1860 the glaciers started a slow retreat that became progressively more rapid during the 20th century, so that they occupied 321 ha by 2008 and 242 ha by 2016 (Rico et al., 2017).

Present-day

René (2013) estimated that there were 52 glaciers in the Pyrenees 1850. By 1984 they were 39 (Arenillas Parra et al., 2008) and by 2016 the number decreased to only 19 (Rico et al., 2017). All of the remaining glaciers have suffered a strong reduction in extent and volume. At present the area covered with glaciers is 242 ha, with the Aneto glacier (56.1 ha) as the largest ice mass, followed by the Monte Perdido glacier (37.8 ha), the Ossoue glacier (37.2 ha) and the Maladeta glacier (29.4 ha) (Rico et al., 2017). The rest of Pyrenean glaciers have less than 10 ha and face a severe risk of melting in the next decade under the current climatic regime, given the negative trend in winter snow accumulation (López-Moreno et al., 2005). All of them are sheltered on shady, north-face exposures, well protected by the cirque walls and partially covered with debris. Even the largest glaciers, like the Monte Perdido glacier, are affected by intense thinning and spatial shrinkage, with reduction even in years that could be considered as relatively favourable (López-Moreno et al., 2016).

4.2 Cantabrian Mountains

Geologically considered the western extension of the Pyrenees (Alonso et al., 1996), this mountain range is disposed parallel to the Cantabrian Coast for about 400 km, showing a general W-E strike and reaching a top elevation of 2648 m (Torrecerredo; Central Massif of the Picos de Europa). Bedrock geology in the central and eastern sectors of the Cantabrian Mountains mostly corresponds to alternating carbonate and detrital sedimentary rocks of both Paleozoic (the highest massifs) and Mesozoic age (easternmost massifs like Pas Mountains and Castro Valnera), with some exceptional outcrops of Paleozoic igneous rocks (e.g. Fuentes Carrionas). In contrast, the westernmost end of the range corresponds to metamorphic rocks of Proterozoic and Paleozoic age (e.g. Ibias and Sil valleys).

The divide of the Cantabrian Mountains is placed just 27–70 km inland from the Cantabrian Sea, conditioning greater incision of the drainage network in the northern slope of the range, where rivers flow directly to sea level, than in the southern slope where they flow towards the Duero basin (deepest area located ca. 160 km to the South at 630 m altitude). On the other hand, due to its distribution parallel to the Cantabrian Sea, the Cantabrian Mountains act as a moisture barrier for incoming humid winds from the Atlantic Ocean (Felicísimo, 1992), resulting in higher precipitation in the northern slope that strongly decreases towards the Duero basin. The strong maritime influence of local climate favored the development of extensive mountain glaciation during the Pleistocene, reaching remarkably low elevations compared to other Iberian mountain settings.

Table 3

Figure 5

Glaciations prior to the Last Glacial Cycle

The idea that, at least, two glaciations contributed to shape the glacial record of broad areas of the Cantabrian Mountains was embraced in the early 19th century (Hernández-Pacheco, 1914). Subsequently, Hernández-Pacheco (1944) ascribed the three sets of moraines preserved at altitudes of 1385–1645 m in Peña Labra and Sierra de Híjar to the Mindel, Riss and Würm glaciations, whereas Lotze (1962) interpreted the two moraine systems existing in the Pas Mountains as deposited during the Riss and Würm glaciations. Probably, the most controverted evidence is the heavily cemented breccia deposits (locally named *gonfolitas*) described by Obermaier (1914) in the Picos de Europa (Table 3). Based on the cross-cut relationships between cemented breccia deposits and glacial evidence, Obermaier (1914) ascribed the sedimentation of these deposits to the Riss-Würm interglacial and proposed the existence of at least two glaciations arguing that breccia deposits appear buried by the Last Glacial Cycle moraines in the Duje valley and, at the same time, fossilize an ancient glacial polished surface. Although some authors cast serious doubts on the glacial origin of the surface preserved below the cemented breccia (e.g. Castañon and Frochoso, 1992), a recent study supports Obermaier's interpretation and sustains the existence of a Middle Pleistocene glaciation (coevally with MIS-12) based on U/Th analysis of two samples from the calcareous cement, whose precipitation started at a minimum age of 394 ka (Villa et al., 2013).

Evidence of highly weathered till deposits has been reported at an altitude of 980 m in Somiedo (Menéndez-Duarte and Marquínez, 1996) and 890 m in the Sil valley (García de Celis and Martínez-Fernández, 2002), suggesting their possible linkage to former glaciations. However, up to date only a few numerical ^{10}Be CRE ages from erratic and moraine boulders from the terminal zone of the Porma paleoglacier provided results of 173–131 ka that suggest glacial activity during MIS 6 (Rodríguez-Rodríguez et al., 2016).

Last Glacial Cycle

During the MIE of the last glacial cycle, glaciers covered a total surface extent of about 2240 km^2, showing remarkable asymmetry on glacier distribution between both sides of the range (Rodríguez-Rodríguez et al., 2015). The combination of pre-glacial topography, distance to the sea, and climate most likely controlled the distribution of glaciers, whose longest glacier tongues were shorter in the steeper northern slope (<15 km) compared to the gentler southern one of the range (15 to 51 km) (Serrano et al., 2017). In the central Cantabrian Mountains, where broad land areas are above 2000 m asl, some extensive ice fields formed close to the N-S divide showing asymmetric development towards the southern slope of the range, with the exception of Picos de Europa and Pas Mountains. Occasionally, outlet glaciers were thick enough to fulfill the valleys and overflowed towards adjacent tributaries (Figure 5), forming interconnected systems of valley glaciers or transection glaciers (e.g. the Porma paleoglacier; Rodríguez-Rodríguez et al., 2016). The front of the longest glaciers reached minimum elevations that were generally lower in the northern slope of the range (most frequently between 800 and 1200 m altitude, locally down to 400–500 m) compared to the southern one (1100–1250 m, locally down to 725–905 m). Regional paleoELA varied from ca. 1000 to 2000 m during the MIE, showing a distribution pattern similar to the present-day winter precipitation and summer temperature (Santos-González et al., 2013). The lowest ELA values were recorded towards the eastern and western ends of the range (ca. 1000 m), while it remained at ca. 1500 and 1600 m in the Central Cantabrian Mountains divide. The highest ELA values (> 1750 m) were recorded further inland, in Peña Prieta Massif (Pellitero, 2013).

Regarding the timing of glacial stages, the application of radiocarbon in glacio-lacustrine environments, deposited synchronously or subsequently to the MIE moraines, provided minimum ages in the range 45–35 ^{14}C cal ka BP for the Western and Central massifs of Picos de Europa (Jiménez-Sánchez and Farias, 2002; Moreno et al., 2010; Serrano et al., 2012; Nieuwendam et al., 2015; Ruíz-Fernández et al., 2016), > 44–35 ^{14}C cal ka BP in Somiedo-Laciana (Jalut et al., 2010), > 33.5 ^{14}C cal ka BP in the Redes Natural Park (Jiménez-Sánchez and Farias, 2002), and > 30 cal ka BP in the Pas Mountains (Serrano et al., 2013). In the Cares valley, at least two fluvial terraces were deposited at 41.1–42.4 ^{14}C cal ka BP (+8–10 m) and >48 ka (+20–22 m) coevally with glacier occupation in the Picos de Europa (Ruíz-Fernández and Poblete-Piedrabuena, 2011). The OSL analysis performed in supraglacial tills from Vega del Naranco moraine complex, in Fuentes Carrionas Massif, provides a reference age of ca. 36 ka for the local MIE and involves younger ages for the six moraine ridges preserved upvalleys (Serrano et al., 2013). Similarly, the second outermost ridge of the Brañagallones lateral moraine complex, in the Redes Natural Park, yielded an OSL age of ca. 24 ka for a glacier re-advance of similar extent than the previous MIE (Jiménez-Sánchez et al., 2013). Numerical ages obtained in the Porma valley using a combination of ^{10}Be CRE, OSL and ^{14}C have provided the most complete record up to date of past glaciations in the Cantabrian Mountains (Rodríguez-Rodríguez et al., 2016, 2018a). Results suggest continuous glacial occupation of the valley during the Last Glacial Cycle, recording at least three major glacial stages at ca. 110 ka (MIS-5d), ca. 56 ka (MIS-3); and 33–24 ka (MIS-2) for which the glacier front reached minimum elevations of 1110–1130 m. The OSL analysis performed on till samples in the northern slope of Pas Mountains also suggest glacial occupation from 78.5 to 40 ka in the Ason valley and 45–41.6 ka in the Gandara valley (Frochoso et al., 2013). The glacial re-advances recorded in some Cantabrian valleys such as the Porma, Monasterio or Vega del Naranco are synchronous with the global LGM.

Termination-1

The minimum ^{10}Be CRE ages obtained from lateral moraines in the Porma catchment place the onset of the last Termination at ca. 22–20 ka (Rodríguez-Rodríguez et al., 2018a), and both ^{10}Be CRE and ^{14}C dating suggest considerably glacier thinning by ca. 18–17.5 ka (Rodríguez-Rodríguez et al., 2016, 2018a). Ruiz-Fernández et al (2016) showed evidence of intense periglacial conditions with thinner glaciers between 22.5 and 18.7 ^{14}C cal ka BP in the Western Massif of Picos de Europa. The sequence of recessional moraines dated in the Monasterio valley provides consistent evidence for deglaciation in the opposite mountain slope (Rodríguez-Rodríguez et al., 2017), suggesting glacier front stagnations and/or minor re-advances at ca. 19, 17.5 and 14.6 ^{10}Be ka, for which the glacier front was located at altitudes between 1150 and 1540 m.

In the northern slope of Fuentes Carrionas massif, proglacial lacustrine sedimentation occurred at 18.9–18.8 cal ka BP in Vega del Naranco (1540–1550 m altitude) due to valley impoundment by the moraine complex (Serrano et al., 2013). Westward, the minimum radiocarbon age obtained at the basis of Lago de Valle (also known as Lago de Ajo, placed at 1566 m altitude) suggests remarkable retreat of NW-oriented valley glaciers in Somiedo by ca. 17.6–17.1 ^{14}C cal ka BP (Allen et al., 1996). Thus, broad areas of the Central Cantabrian Mountains with top elevations between 1900 and 2100 m, like Monasterio valley in Redes Natural Park or Lago de Valle in Somiedo, were possibly fully deglaciated after the OD. A phase of glacier tongue individualization or disjunction with the fronts reaching 1600–1700 m is identified in some massifs, suggesting an ELA pattern similar to the local MIE, recording minima values of 1310 and 1500 m in the eastern and western ends of the range and increasing towards the middle part (Serrano et al., 2017).

Besides an advanced retreat of valley glaciers, the Late-glacial was characterized by a progressive replacement from glacial to periglacial processes with development of large rock glaciers that could possibly be active intermittently during the Holocene and the LIA (Alonso and Trombotto-Liaudat, 2009). The distribution of relict rock glaciers shows initiation lines between 1600 and 2000 m and toes reaching minimum elevations of 1500 m (Gómez-Villar et al., 2011). Up to date, the ^{10}Be CRE dating of two rock glacier toes located at altitudes of 1540 and 1650 m provided reference ages of ca. 16.2–13.6 ka for the stabilization of their lowest ridge (Rodríguez-Rodríguez et al., 2016, 2017). Paraglacial rock slope instabilities started during the OD, soon after glacier retreat (ca. 16–15 ka) as indicates preliminary numerical ages from Braña Creek in the San Isidro mountain pass area, and continued during the Holocene (Rodríguez-Rodríguez et al., 2018b).

Although the occurrence of a YD re-advance of glaciers has been hypothesized for the highest massifs of the Cantabrian Mountains, such as the Picos de Europa and Fuentes Carrionas as well as local settings like Peña Ubiña, no dating evidence is yet available (Serrano et al., 2013, 2017). In the Central Massif of Picos de Europa, small glaciers reaching up to 1 km in length developed, leaving a thick debris cover on moraines at altitudes of 1800–2000 m in shelter areas of glacier cirques, suggesting that the local ELA was at about 2200 m altitude (Serrano et al., 2017). Similarly, moraines preserved in Fuentes Carrionas at altitudes between 1900–2000 m and 2100–2200 m suggests two stages of glacier stabilization that could correlate with the YD for which the ELA was set at 2300 and 2350 m, respectively (Pellitero, 2013). However, broad areas of the Central Cantabrian Mountains where the highest peaks do not exceed 2000–2100 m remained glacier-free during the YD, possibly because the regional ELA was set at about 2500 m altitude (Serrano et al., 2017).

Little Ice Age

Only six glaciers existed in the highest cirques of Picos de Europa at the end of the LIA, extending over a surface of 25.5 ha (15.5 ha in the Central Massif and 10 ha in the Western Massif), and always distributed at the foot of northern walls in sheltered environments snow-fed by avalanches and wind action (Miotke, 1968; González-Trueba et al., 2008). During the mid-19th century these glaciers reached their maximum extent and built frontal moraines at 2200–2320 m, and the ELA was located slightly lower in the Western Massif (2252 m) than in the Central Massif (2341 m; González-Trueba, 2005; González-Trueba et al., 2008).

Present-day

Four ice-patches remains in the Western and Central massifs of Picos de Europa, nested within the LIA moraines but showing remarkably reduced surface extent compared to the former LIA glaciers (52 to 76% total surface reduction; González-Trueba et al., 2007). The most controverted one is the Jou Negro ice-patch, the single one that is not fully covered by debris. Although some authors described it as a glacier (González-Suárez and Alonso, 1994; Alonso and González, 1998), most authors agree that it cannot be considered a glacier because it lacks movement (Frochoso and Castañon, 1995; González-Trueba et al., 2005). The Forcadone buried ice-patch is another remnant of a LIA glacier with permanent negative temperature values at deeper layers (Ruiz-Fernández et al., 2017).

4.3 NW ranges

The NW ranges comprise a series of mountain ranges that continue the relief of the Cantabrian Mountains towards the NW corner of the Iberian Peninsula (longitude between 6ºW and 8ºW), acquiring W-SW distribution trends. Bedrock geology mostly corresponds to Palaeozoic metamorphic and igneous rocks. Like in the Cantabrian Mountains, the distribution of Pleistocene glaciations in the NW ranges of the Iberian Peninsula was strongly conditioned by both the preglacial landscape topography and the proximity to the Atlantic Ocean. The NW ranges are generally arranged as smooth, near horizontal topographic highs set at increasing altitudes inland. Glacial evidence has been extensively documented since the 1910s in the highest massifs of Trevinca (2128 m), Serra dos Ancares (1998 m) and Manzaneda (1781 m) (Taboada, 1913), but also in other relatively low mountain settings like Serra do Courel (1654 m), Serra de Xurés-Gerêz (1548 m), Serra do Oribio (1484 m), Montes do Cebreiro (1474 m), and Serra do Xistral (1031 m) (Pérez-Alberti et al., 2004, 2018).

Glaciations prior to the Last Glacial Cycle

The idea of mountain glaciations occurring prior to the Last Glacial Cycle was initially proposed by Hernández-Pacheco (1949, 1957) to explain the glacial record existing in the Manzaneda massif. He ascribed the lowest moraines to the Riss glaciation – following the Alpine terminology – and estimated the altitude of the paleoELA in 1428 m. Similarly, Llopis (1957) interpreted the Sanabria Lake moraine complex preserved in the eastern slope of the Trevinca massif at ca. 1000 m as the result of three superimposed glaciations (Mindel, Riss and Würm). However, absolute ages based on ^{10}Be CRE dating indicate that the Sanabria Lake moraine complex was deposited during the Last Glacial Cycle (Rodríguez-Rodríguez et al., 2014), showing time consistence with OSL analysis of glacio-fluvial sediments from the proglacial site of Pias in the opposite slope (Pérez-Alberti et al., 2011).

Preliminary CRE dating carried out in the Manzaneda and Xurés-Gerêz massifs provided non-conclusive results to support the occurrence of glaciations before the Last Glacial Cycle (Table 4). Glacial evidence in the Manzaneda massif is indicative of a mountain ice cap covering a total surface area of 130 km^2 (Vidal-Romaní and Santos-Fidalgo 1994) drained by glacier outlets up to 7-10 km in length and glacier thickness up to 150-200 m (Pérez-Alberti et al., 1993). The ^{21}Ne dating of a single boulder from the Castañeda moraine (1210 m) yielded an age older than 120 ka, whereas other three landforms sampled just 0.5 km upstream in the Cenza valley revealed ^{10}Be and ^{21}Ne ages ascribable to the Last Glacial Cycle (Vidal-Romaní et al., 1999, 2015). Similarly, two ^{21}Ne analysis from two glacial polished surfaces sampled 4 km downslope in the Vilameá valley and at the mountain divide in the Serra de Xurés-Gerêz yielded surprisingly old age results of 238 ka and 130 ka for the maximum extent of an ice cap of ca. 64 km^2 surface that was installed on the Xurés-Gerêz massif (Vidal-Romaní et al., 1999) and drained to the N by outlet glaciers up to 5-6 km long (Vidal-Romaní et al., 1990). If correct, these ^{21}Ne ages would imply that glaciers did not grow in mountain environments below 1500 m altitude during the Last Glacial Cycle, which mismatches the chronological results obtained in the nearby Trevinca massif. Although preliminary numerical ages are still scarce to sustain that glaciations older than the last glacial Pleistocene cycle occurred, the presence of poorly preserved evidence like big erratic boulders distributed outside the limits of the lowest moraines in some moraine complexes (e.g. the Sanabria moraine complex) might probably represent the last evidence remaining from old glaciations (Figure 6).

Table 4

Last Glacial Cycle

Most authors have interpreted the glacial record preserved in the NW ranges as formed during multiple stages of the Last Glacial Cycle (Pérez-Alberti et al., 2004). Glacial evidence suggests that mountain glaciers developed extensively in the highest massifs of the NW Iberian corner (e.g. Pérez-Alberti et al., 1992, 1993, 2002; Vidal-Romaní and Santos-Fidalgo, 1994), but also in relatively low mountainous areas (e.g. Valcárcel, 1998, Valcárcel et al., 2002a), being possible to distinguish up to four glacier typologies (Pérez-Alberti et al., 1993; Pérez-Alberti and Valcárcel, 1998): (i) mountain ice caps drained by outlet glacier; (ii) Alpine glaciers with coalescent tributaries; (iii) Alpine glaciers composed by a single ice tongue; and (iv) cirque glaciers displaying incipient ice tongue development (Figure 6).

Up to date, the best studied glacial record in the NW ranges is that located in the Trevinca massif. Glacial evidence suggests that a mountain ice cap developed across an area of 475 km^2 drained by several outlet glaciers radially disposed along the pre-existing fluvial valleys (Rodríguez-Rodríguez et al., 2014). Numerical reconstructions indicate that the Trevinca ice cap reached an ice thickness up to 200–300 m on the high plateau (Cowton et al., 2009; Rodríguez-Rodríguez et al., 2014), while the Cepedelo moraines suggest that the Bibei outlet glacier was up to 500 m thick, being by far the thickest one in the entire NW Iberian corner (Pérez-Alberti et al., 1993, 2002). The Bibei paleoglacier was also the longest outlet glacier (30 km; SW aspect), followed by the Tera ice tongue (24 km; SE aspect), which had their glacier fronts at minimum altitudes of 900 to 950 m, respectively (Pérez-Alberti et al., 1993; Rodríguez-Rodríguez et al., 2011). Glacio-fluvial sediments from the Pias proglacial site, deposited within the margins of the lowest front in the Bibei valley, have provided minimum ages in the range between 27 and 31 OSL ka for the local MIE of the Last Glacial Cycle (Pérez-Alberti et al., 2011). Similarly, radiocarbon analysis of pollen concentrates retrieved from the base of the Sanabria Lake sedimentary record also revealed a minimum age of 25.7–25.9 ^{14}C ka cal BP for the local MIE (Rodríguez-Rodríguez et al., 2011).

Few chronological data are available for other massifs of the NW ranges, though it is likely to consider that they followed a similar temporal pattern than that documented in Trevinca. The preglacial topography in other mountain areas like Serra dos Ancares or Serra do Courel did not favour the formation of ice caps, and Alpine-type glaciers of different complexity developed instead (Pérez-Alberti et al., 1993; Pérez-Alberti and Valcárcel, 1998). Valley glaciers featured asymmetric distribution patterns between opposite mountain slopes, most probably influenced by a combination of controlling factors such as the preglacial landscape topography, variable topoclimatic conditions and the snowdrift effect of wind (Hernández-Pachecho, 1957; Pérez-Alberti et al., 1993; Vidal-Romaní et al., 1994; Valcárcel et al., 2009). In Serra dos Ancares, coalescent alpine glaciers up to 7-13 km long flowed along the SE slope whereas alpine glaciers did not overcome 10 km in length in the NW slope. However, the glacier fronts reached, in general, lower elevations in the NW slope (700–1000 m) compared to the SE one (825–920 m), most likely due to differences in the regional slope angle and relief between both mountain sides (Pérez-Alberti et al., 1992, 1993; Valcárcel et al., 2002b). Glaciers were slightly shorter in lower ranges like Serra do Courel (Pérez-Alberti, 2018), forming coalescent Alpine glaciers up to 5.5 to 7.8 km long along the Seara (150 m thick; front at 950 m) and Vilarbacú valleys (100 m thick; front at 900 m), while other valleys recorded simple Alpine glacier tongues significantly shorter (1.5 to 3 km; front at 650–950 m). The shortest glaciers of the NW ranges have been documented in Montes do Cebreiro and Serra do Oribio, where cirque glaciers with incipient glacier tongues up to 0.7–2.5 km long and less than 80 m thick developed, reaching minimum elevations of 900–1000 m (Pérez-Alberti et al., 1993; Valcárcel et al., 2002a). The fact that these two massifs do not reach 1500 m altitude, suggests that climate conditions during the Last Glacial Cycle in the NW ranges allowed sustaining glaciers at extremely low elevations possibly favoured by remarkable moisture supply from the Atlantic Ocean. Moreover, glacial evidence described in the coastal ranges of Serra do Xistral and Faro do Avión, distributed at elevations as low as 600–700 m indicating extremely low ELA conditions (ca. 900 m altitude) during the MIE of the Last Glacial Cycle (Schmizt, 1969; Pérez-Alberti et al., 1993). An extreme case is detected in the Capelada massif, where moraines formed during the MIE of the Last Glacial Cycle are located just above present-day sea level (Pérez-Alberti, 2014; Figure 6c). In contrast, the paleoELA rose progressively inland to 1250–1350 m in Serra do Courel, 1350–1450 m in

Serra dos Ancares and up to 1500–1600 m altitude in the Trevinca massif (Valcárcel et al., 2002b; Pérez-Alberti et al., 2004).

Figure 6

Thus, the well-constrained glacial chronology of the Trevinca massif indicates that the MIE of Last Glacial Cycle probably took place prior to 26–31 ka. Glacier fronts remained stable until 22 ka, as suggests the oldest ^{10}Be ages obtained in the outermost lateral moraine of the Sanabria Lake moraine complex (Rodríguez-Rodríguez et al., 2014). Radiocarbon analysis of the lowest unit retrieved from the San Martin de Castañeda kame terrace – deposited outside this lateral moraine – also provided a minimum age of 21.8–22.1 ^{14}C ka cal BP for the impoundment of the lateral tributary due to moraine build-up (Rodríguez-Rodríguez et al., 2011).

Non-glaciated mountain areas and lower coastal ranges about 600 m were affected by periglaciation, with sedimentary sequences that alternate colluvium deposits with organic-rich paleosoil intervals indicating periglacial activity between 33 and 48.7 ^{14}C ka cal BP (Butzer, 1967; Brosche, 1982; Costa-Casais et al., 1994, 1996; Cano et al., 1997; Costa-Casais, 2001; Blanco-Chao et al., 2007; Pérez-Alberti et al., 2009; Oliva et al., 2016). Therefore, the periglacial belt was close to the coastline during the Last Glacial Cycle, supporting the idea that the glacial record preserved in most mountain areas of the NW ranges corresponds to the Last Glacial Cycle.

Termination-1

The moraine complex preserved around the Sanabria Lake (1000 m), in the Trevinca massif, is the only one that has provided detailed numerical age to constrain the timing of the onset of Termination-1 based on ^{10}Be CRE dating of moraine boulders (Rodríguez-Rodríguez et al., 2014). Recalibrated results support that glacier recession started after 22 ^{10}Be ka and recorded multiple glacier front stagnations with construction of recessional moraines enclosing the lake until 18.5 ^{10}Be ka (Figure 6b). The basal age of lacustrine sequences like Laguna de las Sanguijuelas, deposited between two recessional moraines, provided basal radiocarbon ages of 17.8–18.2 ^{14}C ka cal BP (Muñoz-Sobrino et al., 2004) that are time consistent with moraine ages. Radiocarbon ages from the base of Laguna La Roya (15.3–15.6 ^{14}C ka cal BP; Allen et al., 1996), located at ca. 1630 m on top of the Trevinca high plateau, suggests that the lowest sectors of the Segundera highlands were deglaciated by the time of the OD. Similar conclusions are obtained from Lagoa Grande o das Lamas Lake (1364 m) in the Manzaneda massif, which basal age of 15.0–15.6 ^{14}C ka cal BP indicates that glaciers also disappeared from the lowest sector of this massif during the OD (Maldonado, 1994), consistently with the ^{21}Ne age of 15.4 ka obtained in a drumlin of the Cenza valley (Vidal-Romaní et al., 1999); however, the existence of a drumlin in the area is highly controversial and is not supported by most of the scientific community. The radiocarbon date obtained from a pollen concentrate at the top of the Sanabria Lake basal unit, characterized by inorganic massive sand, suggests that the influence of ablation waters discharge from the glacier disappeared from the eastern sub-basin of the lake around 14.1–14.5 ^{14}C ka cal BP (Rodríguez-Rodríguez et al., 2011; Jambrina-Enríquez et al., 2014). The basal age of the Lleguna sequence, deposited in a glacial over-deepening depression located to the South of the Sanabria Lake, also provided a minimum age of 13.8–14.1 ^{14}C ka cal BP for the time of deglaciation (Muñoz-Sobrino et al., 2004). Thus, numerical ages from the Sanabria Lake and Lleguna sequence suggests that the recession of the Tera glacier front accelerated at ca. 14.5 ^{14}C ka cal BP, at the beginning of the BO. A thin inorganic interval inter-bedded in the organic-rich sequence of Sanabria Lake record has been interpreted as a possible short-lived glacier readvance between 12.1 and 13.1 ^{14}C ka cal BP, before the YD (Jambrina-Enríquez et al., 2014). Most moraines preserved at higher elevations than the Sanabria moraine complex in the Tera valley (1600–1880 m) have not been dated yet, nor those preserved in other massifs (e.g. at 1200–1800 m in Ancares, 1200–1500 m in Courel and Manzaneda). In any case, glacier retreat was probably faster in mountain settings with top elevations under 1700 m altitude, as suggests the basal radiocarbon age obtained in Lucenza Lake (1374 m), in Serra do Courel (20.6–21.4 ^{14}C ka cal BP; Muñoz-Sobrino et al., 2001).

Present day

Since 12.1 ^{14}C ka cal BP (Jambrina-Enríquez et al., 2014), there is neither geomorphic nor sedimentological evidence of recent glacial activity in the NW ranges. Currently, there is only evidence of active nivation processes related to long-lying snow patches in some mountain environments, with formation of protalus ramparts, intense abbrasion of rock surfaces – even forming striations – and mobilization of a large amount of material down-slope (Carrera-Gómez and Valcárcel, 2018). Based on lichenometric measurements, these authors also suggest the occurrence of different stages with more intense nivation processes during the LIA in some NW ranges.

