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Research history on glacial geomorphology and geochronology of the Cantabrian Mountains, north Iberia (43–42°N/7–2°W)

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ABSTRACT

The study of glacial geomorphology in the Cantabrian Mountains, a mountain range that extends 460 km along the northern coast of the Iberian Peninsula (SW Europe), started late in the 19th century and continues nowadays with a growing number of research papers. However, the number and timing of glaciations remains poorly understood, partially due to the still limited number of numerical ages. Its southerly location and proximity to the Atlantic Ocean make this mountain range potentially sensitive to past climate fluctuations. This work updates the glacial knowledge evolution for the whole range, from the Queixa-Invernadoiro Massif to the Basque Mountains, reviewing: (i) the history of glacial research since the late 19th century; (ii) the methodological approaches applied to reconstruct both the spatial extent and timing of past glacial stages; and (iii) the main geomorphological and geochronological evidence reported until date, including glacial features attributed to the Last Glacial Cycle (last 120 ka) and previous glaciations. According to current knowledge, glaciers extended over the Cantabrian Mountains covering a total area of 3150 km^2, showing asymmetric development conditioned by variations of the topographic configuration and moisture supply along the range. Available geochronology based on radiocarbon, optically stimulated luminescence and terrestrial cosmogenic nuclides suggests the occurrence of at least 2 glacial advances during the Last Glacial Cycle: (i) a glacial maximum stage that took place at a minimum age of 36–45 ka (Marine Isotope Stage 3) and (ii) a second glacial advance at 19–23 ka (MIS 2). In some areas the extent of the glacier tongues during the second glacial advance was comparable to previous glacial maximum and was followed by glacial retreat conditions with formation of recessional moraines. Asynchronous glacial maximum conditions have been reported only for the Castro Valnera (MIS 4, 3 numerical ages) and Queixa-Invernadoiro (MIS 6, 1 numerical age) massifs until now. Finally, geomorphological evidence reported in Picos de Europa has been attributed to prior glaciations and correlated to cold conditions recorded during MIS 12 and MIS 22 based on a very limited number of numerical ages.

1. Introduction

The main mountain ranges of the Iberian Peninsula contain well-preserved evidence of past glaciations. Due to its southern location in Europe, right at the transition between the Atlantic Ocean and the Mediterranean Region, the geomorphological and geochronological evidence of past glaciations in this area has a special interest as a terrestrial record of past temperature and moisture variations. Particularly, the research on the extent and number of glacial advances in north Iberia Mountains has been developed since the end of the 19th century at the same time that methodologies have evolved. Now a growing number of researchers are interested on the improvement of glacial reconstructions and chronologies (e.g. Jiménez-Sánchez et al., 2013; Serrano et al., 2013a), which is necessary to establish good correlations with other Mediterranean mountain records and untangle the hindered palaeoclimate signal.

The Cantabrian Mountains (CM) is a coastal range that extends from the westernmost Galaico/Leonés Massif to the Basque Mountains disposed along the northern margin of the Iberian Peninsula, 20–150 km inland from the Cantabrian Sea (Fig. 1). Geologically considered the westward extension of the Pyrenees

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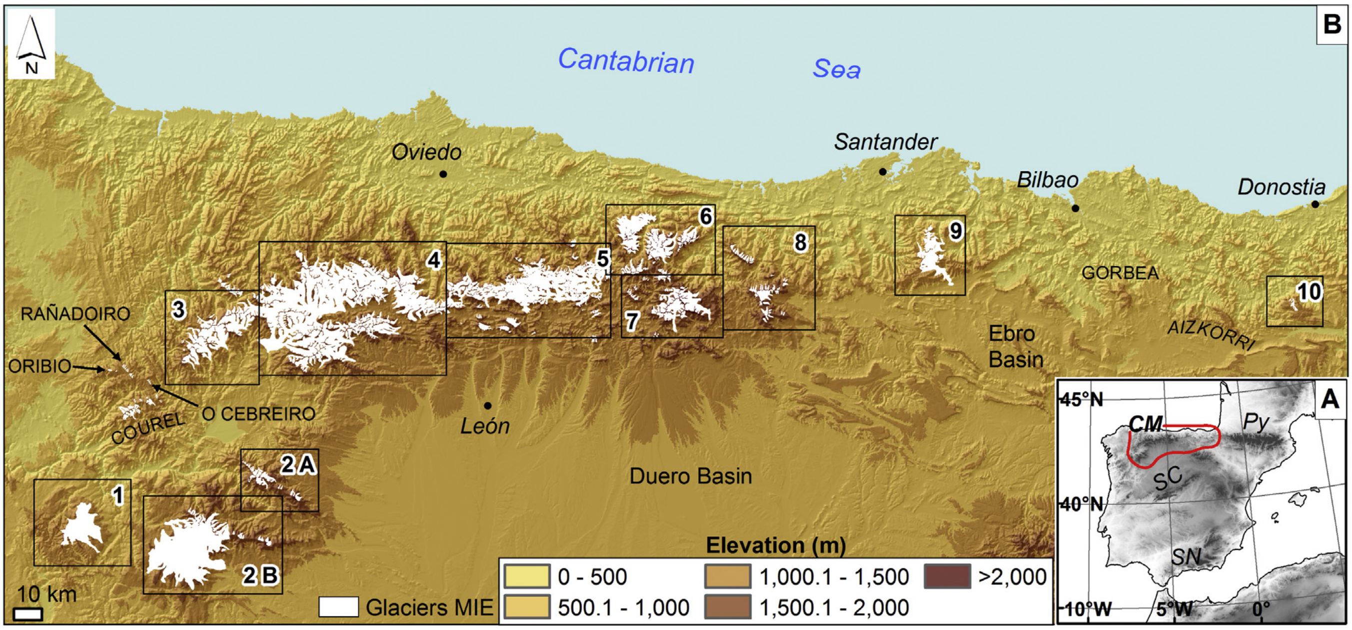

Fig. 1. (A) Geographic location of the study area in the Iberian Peninsula: Py- Pyrenees; CM-Cantabrian Mountains; SC