4.4 Central Range

The Central Range, running SW-NE between parallels 40–41ºN, divides in part the Iberian Peninsula approximately in the center. This mountain range is composed of a series of sierras, which are in fact tectonic blocks, formed mostly by crystalline Paleozoic and Precambrian rocks, arranged longitudinally along the axis of the range and separated by large fractures and grabens. At present, there are no active glaciers in the Central Range, but most of its sierras conserve glacial landforms on their summits, which become more significant depending on how far west they are located, and therefore how close they are to the influence of the humid Atlantic air masses. At the western end of the range, the Serra da Estrela (Pico Torre, 1993 m) has glacial valleys more than 13 km long. At the central part, the Sierra de Gredos (Pico Almanzor, 2591 m) and Sierra de Béjar (Pico Calvitero, 2399 m) include also glacial valleys more than 14 km long. The Sierra de Guadarrama (Pico Peñalara, 2428 m) and Sierra de Ayllón (Pico Lobo, 2274 m) at the eastern end of the range, have only glacial cirques less than 2 km long.

Glaciations prior to the Last Glacial Cycle

In the Central Range, the existence of glacial landforms predating the Last Glacial Cycle was proposed for the Laguna Cirque, Sierra de Guadarrama, under the eastern face of Pico Peñalara (Table 5), where there are small maximum advance moraine ridges formed in the Riss glaciation, following the Alpine terminology (Penck, 1883). This relative chronology was accepted later by several other researchers (Fernández Navarro, 1915; Obermaier and Carandell 1917, and others) until the mid-20th century, when these moraines were assigned to the Würm, although no dates were provided (Butzer and Fränzle, 1959). In the early 21st century, CRE dating methods were applied to these moraines (Palacios et al., 2012a), obtaining results that show that they formed during the last glacial cycle, synchronous with or slightly earlier than the LGM. This chronology was confirmed in subsequent studies also in the Sierra de Guadarrama that also used CRE dates, both in the moraines of the Laguna Cirque (Domínguez-Villar et al., 2013) and in the Pelados-El Nevero massif (Carrasco et al., 2016). By contrast, in the Sierra de Gredos and nearby mountains similar evidence of glacial landforms that may have originated during previous glaciations has never been found (Schmieder, 1915; Huget del Villar, 1915, 1917; Obermaier and Carandell, 1916; Vidal Box, 1936; Martínez de Pisón and Muñoz, 1972; Pedraza and Fernández, 1981), and this has been confirmed by more recent studies (Palacios et al., 2011, 2012b; Pedraza et al., 2013; Carrasco et al., 2013, 2015; Domínguez-Villar et al., 2013). The same also occurs in the Serra da Estrela, from the earliest studies of relative chronology (Lautensach, 1929; 1932; Daveau, 1971; Daveau et al., 1997) to the most recent using TL absolute dating techniques (Vieira et al., 2001; Vieira, 2004, 2008); however, ongoing studies have revealed MIS 6 ages for the most external lateral moraines using CRE techniques (Vieira, Palacios and Lorenzo, unpublished data).

Table 5

Last Glacial Cycle

Our current knowledge of the glacial evolution of the Central Range limits the chronology of the glacial landforms to the last Quaternary glacial cycle, and specifically, to its last phases, with the MIE occurring slightly prior to the LGM and important advance and retreat stages during Termination I, but with no geomorphic evidence of Neoglacial ice expansion.

As mentioned above, the distribution and typology of glacial landforms in the Central Range change significantly from the W to the E. In the eastern Sierras de Ayllón and Guadarrama only small cirques are preserved, mostly to leeward of winds bringing the westerly storms (Hernández-Pacheco, 1930) and in most cases there is only a single moraine ridge, or at most two. These small glaciers formed under summits at altitudes higher than 2100 m and their fronts reach elevations of ca. 1800 m. The paleoELA for the Sierra de Guadarrama was estimated at 1900-2000 m (Sanz-Herráiz, 1988). The largest of these cirques is the Laguna cirque in the Peñalara massif, which is approximately 1.8 km long. In this cirque, small moraine ridges – which were considered older than the last glacial cycle (Fernández Navarro, 1915; Obermaier and Carandell 1917) – are located in front of a large complex frontal moraine. CRE dating using ^{36}Cl revealed the ages of these small moraines of the maximum advance ranging from 29–31 ka for a boulder on a northern side of the ridge to 16–22 ka for various boulders on a southern slope (Palacios et al., 2012a). In parallel, the main moraine system composed of several ridges superimposed on the front and aggregated into only one on the laterals yielded ages ranging from 16 to 27 ka. Consequently, these data suggest that the local MIE in this massif preceded the LGM by several thousand years, when the front was relatively stable, with subsequent minor advances and retreats resulting in a large polygenic moraine. The magnitude of this moraine was such that large snow patches developed on its fronts to leeward of the westerly winds, displacing boulders which then formed what seem to be small maximum advance ridges. This process may explain why the same ages are found in the main moraine as well as in the small ridges outside the glaciated environment (Palacios et al., 2012a). In the same Peñalara massif, CRE dating also confirmed a LGM age of 26 ^{36}Cl ka for the main moraine of the Pepe Hernando cirque (Palacios et al., 2012a).

The chronological framework for Peñalara massif coincides with CRE ^{10}Be dates in other small Guadarrama cirques, such as in the Los Pelados-El Nevero massif, 16 km NE of the Peñalara massif (Domínguez-Villar et al., 2013; Carrasco et al., 2016). Other glacial landforms existing in Guadarrama cirques are possibly synchronous to those of Peñalara massif based on their similar morphology and degree of preservation, though no chronological data are available to date (Fernández Navarro, 1915; Obermaier and Carandell, 1917, Fränzle, 1959; Sanz-Herráiz, 1988; among others).

A block field located on the Peñalara summit has been CRE dated at 80 ^{36}Cl ka, which confirms that in most of the eastern sierras of the Central Range the summits were ice-free during the local MIE (Palacios et al., 2012a). A small plateau glacier with some ice-free summits has only been described in the Pelados-el Nevero massif, a very small area in these mountains. The age of these nunataks protruding the glacial ice ranged from 33.5 to 59.7 ^{10}Be ka, which is slightly younger than those obtained on the summit of Peñalara, but they confirm that these surfaces were ice-free during the MIE (Carrasco et al., 2016). On the north face of the Pico Mujer Muerta, also in the Sierra de Guadarrama, some sedimentary formations have been classified as alluvial fans formed during the paraglacial stage and dated at 30-35 OSL ka (Bullón, 2016).

Contrary to what occurs in the eastern sierras of the Central Range, the central Sierras de Gredos and Béjar were covered by ice caps with a larger extension to the N and E, and with a few short tongues descending to the S (Pedraza et al., 2013, Carrasco et al., 2013). These authors synthesized the geomorphological evolution that is common to most glaciated valleys in these central sierras of the Central Range, where a large moraine was formed. But in many cases, in sectors further from the sides or front of the main moraine, there are isolated glacial boulders or small moraine ridges (Figure 7a). These deposits were dated by CRE methods using ^{10}Be isotope, and as in Peñalara, the ages obtained resulted in a glacial stage that occurred several thousand years before the LGM (26–31 ka) (Domínguez-Villar et al., 2013, Carrasco et al., 2013, 2015). This period of maximum ice extent would have coincided with a wet, cold phase, as shown by the U-Th speleotheme dating in a cave in the southern foothills of the Sierra de Gredos (Domínguez-Villar et al., 2013).

Figure 7

There have been several atempts to constrain the age of the main moraine in some valleys in Gredos and Béjar, which must have formed during several stages of advance and stabilization. The largest glaciers (ca. 14 km long) formed in the highest northern valleys of the Sierra de Gredos and reached elevations down to 1400 m, with the ELA estimated at 1830 m (Palacios et al., 2011). In the Gredos valley, under the north face of the Pico Almanzor, some boulders of the main moraine system were dated in areas just where the valley widens and the slope gradient decreases. This moraine, which was a single lateral polygenic ridge, divides in this sector to form several very stable ridges. CRE dating using ^{36}Cl isotope reported ages of 20–26 ka for these boulders, suggesting a LGM age (Palacios et al., 2011). In the nearby Pinar valley, the same dating method applied to several boulders of the main moraine system showed very similar results, with ages ranging from 19 to 24 ka (Palacios et al., 2012b).

The Sierra de Béjar was covered by an ice cap of 57 km^2, with the glacier tongues (max. length 8 km) descending to around 1200 m, and a mean ELA of 2010 m (Carrasco et al., 2013). Boulders from moraine formations in the Duque, Trampal, Endrinal and Cuerpo de Hombre valleys dated by CRE using isotope ^{10}Be yielded ages from 19 to 27 ka (Carrasco et al., 2013, 2015), very similar to those of Gredos. The largest ice cap of the Central Range was located in its western fringe, the Serra da Estrela, encompassing a surface of 66 km^2 and a thickness of 340 m in some valleys. At that time, the ELA was placed at 1640 m (Vieira, 2004, 2008). Only few data on glacial landforms are available; some fluvio-glacial deposits were dated through OSL at 30–35 ka (Vieira et al., 2001) and a preliminary approach using CRE dating by the ^{36}Cl isotope on boulders of the large moraine complexes yielded ages around 21–26 ka, very similar to the rest of the Central Range (Palacios et al., 2012c).

In the Serra da Estrela, the largest moraines were dated at 31–26 ^{36}Cl ka, with a sequence of internal moraine ridges indicative of several minor advances and retreats until 18–16 ^{36}Cl ka (Vieira and Palacios, 2010; Vieira, Palacios and Lorenzo, unpublished data).

In summary, the available data suggest that the maximum ice extent occurred slightly before the LGM, at 27–35 ka, although it was a short glacial advance that left only minor landforms. The LGM advance was very significant and lasted for thousands of years, with small advances and retreats, which led to the development of a large polygenic moraine in each valley.

Termination-1

In the Peñalara massif, moraines that may have formed during the OD are spatially close to those of the LGM, with ages of 16–17 ^{36}Cl ka. Some of these areas were affected by intense paraglacial dynamics that triggered the development of rock glaciers, though they stabilized shortly after their formation at around 15 ^{36}Cl ka (Palacios et al., 2012a). Something similar occurred in the Gredos valley where polished surfaces located behind the main moraines have been dated at around 16 ka ^{36}Cl. In the Pinar valley and in Peñalara, moraines of 16–17 ^{36}Cl ka are located next to those of the LGM features. Similarly, in the Cuerpo de Hombre valley, moraines dated at 15–17 ^{10}Be ka are very close to the LGM. This evidence highlights the occurrence of important glacial advances in the Central Range during the OD, with slightly smaller glaciers than during the LGM and even, in come cases, next to them (Palacios et al., 2017). In the Serra da Estrela, a polished threshold near the summit shows that the ice cap disappeared at 15 ^{36}Cl ka (Vieira and Palacios, 2010; Palacios et al., 2012c). Only recently, some data are indicative of small glacial advances during the YD in the Cuerpo de Hombre valley, with moraines dated at 11–13 ^{10}Be ka (Carrasco et al., 2015).

In conclusion, the deglaciation of the Central Range seems to have followed a similar pattern to that detected in other European mountains, with a major advance during the OD that favoured the expansion of glaciers until almost the LGM moraines or until a few hundred meters from them (Palacios et al., 2017). The recent dating of a moraine of the YD in the Sierra de Béjar may suggest that the YD also promoted glacial expansion in the Central Range, though few dates are already available for this period in contrast to in other Iberian mountains where YD moraines are widespread (García-Ruiz et al., 2016).

Holocene

Three CRE datings reveal the definitive disappearance of glaciers in the Central Range during the Early Holocene. A polished bedrock surface below the summit of Peñalara indicates an approximate age of 11 ^{36}Cl ka (Palacios et al., 2012a). At the head of the Pinar valley, the dating of a abraded surface also yielded an age between 10 and 11 ^{36}Cl ka (Palacios et al., 2012b). In the Cuerpo de Hombre valley, the moraine located under the headwall yielded a minimum age of 11 ^{10}Be ka (Carrasco et al., 2015).

Although there is still much to research, the available data seem to indicate that the glaciers of the Central Range disappeared definitively in the transition between the Pleistocene and the Holocene, or in the onset of the Holocene.

LIA

There is no geomorphic evidence of subsequent formation of glaciers, neither during the Neoglacial period nor during the LIA. There is only one protalus rampart located in the Gredos cirque that was dated by lichenometry and showed its development during the LIA (García-Sancho et al., 2001), although there might be other similar landforms in other Central Range cirques.

Present day

Current cold-climate geomorphological processes in the Central Range are only limited to the erosive activity of long-term snow patches, particularly during colder periods, such as the late 1960s and early 1970s (Palacios et al., 2003).

4.5 Iberian Range

The Iberian Range limits the Central Iberian plateau by its N and NE sides. This range, extended in NW-SE disposition along 500 km, is composed both by basement fragments and sectors of sedimentary cover with variable thickness. From N to S and W to E the main ranges are: Sierra de la Demanda (San Lorenzo, 2271 m), Sierra de Neila (Campiña, 2049 m), Picos de Urbión (Urbión, 2228 m), Sierra Cebollera (La Mesa, 2168 m) and Sierra del Moncayo (Moncayo Peak, 2314 m). The first approach to the Iberian Range glaciers corresponded to Carandell and Gómez de Llarena (1918), mainly focused on the Sierra de Urbión, which was also studied in detail by Thornes (1968). The Sierra de la Demanda was analyzed by García-Ruiz (1979), Antón-Burgos (1985), Arnáez-Vadillo (1987), Arnáez-Vadillo and García-Ruiz (1990) and recently, Fernández-Fernández et al. (2017), whereas the Sierra Cebollera was studied by Ortigosa (1985, 1986), Sanz Pérez and Pellicer (1994) and García-Ruiz et al. (2007), who published a geomorphologic map of the Sierra Cebollera. A brief description of the geomorphology of the Sierra de Neila was performed by Ortega and Centeno (1987). The Sierra del Moncayo has been the object of detailed studies by Martínez de Pisón and Arenillas (1976) and Pellicer (1984). Besides, García-Ruiz et al. (1998) synthesized the available information on glacial landforms and deposits in the Iberian Range.

Table 6

Glacier snouts reached 1650 m during the MIE in the Sierra de la Demanda, similarly to the Sierra del Moncayo, where glaciers remained confined in three cirques of steep slopes. By contrast, glaciers in the Neila, Urbión and Cebollera massifs were hosted in larger cirques favoured by the structural setting shaped by the main divide formed by a cuesta scarp with low-dip strata (Ortigosa, 1986). The best examples of glacial valleys in the Iberian Range are found in these ranges, with well-developed glacial troughs that can reach 6-km long in the Urbión valley, and over 3-km long in the NE cirque of La Mesa de Cebollera Peak. The Urbión valley encompasses the glacial deposits at elevations of ca. 1270 m, and even lateral obturation deposits at the confluence with tributary ravines (García-Ruiz et al., 1998).

CRE dating techniques, through ^{10}Be, have only been applied in the Sierra de la Demanda, in the westernmost cirque of the Mencilla Peak and in the SE cirque of the San Lorenzo peak (Fernández-Fernández et al., 2017).

Figure 8

Glaciations prior to the Last Glacial Cycle

Lotze (1962) attributed the glacial morphologies existing in the Sierra de la Demanda to the Riss glaciation but did not provide any absolute date. Nonetheless, the hypothesis of glacial landforms being originated in a previous glaciation in Sierra de la Demanda was rejected by García-Ruiz (1979) in favor of the Würm glaciation as the only glacial stage including different climatic oscillations. The author defended this origin based on their fresh morphology, with scarcely developed landforms and absence of postglacial regressive erosion, together with the similar grain size and composition of the moraines as well as the short distance between them. The best example of this fact was found in the westernmost cirque of the Mencilla Peak (García-Ruiz, 1979), although the author did not dismiss the possibility that the outermost moraine in the SE San Lorenzo cirque could have formed during a previous glaciation as suggested by the existence of undifferentiated till distributed across the slope as well as the presence of a soil layer on the surface. Based on the similar gran size of the frontal moraines, Thornes (1968) also attributed the glacial features existing in Urbión to the Würm glaciation. In fact, the existence of older moraines in the SE cirque of the San Lorenzo peak cannot be discarded due to the presence of erratic boulders outside the outermost moraine (Fernández-Fernández et al., 2017).

Last Glacial Cycle

The outermost moraine of the Mencilla cirque, Sierra de la Demanda, could not be dated due to the fact that intense weathering has resulted in the inexistence of suitable boulders for CRE dating. In the case of the SE San Lorenzo cirque, the outermost moraine yielded a minimum age of 18.1 ± 2.3 ^{10}Be ka (Table 6). Although the intermediate moraine could not be dated, considering the Late Pleistocene chronology of neighbouring glaciated areas, the relative position of the moraines within the cirque and the partial overlapping of the age of the outermost and the innermost (16.8 ± 1.4 ^{10}Be ka) moraines, it could be argued that the intermediate moraine could have been formed during the LGM (Figure 8). Thus, the outermost moraine might have been deposited during a previous glacial expansion (Fernández-Fernández et al., 2017). Glaciers hardly reached 1 km long during their maximum extent, and their ELAs descended to 1480 m in the Mencilla peak cirques and to 1671 m in the SE cirque of the San Lorenzo peak.

The different massifs of the Iberian Range include abundant examples of moraine systems, sometimes up to three frontal moraines suggesting different stages of advance and retreat. Some of these moraines can be of great size, with large boulder accumulations resulting from the intense network of fractures affecting the cirque headwalls. Apart from those existing in the Sierra de la Demanda, there are also several good moraine complexes, such as in the Laguna Negra valley (Sierra de Urbión), in the NE valley of La Mesa de Cebollera (Sierra de Cebollera) and in the Morca and San Miguel cirques in the Sierra del Moncayo (Martínez de Pisón and Arenillas Parra, 1976; Pellicer, 1984). A well-developed moraine arc has been recently identified close to Orihuela del Tremedal, Albarracín Massif, in the SE limit of the Iberian Range, dominated by a quartzitic crest at 1920 m. This deposit has not been yet dated, although it most likely represents the maximum extent of a small, isolated glacier in a relatively low and southern massif (González-Sampériz et al., 2006-2007).

Termination-1

As in other Iberian mountain areas, the sequence of deglaciation at the end of the LGM is not properly constrained (Table 6). The only reference comes from the Sierra de Neila, where the ^{14}C dating of lacustrine sediments of the Laguna Grande suggests that the end of the MIE of the San Salvador glacier and the onset of glacial retreat started at 21 ^{14}C ka cal BP, thus at the end of the LGM (Vegas, 2007a, 2007b). The maximum glacial advance was also prior to the LGM in the nearby Laguna del Hornillo (Sierra de Urbión), at 31.3 ^{14}C ka cal BP (Vegas, 2006).

In the Mencilla and San Lorenzo cirques a similar number of moraines has been found, which may be indicative of a simultaneous deposition in both areas, or at least, similar response to the climatic fluctuations (Fernández-Fernández et al., 2017). Here, although several attempts to date these moraines systems have been done, the abovementioned issues made also difficult to constrain the chronology of events leading up to Termination-1. The innermost moraine of the San Lorenzo cirque was the only ridge dated with accuracy, with a mean age of 16.8 ± 1.4 ^{10}Be ka; it thus corresponds to a glacial readvance occurred during the OD (Table 6). Although the inner moraines of the other Mencilla cirques could not be dated, they might have been deposited simultaneously.

In the Mencilla and San Lorenzo cirques, 2-m-thick loose accumulations of boulders, with longitudinal ridges and furrows and collapse depressions, have been identified as fossil debris-covered glaciers (Fernández-Fernández et al., 2017) rather than rock glaciers as they had been previously classified (García-Ruiz et al., 1998). These accumulations appear at similar relative positions within the cirques, between the intermediate and innermost moraines. This fact demonstrates that the debris-covered glacier in the SE San Lorenzo cirque developed prior to the OD, probably during the deglaciation initiated at the end of the LGM. The context of formation would correspond to a residual small-sized glacier nested at the bottom of the cirque, over which large volumes of rocks fell from the ice-free headwalls (Fernández-Fernández et al., 2017). Consequently, the debris mantle protected and isolated the underlying ice, reducing and delaying its melting. The ages of two boulders sampled from the debris mantle at the SE San Lorenzo cirque (around 16.4 and 15.8 ^{10}Be ka) indicated that melting started earlier than in the westernmost cirque of the Mencilla cirque due to the higher solar radiation received in a SE aspect (Fernández-Fernández et al., 2017). Lake sediments from the Laguna Grande (Sierra de Neila) evidenced a massive retreat of the San Salvador glacier during the Bølling sub-interestadial at 14.0–13.8 ^{14}C ka cal BP and the reactivation of the glacial and periglacial processes in the higher areas of the catchment at 13.4–13.1 ^{14}C ka cal BP (Vegas, 2007a, 2007b). Glaciers in Sierra de Neila disappeared between 13.1 and 12.5 ^{14}C ka cal BP, when no evidence of glacial activity was detected in the lacustrine sediments from Laguna Grande (Vegas, 2007a, 2007b).

Although glacial activity during the YD has not been found yet in these areas, García-Ruiz et al. (2016) suggested a Late-glacial origin for the uppermost moraine of the easternmost cirque of the Mencilla Peak, based on its fresh appearance, i.e. acute crest, and the absence of soil development and vegetation.

Holocene

Four ^{10}Be ages from the debris mantle distributed in the cirque floor of San Lorenzo, ranging from 16.4 ± 1.7 ka to 8.9 ± 0.8 ka (Supplementary material), indicate that the ice of the debris-covered glacier gradually melted out until it completely disappeared at 8.9 ka (Fernández-Fernández et al., 2017). The ages obtained at the westernmost Mencilla cirque are less scattered, clustering at 8.2–5.9 ^{10}Be ka. This indicates a longer persistence of the debris-covered ice until well the Mid-Holocene, favoured by the NNE aspect of the cirque, and a sudden and faster melting during the Holocene Thermal Optimum, when the climate was warm enough to counterbalance the protecting and isolating effect of the debris mantle (Fernández-Fernández et al., 2017). The intermediate moraine enclosing the debris mantle of the westernmost cirque of Mencilla reported ages of 6.6–6.2 ^{10}Be ka, which shows evidence of a late stabilization of the moraine together with the debris-mantle rather than the age of sedimentation (Fernández-Fernández et al., 2017). It is likely that in other massifs of the

Iberian Range, a similar calendar for the final disappearance of the remnants of Late Pleistocene glaciers existed in sheltered northern slopes, at the foot of steep headwalls in the highest cirques.

4.6 Betic Range

Within the Betic Range, the Sierra Nevada is the only massif that encompassed glaciers during the Last Glacial Cycle as well as during most of the deglaciation process until the second half of the 20th century, when the LIA remnants of the large Quaternary glaciers finally melted away. Depending on the combination of cold and moisture conditions, glaciers in the Sierra Nevada concentrated more or less ice. By contrast, other Betic massifs, namely Sierra de Gádor (Sermet, 1942), may have encompassed small glaciers during periods of maximum ice accumulation during the Last Glacial Cycle, but they must have melted away soon after temperatures start rising at 19–20 ka (Clark et al., 2009).

Sierra Nevada includes the highest summits in the Iberian Peninsula, with several peaks above 3000 m in its westernmost fringe (Mulhacén, 3478 m; Veleta, 3398 m; Alcazaba, 3371 m), which is mainly composed of micaschists. The configuration of the landscape of the high lands in the Sierra Nevada conditioned the geography of the glaciated environment, with glaciers confined within the valleys and few convergence of tongues or transfluence between cirques, but never reaching the lowlands (Gómez-Ortiz, 2002). Besides, the location of the massif between two oceans (the “cool” Atlantic vs the “warm” Mediterranean) conditioned the geography of paleoglaciers and the distribution of moraine complexes.

Table 7

Glaciations prior to the Last Glacial Cycle

In the 1960s and 1970s, some authors proposed the existence of large glaciations in the Sierra Nevada that occurred prior to the last Pleistocene glacial cycle, with glaciers flowing down-valleys until elevations of ca. 1100 to 1600 m (Hempel, 1960; Messerli, 1965; Lhenaff, 1977; Sánchez-Gómez, 1990). These observations were made based on geomorphic evidence, namely eroded moraines and glacio-fluvial sediments located several hundreds of meters downslope the glaciated environments of the Last Glacial Cycle (Gómez-Ortiz and Pérez-González, 2001). Recently, new datings have confirmed these observations, yielding CRE ages of ca. 130-135 ^{10}Be ka for the outermost moraines at 2160-2260 m at the Naute valley (Palacios et al, 2019) (Figure 9a). In addition, new observational data suggest other potential sites for reconstructing the extent and chronology of glaciers during the “Riss” glaciation, such as the erratic boulders distributed in the southern gentle slope of the gentle Mulhacén plateau or other low-altitude glacigenic features (i.e. till, dismantled moraines) in lower parts of some valleys. However, the time passed since that glacial stage, the semi-arid climate regime with occasional torrential rainfall events together with the intensity of postglacial environmental dynamics, namely slope processes, make it difficult to infer old glaciations (Gómez-Ortiz et al., 2013a; Oliva et al, 2014b; Palacios et al., 2016).

Figure 9

Last Glacial Cycle

A recent spatial reconstruction of the MIE of the Last Glacial Cycle based on the limits of the well-defined outermost moraines generated during this stage has revealed a glaciated environment extending across 105 km^2 in the western side of the massif (Palma et al., 2017). The chronology of the MIE of the Last Glacial Cycle shows an asynchronous pattern with respect to other Iberian mountains, with the MIE occurring at ca. 30 ^{36}Cl ka (Gómez-Ortiz et al., 2012a; Palacios et al., 2016). A second maximum glacial expansion occurred at 19–20 ka, with the construction of moraines close to the location of the MIE outermost moraines (Palacios et al, 2019). This stage has been dated at ca. 19.6 ^{36}Cl ka (at 1975 m, on the north slope) and ca. 19 ^{36}Cl ka (at 2445 m, on the south slope) (Gómez-Ortiz et al., 2012a). No data on glacial dynamics are yet available from 30 to 20 ka.

In northern valleys, the paleoELA was placed ca. 100–150 m below than in southern valleys due to greater continentality, and the influence of warmer temperatures of the Mediterranean Sea conditioned an elevation difference of ca. 200-300 m of MIE moraines between the W and E in both sides of the massif (Oliva, 2009; Oliva et al., 2014a). Glaciers flowed down-valleys to elevations slightly below 2000 m on the north-facing slope of the massif and ca. 2500 m on the south (Gómez-Ortiz et al., 2002). The western valleys exposed to the maritime Atlantic flows were those encompassing the largest glacial systems, reaching in some cases 8–9 km, such as the Dílar, Monachil and the Guarnón-Valdeinfierno-Valdecasillas complex. In the case of the southern slope of the massif, glaciers descended between 3 and 6 km (Poqueira system, Trevélez), with a maximum of 8 km in the narrow but SW-exposed Lanjarón valley. The lower precipitation, higher temperatures and lower altitudes of the eastern side of the massif conditioned the absence of well-developed glaciers, with just a few glacio-nival spots in both sides of the massif.

In the highest lands of the Sierra Nevada, above the ELA, the relatively flat topography of some areas together with wind action did not favour snow accumulation and subsequent transformation into ice. In these areas, periglacial activity was very intense with the formation of metric sorted-circles associated to permafrost conditions (Oliva et al., 2016a; Palma et al., 2017). Besides, the dating of the bedrock of the Veleta peak resulted in ca. 30 ^{36}Cl ka (Gómez-Ortiz et al., 2012a, 2015), suggesting that the highest peaks were ice-free during the coldest stages of the Last Glacial Cycle, and therefore functioned as nunataks (Oliva et al., 2014a, b). The periglacial belt also extended below the present-day cryonival environment established at ca. 2650 m, reaching elevations of 1000–1100 m according to the existence of stratified debris in the lowlands surrounding the Sierra Nevada (Gómez-Ortiz and Salvador-Franch, 1992).

Termination-1

The temperature increase recorded globally since 19–20 ka (Clark et al., 2009) caused a rapid glacial retreat in the Sierra Nevada, with glaciers shrinking upslope to the head of the valleys. Glaciers probably (almost?) disappeared from the massif a few millennia later, though a new cooling recorded during the OD favoured their expansion at ca. 17 ^{36}Cl ka (Palacios et al., 2016b). The role of topography was crucial for the development of glaciers during the coldest stages of the deglaciation: the W-E alignment of the massif conditioned the accumulation of more snow in the western slopes of the valleys due to wind redistribution, thus favouring the persistence of glaciers in these areas.

During the OD, the volume of glaciers was slightly lower than during the MIE and the ice filled the valley bottoms but did not reach the heads of the valleys, as occurred in San Juan valley (Palacios et al., 2016a) (Figure 9c). In other cases, such as in the Hoya de la Mora, OD glaciers deposited debris on the internal side of the LGM moraine, thus forming polygenic moraine systems. However, the temperature increase registered at the end of the OD and onset of the BO, at ca. 14.5–15^{36}Cl ka, favoured a massive deglaciation (Palacios et al., 2016a).

Following the warm BA stage – when glaciers must have been very small or even absent in the Sierra Nevada –, the cooling recorded during the YD also promoted the development of small glaciers in cirques shaped on east-facing slopes. In some cases, these glaciers flowed down-valleys along 2–3 km, e.g. San Juan valley, forming longitudinal moraine ridges parallel to the main valley axis (Palacios et al., 2016a). At the end of the YD, glaciers disappeared from the lowest cirques as well as from most of the highest southern cirques of the massif, e.g. Rio Seco (Oliva et al., 2011, 2014a), and only persisted in the highest sheltered environments at the foot of vertical headwalls.

Holocene

In contrast to what happens in other Iberian mountain ranges, in the Sierra Nevada there is geomorphic evidence of glacial activity during the Holocene. The shrinking YD glaciers distributed in the highest cirques, particularly in east-facing slopes, melted away during the Early Holocene at ca. 9–10 ^{36}Cl ka as temperatures keep rising (Palacios et al., 2016a). At the foot of cirque headwalls, paraglacial activity during this stage favoured slope activity, with rock falls and landslides covering of debris the remnants of glacial ice (Oliva et al., 2014a). These frozen ice bodies trapped under the debris cover triggered the formation of several generations of rock glaciers within the glacial cirques that finally stabilized at ca. 6-7 ^{36}Cl ka (Palade et al., 2011; Gómez-Ortiz et al., 2012a, 2013b; Palacios et al., 2016a).

There is also sedimentological evidence of the presence of glaciers in the Sierra Nevada during the Late Holocene, namely inferred through the La Mosca Lake record in the northern Mulhacén cirque. Three stages with sand deposition and very low organic carbon content suggest the existence of a small glacial spot at the foot of the northern wall of the Mulhacén peak at ca. 2.8–2.7, 1.4–1.2 ^{14}C ka cal BP and 510–240 ^{14}C cal yr BP (Oliva and Gómez-Ortiz, 2012). In addition, the sequence of several moraine ridges distributed across this cirque floor above the La Mosca Lake suggests the existence of several other glacial stages during the Holocene (Oliva et al., 2015).

Little Ice Age

The last of these glacial stages corresponds to the LIA, when the Sierra Nevada's glaciers were the southernmost in Europe (Gómez-Ortiz et al., 2001). Historical documents and cirque moraines show evidence of the presence of glaciers in the highest northern cirques stretching from the Mulhacén to the Veleta peaks during the LIA (Gómez-Ortiz et al., 2009, 2014, 2018; Oliva and Gómez-Ortiz, 2012). Recently, the first attempt to date LIA moraines by CRE in the Iberian Peninsula provided new absolute ages for the moraines existing in the Veleta cirque. CRE ^{10}Be ages suggest that the outermost moraine ridge formed during the early 14th century, whereas the innermost ridge developed during the 17th century (Palacios et al., 2019). These ages correspond, respectively, to the onset and the coldest climate conditions of the LIA reconstructed for Iberian mountains (Oliva et al., 2018).

The glacier held in the Mulhacén cirque appeared around 1440 CE and disappeared by 1710 CE, when temperatures increased from the Maunder Minimum (Oliva and Gómez-Ortiz, 2012; Oliva, 2018). By contrast, the glacier installed in the Veleta cirque persisted until the mid-20th century (Schulte, 2002; Gómez-Ortiz et al., 2018). This age difference spanning more than two centuries is explained by the higher elevation of the valley floor in the Veleta cirque with respect to the Mulhacén cirque (3100 vs 2950 m) as well as its prevailing aspect determining lower solar radiation (N vs NNW) (Oliva and Gómez-Ortiz, 2012).

Present-day

A temperature increase of 0.93 ºC from mid-19th century until the early 21st century led to the disappearance of LIA glaciers in the Sierra Nevada as well as gradual shrinking of the snow fields in the highest lands (Oliva and Gómez-Ortiz, 2012). Post-LIA glacial processes are reshaping the sequence of small moraines in the Mulhacén cirque and the frontal moraine closing the head valleys of the Guarnón Valley at the foot of the Veleta northern wall through alluvial, slope and periglacial processes. The last traces of LIA glaciers are still trapped under the debris cover in the Mulhacén and Veleta cirques (Oliva et al., 2014a, 2016b). These frozen bodies have favoured the development of isolated permafrost patches that led to the formation of permafrost-derived landforms showing visible signs of degradation by means of collapses and subsidence of the debris cover. This is the case of the rock glacier existing in the Veleta cirque (Gómez-Ortiz et al., 2001, 2014) as well as the protalus lobe placed at the foot of the Mulhacén northern wall (Serrano et al., 2018).

5- Discussion

The Quaternary period has been characterized by a long-term gradual decline of temperatures as well as an amplification of the magnitude of cold and warm cycles (Lisiecki and Raymo, 2005). This resulted in changing patterns of environmental dynamics prevailing across the Earth's surface. In mid-latitude mountain environments, such as Iberian ranges, the low temperatures during Quaternary cold stages favoured glacial expansion whereas warm periods promoted periglacial dynamics reshaping the formerly glaciated environments (Oliva et al., 2016a).

In the Iberian Peninsula, Quaternary glacial processes shaped the highest ranges (reaching up to 3478 m), with geomorphic evidence of past glaciations also present in relatively mountain ranges (<1000 m) in the far NW (Figure 6c). Unlike periglacial dynamics during the Last Glacial Cycle, which was was not only intense throughout the mountains but also in some Iberian basins (Oliva et al., 2016a), glaciers did not reach the lowlands and remained always confined within the mountain systems. Nevertheless, wide altitudinal range of glacial features in the mountains suggests the occurrence of different glacial stages associated with different climatic conditions. Remarkably, there is also a large elevation range between the lowest glacial deposits of the MIE across Iberia, with the lowest records in the NW corner located at 600–700 m (Pérez-Alberti et al., 1993) and MIE moraines in the Sierra Nevada distributed at 1900–2000 m (Gómez-Ortiz et al., 2012a; Palacios et al., 2016). The spatial distribution of glaciated environments during the Quaternary is explained by the both latitude effects and well as regional patterns of regional precipitation, which closely match the patterns observed today, with the wettest and coldest area associated with NW Spain. The similarity between former glaciers ELAs and modern precipitation isohyets indicates that the drivers of moisture supply were the same in the Pleistocene as they are today, namely Atlantic westerlies. Patterns of glaciation were affected through time by shifting positions of the North Atlantic Polar Front which was situated to the west of Iberia during the Last Glacial Cycle and through Termination I (Ruddimann and McIntyre 1981a, b).

Whereas climate is the main factor driving the type and intensity of cold-climate geomorphological processes (glacial vs periglacial) in mid-latitude mountains, other factors such as preglacial relief, topography and lithological conditions determine the degree of preservation of certain landforms as well as the morphometry of some glacial features. Lithology exerts a clear control on the morphometry of glacial cirques, which are shaped in all type of bedrocks existing in the Iberian mountains (Ruiz-Fernández et al., 2009; García-Ruiz et al. 2000; Delmas et al., 2014; Gómez-Villar et al., 2015) but tend to be larger in granitic substrates (Lopes et al., 2018), or on the preservation of certain glacial erosional morphologies, such as glacial striations on limestones, which are scarce due to intense chemical weathering. Topographic constraints – namely elevation, aspect and slope angle – are crucial elements controlling the extent of glaciations, but also condition the morphometry (and postglacial preservation) of glacier-derived features. In the Northern Hemisphere, glacial cirques are significantly larger in northern slopes where ice accumulation is greater (Evans, 2006), though northern winds during Quaternary glacial stages may have also promoted the transport of snow from the summit plateaus to S and SE cirques and favoured the enlargement of these landforms (Delmas et al., 2014). Another factor that needs to be considered in order to interpret the geography of past glaciations is the long time passed since the oldest glaciations. Intense postglacial erosive processes may have significantly degraded moraines or removed the sedimentary evidence entirely (Palacios et al., 2019). This may explain the absence of glacial features corresponding to certain stages in some massifs. Therefore, the data discussed in this paper cannot account for past glacial periods that are not preserved in the geological record or have not been yet detected.

Consequently, determining the succession of glacial stages and their traces on present-day mountain landscape requires combining accurate geomorphological observations with a thorough understanding of the different past and present climate and geographical influences. In order to reconstruct spatio-temporal patterns of past glaciations, we need to take into account different geographical scales (from macro- to micro-) along with the diversity of factors influencing environmental dynamics in these mountains (climate, lithology, topography) operating at both long- and short-term scales. Based on geomorphic evidence and chronological data, we can distinguish several glacial phases in the Iberian Peninsula during the Late Quaternary (Figure 10):

Figure 10

5.1 Glaciations prior to the Last Glacial Cycle

The Alpine terminology that was widely accepted by the scientific community until the last decades of the 20th century described four main glacial stages during the Quaternary (Penck and Brückner, 1909). According to this old literature, the glaciation occurred before the last interglacial (Eemian) was named Riss. Subsequently, marine sediment cores provided evidence of the several other glacial periods during the Quaternary and the use of the isotopic nomenclature became widespread (Emiliani, 1955, 1966; Shackleton, 1967). Today, this penultimate glaciation of the Pleistocene epoch corresponds to MIS 6.

In the Iberian Peninsula, the first researcher proposing the existence of glaciations predating the Last Glacial Cycle was Penck (1883), who suggested three glacial stages in the Pyrenees (Würm, Riss and Mindel) based on the existing glacial deposits. The widespread use of this Alpine chronology pushed scientists to find geomorphic evidence of these older glaciations in different Iberian massifs, and thus several researchers suggested the possible existence of older glaciations. Geomorphic evidence came from very eroded moraines, fluvio-glacial terraces and erratic boulders distributed at very high elevations from the valley floor. This was proposed for the Pyrenees (Panzer, 1926), Cantabrian Mountains (Hernández-Pacheco, 1944), NW ranges (Taboada, 1913), and Sierra Nevada (Messerli, 1965).

However, very few absolute dates are available for MIS 6 that confirm the occurrence of glaciations that took place before the last Pleistocene glacial cycle. Based on CRE dating using ^{21}Ne, Vidal-Romaní et al., (2015) reported controversial ages for the maximum glacial advance in two NW massifs at 155 ± 30 ka (Serra da Queixa) and two glacial episodes at 231 ± 48 and 135 ± 31 ka (Serra do Gerês-Xurés). In the Sierra Nevada, recent data based on ^{10}Be revealed that the largest glacial advance – slightly greater than that of the LGM – occurred at ca. 130–135 ka (Palacios et al., 2019). In the Central Pyrenees, a stage of glacial expansion occurred at ca. 170 ka (García-Ruiz et al., 2013). Therefore, it is likely to consider that most Iberian ranges recorded a period of glacial expansion between ca. 130 and 170 ka (Figure 11), which may be associated with the Riss glaciation described by scientists several decades before.

Figure 11

Very low temperatures led to the most extensive glaciation in the Alps that took place before the last interglacial during MIS 6 (186–127 ka), with a minimum estimated age for the MIE of 155 ka (Ivy-Ochs et al., 2006). CRE dating reported a range between 126 and 184 ^{10}Be ka for the deposition of large erratic boulders of Alpine origin in the Swiss Jura Mountains (Graf et al., 2007), with widespread evidence also of the existence of large glaciers based on OSL dating at ca. 150 ka (Bickel et al., 2015), slightly younger (between 135 and 149 ka; Preusser and Schlüchter, 2004) or older (between 153 and 160 ka; Dehnert et al., 2010), depending on the area. A large number of records indicate also the occurrence of a massive glacial advance during this time in northern Europe (Böse et al., 2012), such as in the British Isles (Gibbard et al., 2018) and continental Europe with the Saalian Stage glaciation being the most extensive ever recorded in some places such as the Netherlands (Laban and van der Meer, 2011). However, in most places an even larger glaciation pre-dates MIS 6 which is usually correlated with MIS 12 (or 16). The largest glaciation recorded in northern Europe is associated with Anglian/Elsterian Stage in the British Isles and continental Europe, respectively, whilst the largest glaciation recorded in Russia/Ukraine occurred in the Donian Stage (MIS 16) (Ehlers et al., 2011). MIS 12 has also been identified as the most extensive recorded glaciation in the Greek Pindus (Hughes et al., 2006b), Montenegro (Hughes et al., 2010, 2011), Croatia (Marjanac, 2012). However, in Iberia, the only dating evidence related to this earlier phase of glaciation comes from the Cantabrian Mountains (Villa et al., 2013) and it is likely that either MIS 6 glaciations were larger in much of Iberia or that MIS 12 deposits have been largely eroded or degraded. Even older Early Pleistocene glaciations have been argued for some glacial valleys in the Picos de Europa based on subterranean speleothem U-series ages (Gale and Hoare, 1997). It is likely that glaciers formed in Iberia in all Pleistocene cold stages, only that the glacialgeomorphological record is inherently fragmentary. For example, in the Italian Appennines evidence for glaciations have been identified in a proglacial lake basin dating to MIS 14, 12, 10, 8 and 6, in addition to moraines dating to the Last Glacial Cycle (Giraudi and Giaccio, 2017).

5.2 Chronology of the maximum ice extent of the Last Glacial Cycle

The Last Glacial Cycle corresponds to the period MIS 5d-2 following the Eemian interglacial (MIS 5e) that ended at 115 ka (Dahl-Jensen et al., 2013). It was a period with highly variable temperatures alternating extreme cold stages (stadials; MIS-2, 4) with warmer stages with temperatures almost as high as present-day (interstadial; MIS-3). As a result of the combined effect of decreased northern summer insolation, lower tropical Pacific sea surface temperatures as well as low atmospheric CO_2, ice accumulated in large ice sheets of the Northern Hemisphere between 33.0 and 26.5 ka, reaching their maximum position between 26.5 and 19 ka (Clark et al., 2009; Hughes et al., 2016a). This time period constitutes the so-called LGM, though some authors suggest a slightly older age of 27.5–23.3 ka (Hughes and Gibbard, 2015) based on the global dust record in polar ice cores. This is the coldest stage of MIS-2 and corresponds to the global LGM, when the greatest ice volume was stored in land masses, and thus sea level was lower.

In the case of Iberian mountains, radiocarbon dating was the most widespread technique to determine the age of glacial activity during the Last Glacial Cycle until the implementation of other techniques, such as OSL and CRE dating. In the late 1990 and early 2000s several authors proposed a MIE of the Last Glacial Cycle occurring during MIS-4. These studies were based on OSL dating on fluvio-glacial sediments located near the outermost moraine complexes and suggested that the largest glacial advance had occurred between 50 and 70 ka. This is the case of several valleys in the Central Pyrenees (García-Ruiz et al., 2013) and is time consistent with the coldest global temperatures of MIS-4 recorded at 65–70 ka (Kindler et al., 2014). Some authors also suggested that older dates than those reported by ^{14}C dating could reveal periods of glacial expansion at that stage, but the chronological limitations of radiocarbon dating impeded confirming this fact. Consequently, radiocarbon dating constrained the age of the MIE in most ranges at ca. 40–50 ^{14}C cal ka BP or older than this age, but without providing approximate dates. It must be taken into account that ^{14}C requires the dating of organic fragments, but biological particles near glaciated environments must have been scarce during the deposition of the glacial features where these particles were trapped, namely moraines and till, due to the very cold climate regime; in addition, the long time passed since their deposition and often the poor degree of preservation of these deposits makes it difficult to find appropriate samples to be dated. Despite these limitations, in some mountain environments, such as in most NW massifs, this has been an extensively used dating approach; here, the available data indicate that very intense periglacial conditions probably associated to the MIE occurred within the range 33–48 ^{14}C cal ka BP, or even older (Table 4). Similarly, in the Cantabrian Mountains ^{14}C dates also suggest a MIE of the Last Glacial Cycle occurring between 35 and 45 ^{14}C cal ka BP (Figure 12).

Figure 12

The accuracy on the reconstruction of glacial oscillations has improved substantially the last decade with the use of CRE dating. This technique allowed inferring the age directly from glacial records (moraines, erratic boulders and polished bedrock) and expanding the number of sites from which chronological data are available. Consequently, we can infer the sequence of environmental events occurred in the Iberian massifs since the Last Glacial Cycle, which has major implications for paleoclimate reconstructions. In addition, the use of CRE allows the validation of ^{14}C and OSL dates but has also introduced new uncertainties on the chronology of past glaciations. In most areas where CRE dating has been applied, age results suggest a MIE occurring during MIS-2 but show also contrasting temporal and spatial patterns. In some areas, such as in some valleys of the Eastern Pyrenees (Delmas et al., 2008; Palacios et al., 2015a; Andrés et al, 2018) and Central Range (Palacios et al., 2012a; Domínguez-Villar et al., 2013; Carrasco et al., 2016), CRE yielded ages for the MIE almost synchronous to the LGM (Figure 10). In other massifs, glaciers reached their maximum extent several millennia before the LGM, at 30–35 ka, such as in the Sierra Nevada at ca. 30 ^{36}Cl ka (Gómez-Ortiz et al., 2012a; Palacios et al., 2016a) and in the Trevinca massif, NW ranges, at 33 ^{10}Be ka (Rodríguez-Rodríguez et al., 2011).

In other mid-latitude mountain environments of the European continent, the LGM promoted the most extensive glaciers of the Last Glacial Cycle, such as in the Alps (Ivy-Ochs et al., 2008; Scapozza et al, 2015; Federici et al., 2016; Wirsig et al., 2016), Apennine (Giraudi, 2011, 2015), Tatra Mountains (Makos et al., 2014), Krkonoše Mountains (Engel et al., 2014) or Balkan mountain ranges (Hughes et al., 2010; 2011; Kuhlemann et al., 2013). The LGM coincided with a minima in solar radiation in the northern hemisphere at 24 ka (Alley et al., 2002). After this, during a period of increasing northern hemisphere insolation a massive and rapid deglaciation was underway at 19-20 ka both in the large northern ice sheets (Hughes et al., 2016a) and in mid-latitude mountain environments due to changing orbital forcing patterns (Alley et al., 2002; Clark et al., 2009; Shakun et al., 2015).

5.3 Glacial advances and retreats during Termination-1

Orbital forcing variations induced changes on the northern summer insolation that resulted in the onset of Termination-1 at high latitudes and mountain regions at 19–20 ka, as well as an abrupt rise in sea level (Clark et al., 2009; Shakun et al., 2015). Changing orbital patterns together with large-scale events in the North Atlantic region induced a number of centennial to millennial-scale climatic fluctuations during the long-term deglaciation that favoured glacial expansion (Clark et al., 2012). For example, the OD occurred close in time to a major phase of iceberg rafting during Heinrich Event I (Palacios et al., 2016a) whilst the YD was associated with major meltwater discharge into the North Atlantic from the Laurentide ice sheet (Renssen et al., 2018).

Greenland ice cores and Laurentine initial retreating point to a temperature increase at ca. 19 ka following the LGM (Lambeck, et al, 2014), which induced a major deglaciation of the large ice sheets of the Northern Hemisphere as well as of mountain glaciers that dramatically reduced their dimensions by 17–18 ka (Marks, 2015; Vasskog et al., 2015; Stroeven et al., 2016; Wirsig et al., 2016). The deglaciation was a rapid process in most Iberian mountains and in only few millennia glaciers were probably confined within the high lands of the highest massifs. This pattern also occurred in other European mountains, such as in the Alps, where by 18 ka the Rhine Valley had lost 80% of its ice mass (Ivy-Ochs et al., 2004).

Subsequently, at ca. 17 ka there was a period of significant cooling across the Northern Hemisphere, the OD, with severe winters and mild summers that resulted in glacial expansion (Denton et al., 2005; Williams et al., 2012). In the Iberian mountains glaciers expanded again across the valley floors and deposited moraines at ca. 16.8–16.5 ka relatively close to the LGM advance, with a second readvance at 15.5 ka followed by a major retreat (Figure 13): 1 ka later glaciers were again confined within the limits of the cirques (Palacios et al., 2017a). This is the case of the Central (Palacios et al., 2015b; 2016b) and Eastern Pyrenees (Palacios et al., 2015a), Central Range (Palacios et al., 2012c, 2017b) and Sierra Nevada (Palacios et al., 2016a). Evidence of the OD is widespread in the Alps between 17 and 16 ka (Ivy-Ochs, 2015; Wirsig et al., 2016) as well as in several other mountain ranges of the Mediterranean region, where glaciers expanded significantly between 17 and 16 ka and formed moraines at only a few km from LGM moraines, such as in the Tatra Mountains (Makos et al., 2013, 2014), Carpathian Mountains (Reuther et al., 2007) and mountains of Anatolia (Sarikaya et al., 2008; Zahno et al., 2010; Akçar et al., 2014).

Figure 13

However, the OD was followed by the BO, a period of abrupt warming of ca. 9 ºC inferred from Greenland ice cores (Clark et al., 2012; Buizert et al., 2014), slightly less in western Europe of 3–5 ºC (Clark et al., 2012). This warming was detected in the entire North Atlantic region and led to a major shrinking of Northern Hemisphere ice sheets (Briner at al., 2014; Marks, 2015; Stroeven et al., 2016) as well as to the disappearance of glaciers from Alpine environments or their spatial confinement in the highest cirques from the highest massifs. In the case of Iberia, during the BA glaciers probably melted away completely or only persisted as very small features in the Central Pyrenees (Palacios et al., 2017a). Outside the Alps, where glaciers persisted during the OD due to their much higher altitudes (Ivy-Ochs, 2015), ice volumes shrunk in most Mediterranean massifs (Palacios et al., 2017a).

Greenland ice cores suggest that the YD was ca. 4.5° ± 2°C warmer than the OD (Buizert et al., 2014), with temperatures in western Europe significantly lower (5–10 ºC) than those prevailing during the BA (Clark et al., 2012). The cooling across Europe was more remarkable in northern (4–5 ºC) than in southern latitudes (2–3 ºC) (Moreno et al, 2014; Heiri et al., 2015). This cold stage has been reported in many Iberian records associated with cold and dry conditions that resulted in hydrological changes in lakes and rivers with the development of fluvial terraces, reduction of speleothems growth, soil development in high cirques, forest decline, etc. (Fletcher et al. 2010; Moreno, 2014; García-Ruiz et al., 2014; Oliva et al., 2014a). Some terrestrial records in the Iberian Peninsula suggest a temperature decrease of 2.5 ºC with respect to the BA period (Iriarte-Chiapusso et al, 2017), a trend that was even higher than 4–5 ºC in sea surface temperatures in SE Iberia (Cacho et al., 2002) and Portuguese coast (Rodrigues et al., 2010), with values similar or lower than during the LGM. Despite the prevailing aridity in the Iberian Peninsula (Naughton et al., 2015), the intense cold allowed the development of small glaciers in the Pyrenees (García-Ruiz et al., 2014), Central Range (Carrasco et al., 2015) and Sierra Nevada (Gómez-Ortiz et al., 2012a; Palacios et al., 2016a), and probably in the Cantabrian Mountains (Figure 14). Ice tongues during this stage were short and exceeded only the limits of the glacial cirques in a few km. YD glaciers are recorded elsewhere in European mountains, such as the Alps where two moraine systems developed between 13.5 and 12 ka (Ivy-Ochs, 2015) or Tatra Mountains where moraines date to 12.5 ka (Makos et al., 2013). In other mountains of the Mediterranean region moraines of similar ages to those dated in the Iberian Peninsula have been reported; this is the case in the Italian Apennines where radiocarbon ages from an ice-marginal lake basin suggests a YD age (Giraudi and Frezzotti, 1992; Giraudi, 2015), the Moroccan High Atlas where moraines have yielded an average CRE age of 12.2 ± 1.6 ka (Hughes et al., 2011) and Anatolia where moraines date to between 11.5 ± 0.8 and 13.0 ± 0.8 ^{10}Be ka in the Kaçkar Mountain range (Akçar et al., 2007) and around 11.5 ± 1.0 and 13.3 ± 1.1 ^{10}Be ka in the Uludağ Mountain (Zahno et al., 2010). Whilst glaciers were present in many of the mountains of Iberia and the wider Mediterranean during the YD, it is unclear whether the YD was a phase of significant glacier expansion or simply a phase of glacier stabilisation in a period of overall glacier retreat during Termination I. Evidence from further north along the NE Atlantic margin in the British Isles now suggests that the YD glaciers may have been smaller than those during the preceding BA (Bromley et al., 2018) indicating a period of overall glacier recession from the OD through the BA to the YD. As noted above, in Iberia the climate conditions were less favourable for glaciers in the YD compared with earlier OD and glaciers are likely to have stabilised as a result of the large depression in temperatures between the BA and YD despite the latter being a very dry. How widely this climatic scenario can be applied is open to debate and further research is needed to understand the glacier fluctuations across the Mediterranean mountains close to Termination I.

Figure 14

5.4 Holocene glacial stages in the Iberian highest ranges

Following the YD, temperatures increased substantially on the order of ca. 10 ºC in Greenland and 4 ºC in western Europe (Clark et al., 2012), which led to a migration of cold-climate processes to higher elevations in the entire North Atlantic region. The Holocene Thermal Optimum was a period of higher temperatures associated with the local orbitally forced summer insolation maximum in the Northern Hemisphere lasting from 11 to 5 ka (Renssen et al., 2018). Consequently, glaciers developed during the YD gradually shrunk and many finally disappeared during the Early Holocene, such as the large Pleistocene ice sheets existing in North America (Stokes et al., 2017) and Fennoscandia (Stroeven et al., 2016). In the case of Iberian glaciers, they only persisted during the Early Holocene as features of reduced dimensions in the highest mountain ranges, namely in the Central Pyrenees (Palacios et al., 2017a; Tomkins et al., 2018), Central Range (Palacios et al., 2012a, 201b; Carrasco et al., 2015) and Sierra Nevada (Palacios et al., 2016a). As temperatures kept rising, their disappearance favoured paraglacial activity and the development of permafrost-related features, such as rock glaciers, which became inactive soon after their formation (Oliva et al., 2016a; Palacios et al., 2016b; Andrés et al., 2018). The temperature increase recorded during the Early Holocene in other Alpine regions of the European continent also led to significant glacial retreat, such as in the Alps (Ivy-Ochs et al., 2009; Scapozza et al, 2015; Federici et al., 2016).

Climate variability increased in the North Atlantic region during the Mid and Late Holocene, with temperature oscillations on the order of ± 2 ºC (Mayewski et al., 2004). However, there is little evidence of glacial activity during the Mid and Late Holocene in the Iberian mountains, with glacier occurrence only identified in the Central Pyrenees and Sierra Nevada. It is likely that some of the moraines systems existing in other massifs of the Central Pyrenees and Cantabrian Mountains formed during Holocene glacial advances, but no absolute dates confirm that fact yet. García-Ruiz et al. (2014) dated a glacial advance at 5.1 ± 0.1 ^{36}Cl ka in the Marboré Cirque as well as another Neoglacial expansion that was followed by a period of glacial shrinking between ca. 3.4 and 2.5 ^{36}Cl ka and another glacial stage at 1.4–1.2 ^{36}Cl ka. Oliva and Gomez Ortiz (2012) found evidence of the development of glaciers in the Sierra Nevada during Bond events at 2-8–2.7 and 1.4–1.2 ^{14}C cal ka BP. In both cases, the last stage of glacier expansion during the Holocene recorded in both cirques occurred during the Dark Ages and the LIA. These two last glacial advances have been also recorded in many mountain regions and polar environments (Solomina et al., 2016). Yet, as highlighted by Matthews (2013), the chronology of Neoglacial glacial advances in European mountains is still not properly understood and needs to be reassessed. However, in some cases, there are no moraine systems between the YD and LIA moraines, which may suggest that the terminal moraines correspond to polygenic systems that make impossible to differentiate previous Holocene glacial stages from LIA moraines (Crest et al., 2017), such as in the Alps and Norway (Matthews, 2013) and other mountain regions across the Northern Hemisphere (Solomina et al., 2015).

5.5 The LIA, background of present-day glacial retreat

Climate variability during the Late Holocene includes several warm (e.g. Medieval Climate Anomaly, recent warming) and cold stages (e.g. Dark Ages, LIA). Precisely, the LIA has been defined as one of the coldest stages in the Northern Hemisphere of the last 10000 years (Bradley and Jones, 1992). In the Iberian Peninsula, a recent multi-proxy reconstruction for that period indicates that the onset of colder conditions following the medieval warm epoch started around 1300 and ended by 1850 (Oliva et al., 2018). The progressive decline of temperatures during the early 14th century in the Iberian Peninsula favoured the gradual development of glaciers at the foot of the highest peaks, namely in the Central Pyrenees, Picos de Europa and Sierra Nevada. The combination of precipitation and temperatures conditioned their dimensions, enlarging during cold and wet stages and shrinking (and possibly disappearing) during warm and dry phases within the LIA.

During the LIA, the Sierra Nevada and Picos de Europa only encompassed 2 and 6 glaciers, respectively, whereas 111 glaciers existed in 15 different massifs in the Central Pyrenees. In all cases, glaciers were of reduced dimensions (several ha) – Aneto glacier was the largest, with a glaciated surface of 236 ha (González-Trueba et al., 2005), and 610 ha for the entire Aneto-Maladeta massif (Rico et al., 2017) –, north exposed at the foot of steep cirque walls protecting ice and snow melting and favouring its accumulation by wind effect. Glaciers in the Sierra Nevada and Picos de Europa massifs remained confined within the cirques, whereas in the Pyrenees there were some small alpine glaciers flowing down-valleys as well as some glaciers in southern cirques of the highest massifs of this mountain range. The elevation difference between the ELA and the highest summits as well as the steepness of the cirques conditioned the amount of ice stored in these mountains. The ELA in the Picos de Europa was located at 2250–2340 m, in the Pyrenees was placed at 2620–2945 m, and in the Sierra Nevada around 3000–3100 m (Oliva et al., 2018).

However, little is known about when these LIA glaciers started to form, except for Sierra Nevada. There is a well-established age of formation of the ice mass in the Mulhacén cirque, which was reconstructed based on the sediments of La Mosca Lake that revealed its appearance by 1440 and disappearance by 1710, at the end of the Maunder Minimum cold stage (1645-1715). In the nearby Veleta cirque, a glacier formed during the early 14th century and readvanced during the 17th century (Palacios et al., 2019). During this time, solar radiation minimum conditioned MAAT ca. 2 °C below present-day values (Oliva et al., 2018), with glaciers reaching their maximum volume of the LIA in the Sierra Nevada and the Pyrenees. A significant expansion was also recorded between 1805 and 1830 following the Dalton Minimum (1790–1820) (García-Ruiz et al., 2014). A similar timing was also recorded in the Alps, when glaciers expanded during these stages (Zemp et al., 2015; Zumbuhl et al., 2018), as well as in several other mid-latitude mountain regions across the world (Solomina et al., 2016). In other Mediterranean massifs glaciers generally reached their maximum advance of the LIA – and, in some cases, of the Holocene – during the 17th century with a significant expansion also during the mid-19th century (Hughes, 2014).

5.6 The Pyrenean, last Iberian current glaciers

MAAT have increased by approximately 1 ºC since the end of the LIA by 1850, which has conditioned a shift of cold geomorphological processes to higher elevations, with the complete deglaciation of the Picos de Europa and Sierra Nevada as well as of most massifs in the Pyrenees (Oliva et al., 2018).

Warmer temperatures determine an ELA above (or very close to) the summits in the Picos de Europa and Sierra Nevada, therefore impeding glacial development in these massifs. In LIA glaciated environments, paraglacial processes have supplied abundant debris covering the remnants of those glaciers. In Picos de Europa, two of the six LIA glaciers are (semi-)permanent snow fields and the other four constitute (exposed or buried) ice patches (González-Trueba, 2005, 2006, 2007; González-Trueba et al., 2008; Serrano et al., 2011; Ruiz-Fernández et al., 2016, 2017). In the Sierra Nevada, the debris cover distributed inside the LIA moraine complexes shows evidence of subsidence and collapse, which is related to the degradation of the permafrost and buried ice masses located beneath them (Gómez-Ortiz et al., 2012b). In the same line, the kinematic monitoring of a rock glacier existing in the Veleta cirque revealed higher vertical than horizontal displacement rates, which is also indicative of the degradation of the frozen body existing in its interior (Gómez-Ortiz et al., 2014, 2018).

In the case of the Pyrenees, the decrease of the glaciated surface from 1850 to present-day almost accounts for ca. 90% of the LIA area, decreasing from 2060 ha to 321 ha in 2008 (René, 2013), and to 244.6 ha in 2016 (Rico et al., 2017). This decrease has not been continuous, with several periods of glacial advance, stabilization and retreat, as also recorded in several other mid-latitude environments such as the Alps (Zemp et al., 2015). However, the strong disequilibrium between glaciers and present-day climate conditions has favoured an accelerated shrinking of the ice volume stored in the still glaciated massifs over the last two decades (Chueca et al., 2007; López-Moreno et al., 2016). The rate of shrinkage depends on the local topographical setting and microclimatic conditions, with solar radiation playing the major role on present-day glacier mass balances (López-Moreno et al., 2006). Some LIA glaciers have originated semi-permanent snow fields or ice patches whereas in other glaciated cirques during the LIA there is only a thick debris cover resulting from intense post-LIA paraglacial dynamics (Serrano et al., 2018).

In the Pyrenees, as in other mountains of the Mediterranean region still encompassing small glaciers, only avalanche-fed glaciers – which are the most resilient to climate change (Hughes, 2018) –, are those more likely to survive over the next few decades in an area where temperatures will increase more than global average and precipitation is also expected to decrease (IPCC, 2013).

6- Conclusions

The location of the Iberian Peninsula between the Atlantic Ocean and the Mediterranean Sea, between polar and subtropical air masses and between the shifting major high and low pressure systems affecting the peninsula has led to significant changes in climate regimes during the Quaternary period. This strong climate sensitivity depicted in the rough Iberian terrain has determined the environmental dynamics prevailing in the highest mountain ranges, resulting in changing glacial to periglacial regimes following climate oscillations.

The impact of Quaternary glaciers on mid-latitude alpine landscapes has been profusely examined from different perspectives over the last two centuries. In the Iberian Peninsula, a deep knowledge on the spatial distribution of glacial features is generally known since the 1970s and 1980s, although the temporal framework of glacial activity has been a matter of debate until nowadays, when only exist few and very small remnants of the large glaciers extending across the main mountain systems during the Late Quaternary. The use of different dating techniques over time has conditioned our understanding of glacial stages in the Iberian mountains. Despite the need to improve the accuracy of these techniques, as well as to extend it to other unexplored areas and different glacial records (moraines, polished bedrock and erratic boulders), results show evidence of different contrasting spatio-temporal patterns for past glaciations resulting from the high sensitivity of Iberian climate. Today, the Iberian mountains are one of the best examined mid-mountain environments with regards to its glacial evolution.

Whereas ^{14}C and OSL usually reported older ages for the MIE of the Last Glacial Cycle, CRE data suggest that it took place almost synchronously to the LGM or slightly before it in most mountain regions. There is evidence in some ranges of the occurrence of past glaciations prior to the Last Glacial Cycle between ca. 130 and 170 ka, as well as of several phases of advance and retreat within this last glacial Pleistocene cycle. Following the massive deglaciation of most Iberian ranges around 19–20 ka, the coldest stages recorded until the Holocene, namely the OD and YD, also promoted the expansion of glaciers. Finally, during the present interglacial, glaciers have been almost inexistent in the Iberian mountains, only reappearing as small spots during the coldest periods, such as the LIA. Post-LIA warming favoured the gradual disappearance of those small glaciers, which only persist nowadays in the highest massifs of the Central Pyrenees undergoing an accelerated melting process.

However, from a critical perspective, our current understanding of glacial processes in the Iberian Peninsula during the Quaternary still presents several gaps that need to be addressed by the scientific community in the near future:

- Glacial chronology for certain periods needs to be improved (e.g. Holocene). Did the 8.2 ka event promoted glacial expansion in the Iberian Peninsula?
- There is increasing evidence of the occurrence glaciations predating the MIE of the Last Glacial Cycle, though they have been only detected in the Pyrenees, NW ranges and Sierra Nevada. Is there geomorphic evidence from these periods also in other ranges?
- Chronological data in some areas (e.g. NW ranges, Iberian Range) are scarce and disconnected both in space and time.
- There is the need to validate results with other complementary dating techniques. In some areas (e.g. Iberian Range) the chronology is (almost uniquely) based on one dating method (CRE) and this should be contrasted with other dating techniques (OSL and ^{14}C).
- The impact of past glaciations has been mostly studied in mountain environments but the connection with other processes in the lowlands has not been addressed. What is the impact of glacial stages on other records located down-valley of the glaciated environments (lacustrine, fluvial)?
- Environmental dynamics following the deglaciation have not been examined in detail. What processes control the geography, intensity and timing of paraglacial response and postglacial periglacial dynamics in the different Iberian mountain ranges formerly glaciated to a greater or lesser extent?

Chronological data of glacial oscillations are a consequence of climate fluctuations, and therefore should be incorporated in other paleoclimate data sources to better understand climate variability during the Late Quaternary in the North Atlantic region, and particularly in southern Europe and the Mediterranean basin, one of the regions of the global climate system with the greatest climate sensitivity.

Acknowledgements

Marc Oliva is supported by the Ramón y Cajal Program (RYC-2015-17597) and the Research Group ANTALP (Antarctic, Arctic, Alpine Environments; 2017-SGR-1102) funded by the Government of Catalonia through the AGAUR agency. Laura Rodríguez is supported by the Marie Curie- Clarín COFUND program financed jointly by Gobierno del Principado de Asturias and the 7th WP of the European Union / Marie Curie Actions (reference ACA-17-19). The work complements the research topics examined in the PALEOGREEN project (CTM2017-87976-P), ESPAS project (CGL2015-655698-R), CGL2016-78380-P and CGL2015-65813-R project of the Ministry of Economy, Industry and Competitiveness, Spain, and the NUNANTAR project (02/SAICT/2017 - 32002) of the Fundação para a Ciência e a Tecnologia, Portugal. Research conducted in the Central Range is also supported by the National Parks Autonomous Agency (OAPN, MAGRAMA, project 1092/2014).

References

Agassiz, L., 1840. Etudes sur les glaciers. Neuchatel.

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.

Akçar, N., Yavuz, V., Ivy-Ochs, S., Reber, R., Kubik, P.W., Zahno, C., Schlüchter, C., 2014. Glacier response to the change in atmospheric circulation in the eastern Mediterranean during the Last Glacial Maximum. Quat Geochronol. 19, 17-41.

Alonso, V., González-Suárez, J.J., 1998. Presencia de hielo glaciar en los Picos de Europa (Cordillera Cantábrica). El helero del Jou Negro. Cuatern. Geomorfol. 12(1-2), 35-44.

Alonso, V., Trombotto-Liaudat, T., 2009. Periglacial geomorphology of El Miro area, Cantabrian Mountains, NW Spain. Z. Geomorphol. 53(3), 335-357.

Alonso, J.L., Pulgar, J.A., García-Ramos, J.C., Barba, P., 1996. Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain), in: Friend, P., Dabrios, C. (Eds.), Tertiary basins of Spain: the stratigraphic record of crustal kinematics. Cambridge University Press, Cambridge, pp. 214-227.

Allen, J.R.M., Huntley, B., Watts W.A., 1996. The vegetation and climate of northwest Iberia over the last 14000 yr. J. Quat. Sci. 11, 125-147.

Alley, R.B., Brook, E.J., Anandakrishnan, S., 2002. A northern lead in orbital band: north-south phasing of Ice-Age events. Quat. Sci. Rev. 21, 431-441.

Andrés, N., Gómez-Ortiz, A., Fernández-Fernández, J.M., Tanarro, L.M., Salvador-Franch, F., Oliva, M., Palacios, D., 2018. Deglaciation timing and rock glacier origin in La Cerdanya Mountains and Puigmal massif, Southeastern Pyrenees. Boreas 47(4), 1050-1071.

Andrieu, V., 1991. Dynamique du paléoenvironnement de la vallée montagnarde de la Garonne (Pyrénées centrales, France) de la fin des temps glaciaires à l'actuel. PhD Thesis, Toulouse 2.

Andrieu, V., Hubschman, J., Jalut, G., Hérail, G., 1988. Chronologie de la déglaciation des Pyrénées françaises, dynamique de sedimentation et contenu pollinique des paleolacs: Application à l’interprétation du retrait glaciaire. Quaternaire 2-3, 55-67.

Arenillas-Parra, M., Cobos-Campos, G., Navarro-Carballo, J., 2008. Datos sobre la nieve y los glaciares en las cordilleras españolas. El Programa ERHIN (1984-2008). Ministerio de Medio Ambiente y Medio Rural y Marino, Madrid.

Arnaez-Vadillo, J., 1987. Formas y procesos en la evolución de vertientes de la Sierra de la Demanda (Sistema Ibérico). Cuad. Invest. Geogr. 13, 9-153.

Arnáez-Vadillo, J., García-Ruiz, J.M., 1990. Mapa geomorfológico de España. Hoja 240 (Ezcaray). Geoforma Ediciones, Logroño.

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from 10Be and 26Al measurements. Quat. Geochronol. 3, 174-195.

Barrère, P., 1963. La période glaciaire dand l’Ouest des Pyrénées centrales Franco-Espagnoles. Bull. Soc. Geol. Fr. 7(5), 516-525.

Bickel, L., Lüthgens, C., Lomax, J., Fiebig, M., 2015. The timing of the penultimate glaciation in the northern Alpine Foreland: new insights from luminescence dating. P. Geol. A. 126(4-5), 536-550.

Bide, J.B., 1893. Deuxième excursion dans la Sierra Nevada. Annuaire du Club Alpin Français 20, 276-305.

Blanco-Chao, R., Pérez-Alberti, A., Trenhaile, A.S., Costa-Casais, M., Valcárcel, M., 2007. Shore platform abrasion in a para-periglacial environment, northwestern Spain. Gemorphology 83, 136-151.

Boissier, E., 1839. Voyage botanique dans le midi de l´Espagne pendant l´année 1837. Fundación Caja de Granada y Universidad de Málaga. Granada, 1995.

Bordonau, J., 1992. Els complexos glacio-lacustres relacionats amb el darer cicle glacial als Pirineus. Geoforma Ediciones, Logroño.

Böse, M., Lüthgens, C., Lee, J.R., Rose, J., 2012. Quaternary Glaciations of northern Europe. Qua. Sci. Reviews 44, 1-25.

Bradley, R.S., Jones, P.D., 1992. Climate Since 1500 AD. Routeledge, London.

Briet, L., 1902. Le glacé de Mont-Perdú. Revue Club Alpine Francaise, secc. Sud Ouest. 1500, 183-186.

Briner, J.P., Svendsen, J.I., Mangerud, J., Lohne, Ø.S., Young, N.E., 2014. A 10Be chronology of south-western Scandinavian Ice Sheet history during the Lateglacial period. J. Quat. Sci. 29, 370-380.

Bromley, G., Putnam, A., Borns, H., Lowell, T., Sandford, T., Barrell, D., 2018. Interstadial Rise and Younger Dryas Demise of Scotland’s Last Ice Fields. Paleoceanography and Paleoclimatology 33, 412-429.

Brosche K.U., 1982. Studien zu jungpleistozänen un holozänen sedimenten und fossilen böden in Küstengebiet von West-Galizien (NW Spanien). Eiszeitalter und Gegenwart 32, 63-80.

Bru, M.J., 1985. Estudi geomorfologic: el modelatge glacial d'un sector del Pirineu Central (Valls Ferrera i de Cardos). PhD Thesis, University of Barcelona.
Burgos, F.J.A., 1985. Características morfológicas de la Sierra de la Demanda. Actas del I Coloquio sobre Geografía de La Rioja: Geografía Física 31-42.
Buizert, C., Gkinis, V., Severinghaus, J.P., He, F., Lecavalier, B.S., Kindler, P., Leuenberger, M., Carlson, A.E., Vinther, B.M., Masson-Delmotte, V., White, J.W.C., Liu, Z.Y., Otte-Bliesner, B., Brook, E.J., 2014. Greenland temperature response to climate forcing during the last deglaciation. Science 345(6201), 1177-1180.
Bullón, T., 2016. The upper Pleistocene on the northern face of the Guadarrama Mountains (central Spain): Palaeoclimatic phases and glacial activity. Geomorphology 268, 233-245.
Butzer K.W., 1967. Geomorphology and stratigraphy of the Paleolithic site os Budiño (Pontevedra, Spain). Eiszeitalter und Gegenwart 33, 95-117.
Butzer, K.W., Franzle, O., 1959. Observations on pre-Würm glaciations of the Iberian Peninsula. Z. Geomorphol. 3(1), 85-87.
Cacho, I., Grimalt, O., Canals, M., 2002. Response of the Western Mediterranean Sea to rapid climatic variability during the last 50,000 years: a molecular biomarker approach. J. Mar. Syst. 33-34, 253-272.
Cano J., Fumanal M. P., Ferrer C., Usera J., Blázquez A. M., Olmo, J., 1997. Evolución de la costa meridional de Galicia durante el Cuaternario superior, in Rodríguez-Vidal, J., (Ed.), Cuaternario Ibérico, AEQUA, Huelva, pp. 33-46.
Carandell, J., de Llarena, J.G., 1918. El glaciarismo cuaternario en los Montes Ibéricos. Trabajos del Museo Nacional de ciencias Naturales. Serie Geología 22, 104 pp.
Carrasco, R.M., Pedraza, J., Domínguez-Villar, D., Villa, J., Willenbring, J.K. 2013. The plateau glacier in the Sierra de Béjar (Iberian Central System) during its maximum extent. Reconstruction and chronology. Geomorphology 196, 83-93.
Carrasco, R.M., Pedraza, J., Domínguez-Villar, D., Willenbring, J.K., Villa, J., 2015. Sequence and chronology of the Cuerpo de Hombre paleoglacier (Iberian Central System) during the last glacial cycle. Quat. Sci. Rev. 129, 163-177.
Carrasco, R.M., de Pedraza, J., Willenbring, J.K., Karampaglidis, T., Soteres, R.L., Martín-Duque, J.F., 2016. Morfología glaciar del Macizo de Los Pelados-El Nevero (Parque Nacional de la Sierra de Guadarrama). Nueva interpretación y cronología. Bol. R. Soc. Esp. Hist. Nat. Sec. Geol. 110, 49-66.
Castañón, J.C., Frochoso, M., 1992. La glaciación Würm en las montañas cantábricas, in: Cearreta, A., Ugarte, F.M. (Eds.), The late quaternary in the Western Pyrenean region. Universidad del País Vasco. Bilbao, pp. 319-332.
Carrera-Gómez, P., Valcárcel, M., 2018. The geomorphological role of snow since the Little Ice Age in the Sierra de Ancares (NW Spain). Cuad. Invest. Geogr. 44(1), 171-185.
Chueca, J., Peña, J.L., Lampre, F., García-Ruiz, J.M., Martí-Bono, C., 1998. Los glaciares del Pirineo aragonés: Estudio de su evolución y extensión actual. Universidad de Zaragoza, Zaragoza.
Chueca, J., Julián, A., Saz-Sánchez, M.A., Creus, J., López-Moreno, J.I., 2005. Responses to climatic changes since the ‘Little Ice Age’ on Maladeta Glacier (Central Pyrenees). Geomorphology 68, 167-182.
Chueca, J., Julián, A., López-Moreno, J.I., 2007. Recent evolution (1981–2005) of the Maladeta glaciers, Pyrenees, Spain: extent and volume losses and their relation with climatic and topographic factors. J. Glaciol. 53, 547-557.
Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. Science 325, 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. U. S. 109, E1134-E1142.
Crest, Y., Delmas, M., Braucher, R., Gunnell, Y., Calvet, M., ASTER Team, 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.
Costa-Casais M., 2001. Análise sedimentaria e reconstrucción da costa Atlántica de Galicia. PhD. Thesis, Universidade de Santiago de Compostela.
Costa-Casais, M., Martínez-Cortizas, A., Pérez-Alberti, A., 1994. Caracterización de un depósito costero de la Ría de Muros-Noia (A Coruña, Galicia), in: Arnáez-Vadillo, J., García-Ruíz J.M., Gómez-Villar, A.,

(Eds.), Geomorfología en España. III Reunión de Geomorfología. Sociedad Española de Geomorfología. Universidad de La Rioja. Logroño, pp. 356-368.
Costa-Casais, M., Martínez-Cortizas, A., Pérez-Alberti, A., 1996. Tipo de depósitos costeiros antigos entre Cabo de Fisterra e o Cabo de Corrubedo, in: Pérez-Alberti, A., Martini, P., Chesworth, W., Martínez-Cortizas, A. (Eds.). Dinámica y Evolución de Medios Cuaternarios. Xunta de Galicia. Santiago de Compostela, pp. 417-430.
Cowton, T., Hughes, P.D., Gibbard, P.L., 2009. Palaeoglaciation of Parque Natural Lago de Sanabria, northwest Spain. Geomorphology 108(3-4), 282-291.
Dahl-Jensen, D., NEEM community, 2013. Eemian interglacial reconstructed from a Greenland folded ice core. Nature. 493(7433): 489-494.
Daveau, S., 1971. La Glaciation de la Serra de Estrela. Finisterra 6(11), 5-40.
Daveau, S., Ferreira, A. B., Ferreira, N., Vieira, G., 1997. Novas observações sobre a glaciação da Serra da Estrela. Estud. Quat. 1, 41-51.
Dehnert, A., Preusser, F., Kramers, J.D., Akcar, N., Kubik, P.W., Reber, R., Schlüchter, C., 2010. A multi-dating approach applied to proglacial sediments attributed to the Most Extensive Glaciation of the Swiss Alps. Boreas 39, 620-632.
Delmas, M., 2015. The last maximum ice extent and subsequent deglaciation of the Pyrenees: an overview of recent research. Cuad. Invest. Geogr. 41, 359-387.
Delmas, M., Gunnell, Y., Braucher, R., Calvet, M., Bourlès, D., 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. Palaeogeography and 10Be exposure age chronology of Middle and Late Pleistocene glacier systems in the northern Pyrenees: implications for reconstructing regional palaeoclimates. Paleogeogr. Paleoclimatol. Paleoecol. 305. 109-122.
Delmas, M., Gunnell, Y., Calvet, M., 2014. Environmental controls on alpine cirque size. Geomorphology 206, 318-329.
Denton, G.H., Alley, R.B., Comer, G.C., Broecker, W.S., 2005. The role of seasonality in abrupt climate change. Quat. Sci. Rev. 24, 1159-1182.
Domínguez-Villar, D., Carrasco, R.M., Pedraza, J., Cheng, H., Edwards, R.L., Willenbring, J.K., 2013. Early maximum extent of paleoglaciers from Mediterranean mountains during the last glaciation. Sci Rep-UK. 3, 20-34.
Dresch, J., 1937. De la Sierra Nevada au Grand Atlas, formes glaciaires et de nivation. Mélanges de géographie et d´orientalisme offerts à E.F. Gautiers. Tours. 194-212.
Ehlers, J., Gibbard, P.L., Hughes, P.D., 2011. Introduction, in: Ehlers, J., Gibbard, P.L., Hughes, P.D., (Eds.) Quaternary Glaciations-Extent and Chronology. A Closer Look. Elsevier, Amsterdam, pp. 1-14.
Ehlers, J., Hughes, P.D., Gibbard, P.L., 2016. The Ice Age. John Wiley & Sons, New Jersey.
Emiliani, C., 1955. Pleistocene temperatures. J Geol. 63, 538-578.
Emiliani, C., 1966. Paleotemperature analysis of Caribbean cores P6304-8 and P6304-9 and a generalized temperature curve for the past 425,000 years. J Geol. 74, 109-126.
Engel, Z., Braucher, R., Traczyk, A., Laetitia, L., ASTER team, 2014. 10Be exposure age chronology of the last glaciation in the Krkonoše Mountains, Central Europe. Geomorphology 206, 107-121.
Evans, I.S., 2006. Local aspect asymmetry of mountain glaciation: A global survey of consistency of favored directions for glacier number and altitudes. Geomorphology 73, 166-184.
Federici, P.R., Ribolini, A., Spagnolo, M., 2016. The glacial history of the Maritime Alps from the Last Glacial Maximum to the Little Ice Age. Geol. Soc. Spec. Publ. 433, 433-439.
Felicísimo, A.M., 1992. El clima de Asturias. Geografía de Asturias, vol 1. Editorial Prensa Asturiana, pp. 17-32.
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, 1282-1299.
Fernandes, M.; Palma, P.; Lopes, L.; Ruiz-Fernández, J.; Pereira, P., Oliva, M., 2018. Spatial distribution and morphometry of permafrost-related landforms in the Central Pyrenees and associated paleoclimatic implications. Quat. Int. 470(A), 96-108.
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.

Fernández-Navarro, L., 1915. Sobre falsas huellas de glaciarismo cuaternario en la Sierra de Guadarrama. Bol. Real. Aca. Esp. Hist. Nat. 15, 396-400.
Fink, D., Vogt, S., Hotchkis, M., 2000. Cross-sections for 36Cl from Ti at Ep = 35-150 MeV: Applications to in-situ exposure dating. Nucl. Instrum. Methods Phys. Res. Sect. B-Beam Interact. Mater. Atoms. 172(1-4), 861-866.
Fletcher, W.J., Sánchez-Goñi, M.F., Peyron, O., Dormoy, I., 2010. Abrupt climate changes of the last deglaciation detected in a Western Mediterranean forest record. Clim. Past. 6, 245-264.
Fontboté, J.M., 1948. La Ribera de Biescas. Pirineos. 7, 39-88.
Fränzle, D., 1959. Glaziale und periglaziale Formbildung im östlichen Kastilichen Scheidegebirge (Zentralspanien). Bonner Geogr. Abh. Ht. 26.
Frochoso, M., Castañón, J.C., 1995. Comments on “Glaciers in Picos de Europa, Cordillera Cantábrica, northwest Spain” by González-Suárez and Alonso. J. Glaciol. 41(138), 430-432.
Frochoso, M., González-Pellejero, R., Allende, F., 2013. Pleistocene glacial morphology and timing of Last Glacial Cycle in Cantabrian Mountains (Northern Spain): New chronological data from the Asón Area. Open Geosci. 5(1), 12-27.
Gale, S.J., Hoare, P.G., 1997. The glacial history of the northwest Picos de Europa of northern Spain. Z. Geomorphol. 41, 81-96.
García de Celis, AJ., Martínez-Fernández, L. C., 2002. Morfología glaciar de las montañas de la cuenca alta de los ríos Sil, Omaña, Luna y Bernesga: revisión y nuevos datos (Montaña Occidental de León), in: Redondo-Vega, J.M., Gómez Villar, A., González-Gutiérrez, R.B., Carrera-Gómez, P. (Eds.), El modelado de origen glaciar en las montañas leonesas. Universidad de León, León, pp. 137-193.
García-Ruiz, J.M., 1979. El glaciarismo cuaternario en la Sierra de la Demanda (Logroño-Burgos, España). Cuad. invest. Geografía e Hist. 5(2), 325.
García-Ruiz, J.M., Martí-Bono, C., 2011. Los depósitos glaciares del valle del Aragón Subordán, Pirineo Centro-occidental español. Cuatern. Geomorfol. 25, 57-81.
García-Ruiz, J.M., Bordonau, J., Martínez de Pisón, E., Vilaplana, J.M., 1992. Benasque (M.T.N. 180). Mapa geomorfológico. Geoforma Ediciones, Logroño.
García-Ruiz, J.M., Ortigosa, L., Pellicer, F., Arnáez-Vadillo, J., 1998. Geomorfología glaciar del Sistema Ibérico, in: Gómez-Ortiz, A., Pérez-Alberti, A., (Eds.), Las huellas glaciares de las montañas españolas. Universidad de Santiago de Compostela. Santiago de Compostela, pp. 347-381.
García-Ruiz, J.M., Gómez-Villar, A., Ortigosa, L., Martí-Bono, C., 2000. Morphometry of glacial cirques in the Central Spanish Pyrenees. Geogr. Ann. Ser. A-Phys. Geogr. 82A(4), 433-442.
García-Ruiz, J.M., Valero-Garcés, B.L., González, P., Lorente, A., Martí-Bono, C., Beguería, S., Edwards, L., 2001a. Stratifies scree in the Central Spanish Pyrenees: Paleoenvironmental implications. Permafrost Periglacial Process. 12, 233-242.
García-Ruiz, J.M., Martí-Bono, C., Valero-Garcés, B.L., González-Sampériz, P., 2001b. La evolución de los glaciares del Pleistoceno Superior en el Pirineo Central español. El ejemplo de los glaciares de Escarra y Lana Mayor, Alto Valle del Gállego. Cuatern. Geomorfol. 15, 103-120.
García-Ruiz, J.M., Valero-Garcés, B.L., Martí-Bono, C., González-Sampériz, P., 2003. Asynchroneity of maximum glacier advances in the central Spanish Pyrenees. J. Quat. Sci. 18(1), 61-72.
García Ruiz, J.M., Gómez Villar, A., Arnáez Vadillo, J., Ortigosa Izquierdo, L., 2007. Villoslada de Cameros, La Rioja (MTN 279). Instituto de Estudios Riojanos, Logroño.
García-Ruiz, J.M., Moreno, A., González-Sampériz, P., Valero-Garcés, B.L., Martí-Bono, C., 2010. La cronología del último ciclo glaciar en las montañas del Sur de Europa. Una revisión. Cuatern. Geomorfol. 24(1-2), 35-46.
García-Ruiz, J.M., Martí-Bono, C., Peña-Monné, J.L., Sancho, C., Rhodes, E., Valero-Garcés, B.L., González-Sampériz, P., Moreno, A., 2012. Glacial and fluvial deposits in the Aragón Valley, Central-Western Pyrenees: chronology of the Pyrenean Late Pleistocene glaciers. Geogr. Ann. Ser. A-Phys. Geogr. 95(1), 15-32.
García-Ruiz, J.M., Martí-Bono, C., Peña-Monné, J.L., Sancho, C., Rhodes, E.J., Valero-Garcés, B.L., González-Sampériz, P., Moreno, A., 2013. Glacial and fluvial deposits in the Aragón valley, central-western pyrenees: chronology of the Pyrenean late Pleistocene glaciers. Geogr. Ann. Ser. A-Phys. Geogr. 95(1), 15-32.
García-Ruiz, J.M., Palacios, D., 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(11), 1439-1452.

García-Ruiz, J.M., Palacios, D., González-Sampériz. P., Andrés, N., Moreno, A., Valero-Garcés, B.L., Gómez-Villar, A., 2016a. Mountain glacier evolution in the Iberian Peninsula during the Younger Dryas. Quat. Sci. Rev. 138, 16-30.
García-Ruiz, J.M., Palacios, D., González-Sampériz, P., Andrés, N., Moreno, A., Valero-Garcés, B.L., Gómez-Villar, A., 2016b. Evidencias de actividad glaciar durante el Dryas reciente (12,9-11,7 ka BP) en la Península Ibérica. Cuatern. Geomorfol. 30, 9-21.
García-Sainz, L., 1935. Morfología glaciar y periglaciar de la región de la Noguera (cuenca Cinca-Segre). Boletín de la Sociedad Geográfica Nacional 54, 64-110.
García-Sancho, L., Palacios, D., Marcos, J., Valladares F., 2001. Geomorphological significance of lichen colonization in a present snow hollow: Hoya del Cuchillar de las Navajas, Sierra de Gredos (Spain). Catena 43. 323-340.
Gellatly, A.F., Grove, J.M., Switsur, V.R., 1992. Mid-Holocene glacial activity in the Pyrenees. Holocene 2-3, 266-270.
Gibbard, P.L., West, R.G., Hughes, P.D., 2018. Pleistocene glaciation of Fenland, England, and its implications for evolution of the region. Royal Society Open Science 4, 170736.
Giraudi, C., Frezzotti, M., 1997. Late Pleistocene glacial events in the Central Apennines, Italy. Quat. Res. 48, 280-290.
Giraudi, C., 2011. Middle Pleistocene to Holocene glaciations in the Italian Apennines, in: Ehlers, J. Gibbard, P.L., Hughes, P.D. (Eds.), Developments in Quaternary Science 15, 211-219.
Giraudi, C., 2015. The Upper Pleistocene deglaciation on the Apennines (Peninsular Italy). Cuad. Invest. Geogr. 41(2), 337-358.
Giraudi, C., Giaccio, B., 2016. Middle Pleistocene glaciations in the Apennines, Italy: new chronological data and preservation of the glacial record, in: Hughes, P.D., Woodward, J.C. (Eds.), Quaternary Glaciation in the Mediterranean Mountains. Geol. Soc. Spec. Publ. 433, 161-178.
Gómez-Ortiz, A., 1980. Estudio geomorfológico del Pirineo catalán: morfogénesis glacial y periglacial de los altos niveles y vertientes merdionales de los macizos de Calmquerdós, Tossa Plana de Llés y Port Negre (Cerdanya-Alt Urgell). PhD Thesis, University of Barcelona.
Gómez-Ortiz, A., 1987. Contribució geomorfológica a l'estudi dels espais supraforestals pirenencs. Gènesi, organització I dinàmica dels modelats glacials i periglacials de la Cerdanya I l'Alt Urgell. Institut Cartografic de Catalunya. Barcelona.
Gómez-Ortiz, A., Salvador-Franch, F., 1992. Aportaciones significativas al conocimiento del glaciarismo y periglaciarismo de Sierra Nevada. Notes geogr. fís. 20-21, 89-101.
Gómez-Ortiz, A., Palacios, D., 1995. La investigación española sobre geomorfología de regiones frías. Áreas geográficas, estudios actuales y resultados. Revi. geogr. (1), 7-19.
Gómez-Ortiz, A., Pérez-González, A., 2001. Evolución reciente de la Geomorfología española 1980-2000. Sociedad Española de Geomorfología and Servei de Gestió i Evolució del Paisatge of the University of Barcelona, Barcelona.
Gómez-Ortiz, A., Plana-Castellví, J.A., 2006. La Pequeña Edad del Hielo en Sierra Nevada a partir de los escritos de la época (siglos XVIII y XIX) y relaciones con el progreso de la geografía física y geomorfología española. Bol. Asoc. Geogr. Esp. 42, 71-98.
Gómez-Ortiz, A., Vieira, G., 2006. La investigación en geomorfología periglaciar en España y Portugal. Evolución reciente y estudios actuales. Finisterra 41(82), 119-137.
Gómez-Ortiz, A., Palacios, D., Ramos, M., Tanarro, L.M., Schulte, L., Salvador, F., 2001. Location of permafrost in marginal regions: Corral del Veleta, Sierra Nevada, Spain. Permafrost Periglacial Process. 12, 93-110.
Gómez-Ortiz, A., Schulte, L., Salvador, F., Sánchez, S., Simón, M., 2002. Mapa geomorfológico de Sierra Nevada. Morfología glaciar y periglaciar. Granada: Consejería de Medio Ambiente, Junta de Andalucía.
Gómez-Ortiz, A., Palacios, D., Schulte, L., Salvador-Franch, F., Plana-Castellví, J.A., 2009. Evidences from Historical Documents of Landscape Evolution after Little Ice Age of a Mediterranean High Mountain Area, Sierra Nevada, Spain (Eighteenth to Twentieth Centuries). Geogr. Ann. Ser. A-Phys. Geogr. 91(4), 279-289.
Gómez-Ortiz, A., Palacios, D., Palade, B., Vázquez-Selem, L., Salvador-Franch, F., 2012a. The deglaciation of the Sierra Nevada (southern Spain). Geomorphology. 159-160, 93-105.
Gómez-Ortiz, A.; Salvador-Franch, F.; Sanjosé, J.J.; Palacios, D.; Oliva, M.; Salvà-Catarineu, M.; Tanarro, L.; Raso, J.; Atkinson, A.; Schulte, L.; Plana, J.; Milheiro, B., Serrano, D., 2012b. Degradación de hielo fósil y permafrost y cambio climático en Sierra Nevada, in: Ramírez, L., Asensio, B., (Eds.), Proyectos de investigación en parques nacionales: 2008-2011. Book of National Parks. Colección Naturaleza y

Parques Nacionales. Organismo Autónomo Parques Nacionales. Ministerio de Agricultura, Alimentación y Medio Ambiente. Madrid, pp. 25-43.
Gómez-Ortiz, A., Oliva, M., Salvà-Catarineu, M., Salvador-Franch, F., 2013a. The environmental protection of landscapes in the high semiarid Mediterranean mountain of Sierra Nevada National Park (Spain): historical evolution and future perspectives. Appl Geogr. 42, 227-239.
Gómez-Ortiz, A., Palacios, D., Palade, B., Vázquez Selem, L., Salvador-Franch, F., Tanarro, L., Oliva, M., 2013b. La evolución glaciar de Sierra Nevada y la formación de glaciares rocosos. Bol. Asoc. Geogr. Esp. 61, 139-162.
Gómez-Ortiz, A., Oliva, M., Salvador-Franch, F., Salvà-Catarineu, M., Palacios, D., Sanjosé, J.J., Tanarro, L.M., Galindo-Zaldívar, J., Sanz de Galdeano, C., 2014. Degradation of buried ice and permafrost in the Veleta cirque (Sierra Nevada, Spain) from 2006-2013. Solid Earth. 979-993.
Gómez-Ortiz, A., Palacios, D., Oliva, M., Salvador-Franch, F., Salvà-Catarineu, M., 2015. The deglaciation of Sierra Nevada (Spain): synthesis of current knowledge and new contributions. Cuad. Invest. Geogr. 41(2), 409-426.
Gómez-Ortiz, A., Oliva, M., Salvador-Franch, F., Salvà-Catarineu, M., Plana-Castellví, J.A., 2018. The geographical interest of historical documents to interpret the scientific evolution of the glacier existing in the Veleta cirque (Sierra Nevada, Spain) during the Little Ice Age. Cuad. Invest. Geogr. 44(1), 267-292.
Gómez-Villar, A., Santos-González, J., González-Gutiérrez, R.B., Redondo-Vega, J.M., 2015. Glacial cirques in the southern side of the Cantabrian Mountains of southwestern Europe. Geogr. Ann. Ser. A-Phys. Geogr. 97, 633-651.
González-Sampériz, P., Valero-Garcés, B.L., Moreno, A., Jalut, G., García-Ruiz, J.M., Martí-Bono, C., Delgado-Huertas, A., Navas, A., Otto, T., Dedoubat, J.J., 2006. Climate variability in the Spanish Pyrenees during the last 30,000 yr revealed by the El Portalet sequence. Quat. Res. 66, 38-52.
González-Sampériz, P., Valero-Garcés, B.L., Moreno Caballud, A., Peña-Monné, J.L., Longares-Aladrén, L.A., García-Ruiz, J.M., Lozano-Tena, M.V., Navas, A., Sancho-Marcén, C., Delgado-Huertas, A., 2006-2007. Aportación al conocimiento de los paleoambientes cuaternarios del Macizo del Tremedal (Sierra de Albarracín, Teruel). Teruel.
González-Sampériz, P., Aranbarri, J., Pérez-Sanz, A., Gil-Romera, G., Moreno, A., Leunda, M., Sevilla-Callejo, M., Corella, J.P., Morellón, M., 2017. Environmental and climate change in the southern Central Pyrenees since the Last Glacial Maximum: A review from the lake records. Catena 149, 668-688.
Gonzalez-Suárez, J.J., Alonso, V., 1994. Glaciers in Picos de Europa, Cordillera Cantábrica, northwest Spain. J. Glaciol. 40(134), 198-199.
González-Trueba, J.J., 2005. La Pequeña Edad del Hielo en los Picos de Europa (Cordillera Cantábrica, NO de España). Análisis morfológico y reconstrucción del avance glaciar histórico. Cuatern. Geomorfol. 19(3-4), 79-94.
González-Trueba, J.J., 2006. Topoclimatical factors and very small glaciers in Atlantic mountain of SW Europe: Little Ice Age glacial advance in Picos de Europa (NW Spain). Zeitschrift für Gletscherkunde und Glazialgeologie 39, 115-125.
González-Trueba, J.J., 2007. La Pequeña Edad del Hielo en los Picos de Europa. Servicio de Publicaciones de la Universidad de Cantabria-Fundación Marcelino Botín, Santander.
González-Trueba, J.J., Martín-Moreno, R., Serrano, E., 2005. El glaciarismo de la Pequeña Edad del Hielo en las montañas Ibéricas. Síntesis y estado actual de conocimiento. Cuatern. Geomorfol. 21. 57-86.
González-Trueba, J.J., Martín-Moreno, R., Martínez de Pisón, E., Serrano, E., 2008. Little Ice Age glaciation and current glaciers in the Iberian Pennsula. Holocene 18(4), 551-68.
Graf, A.A., Strasky, S., Ivy-Ochs, S., Akçar, N., Kubik, P.W., Burkhard, M., Schlüchter, C., 2007. First results of cosmogenic dated pre-Last Glaciation erratics from the Montoz area, Jura Mountains, Switzerland. Quat. Int. 164-165, 43-52.
Guerrero, J., Gutiérrez, F., García-Ruiz, J.M., Carbonel, D., Lucha, P., Arnold, L.J., 2018. Landslide-dam paleolakes in the Central Pyrenees, Upper Gállego River Valley, NE Spain: timing and relationship with deglaciation. Landslides. 15(10), 1975-1989.
Heiri, O., Ilyashuk, B., Millet, L., Samartin, S., Lotter, A.F., 2015. Stacking of discontinuous regional palaeoclimate records: chironomid-based summer temperatures from the Alpine region. Holocene 25(1), 137-149.
Hempel, L., 1960. Límites geomorfológicos altitudinales en Sierra Nevada. Cuad. Invest. Geogr. 21(78), 8.
Hernández Pacheco, E., 1914. Fenómenos de glaciarismo cuaternario en la Cordillera Cantábrica. Bol. R. Soc. Esp. Hist. Nat. 45, 407-408.

Hernandez-Pacheco, F., 1930. Sobre localizaciones de glaciares en el Guadarrama. Bol. R. Soc. Esp. Hist. Nat, 30, 122.
Hernández-Pacheco, F., 1944. Fisiografía, geología y glaciarismo cuaternario de las montañas de Reinosa. Real Academia de Ciencias, Exactas, Físicas y Naturales.
Hernández-Pacheco, F., 1949. Huellas glaciares en la Sierra de Queija. Bol. R. Soc. Esp. Hist. Nat. 47, 97-102.
Hernández-Pacheco, F., 1957. EI glaciarismo cuaternario en la Sierra de Queija (Orense). *Bol.* R. Soc. Esp. Hist. Nat. 55, 27-74.
Höllermann, P., 1971. Zurundungsmessungen and Ablangerungen im Hochgebirge. Z. Geomorphology. 12, 205-237.
Hughes, P.D., 2014. Little Ice Age glaciers in the Mediterranean mountains. Mediterranée 122, 63-79.
Hughes, P.D., 2018. Little Ice Age glaciers and climate in the Mediterranean mountains: a new analysis. Cuad. Invest. Geogr. 44(1), 15-45.
Hughes, P.D., Gibbard, P.L., 2015. A stratigraphical basis for the Last Glacial Maximum (LGM). Quat. Int. 383, 174-185.
Hughes, P.D., Gibbard, P.L., 2018. Global glacier dynamics during 100 ka Pleistocene glacial cycles. Quat. Res. 90, 222-243.
Hughes, P.D., Woodward, J.C., 2008. Timing of glaciation in the Mediterranean mountains during the last cold stage. J. Quat. Sci. 23(6-7), 575-588.
Hughes, P.D., Woodward, J.C., Gibbard, P.L., 2006a. Quaternary glacial history of the Mediterranean mountains. Prog. Phys. Geogr. 30(3), 334-364.
Hughes, P.D., Woodward, J.C., Gibbard, P.L., Macklin, M.G., Gilmour, M.A., Smith G.R. 2006b. The glacial history of the Pindus Mountains, Greece. J. Geol. 114, 413-434.
Hughes, P.D., Woodward, J.C., van Calsteren, P.C., Thomas, L.E., Adamson, K.R., 2010. Pleistocene ice caps on the coastal mountains of the Adriatic Sea. Quat. Sci. Rev. 29, 3690-3708.
Hughes, P.D., Frenton, C.R., Gibbard, P.L., 2011. Quaternary glaciations of the Atlas Mountains, North Africa, in: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Quaternary Glaciations. Extent and Chronology: a Closer Look. Developments in Quaternary Sciences 15, pp. 1065-1074.
Hughes, P.D., Gibbard, P.L., 2015. A stratigraphical basis for the Last Glacial Maximum (LGM). Quat. Int. 383, 174-185.
Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., Svendsen, J.I., 2016a. The last Eurasian ice sheets - a chronological database and time-slice reconstruction, DATED-1. Boreas. 45, 1-45.
Hughes, P.D., Glasser, N.F., Fink, D., 2016b. Rapid thinning of the Welsh Ice Cap at 20-19 ka based on ^{10}Be ages. Quat. Res. 85, 107-117.
Huguet del Villar, E., 1915. Los glaciares de Gredos. Real Sociedad Española de Historia Nacional 15, pp. 379-390.
Huget del Villar, E., 1917. Nueva contribución a la glaciología de Gredos, las Hoyuelas del Hornillo. Bol. R. Soc. Esp. Hist. Nat. 17, 558-567.
IPCC Climate Change 2013, 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Iriarte-Chiapusso, M.J., Muñoz-Sobrino, C., Gomez-Orellana, L., Hernández-Beloqui, B., García-Moreiras, I., Fernández-Rodríguez, C., Heiri, O., Lotter, A.F., Ramil-Rego, P., 2016. Reviewing the Lateglacial-Holocene transition in NW Iberia: a palaeoecological approach based on the comparison between dissimilar regions. Quat. Int. 403, 211-236.
Ivy-Ochs, S., 2015. Glacier variations in the European Alps at the end of the Last Glaciation. Cuad. Invest. Geogr. 41, 295-315.
Ivy-Ochs, S., Schäfer, J., Kubik, P.W., Synal, H. A., Schlüchter, C., 2004. Timing of deglaciation on the northern Alpine foreland (Switzerland). Eclogae Geol. Helv. 97(1), 47-55.
Ivy-Ochs, S., Kerschner, H., Reuther, A., Maisch, M., Sailer, R., Schaefer, J., Kubik, P.W., Synal, H., Schlüchter, C., 2006. The timing of glacier advances in the northern European Alps based on surface exposure dating with cosmogenic 10Be, 26Al, 36Cl, and 21Ne. Geol. Soc. Spec. Publ. 415, 43-60.
Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W., Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. J. Quat. Sci. 23, 559-573.
Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., F., Kubik, P.W., Schlüchter, C., 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. Quat. Sci. Rev. 28, 2137-2149.
Jalut, G., Turu, V., Dedoubat, J.J., Otto, T., Ezquerra, J., Fontugne, M., Belet, J.M., Onnet, L, Gacía de Celis, A., Redondo-Vega J.M., Vidal-Romaní, J.R., Santos, L., 2010. Palaeoenvironmental studies in NW Iberia

(Cantabrian range): Vegetation history and synthetic approach of the last deglaciation phases in the western Mediterranean. Paleogeogr. Paleoclimatol. Paleoecol. 297(2), 330-350.
Jambrina-Enríquez, M., Rico, M., Moreno, A., Leira, M., Bernárdez, P., Prego, R., Recio, C., Valero-Garcés, B.L., 2014. Timing of deglaciation and postglacial environmental dynamics in NW Iberia: the Sanabria Lake record. Quat. Sci. Rev. 94, 136-158.
Jiménez-Sánchez, M., Farias, P., 2002. New radiometric and geomorphologic evidence of Last Glacial maximum older than 18 ka in SW European mountains: the example of Redes Natural Park, Cantabrian Mountains. NW Spain. Geodin. Acta. 15, 93-101
Jiménez-Sánchez, M., Rodríguez-Rodríguez, L., García-Ruiz, J.M., Domínguez-Cuesta, M.J., Farias, P., Valero-Garcés, B.L, Moreno, A., Valcárcel, M., 2013. A review of glacial geomorphology and chronology in northern Spain: timing and regional variability during the last glacial cycle. Geomorphology 196, 50-64.
Kindler, P., Guillevic, M., Baumgartner, M., Schwander, J., Landais, A., Leuenberger, M., 2014. Temperature reconstruction from 10 to 120 kyr b2k from the NGRIP ice core. Clim. Past. 10, 887-902.
Kuhlemann, J., Gachev, E., Gikov, A., Nedkov, S., Krumrei, I., Kubik, P., 2013. Glaciation in the Rila Mountains (Bulgaria) during the Last Glacial Maximum. Quat. Int. 293, 51-62.
Laban, C., van der Meer, J.J.M., 2011. Pleistocene Glaciation in the Netherlands, in: Ehlers, J., Gibbard, P.L., Hughes, P.D., (Eds.) Quaternary Glaciations – Extent and Chronology. A Closer Look. Elsevier, Amsterdam, p. 247-260.
Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the last glacial maximum to the Holocene. Proc. Natl. Acad. Sci. U.S.A. 111, 15296-15303.
Lautensach, H., 1929. Eiszeitstudien in der Serra da Estrela (Portugal). Zeitschrift für Gletscherkunde. 17, 324-369.
Lautensach, H., 1932. Estudo dos glaciares da Serra da Estrela. Memórias e Noticias, VI. Coimbra.
Lewis, C.J., McDonald, E.V., Sancho, C., Peña, J.L., Rhodes, E.J., 2009. Climatic implications of correlated Upper Pleistocene glacial and fluvial deposits on the Cinca and Gállego Rivers (NE Spain) based on OSL dating and soil stratigraphy. Glob. Planet. Change. 67, 141-152.
Lhenaff, R., 1977. Recherches géomorphologiques sur les Cordillères Bétiques Centro-Occidentales (Espagne). Thesis d'Etat. Univ. Paris.
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.
Lifton, N., 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.
Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic d18O records. Paleoceanography 20, PA1003
Llopis-Lladó, N., 1947. El relieve del Alto Aragón. Pirineos 5, 81-166.
Llopis-Lladó, N., 1957. Estudio del glaciarismo cuaternario de Sanabria, in: El Cuaternario de la Región Cantábrica. INQUA–V Congreso Internacional, Guía de la Excursión. Excma. Diputación Provincial de Asturias, Oviedo, pp. 38-41.
Lopes, L., Oliva, M., Fernandes, M., Pereira, P., Palma, P., Ruiz-Fernández, J., 2018. Spatial distribution of morphometric parameters of glacial cirques in the Central Pyrenees (Aran and Boí valleys). J Mt. Sci. 15(10), 2103-2119.
López-Moreno, J.I., 2000. Los glaciares del Alto Valle del Gállego (Pirineo aragonés) desde la Pequeña Edad del Hielo. Implicaciones en la evolución de las temperaturas. Geoforma Ed. Logroño.
López-Moreno, J.I., 2005. Recent variations of snowpack depth in the Central Spanish Pyrenees. Arct. Antarct. Alp. Res. 37, 253-260.
López-Moreno, J.I., Nogués-Bravo, D., Chueca, J., Julián, J., 2006. Change of topographic control on the extent of cirque glaciers since the Little Ice Age. Geophys. Res. Lett. 33, L24505.
López-Moreno, J.I., Revuelto, J., Rico, I., Chueca-Cía, J., Julián, A., Serreta, A., Serrano, E., Vicente-Serrano, S.M., Azorín-Molina, C., Alonso-González, E., García-Ruiz, J.M., 2016. Thinning of the Monte Perdido Glacier in the Spanish Pyrenees since 1981. Cryosphere 10(2), 681-694.
Lotze, F., 1962. Überpleistozane Vergletscherungen in der Valnera Gruppe (Ostliches Kantabrisches Gebirge). Neues. Jahrb. Geol. 7, 377-381.
Makos, M., Nitychoruk, J., Zreda, M., 2013. Deglaciation chronology and paleoclimate of the Pieciu Stawow Polskich/Roztoki Valley, high Tatra mountains, western Carpathians, since the last glacial maximum, inferred from 36Cl exposure dating and glacier climate modelling. Quat. Int. 293, 63-78.

Makos, M., Dzierżek, J., Nitychoruk, J. Zreda, M., 2014. Timing of glacier advances and climate in the High Tatra Mountains (Western Carpathians) during the Last Glacial Maximum. Quat. Res. 82, 1-13.
Maldonado, F.J., 1994. Evolución tardiglaciar y holocena de la vegetación en los macizos del Noroeste Peninsular. PhD Thesis. Universidad Politécnica de Madrid.
Mangerud, J., Andersen, S. T., Berglund, B.E., Donner, J.J., 1974. Quaternary stratigraphy of Norden, a proposal for terminology and classification. Boreas 3, 109-128.
Mardonès, M., Jalut, G., 1983. La tourbière de Biscaye (alt. 409 m, Hautes Pyrénées): Approche paléoécologique des 45.000 dernières années. Pollen et Spores 25(2), 163-212.
Marjanac, L., 2012. Pleistocene glacial and periglacial sediments of Kvarner, northern Dalmatia and southern Velebit Mt. – evidence of Dinaric glaciation. PhD Thesis. University of Zagreb.
Marks, L., 2015. Last deglaciation of northern continental Europe. Cuad. Invest. Geogr. 41(2), 279-293.
Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R., Balco, G., 2016. Cosmogenic nuclide systematics and the CRONUScalc program. Quat. Geochronol. 31, 160-187.
Martí-Bono, C.E., 1973. Nota sobre los sedimentos morenicos del río Aragón. Pirineos 107, 39-46.
Martí-Bono, C.E., 1978. Aspectos de la problemática geomorfológica del Alto Aragón Occidental. Estud. Geogr. 153, 473-493.
Martí-Bono, C.E., García-Ruiz, J.M., 1994. El glaciarismo surpirenaico: Nuevas aportaciones. Geoforma Ediciones, Logroño.
Martin, L., Blard, P.H., Balco, G., Lave, J., Delunel, R., Lifton, N., 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.
Martínez de Pisón, E., 1989. Morfología glaciar del valle de Benasque (Pirineo Aragonés). Ería 18, 51-64.
Martínez de Pisón, E., Jiménez, J. M., 1972. Observaciones sobre la morfología del Alto Gredos. Estud. Geogr. 33(129).
Martínez de Pisón, E., Arenillas, M. 1976. El problema de la sobreexcavación glaciar, arrancamiento, abrasión y estructura. Estud. Geogr.145, 407-434.
Matthews, J.A., 2013. Neoglaciation in Europe, in: Elias, S.A., Mock, C. J. (Eds.), Encyclopedia of Quaternary Science, pp. 257-268. Elsevier, 2nd edition.
Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G. Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. Quat. Res. 62, 243-255.
Menéndez-Duarte, R., Marquínez, J., 1996. Glaciarismo y evolución tardiglaciar de las vertientes en el valle de Somiedo. Cordillera Cantábrica. Cuatern. Geomorfol. 10(3-4), 21-31.
Messerli, B., 1965. Beiträge zur Geomorphologie der Sierra Nevada (Andalusien). Juris Verlag. Zürich.
Montserrat, J., 1992. Evolución glaciar y postglaciar del clima y la vegetación en la vertiente sur del Pirineo: Estudio palinológico. Instituto Pirenaico de Ecología, Zaragoza.
Moreno, A., Stoll, H., Jiménez-Sánchez, M., Cacho, I., Valero-Garcés, B.L., Ito, E., Edwards, R.L., 2010. A speleothem record of glacial (25–11.6 kyr BP) rapid climatic changes from northern Iberian Peninsula. Glob. Planet. Change. 71(3-4), 218-231.
Moreno, A., 2014. Palaeoclimate: Lags within the Younger Dryas. Nat. Geosci. 7, 87-88.
Moreno, A., Svensson, A., Brooks, S.K., Connor, S., Engels, S., Fletcher, W., Genty, D., Heiri, O., Labuhn, I., Persoiu, A., Peyron, O., Sadori, L., Valero-Garcés, B.L., Wulf, S., Zanchetta, G., 2014. A compilation of western European terrestrial records 60-8 ka BO: towards an understanding of latitudinal climatic gradients. Quat. Sci. Rev. 106, 167-185.
Miotke, F.D., 1968. Karstmorphologische Studien in der glazial-überformten Höhenstufe der" Picos de Europa," Nordspanien (4). Selbstverlag der Geographischen Gesellschaft Hannover.
Muñoz, J., 1982. Geografía Física. El relieve, el clima y las aguas, in: Quirós, F. (Ed.): Geografía de Asturias, Ayalga Ediciones. Salinas. (1), 1-271.
Muñoz-Sobrino, C., Ramil-Rego, P., Rodríguez-Guitián, M.A., 2001. Vegetation in the mountains of northwest Iberia during the last glacial-interglacial transition. Veg. Hist. Archaeobot. 7-21.
Muñoz-Sobrino, C., Ramil-Rego, P., Gómez-Orellana, L., 2004. Vegetation of the Lago de Sanabria area (NW Iberia) since the end of the Pleistocene: a palaeoecological reconstruction on the basis of two new pollen sequences. Veg. Hist. Archaeobot. 13(1), 1-22.
Naughton, F., Sánchez Goñi, M.F., Rodrigues, T., Salgueiro, E., Costas, S., Desprat, S., Duprat, J., Michel, E., Rossignol, L., Zaragosi, S., Voelker, A.H.L., Abrantes, F., 2015. Climate variability across the last deglaciation in NW Iberia and its margin. Quat. Int. 414, 9-22.

Nieuwendam, A., Ruiz-Fernández, J., Oliva, M., Freitas, C., Paio, V., Cruces, A., 2015. Postglacial landscape changes and cryogenic processes in the Picos de Europa (Northern Spain) reconstructed from geomorphological mapping and microstructures on quartz grains. Permafrost Periglacial. Process. 27, 96-108.
Nussbaum, F., 1949. Sur les traces des glaciers quaternaires dans la région de l'Aragón. Pirineos 13-14, 497-518.
Nussbaum, F., 1956. Observations morphologiques dans la région de la Noguera Pallaresa. Pirineos 39-42, 57-97.
Obermaier, H., 1914. Estudio de los glaciares de los Picos de Europa. Trabajos del Museo Nacional de Ciencias Naturales: Serie Geológica 9, 1-42.
Obermaier, H., 1921. El glaciarismo cuaternario en el valle del río Ara y en el Parque Nacional de Ordesa (Pirineos). Boletín de la Sociedad Ibérica de Ciencias Naturales 20, 106-110.
Obermaier, H., Carandell-Pericay, J., 1916. Contribución al estudio del glaciarismo cuaternario de la Sierra de Gredos, Trabajos del Museo Nacional de Ciencias Naturales. Serie Geológica, 14, pp. 54.
Obermaier, H., Carandell-Pericay, J., 1917. Nuevos datos acerca de la extensión del glaciarismo cuaternario en la Cordillera Central. Extracto del Bol. Soc. Esp. Hist. Nat., XVII. Madrid.
Oliva, M., 2009. Holocene alpine environments in Sierra Nevada (Southern Spain). Ph.D. Thesis. University of Barcelona.
Oliva, M., 2018. The Little Ice Age, the climatic background of present-day warming in Europe. Cuad. Invest. Geogr. 44(1), 7-13.
Oliva, M., Gómez-Ortiz, A., 2012. Late Holocene environmental dynamics and climate variability in a Mediterranean high mountain environment (Sierra Nevada, Spain) inferred from lake sediments and historical sources. Holocene 22(8), 915-927.
Oliva M, Gómez-Ortiz A, Schulte L., 2010. Tendencia a la aridez en Sierra Nevada desde el Holoceno Medio inferida a partir de sedimentos lacustres. Bol. Asoc. Geogr. Esp. 52, 27-42.
Oliva, M., Schulte, L., Gómez-Ortiz, A., 2011. The role of aridification in constraining the elevation range of Holocene solifluction processes and associated landforms in the periglacial belt of the Sierra Nevada (Southern Spain). Earth Surf. Process. Landf. 36(10), 1279-1291.
Oliva, M., Gómez-Ortiz, A., Palacios, D., Salvador-Franch, F., Salvà-Catarineu, M., 2014a. Environmental evolution in Sierra Nevada (South Spain) since the Last Glaciation based on multi-proxy records. Quat. Int. 353, 195-209.
Oliva, M., Gómez-Ortiz, A., Palacios, D., Salvador-Franch, F., Salvà-Catarineu, M., 2014b. El Cuaternario en el macizo de Sierra Nevada. Evolución paleoambiental y paisaje a partir de la interpretación de registros naturales y documentos de época. Scr. Nova, XVIII (472), 1-16.
Oliva, M., Gómez-Ortiz, A., Palacios, D., Franch, F. S., Catarineu, M. S., 2015. El Cuaternario en el macizo de Sierra Nevada. Estado de la cuestión, in: Gómez-Ortiz, A., Salvador-Franch, F., Oliva, M., Savà-Caterineu, M., (Eds.), Avances, métodos y técnicas en el estudio del periglaciarismo. Universidad de Barcelona, Barcelona, pp. 65.-78.
Oliva, M., Serrano, E., Gómez-Ortiz, A., González-Amuchastegui, M.J., Nieuwendam, A., Palacios, D., Pellitero-Ondicol, R., Pérez-Alberti, A., Ruiz-Fernández, J., Valcárcel, M., Vieira, G., Antoniades, D., 2016a. Spatial and temporal variability of periglaciation of the Iberian Peninsula. Quat. Sci. Rev. 137, 176-199.
Oliva, M., Gómez-Ortiz, A., Salvador-Franch, F., Salvà-Catarineu, M., Ramos, M., Palacios, D., Tanarro, L., Pereira, P., Ruiz-Fernández, J., 2016b. Inexistence of permafrost at the top of Veleta peak (Sierra Nevada, Spain). Sci. Total Environ. 550, 484-494.
Oliva, M.; Ruiz-Fernández, J., Barriendos, M., Benito, G., Cuadrat, J.M., García-Ruiz, J.M., Giralt, S., Gómez-Ortiz, A.; Hernández, A., López-Costas, O., López-Moreno, J.I., López-Sáez, J.A., Martínez-Cortizas, A., Moreno, A., Prohom, M., Saz, M.A., Serrano, E., Tejedor, E., Trigo, R., Valero-Garcés, B.L., Vicente-Serrano, S., 2018. The Little Ice Age in Iberian mountains. Earth-Sci. Rev. 177, 175-208.
Ortega, L.I., Centeno, J.D., 1987. Nota sobre nuevos focos glaciares detectados en la Sierra de Neila (NW del Sitema Ibérico, España). Bol. R. Soc. Esp. Hist. Nat. Sec. Geol. 82(1-4), 147-150.
Ortigosa, L.M., 1985. Glaciares rocosos en la Sierra de Cebollera (Sistema Ibérico). Actas del I Coloquio sobre Geografía de La Rioja. 55-67.
Ortigosa, L.M., 1986. Geomorfología glaciar de la Sierra Cebollera (Sistema Ibérico). Instituto de Estudios Riojanos, Logroño.
Palacios, D., Andres, N., Luengo, E., 2003. Distribution and effectiveness of nivaltion in Mediterranean mountains: Peñalara (Spain). Geomorphology 54, 157-178.

Palacios, D., Marcos, J., Vázquez-Selem, L., 2011. Last Glacial Maximum and deglaciation of Sierra de Gredos, central Iberian Peninsula. Quat. Int. 233, 16-26.
Palacios, D., Andrés, N., Marcos, J., Vázquez-Selem, L., 2012a. Glacial landforms and their paleoclimatic significance in Sierra de Guadarrama, Central Iberian Península. Geomorphology 139-140, 67-78.
Palacios, D., Andrés, N., Marcos, J., Vázquez-Selem, L., 2012b. Maximum glacial advance and deglaciation of the Pinar Valley (Sierra de Gredos, Central Spain) and its significance in the Mediterranean context. Geomorphology 177-178, 51-61.
Palacios, D., Andrés, N., Vieira, G., de Marcos, J., Vázquez-Selem, L., 2012c. Last Glacial Maximum and deglaciation of the Iberian Central System. Geophysical Research Abstracts 14, EGU2012- 3738.
Palacios, D., Gómez-Ortiz, A., de Andrés, N., Vázquez-Selem, L., Salvador-Franch, F., Oliva, M., 2015a. Maximum extent of Late Pleistocene glaciers and last deglaciation of La Cerdanya mountains, Southeastern Pyrenees. Geomorphology 231, 116-129.
Palacios, D., Andrés, N., López-Moreno, J.I., García-Ruiz, J.M., 2015b. Late Pleistocene deglaciation in the upper Gállego Valley, Central Pyrenees. Quat. Res. 83, 397-414.
Palacios, D., Gómez-Ortiz, A., Andrés, N., Salvador, F., Oliva, M., 2016a. Timing and new geomorphologic evidence of the Last Deglaciation stages in Sierra Nevada (southern Spain). Quat. Sci. Rev. 150, 110-129.
Palacios, D., Andrés, N., Gómez-Ortiz, A., García-Ruiz, J.M., 2016b. Evidence of glacial activity during the Oldest Dryas in the mountains of Spain, in: Hughes, P.D., Woodward J.C (Eds.), Quaternary glaciation in the Mediterranean mountains, Geol. Soc. Spec. Publ. 433, 87-110.
Palacios, D., García-Ruiz, J.M., Andrés, N., Schimmelpfennig, I., Campos, N. Leanni, L., ASTER Team, 2017a. Deglaciation in the central Pyrenees during the Pleistocene-Holocene transition: Timing and geomorphological significance. Quat. Sci. Rev. 162, 111-127.
Palacios, D., Andrés, N., Gómez-Ortiz, A., García-Ruiz, J. M., 2017b. Evidence of glacial activity during the Oldest Dryas in the mountains of Spain. Geol. Soc. Spec. Publ. 433(1), 87-110.
Palacios, D., Gómez-Ortiz, A., Alcalá-Reygosa, J., Andrés, N., Oliva, M., Tanarro, L. M., Salvador-Franch, F., Schimmelpfennig I, Fernández-Fernández J. M., Lénni L., ASTER Team. 2019. The challenging application of cosmogenic dating methods in residual glacial landforms: The case of Sierra Nevada (Spain). Geomorphology 325, 103-118.
Palade, B., Palacios, D., Gómez-Ortiz, A., 2011. Los glaciares rocosos de Sierra Nevada y su significado paleoclimático. Una primera aproximación. Cuad. Invest. Geogr. 37(2), 95-118.
Pallàs, R., Rodés, A., Braucher, R., Carcaillet, J., Ortuño, M., Bordonau, J., Bourles, D., Vilaplana, J.M., Masana, E., Santanach, P., 2006. Late Pleistocene and Holocene glaciation in the Pyrenees: a critical review and new evidence from 10Be 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 exposure dating of Pleistocene climate fluctuations, southeastern Pyrenees. Geology. 38, 891-894.
Palma, P., Oliva, M., García-Hernández, C., Gómez-Ortiz, A., Ruiz-Fernández, J., Salvador-Franch, F., Salvà-Catarineu, M., 2017. Spatial characterization of glacial and periglacial landforms in the highlands of Sierra Nevada (Spain). Sci. Total Environ. 584, 1256-1267.
Panzer, W., 1926. Talentwicklung und Eiszeitklima in nordöstlichen Spanien. Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft. 386.
Pedraza, J., Fernández, P., 1981. Cuaternario del Mapa Geológico de de Bohoyo. Mapa Geológico de Bohoyo (577). Madrid.
Pedraza, J., Carrasco, R.M., Domínguez-Villar, D., Villa, J., 2013. Late Pleistocene glacial evolutionary stages in the Gredos mountains (Iberian Central System). Quat. Int. 302, 88-100.
Penck, A., 1883. La période glaciaire dans les Pyrénées. Bulletin de la Société d'Histoire Naturelle de Toulouse 19, 105-200.
Penck, A., Brückner, E., 1909. Die Alpen im Eiszeitalter. 3, Taunitz, Leipzig.
Pellicer, F., 1984. Geomorfología de las Cadenas Ibéricas entre el Jalón y el Moncayo. Cuad. Estud. Borj. 11, 9-378
Pellitero-Ondicol, R., 2013. Evolución finicuaternaria del glaciarismo en el macizo de Fuentes Carrionas (Cordillera Cantábrica), propuesta cronológica y paleoambiental. Cuatern. Geomorfol. 27(1-2), 71-90.
Pérez-Alberti, A., 1979. Nuevas observaciones sobre glaciarismo y periglaciarismo en el NW de la Península Ibérica. La Galicia sud oriental. Acta Geol. Hisp. 14, 441-444.
Pérez-Alberti, A., 2014. Geomorfología, in: Ferreiro, D.A., Macías, F., Calvo de Anta, R., Pérez-Alberti, A., Otero-Pérez, X.L., Verde-Vilanova, J.R., Pérez-Llaguno, C., Saiz-Rubio, R., Díez, E., Bolaños-Guerrón,

D., (Eds.), Complejo Básico-Ultrabásico de Capelada-Cabo Ortegal. Andavira Editorial, Santiago de Compostela, pp. 24-30.
Pérez-Alberti, A., 2018. Xeomorfoloxia das Montañas do Courel and Mapa Xeomorfolóxico do Courel. Grupo de Desenvolvemento Rural Ribeira Sacra-Courel, 70 pp.
Pérez-Alberti, A., Blanco-Chao, R., 1995. Importancia paleoclimática de las formas y depósitos de origen glaciar y periglaciar en la costa noroccidental de la Península Ibérica. (Serra da Capelada, Cedeira, A Coruña). Simposio Internacional Paleoambiente Cuaternario en la Península Ibérica. Resúmenes. Santiago de Compostela.
Pérez-Alberti, A., Valcárcel, M., 1998. Caracterización y distribución espacial del glaciarismo en el Noroeste de la Península Ibérica, in: Gómez-Ortiz, A., Pérez-Alberti, A. (Eds.), Las huellas glaciares de las montañas españolas. Universidade de Santiago de Compostela. Santiago de Compostela, pp. 17-62.
Pérez-Alberti, A., Rodríguez-Guitián, M.A, Valcárcel, M., 1992. El modelado glaciar en la vertiente oriental de la Sierra de Ancares (Noroeste de la Península Ibérica). Pap. geogr. 18, 39-51.
Pérez-Alberti, A., Rodríguez-Guitián, M.A., Valcárcel, M., 1993. Las formas y depósitos glaciares en las Sierras Orientales y Septentrionales de Galicia (NW Península Ibérica), in: Pérez Alberti, A., Ramil-Rego, P., Guitián, L., (Eds.), La evolución del paisaje en las montañas del entorno de los Caminos Jacobeos. Xunta de Galicia. Santiago de Compostela, pp. 61-90.
Pérez-Alberti, A., Valcárcel, M., Martini, P.I., 2002. La deglaciación en la vertiente suroccidental del Macizo de Peña Trevinca (Montañas de Trevinca, NW Ibérico), in: Serrano, E., García, A., Morales, J.C., Ortega, M.Y. (Eds.), Estudios recientes (2000-2002) en Geomorfología, Patrimonio, Montaña, Dinámica Territorial, pp. 205-216.
Pérez-Alberti, A., Valcárcel, M., Blanco, R., 2004. Pleistocene glaciation in Spain, in: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations- Extent and Chronology: Part I: Europe (2). Elsevier, London, pp. 389-394.
Pérez-Alberti, A., López-Bedoya, J., Cunha, P.P., 2009. Sedimentological analysis of cold-climate stratified slope deposits of Galicia, NW Iberia. In IAS 2009 Meeting: Book of Abstracts vol. 6 (nº 6) Alghero, Italy.
Pérez-Alberti, A., Valcárcel, M., Martini, P.I., Pascucci, V., Andreucci, S., 2011. Upper Pleistocene glacial valley-junction sediments at Pias, Trevinca Mountains, NW Spain. Geol. Soc. Spec. Publ. 354(1), 93-110.
Preusser, F., Schlüchter, C., 2004. Dates from an important early Late Pleistocene ice advance in the Aare Valley, Switzerland. Eclogae Geol. Helv. 97(2), 245-253.
René, P., 2013. Le réchauffement climatique en images. Cairn, Pau.
Renssen, H., Seppä, H., Heiri, O., Roche, D.M., Goosse, H., Fichefet, T., 2009. The spatial and temporal complexity of the Holocene thermal maximum. Nat. Geosci. 2, 411-414.
Renssen, H., Goosse, H., Roche, D., Sepp□, H., 2018. The global hydroclimate response during the Younger Dryas event. Quat. Sci. Rev. 193, 84-97.
Reuther, A.U., Urdea, P., Geiger, C., Ivy-Ochs, S., Niller, H.P., Kubik, P.W., Heine, K., 2007. Late Pleistocene glacial chronology of the Pietrele Valley, Retezat Mountains, Southern Carpathians constrained by 10Be exposure ages and pedological investigations. Quat. Int. 164-165, 151-169.
Rico, I., Izagirre, E., Serrano, E., López-Moreno, J.I., 2017. Current glacier area in the Pyrenees: An updated assessment 2016. Pirineos 172, 10-3989.
Rodés, A., Pallàs, R., Braucher, R., Bourlès, D., 2008. La última deglaciación en los Pirineos a partir de la datación de superficies de exposición mediante 10Be. Geo-Temas 10, 755-758.
Rodrigues, T., Grimalt, J.O., Abrantes, F., Naugton, F., Flores, J.A., 2010. The last glacial-interglacial transition (LGIT) in the western mid-latitudes of the North Atlantic: abrupt sea surface temperature changes and sea level implications. Quat. Sci. Rev. 29(15-16), 1853-1862.
Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J. Rico, M.T., Valero-Garcés, B.L., 2011. Last deglaciation in northwestern Spain: New chronological and geomorphologic evidence from the Sanabria region. Geomorphology 135, 48-65.
Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J., Rinterknecht, V., Pallàs, R., Bourlès, D., Valero-Garcés, B.L., 2014. A multiple dating-method approach applied to the Sanabria Lake moraine complex (NW Iberian Peninsula, SW Europe). Quat. Sci. Rev. 83, 1-10.
Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J., Aranburu, A., 2015. Research history on glacial geomorphology and geochronology of the Cantabrian Mountains, north Iberia (43-42ºN/7-2ºW). Quat. Int. 364, 6-21.
Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J., Rinterknecht, V., Pallàs, R., Bourlès, D., 2016. Chronology of glaciations in the Cantabrian Mountains (NW Iberia) during the Last Glacial Cycle based on in situ-produced 10Be. Quat. Sci. Rev.138, 31-48.

Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J., Rinterknecht, V., Pallàs, R., ASTER Team, 2017. Timing of last deglaciation in the Cantabrian Mountains (Iberian Peninsula; North Atlantic Region) based on in situ-produced 10Be exposure dating. Quat. Sci. Rev. 171, 166-181.
Rodríguez-Rodríguez, L., Domínguez-Cuesta, M.J., Rinterknecht, V., Jiménez-Sánchez, M., González-Lemos, S., Léanni, L., Sanjurjo, J., Ballesteros, D., Valenzuela, P., Llana-Fúnez, S., ASTER Team, 2018a. Constraining the age of superimposed glacial records in mountain environments with multiple dating methods (Cantabrian Mountains, Iberian Peninsula). Quat. Sci. Rev. 195, 215-231.
Rodríguez-Rodríguez, L., González-Lemos, S., Ballesteros, D., Valenzuela, P., Domínguez-Cuesta, M.J., Llana-Fúnez, S., Jiménez-Sánchez, M., 2018b. Timing of paraglacial rock-slope failures and denudation signatures in the Cantabrian Mountains (North Iberian Peninsula). Land Degrad. Dev. 29(9), 3159-3173.
Ruddiman, W.F., McIntyre, A., 1981a. The Mode and Mechanism of the Last Deglaciation: Oceanic Evidence. Quat. Res. 16, 125-134.
Ruddiman, W.F., McIntyre, A., 1981b. The North Atlantic Ocean during the Last Deglaciation. Paleogeogr. Paleoclimatol. Paleoecol. 35, 145-214.
Ruiz-Fernández J, Poblete-Piedrabuena M.A, Serrano-Muela M.P., Martí-Bono, C., García-Ruiz, J.M., 2009. Morphometry of glacial cirques in the Cantabrian Range (Northwest Spain). Z. Geomorphol. 53(1), 47-68.
Ruiz Fernández, J., Poblete Piedrabuena, M.A., 2011. Las terrazas fluviales del río Cares: aportaciones sedimentológicas y cronológicas (Picos de Europa, Asturias). The fluvial terraces of the Cares river: sedimentological and chronological contributions (Picos de Europa, Asturias). Estud. Geogr. 72(270), 173-202.
Ruiz-Fernández, J., Oliva, M., Cruces, A., Lopes, V., Freitas, C., García-García, C., Geraldes, M., López-Sáez, J.A., 2016. Environmental evolution in the Picos de Europa (Cantabrian Mountains, SW Europe) since the Last Glaciation. Quat. Sci. Rev. 138, 87-104.
Ruiz-Fernández, J., Oliva, M., Hrbáček, F., Vieira, G., García-Hernández, C., 2017. Soil temperatures in an Atlantic high mountain environment: The Forcadona buried ice patch (Picos de Europa, NW Spain). Catena 149(2), 637-647.
Sanchez-Gómez, S., 1990. Aplicación del estudio de suelos a la dinámica de la cuenca del río Lanjarón: relación suelos-geomorfología. PhD Thesis. University of Granada.
Sancho, C., Arenas, C., Pardo, G., Peña-Monné, J.L., Rodés, E.J., Bartolomé, M., García-Ruiz, J.M., Martí-Bono, C., 2018. Glaciolacustrine deposits formed in an ice-dammed tributary valley in the south-central Pyrenees: New evidence for late Pleistocene climate. Sediment. Geol. 366, 47-66.
Sanz Pérez, E.S, Pellicer-Corellano, F., 1994. El periglaciarismo de la Sierra de Cebollera (Soria y La Rioja). Cuatern. Geomorfol. 8(1-2), 123-138.
Sarikaya, M.A., Zreda, M., Ciner, A., Zweck, C., 2008. Cold and wet Last Glacial Maximum on Mount Sandiras, SW Turkey, inferred from cosmogenic dating and glacier modelling. Quat. Sci. Rev. 27, 769-789.
Santos-González, J., Redondo-Vega, J.M., González-Gutiérrez, R.B., Gómez-Villar, A., 2013. Applying the AABR method to reconstruct equilibrium-line altitudes from the last glacial maximum in the Cantabrian Mountains (SW Europe). Paleogeogr. Paleoclimatol. Paleoecol. 387, 185-199.
Sanz-Herraiz, C., 1988. El relieve del Guadarrama Oriental. Consejería de Política Territorial, Comunidad de Madrid. Madrid.
Scapozza, C., Castelletti, C., Soma, L., Dall'Agnolo, S., Ambrosi, C., 2015. Timing of LGM and deglaciation in the southern Swiss Alps. Geomorphologie 4, 307-322.
Schmieder O., 1915. Die Sierra de Gredos, Mitteilunger der Geographischen Gesellschaft in München, Zehnter Band, 1, 1-55.
Schimmelpfennig, I., Benedetti, L., Garreta, V., Pik, R., Blard, P-H., Burnard, P., Bourles, D., Finkel, R., Ammon, K., Dunai, T., 2011. Calibration of cosmogenic 36Cl production rates from Ca and K-spallation in lava flows from Mt. Etna (38ºN, Italy) and Payun Matru (36ºS, Argentina), Geochim. Cosmochim. Acta. 75, 2611-2632.
Schimmelpfennig, I., Schaefer, J. M., Putnam, A. E., Koffman, T., Benedetti, L., Ivy-Ochs, S., Aster Team and Schlüchter, Ch., 2014. 36Cl production rate from K-spallation in the European Alps (Chironico landslide, Switzerland). J. Quat. Sci. 29. 407-413.
Schmitz, H., 1969. Glazialmorphologische Untersuchungen im Bergland Nordwestspaniens: (Galicien/León). Geographischen Inst. der Univ zu Köln im Selbstverl. Wiesbaden.
Schrader, F., 1895. Sur l'étendue des glaciers des Pyrénées. Annuaire du Club Alpin Français 1894, 403-423.

Schulte, L., 2002. Climatic and human influence on river systems and glacier fluctuations in southeast Spain since the Last Glacial Maximum. Quat. Int. 93, 85-100.
Sermet, J., 1942. Sierra Nevada. Estudios Geográficos 9, 727-749.
Serrano, E., 1998. Geomorfología del Alto Gállego (Pirineo Aragonés). Institución Fernando el Católico. Diputación de Zaragoza. Zaragoza.
Serrano, E., 1991. Glacial evolution of the Upper Gallego Valley (Panticosa Mountains and Ribera de Biescas, Aragonese Pyrenees, Spain). Pirineos 138, 83-78.
Serrano, E., 1992. Huellas de una glaciación pre-pleniglaciar en la Ribera de Biescas (Cuenca del Gállego, Pirineo aragonés), in: Libro Homenaje a Félix Ugarte, Eusko Ikaskuntza, 213-227, San Sebastián.
Serrano, E., Agudo, D., 1988. La deglaciación del valle de los ibones Azules (Panticosa). Estudio glaciomorfológico. Cuatern. Geomorfol. 2, 115-123.
Serrano, E., Martín-Moreno, R., 2018. Surge glaciers during the Little Ice Age in the Pyrenees. Cuad. Invest. Geogr. 44 (1), 213-244.
Serrano, E., González-Trueba, J.J., Sanjosé, J.J., 2011. Dinámica, evolución y estructura de los glaciares rocosos de los Pirineos. Cuadernos de Investigación Geográfica 37(2), 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), 303-31.
Serrano, E., González-Trueba, J.J., Pellitero, R., González-García, M., Gómez-Lende, M., 2013. Quaternary glacial evolution in the Central Cantabrian Mountains. Geomorphology 196, 65-82.
Serrano, E., Gómez-Lende, M., González-Amuchástegui, M.J., González-García, M., González-Trueba, J.J., Pellitero, R., Rico, I., 2015. Glacial chronology, environmental changes and implications for human occupation during the upper Pleistocene in the eastern Cantabrian Mountains. Quat. Int. 364, 22-34.
Serrano, E., González-Trueba, J.J., Pellitero, R., Gómez-Lende, M., 2017. Quaternary glacial history of the Cantabrian Mountains of northern Spain: a new synthesis. Geol. Soc. Spec. Publ. 433(1), 55-85.
Serrano, E., Oliva, M., González-García, M., López-Moreno, J.I., González-Trueba, J.J, Martín-Moreno, R., Martín-Díaz, J., Gómez-Lende, M., Nofre, J., Palma, P., 2018. Post-Little Ice Age paraglacial processes and landforms in the high mountains of the Iberian Peninsula. Land Degrad. Dev. 29, 4186-4208.
Serrat, D., 1977. L 'estudi geomorfològic del Pirineu oriental (Puigmal i Costabona). PhD Thesis, University of Barcelona.
Serrat, D., Vilaplana, J.M., Martí-Bono, C.E., 1983. Some depositional models of glaciolacustrine environments in Southern Pyrenees, in: Evenson, E., Schluchter, Ch., Rabassa, J.P., (Eds.), Tills and related deposits. Balkema, Rotterdam, pp. 231-244.
Serrat, D., Bordonau, J., Bru, J., Furdada, G., Gómez-Ortiz, A., Martí, J., Martí, M., Salvador-Franch, F., Ventura, J., Vilaplana, J.M., 1994. Síntesis cartográfica del glaciarismo surpirenaico oriental, in: Martí Bono, C., García Ruiz, J.M., (Eds.), El glaciarismo surpirenaico: nuevas aportaciones. Geoforma Ediciones, Logroño, pp. 9-15.
Sermet, J., 1942. Sierra Nevada. Estud. Geogr. 3(9), 727.
Shackleton, N.J., 1967. Oxygen isotope analyses and Pleistocene temperatures re-assessed. Nature 215, 15-17.
Shakun, J.D., Clark, P.U., He, F., Lifton, N.A., Liu, Z., Otto-Bliesner, B.L., 2015. Regional and global forcing of glacier retreat during the last deglaciation. Nat. Commun. 6, 8059.
Solé-Sabarís, L., 1941. La Canal de Berdún. Primera Reunión de Estudios Geográficos. Instituto Juan Sebastián Elcano, Madrid, pp. 113-160.
Solé Sabarís, L., 1951. Los Pirineos. El medio y el hombre. Editorial Martín, Barcelona.
Solomina, O.N., Bradley, R.S., Hodgson, D.A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A.N., Nesje, A., Owen, L.A., Wanner, H., Wiles, G.C., Young, N.E., 2015. Holocene glacier fluctuations. Quat. Sci. Rev. 111, 9-34.
Solomina, O.N., Bradley, R.S., Jomelli, V., Geirsdottir, A., Darrell, S K., Koch, J., McKay, N.P., Masiokas M., Miller, G., Nesje, A., Nicolussi, K., Owen, L.A., Putnam, A.E., Wanner, H., Wiles, G., Yan, B., 2016. Glacier fluctuations during the last 2000 years. Quat. Sci. Rev. 149, 61-90.
Stone, J.O., 2000. Air pressure and cosmogenic isotope production. J. Geophys. Res. 105, 23753-23759.
Stone, J.O., Fifield, L.K., Vasconcelos, P., 2005. Terrestrial Chlorine-36 Production from Spallation of Iron, in Abstracts of 10th International Conference on Accelerator Mass Spectrometry, September 5-10, Berkeley.
Stokes, C.R., 2017. Deglaciation of the Laurentide Ice Sheet from the Last Glacial Maximum. Cuad. Invest. Geogr. 43(2), 377-428.

Stroeven, A.P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B.W., Harbor, J.M., Jansen, J.D., Olsen, L., Caffee, M.W., Fink, D., Lundqvist, J., Rosqvist, G.C., Strömberg, B., Jansson, K.N., 2016. Deglaciation of Fennoscandia. Quat. Sci. Rev. 147, 91-121.

Taboada, J., 1913. El lago de San Martín de Castañeda. Bol. Soc. Esp. Hist. Nat. 13, 860-883.

Thornes, J. B., 1968. Glacial and periglacial features in the Urbion Mountains, Spain. Estud. geol. (Madr.). 24, 249-258.

Tomkins, M.D., Dortch, J.M., Hughes, P.D., Huck, J.J., Stimson, A.G., Delmas, M., Calvet, M., Pallàs, R., 2018. Rapid age assessment of glacial landforms in the Pyrenees using Schmidt hammer exposure dating (SHED). Quat. Res. 90(1), 26-37.

Trigo, R.M., Pozo-Vázquez, D., Osborn, T.J., Castro-Diez, Y., Gámis-Fortis S., Esteban-Parra, M.J., 2004. North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. Int. J. Climatol. 24, 925-944.

Turu, V., Calvet, M., Bordonau, J., Gunnell, Y., Delmas, M., Vilaplana, J.M., Jalut, G., 2016. Did Pyrenean glaciers dance to the beat of global climate events? Evidence of the Würmian sequence stratigraphy of an ice-dammed palaeolake depocentre in Andorra, in: Hughes, P.D., Woodward, J.C. (Eds.), Quaternary glaciation in the Mediterranean mountains, Geol. Soc. Spec. Publ. 433, 111-136.

Uppala, S.M., Kållberg, P., Simmons, A., Andrae, U., Bechtold, V., Fiorino, M., Gibson, J., Woollen, J., 2005. The ERA-40 reanalysis. Q.J.R. Meteorological Soc. 131, 2961-3012.

Valcárcel, M., 1998. Evolución geomorfológica y dinámica de las vertientes en el NE de Galicia. Importancia de los procesos de origen frío en un sector de las montañas lucenses. PhD Thesis. Universidade de Santiago de Compostela.

Valcárcel, M., Pérez-Alberti, A., 2002 a. Un ejemplo de glaciarismo de baja cota en el NW de la Península Ibérica: el valle de Queixadoiro, in: Serrano, E., García, A., Morales, J.C., Ortega, M.Y. (Eds.), Estudios recientes en Geomorfología. Patrimonio, montaña y dinámica territorial. Universidad de Valladolid, Valladolid, 205-215.

Valcárcel, M., Pérez-Alberti, A. 2002b. La glaciación finipleistocena en el sector noroccidental de las montañas leonesas: la Sierra de los Ancares, in: Redondo Vega, J.M., Gómez Villar, A., González Gutiérrez, R.B., Carrera Gómez, P., (Eds.), El modelado de origen glaciar en las montañas leonesas. Universidad de León, pp. 67-102.

Valcárcel, M., Blanco-Chao, R., Feal-Pérez, A., 2009. Fases criológicas reconocidas en el NW de la Península Ibérica durante el Pleistoceno Final a partir de datos geomorfológicos: implicaciones en la modelización de las condiciones paleoambientales, in: Flor-Rodríguez, G., Gallastegui, J., Flor-Blanco, G., Martín-Llaneza, J. (Eds.), 6º Simposio sobre el Margen Ibérico Atlántico MIA09. Universidad de Oviedo, pp. 165-168.

Vasskog, K., Langebroek, P., Andrews, J.T., Nilsen, J.E.Ø., Nesje, A., 2015. The Greenland Ice Sheet during the last glacial cycle: Current ice loss contribution to sea-level rise from a palaeoclimatic perspective. Earth-Sci. Rev. 150, 45-67.

Vegas, J., 2006. Los sistemas lacustres de las sierras de Neila y Urbión. Análisis sedimentológico y climático del Pleistoceno superior y Holoceno. PhD Thesis, Complutense University of Madrid.

Vegas, J., 2007a. Análisis digital de imágenes de microscopía electrónica de ritmias siliclásticas. Interpretación limnogeológica de los registros lacustres de origen glaciar. (No sist. Ibérico). Cuatern. Geomorfol. 21, 49-75.

Vegas, J., 2007b. Caracterización de eventos climáticos del Pleistoceno Superior-Holoceno mediante el estudio sedimentológico de la Laguna Grande (Sierra de Neila, NO Sistema Ibérico). Revista de la Sociedad Geológica de España 20(1-2), 53-70.

Vieira, G., 2004. Geomorfologia dos planaltos e altos vales da Serra da Estrela. Ambientes frios do Plistocénico Superior e dinâmica actual. PhD Thesis, Universidade de Lisboa.

Vieira, G., 2008. Combined numerical and geomorphological reconstruction of the Serra da Estrela plateau icefield, Portugal. Geomorphology 97(1-2), 190-207.

Vieira, G., Ferreira, A.B. Mycielska-Dowgiallo, E. Woronko, B. Olszak, I., 2001.Thermoluminiscence dating of fluvioglacial sediments (Serra da Estrela, Portugal). V REQUI/I, Lisboa, pp. 85-92.

Vieira, G., Palacios, D., 2010. New cosmogenic exposure dates for the Serra da Estrela glaciation. Preliminary results, in: Bateira, C., Soares, L., Gomes, A., Chaminé, H.I., (Eds.), Proceedings do V Congresso Nacional de Geomorfologia, pp. 14-25.

Vidal-Romaní, J.R., Vilaplana, J.M., de Brum-Ferreira, A., Zezere, J.L., Rodrigues, L., Monge, C., 1990. Los tills de la Serra de Gerês-Xurés y la glaciación pleistocena (Minho, Portugal-Ourense, Galicia). Cuatern. Geomorfol. 4, 13-25.

Vidal-Romaní, J.R., Santos-Fidalgo, L., 1994. La deglaciación finicuaternaria en el noroeste peninsular (Serra de Queixa-Invernadoiro, Ourense, Galicia): datos geomorfológicos y paleobotánicos. Cuatern. Geomorfol. 8(1-2), 33-44.
Vidal-Romaní, J.R., Fernández Mosquera, D., Marti, K., Ferreira, A.B., 1999. Nuevos datos para la cronología glaciar pleistocena en el NW de la Península Ibérica. Cad. Lab. Xeol. Laxe. 24, 7-29.
Vidal-Romaní, J.R., Fernández-Mosquera D., Marti, K., 2015. The glaciation of Serra de Queixa-Invernadoiro and Serra do Gerês-Xurés, NW Iberia. A critical review and a cosmogenic nuclide (10Be and 21 Ne) chronology. Cad. Lab. Xeol. Laxe. 38, 27-45.
Vidal-Box, C., 1936. Contribución al conocimiento morfológico del segmento occidental de la Sierra de Gredos (Bohoyo). Bol. Soc. Esp. Hist. Nat. 36, 17-31.
Vilaplana, J.M., 1983. Estudi del glacialisme de les valls de la Valira d'Ordino i d'Arinsal. PhD Thesis, University of Barcelona.
Villa, E., Stoll, H., Farias, P., Adrados, L., Edwards, R.L., Cheng, H., 2013. Age and significance of the Quaternary cemented deposits of the Duje Valley (Picos de Europa, Northern Spain). Quat. Res. 79(1), 1-5.
Walker, M.J.C., Berkelhammer, M., Björck, S., Cwynar, L.C., Fisher, D.A., Long, A.J., Lowe, J.J., Newnham, R.M., Rasmussen, S.O., Weiss, H., 2012. Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). J. Quat. Sci. 27, 649-659.
Williams, C., Flower, B.P., Hastings, D.W., 2012. Seasonal Laurentide Ice Sheet melting during the 'Mystery Interval' (15.5–14.5 ka). Geology 40, 955-958.
Wirsig, C., Zasadni, J., Christl, M., Akçar, N., Ivy-Ochs, S., 2016. Dating the onset of LGM ice surface lowering in the High Alps. Quat. Sci. Rev. 143, 37-50.
Zahno, C., Akçar, N., Yavuz, V., Kubik, P.W., Schlüchter, C., 2010. Chronology of Late Pleistocene glacier variations at the Uludag Mountain, NW Turkey. Quat. Sci. Rev. 29, 1173-1187.
Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A.P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L.N., Cáceres, B.E., Casassa, G., Cobos, G., Dávila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V., Portocarrero, C.A., Prinz, R., Sangewar, C.V., Severskiy, I., Sigur□sson, O., Soruco, A., Usubaliev, R., Vincent, C., 2015. Historically unprecedented global glacier decline in the early 21st century. J. Glaciol. 61(228), 745-762.

Figure captions

Figure 1. Location of the study sites in the different Iberian mountain ranges examined in this research.

Figure 2. Number and type of absolute dating methods used in each mountain range.

Figure 3. Glacial deposits and landforms from distinct glacial stages in the Pyrenees: (A) Main moraines and the 60 m fluvioglacial terrace corresponding to stages prior to LGM in the terminal basin of the Aragón valley glacier (M1 was dated at 171 OSL ka, and M2 at 68 OSL ka, whereas the fluvioglacial terrace was dated at 263 OSL ka); (B) LGM moraine at the front of the Malniu-Guils cirque complex, between the Duran valley to the west and the Querol valley to the East, Cerdanya, Eastern Spanish Pyrenees (the oldest boulders were dated at 23 ^{10}Be ka). The flat surface at the background culminates in the Puigpedrós Peak (2914 m a.s.l.); (C) The OD moraine, in a tributary of the Acherito valley, headwater of the Aragón Subordán valley glacier; (D) The YD moraine near the cirque headwall of the Escarra valley, a tributary of the Gállego valley glacier; (E) Mid-Holocene and LIA moraines in the Marboré cirque, at the foot of the Monte Perdido peak (3355 m); (F) LIA moraines above the YD complexes in the Maladeta massif.

Figure 4. (A) Geomorphological map with the location of the main fluvial terrace sand moraine systems in the terminal basin of the Aragón River glacier; (B) Cross profile with the location of the main fluvial and glacial features.

Figure 5. Examples of glacial landforms deposited during the Last Glaciation in the Cantabrian Mountains: (A) Local MIE central moraine developed between the Enol and Ercina lakes in Lagos de Covadonga, Western Massif of Picos de Europa; (B) Lateral moraine complex and related kame terrace deposit marking the local MIE and LGM glacial stages in the Monasterio valley, Redes Natural Park; (C) Erratic boulders deposited during the last deglaciation cold stages on the Fronfría ice-moulded surface in the Porma valley; (D) Recessional moraine and foremost ridge of a rock glacier deposited during the OD at the Valdevezón cirque in the Monasterio valley, Redes Natural Park; (E) Moraine possibly formed during either the YD or the Holocene at the base of Peña Agujas peak, Sierra de Sentiles; (F) Moraine formed during the LIA inside the Jou Negro cirque.

Figure 6. Examples of landforms deposited during thein the NW Ranges: (A) Erratic boulders preserved outside the limits of the moraines of the Last Glaciation in the Tera valley, Trevinca massif; (B) Recessional moraine complex of Sanabria Lake, deposited during the last deglaciation in the Tera valley, Trevinca massif; (C) Moraine system developed in the NW slope of Capelada massif and ascribed to periglacial conditions in the coastal areas of Galicia during the Last Glaciation; (D) As Lamas Lake dammed by recessional moraines dated at ca. 15 ka in Requixo valley, Manzaneda massif; (F) Protalus ramparts formed during the LIA near Pico Cuiña (1998 m), Ancares massif.

Figure 7. Examples of moraine complexes in the Central Range: (A) Principal moraine and peripheral ridges in the Laguna cirque, eastern face of Peñalara peak (Sierra de Guadarrama), both from LGM age; (B) LGM, OD and YD moraines in Cuerpo de Hombre, Sierra de Béjar; (C) Pinar valley in Sierra de Gredos, with peripheral ridges of unknown ages, principal moraine from the LGM and several ridges from the OD; (D) Deglaciation moraine sequences in La Serra paleoglacier, La Nava Massif, Sierra de Gredos; (E) LGM, OD; YD and Holocene glacial features in La Galana cirque, Gredos.

Figure 8. Examples of moraines generated during the different glacial stages in the Iberian range: (A) Overhead view of the complete moraine sequence in the SE San Lorenzo cirque; (B) Oblique field view of the intermediate moraine in such cirque (LGM?) enclosing the fossil debris-covered glacier (DCG), and an older moraine corresponding to an earlier stage (pre-LGM?); (C) Overhead view of the complete moraine sequence in the westernmost Mencilla cirque; (D) Field view of the loose block accumulations interpreted as a fossil debris-covered glacier in such cirque, and the innermost moraine (OD?). Aerial orthophotos were obtained from the CNIG/IGN (http://www.ign.es/web/ign/portal).

Figure 9. Examples of moraines generated during the different glacial stages in Sierra Nevada: (A) Moraines predating the Last Glaciation in Naute valley (dated at 135-140 ka); (B Moraines of the LGM and subsequent glacial advances in Hoya de la Mora cirque; (C) OD and YD moraines in San Juan valley; (D) Holocene moraine sequence at the foot of the highest Iberian peak (Mulhacén, 3478 m); LIA moraine ridge including two glacial advances at ca. 1350 and 1700 AD as revealed by surface exposure dating and historical sources.

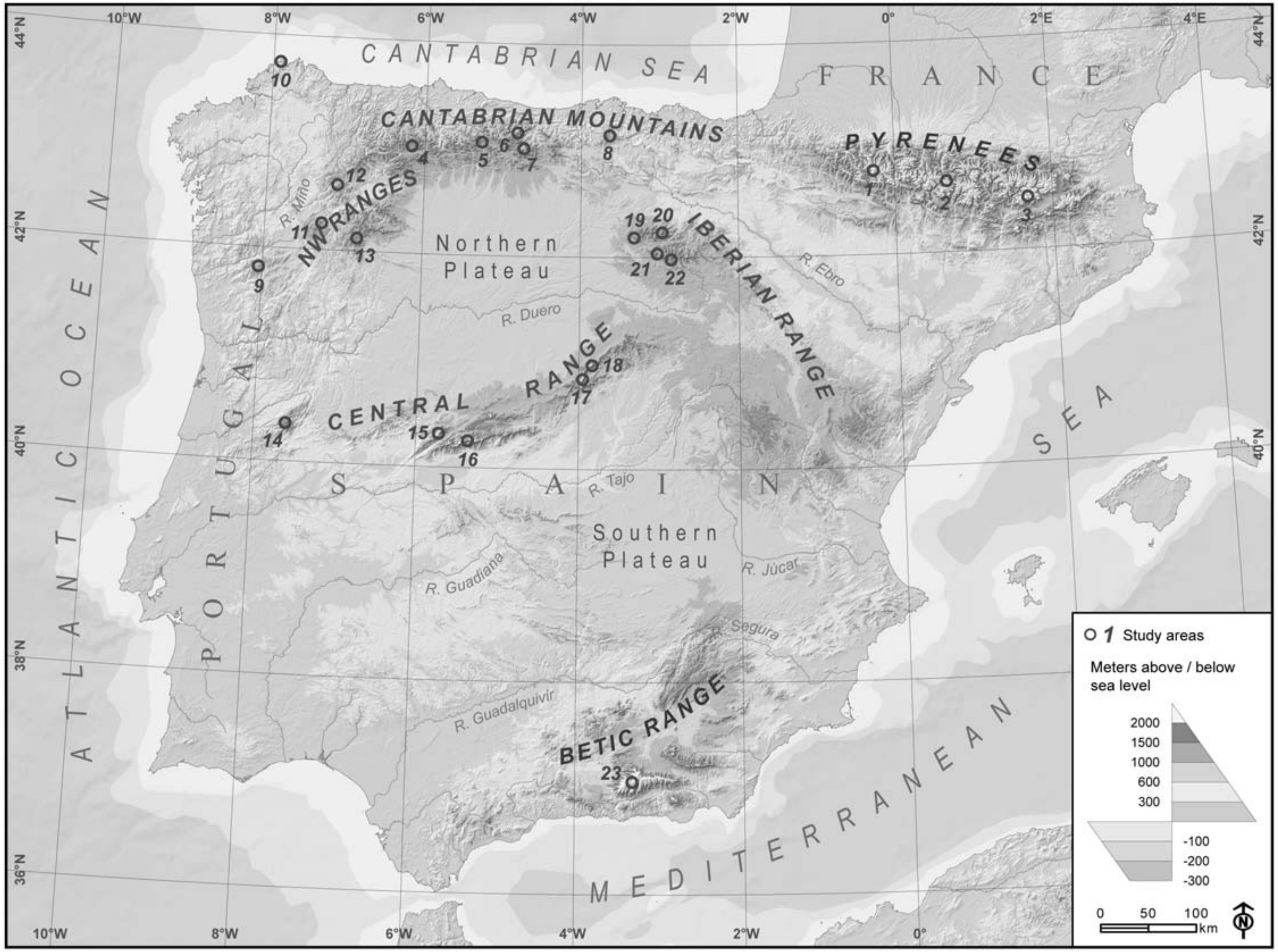
Figure 10. Summary of the chronological framework of glacial phases of the Last Glacial Cycle in Iberian mountains.

Figure 11. Distribution of geomorphic evidence of glacial activity during MIS 6 in Iberian mountain ranges.

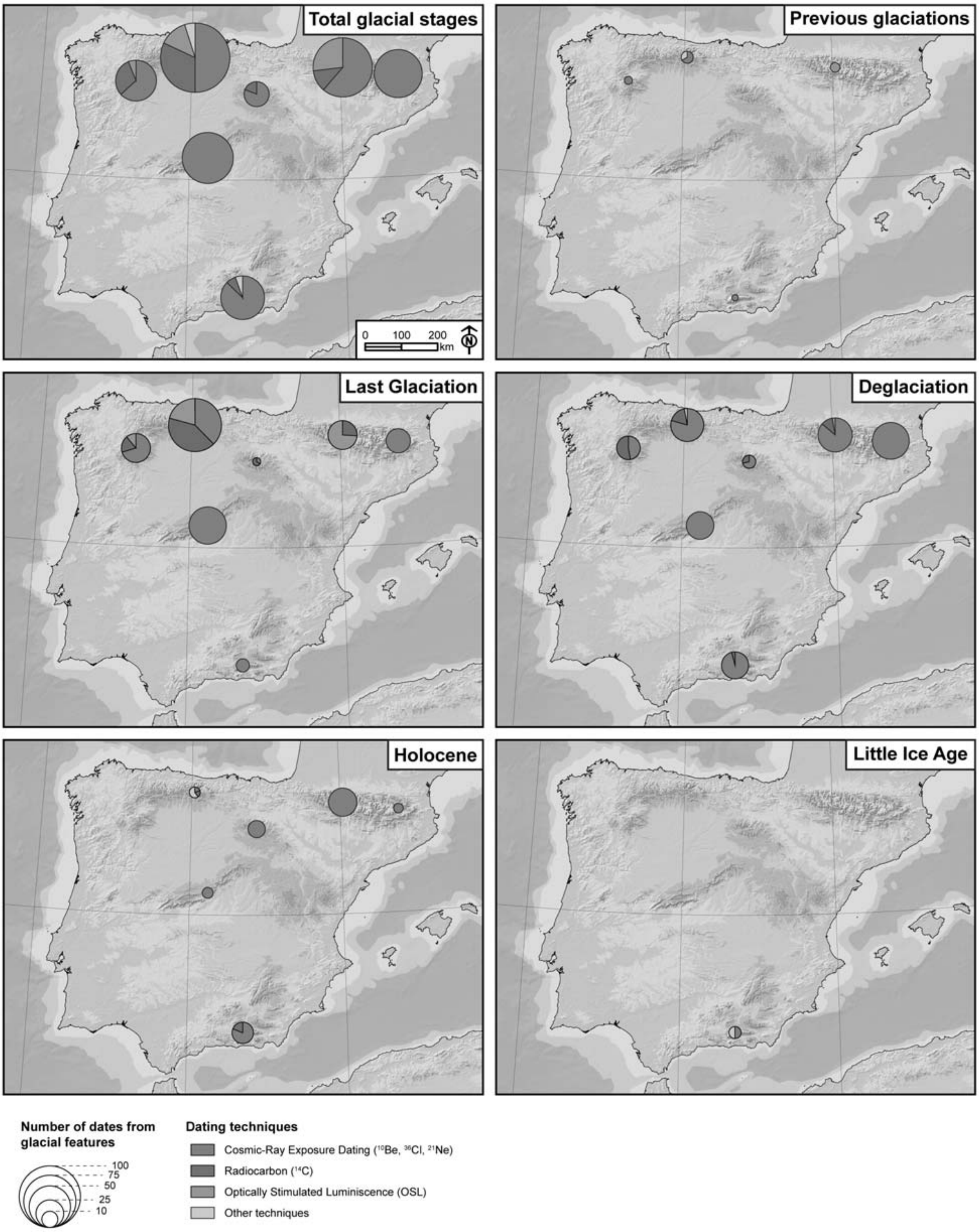
Figure 12. For each of the mountain ranges, the figures include the dates of (a) the MIE of the Last Glaciation, (b) the MIS 4, (c) the MIS 2, and (d) the onset of Termination-1.

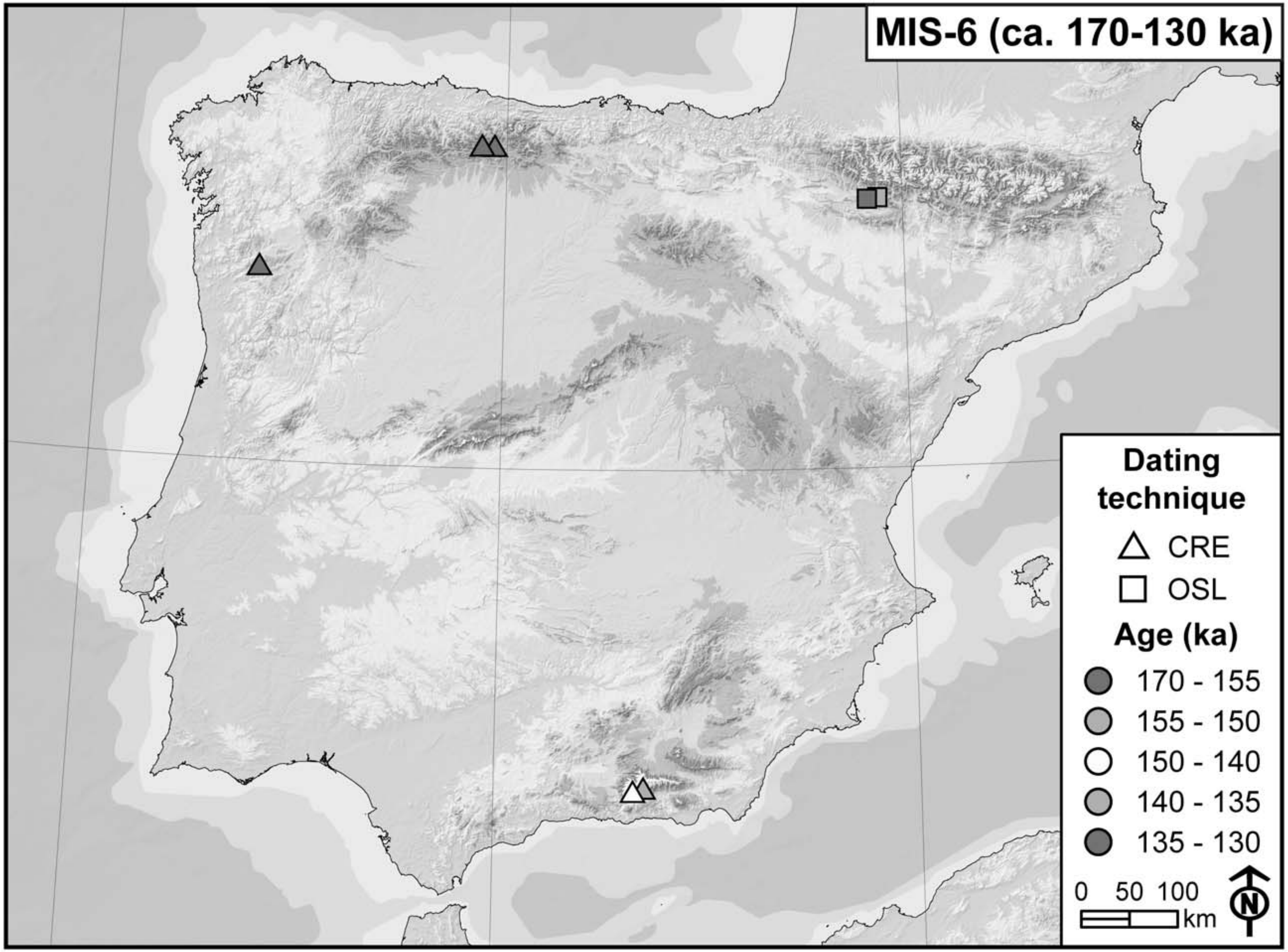
Figure 13. Summary of the chronological framework of glacial stages during the Late Pleistocene-Holocene transition in the Iberian mountains.

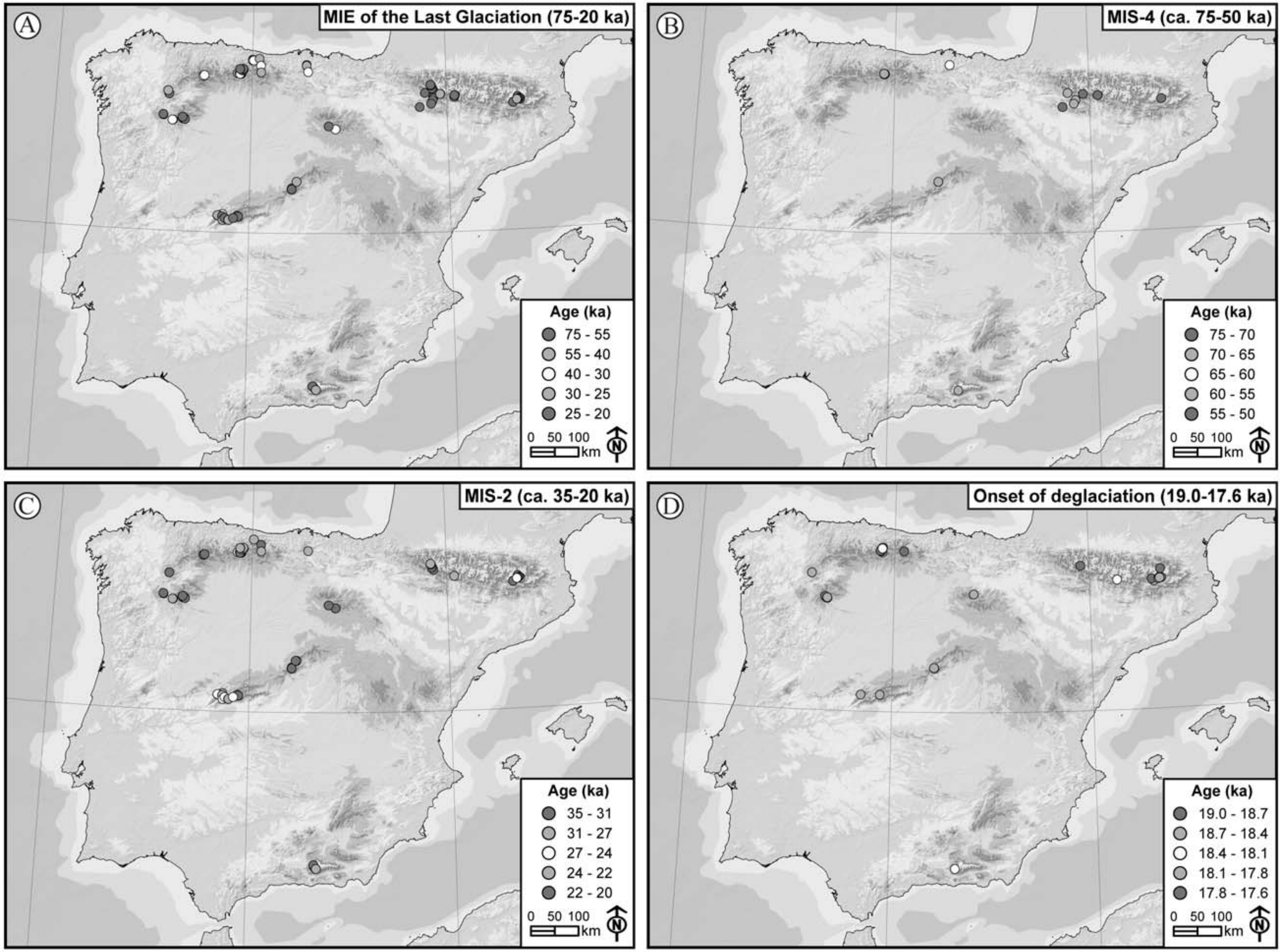
Figure 14. For each of the mountain ranges, the figures include the dates of glacial evidence during (a) the OD, (b) the BO, (c) the YD, (d) the Holocene, and (d) LIA.



1) Western Pyrenees: Aguas Limpias, Arrémoulit, Brazato, Caldarés, Catieras, Gállego-Sabiñánigo, Marboré, Paúl de Búbal, Piniecho Portalet, Salinas de Cinca, Tramacastilla. 2) Central Pyrenees: Ésera, La Madaleta, Noguera-Ribagorçana. 3) Eastern Pyrenees: Arànser, Duran, Escale, La Llosa, Le Carol, Malniu-Guils, Rec de La Grava. 4) Somiedo-Laciana. 5) Montaña Central. 6) Picos de Europa. 7) Fuentes Carrionas. 8) Pas Mountains. 9) Xurés-Gérez. 10) Serra da Capelada. 11) Manzaneda. 12) Serra do Courel. 13) Trevinca. 14) Serra da Estrela. 15) Sierra de Béjar. 16) Sierra de Gredos. 17) Peñalara. 18) Hoyo Grande. 19) Sierra de Mencilla. 20) Sierra de San Lorenzo. 21) Sierra de Neila. 22) Sierra de Urbión. 23) Sierra Nevada: Dílar, La Mora, Lanjarón, Mulhacén, Naute, Río Seco, San Juan, Veleta.


Total glacial stages
0 100 200
km
N
Previous glaciations
Last Glaciation
Deglaciation
Holocene
Little Ice Age
Number of dates from glacial features
100
75
50
25
10
Dating techniques
Cosmic-Ray Exposure Dating (^{10}Be, ^{36}Cl, ^{21}Ne)
Radiocarbon (^{14}C)
Optically Stimulated Luminiscence (OSL)
Other techniques


MIS-6 (ca. 170-130 ka)
Dating technique
CRE
OSL
Age (ka)
170 - 155
155 - 150
150 - 140
140 - 135
135 - 130
0 50 100
km
N


A
MIE of the Last Glaciation (75-20 ka)
Age (ka)
75 - 55
55 - 40
40 - 30
30 - 25
25 - 20
0 50 100
km
N
B
MIS-4 (ca. 75-50 ka)
Age (ka)
75 - 70
70 - 65
65 - 60
60 - 55
55 - 50
0 50 100
km
N
C
MIS-2 (ca. 35-20 ka)
Age (ka)
35 - 31
31 - 27
27 - 24
24 - 22
22 - 20
0 50 100
km
N
D
Onset of deglaciation (19.0-17.6 ka)
Age (ka)
19.0 - 18.7
18.7 - 18.4
18.4 - 18.1
18.1 - 17.8
17.8 - 17.6
0 50 100
km
N

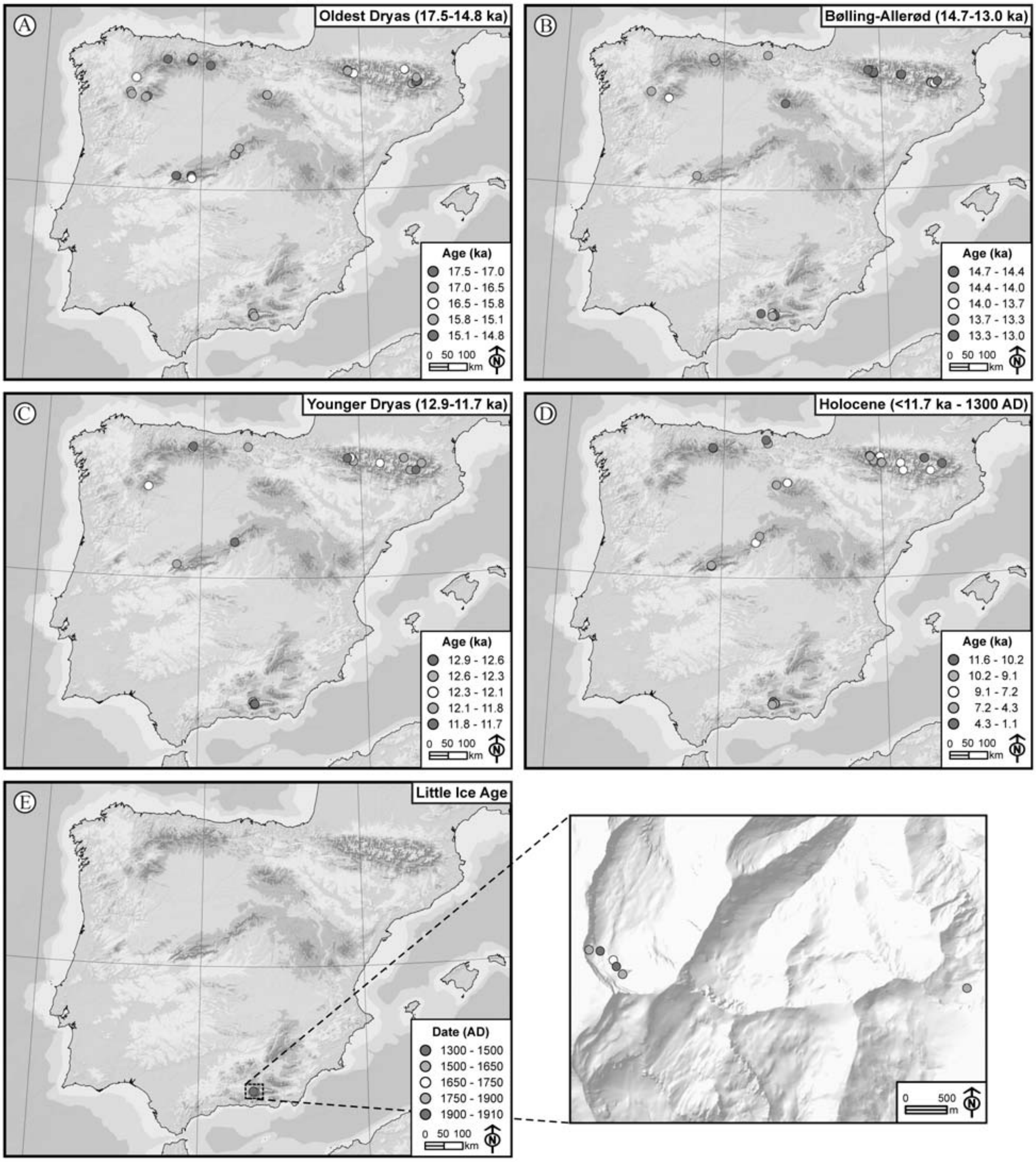

A
Oldest Dryas (17.5-14.8 ka)
Age (ka)
17.5 - 17.0
17.0 - 16.5
16.5 - 15.8
15.8 - 15.1
15.1 - 14.8
0 50 100
km
N
B
Bølling-Allerød (14.7-13.0 ka)
Age (ka)
14.7 - 14.4
14.4 - 14.0
14.0 - 13.7
13.7 - 13.3
13.3 - 13.0
0 50 100
km
N
C
Younger Dryas (12.9-11.7 ka)
Age (ka)
12.9 - 12.6
12.6 - 12.3
12.3 - 12.1
12.1 - 11.8
11.8 - 11.7
0 50 100
km
N
D
Holocene (<11.7 ka - 1300 AD)
Age (ka)
11.6 - 10.2
10.2 - 9.1
9.1 - 7.2
7.2 - 4.3
4.3 - 1.1
0 50 100
km
N
E
Little Ice Age
Date (AD)
1300 - 1500
1500 - 1650
1650 - 1750
1750 - 1900
1900 - 1910
0 50 100
km
N
0 500
m
N

Table 1. Distribution of the different dating methods used to infer the deglaciation in each mountain range.

Phase	Pyrenees	Cantabrian Mountains	NW ranges	Central Range	Iberian Range	Sierra Nevada	Total
Previous glaciations	0 / 0 / 4 / 0	4 / 0 / 0 / 2	3 / 0 / 0 / 0	-	-	3 / 0 / 0 / 0	9 / 0 / 4 / 2
Last Glacial Cycle	20 / 7 / 20 / 0	29 / 32 / 16 / 0	19 / 5 / 3 / 0	42 / 0 / 0 / 0	1 / 2 / 0 / 0	19 / 5 / 3 / 0	118 / 46 / 39 / 0
Termination-1	72 / 4 / 1 / 0	27 / 6 / 0 / 1	9 / 10 / 0 / 0	25 / 0 / 0 / 0	5 / 2 / 0 / 0	9 / 10 / 0 / 0	161 / 23 / 1 / 1
Holocene	30 / 0 / 0 / 0	1 / 1 / 0 / 3	-	5 / 0 / 0 / 0	11 / 0 / 0 / 0	0 / 0 / 0 / 0	60 / 4 / 0 / 3
LIA	-	-	-	-	-	3 / 0 / 0 / 3	3 / 0 / 3 / 0
Total	122 / 11 / 25 / 0	61 / 39 / 16 / 6	31 / 15 / 3 / 0	72 / 0 / 0 / 0	17 / 4 / 0 / 0	48 / 4 / 0 / 3	351 / 73 / 47 / 6

CRE / C14 / OSL / other

Table 2. Glacial activity in the Pyrenees during the Late Quaternary.

Phase	Chronology	Environments, landforms and processes	References
Previous glaciations	~ 263 ka ~ 170-180 ka	Some glacial deposits in the Gállego valley are located several km away from the main moraine system. Previous glaciations are well represented in the main and outermost moraine of the Aragón valley, as well as in fluvial deposits of the Aragón and Gállego valleys	Martí-Bono (1978), Vilaplana (1983), Serrano (1992), Lewis et al. (2009), García-Ruiz et al. (2013)
Last Glacial Cycle	MIE occurred at 55-65 ka Some glaciolacustrine deposits show evidence of glacial expansion between 30 and 45 ka The LGM is well represented in the Eastern Pyrenees at ~21 ka	Occurrence of a clear asynchroneity between the global LGM (MIS-2) and the regional MIE (MIS-4), particularly in the Central Pyrenees. The Gállego, Ara and Cinca Valleys show several examples of MIS-4 moraines. In the Eastern Pyrenees, there is increasing evidence of the presence of moraines of polygenic nature, as a result of the superposition of pulsations along the Last Glacial Cycle.	García-Ruiz et al. (2003), González-Sampériz et al. (2006), Lewis et al. (2009), Pallàs et al. (2010), Turu et al. (2016), Andrés et al. (2018), Sancho et al. (2018), Guerrero et al. (2018)
Termination-1	Intense deglaciation following the LGM, at ca. 19 ka. Most of OD moraines were deposited between 16 and 17 ka. YD moraines between 11.5 and 13 ka	Deglaciation in the Pyrenees is very well represented by a range of deposits whose distance to the headwater is directly related to the altitude of mountain massifs. The OD glacial expansion represented the growth of several km long glaciers leaving a number of morainic deposits. Development of rock glaciers at the end of the OD. A new, short glacial advance occurred during the YD, with deposition of big moraines close to the cirque limits. The longest glaciers were ca. 4 km long.	Pallàs et al. (2006), Palacios et al. (2015a, 2015b, 2016a, 2017), García-Ruiz et al. (2016), Crest et al. (2017)
Holocene	Early to Mid-Holocene	Most of rock glaciers that developed at the end of OD or YD melted out. Mid-Holocene: Reactivation of glaciers in the highest massifs, particularly Monte Perdido and Maladeta. A long and large moraine corresponding to Mid-Holocene has been identified in the Marboré cirque, northern face of the Monte Perdido massif. Probable existence of polygenic moraines formed during successive glacial advances in the Maladeta massif.	García-Ruiz et al. (2014), Crest et al. (2017)
LIA	15th-19th centuries: more than 100 small glaciers controlled by aspect and altitude	Development of large, fresh moraines at the front of Quaternary cirques, mainly in massifs peaking at more than 3000.	González-Trueba et al. (2008), García-Ruiz et al. (2014), Serrano and Martín-Moreno (2018)
Present-day	Approx. 19 small glaciers remaining in north facing, well-protected slopes in the highest massifs. By 2016, glaciers occupy an area of 242 ha.	Glaciers are clearly declining, with spatial and volumetric contraction. Some glaciers appear the more and more covered with debris.	René (2013), López-Moreno et al. (2016), Rico et al. (2017)

Table 3. Glacial activity in the Cantabrian Mountains during the Late Quaternary.

Phase	Chronology	Environments, landforms and processes	References
Previous glaciations	>394 ka (MIS 12?) ~173–131 ka (MIS 6)	Precipitation of carbonate cements in old breccia deposits resting on a possible glacial-polished surface. Some erratic boulders in the terminal zone of the former Porma glacier suggest glaciation during MIS 6.	Villa et al. (2013), Rodríguez-Rodríguez et al. (2016), Rodríguez-Rodríguez et al., (2018a)
Last Glacial Cycle	Pre-MIE at 110 ka (MIS 5d) MIE prior to 45–35 ka (MIS 3) LGM between 33–24 ka (MIS 2)	The front of the Porma glacier reached an elevation of ~1110 m, during MIS 5d and MIS 3, leaving moraines and erratic boulders. Proglacial glacio-lacustrine sequences and kame terraces deposited outside the MIE lateral moraines provide minimum ages of ~45–33 cal ka BP in Picos de Europa, Redes, Somiedo-Laciana and Pas Mountains. Inherited boulders in the Porma lateral moraines in combination with OSL analysis of till and kame terraces suggest continuous glacial occupation from MIS 3 to the LGM of MIS 2.	Jiménez-Sánchez and Farias (2002), Jalut et al. (2010), Moreno et al. (2010), Serrano et al. (2012), Frochoso et al. (2013), Jiménez-Sánchez et al. (2013), Serrano et al. (2013), Ruíz-Fernández et al. (2016), Rodríguez-Rodríguez et al. (2016, 2018a)
Termination-1	Onset of deglaciation between ~22–20 ka Glacier front stagnations until 14 ka Rock glacier stabilization at 15.7–13 ka Onset of paraglacial instabilities	Abandonment of lateral moraines in the Porma valley and its main tributaries after ~22 ka. Glaciers were remarkably thinned and retreated from their MIE position by ~18–17 ka in the different massifs of the Cantabrian Mountains. Recessional moraines deposited in the Monasterio valley at ~19, 17.5, and 14.6 ka. Preliminar ^{10}Be CRE dating of relict rock glaciers toes lying at 1600–1550 m altitude suggest their stabilization between ~16.2–13.6 ka. Start of paraglacial rock slope failures in San Isidro valley at ~16–15 ka.	Rodríguez-Rodríguez et al. (2016, 2017, 2018a, 2018b), Serrano et al. (2013), Allen et al. (1996)
LIA	Mid-19^{th} century	Six glaciers developed in the highest areas of the Central and Western massifs of Picos de Europa, leaving frontal moraines at elevations of 2200–2320 m	Miotke (1968), González-Trueba (2005), González-Trueba et al. (2008),
Present-day	2007	Only a few permanent ice-patches remain in the Central and Western massifs of Picos de Europa, fully or partly cover by debris mounds.	González-Suárez and Alonso (1994), Frochoso and Castañón (1995), Alonso and González (1998), González-Trueba (2005), González-Trueba ~~et al.~~ (2007)

Table 4. Glacial activity in the NW ranges during the Late Quaternary.

Phase	Chronology	Environments, landforms and processes	References
Previous glaciations	238 ka (?) 125-130 ka (?)	Glacial polished surfaces at 1100 and 1300 m in Serra do Xurés-Gerêz. Moraine boulder at 1210 m in Manzaneda Massif. Glacial erratic boulders outside the limits of the MIE moraines.	Vidal-Romaní et al. (1999, 2015)
Last Glacial Cycle	MIE at ca. 33–48 ka Glacier fronts stable until 22–19 ka	The Trevinca ice cap extended over 475 km^2 during the MIE, reaching minimum elevations at the Bibei and Tera glacier fronts (900–950 m). Periglacial slope processes were active in both non-glaciated mountain settings and littoral mountain areas.	Butzer (1967), Brosche (1982), Cano et al. (1997), Costa-Casais et al. (1994, 1996), Costa-Casais (2001), Pérez-Alberti et al. (2011), Rodríguez-Rodríguez et al. (2011, 2014)
Termination-1	Onset of deglaciation between 22–19 ka. Glacier front stagnations until 17.9 ka. Highlands partly exposed by 15 ka, triggering accelerated glacier retreat around 14.5 ka. Possible minor readvance without moraine construction between 13.1–12.1 ka (before the YD)	Tera glacier recorded progressive deglaciation with minor glacier front re-advances and/ or stagnations followed by rapid glacial retreat to the headvalleys. Lacustrine sequences suggest accelerated glacier retreat to the headvalleys and fast deglaciation of plateau areas below 1650 m Other mountain settings with top elevations under 1700 m altitude already recorded important glacier recession by 20 ka.	Maldonado (1994), Allen et al. (1996), Muñoz-Sobrino et al. (2001, 2004), Pérez-Alberti et al. (2009), Rodríguez-Rodríguez et al. (2011, 2014), Jambrina-Enríquez et al. (2014)
Holocene	After 13.1 ka	Glaciers were restricted to the highest cirques (above 1800 m). The Trevinca Massif was possibly the single glaciated massif of the NW Ranges	Cowton et al. (2009)

Table 5. Glacial activity in the Central Iberian Range during the Late Quaternary.

Phase	Chronology	Environments, landforms and processes	References
Previous glaciations	~ 140 ka	Moraines in Peñalara peak (Sierra de Guadarrama) considered of the Riss glaciation in the alpine terminology, but dated during the last decade as slightly previous or contemporaneous to the LGM No evidence was found in the Central Range from previous glaciation advances, except recently in Serra da Estrela with moraines from MIS 6.	Vieira et al. (2001), Palacios (2012a, 2012b), Pedraza et al. (2013), Carrasco et al. (2013, 2015), Domínguez-Villar et al. (2003), (Vieira, Palacios and Lorenzo unpublished data)
Last Glacial Cycle	MIE at ca. 27-32 ka Second largest glacial advance at LGM 19-26 ka with main moraine formation in polygenic processes	Existence of moraine "Peripheral Deposits" that show the maximum extension of the glaciers around 27-32 ka Existence of a "Principal Moraine" of great geomorphological entity, very close to the Peripheral Deposits, with a polygenic nature, result of the superposition of pulsations along the LGM (19-26 ka)	Vieira et al. (2001), Palacios et al. (2011, 2012a, 2012b), Pedraza et al. (2013), Carrasco et al. (2015), Carrasco et al. (2016), Vieira and Palacios (2010)
Termination-1	Onset of deglaciation at ca. 19 ka OD, at ca. 17 ka BO, at ca. 14.5-15 ka YD, at ca. 12-13 ka	The magnitude of the deglaciation after 19 ka and during the BO is unknown. We only know that glaciers disappeared from the Serra da Estrela at the beginning of the BO. There is evidence of important advances during the OD, which left moraines very close to those of the LGM Recently, evidence of short advances during the YD began to be known	Palacios et al. (2011, 2012a, 2012b, 2012c), Pedraza et al. (2013), Carrasco et al. (2015), Vieira and Palacios (2010).
Holocene	Early Holocene, at ca. 9-10 ka	The glaciers in the Central Range disappeared along the Pleistocene-Holocene transition in most of the Sierras and definitively in the initial Holocene	Palacios et al. (2012a, 2012b), Pedraza et al. (2013), Carrasco et al. (2015, 2016)
LIA	No glaciers, but some permanent snow patches under north face walls	Formation of nival protalus rampart	García-Sancho et al. (2001)
Present-day	Long stay snow patches in recession	Nivation processes in long stay snow patches	Palacios et al. (2003)

Table 6. Glacial activity in the Iberian Range during the Late Quaternary.

Phase	Chronology	Environments, landforms and processes	References
Previous glaciations	-	Erratic boulders outside the outermost moraine in the SE cirque of the San Lorenzo Peak.	García-Ruiz (1979)
Last Glacial Cycle	MIE prior to 21 ka cal BP, Sierra de Neila MIE at 18.1 ka, Sierra de la Demanda	Cirque glaciers 1-km long descending to < 1570 m in the Mencilla Peak and to 1671 in the SE cirque of the San Lorenzo Peak, with surfaces up to 0.3 km^2 (ELAs at 1750-1900 m).	Vegas et al. (2007), Fernández-Fernández et al. (2017)
Termination-1	Onset of deglaciation at ca. 21 ka cal BP Sierra de Neila. Moraine formation at 17.8 ± 2.3 ka in SE San Lorenzo cirque, Sierra de la Demanda At ca. 17 ka (OD) At ca. 16.4-15.8 ka (BO)	Deglaciation, ice-free walls and formation of a debris-covered glacier in the SE San Lorenzo cirque. Presence of a small glacier in this cirque (0.07 km^2) disconnected from the debris-covered glacier (ELA at 2007 m). Gradual melting of the debris-covered ice in the SE San Lorenzo cirque.	Vegas et al. (2007), Fernández-Fernández et al. (2017)
Holocene	Early Holocene, at ca. 11 ka Mid Holocene, at ca. 8-6 ka	Gradual melting of the debris-covered ice in the SE San Lorenzo cirque. Definitive melting of the debris-covered glacier in the western Mencilla cirque, and stabilization of the moraine that enclosed it.	Fernández-Fernández et al. (2017)

Table 7. Glacial activity in Sierra Nevada during the Late Quaternary.

Phase	Chronology	Environments, landforms and processes	References
Previous glaciations	~ 140 ka	Eroded moraines and glacio-fluvial sediments at lower elevations than Last Glaciation moraines.	Hempel (1960), Messerli (1965), Lhenaff (1977), Sánchez-Gómez (1990), Gómez-Ortiz and Pérez-González (2001), Palacios et al. (2019)
Last Glacial Cycle	MIE at ca. 30-32 ka Second largest glacial advance at ca. 19-20 ka	Valley glaciers filling the valleys until elevations slightly below ca. 2000 m (north slope) and ca. 2500 m (south slope), lower in the western and northern sides of the massif. Glaciated surface during the MIE of 105 km^2, mainly in the western fringe of the massif.	Gómez-Ortiz et al. (2002, 2012a, 2013a, 2015), Oliva (2009), Oliva et al. (2014a, b), Palacios et al. (2016a), Palma et al. (2017)
Termination-1	Onset of deglaciation at ca. 19 ka OD, at ca. 17 ka BO, at ca. 14.5-15 ka YD, at ca. 12-13 ka	Massive deglaciation. Glacial expansion with formation of moraines close to MIE moraines. Rapid glacial retreat to the headvalleys. Expansion of glaciers in the highest cirques shaped on east-facing slopes. Few glaciers in the southern slope, only in the westernmost valleys.	Gómez-Ortiz et al. (2012, 2013b), Palacios et al. (2016) Oliva et al. (2011, 2014a)
Holocene	Early Holocene, at ca. 9-10 ka Late Holocene: three glacial at ca. 2.8-2.7, 1.4-1.2 ka cal BP and LIA	Melting of YD glaciers and formation of rock glaciers, which stabilized at ca. 6-7 ka. Formation of a small glacier in the Mulhacén cirque, where several moraines suggest other glacial stages during the Holocene.	Palade et al. (2011), Gómez-Ortiz et al. (2012a, 2013b), Palacios et al. (2016a) Oliva et al. (2010, 2015), Oliva and Gómez-Ortiz (2012)
LIA	Mulhacén glacier: from 1440 to 1710 AD Veleta glacier: from 1350 AD to mid-20th century	Small glaciers (several ha) in the highest northern cirques above 2900 m between Mulhacén and Veleta peaks. Disappearance of the Mulhacén glacier by 1710 AD.	Gómez-Ortiz et al. (2001, 2009, 2018), Schulte (2002), Oliva and Gómez-Ortiz (2012), Oliva (2018), Oliva et al. (2018), Palacios et al. (2019)
Present-day	Disappearance of Veleta glacier by mid-20th century	No glaciers exist today in the massif, only buried ice bodies derived from LIA glaciers in the Mulhacén and Veleta cirques.	Gómez-Ortiz et al. (2001, 2009, 2014, 2018), Oliva et al. (2016b), Serrano et al. (2018)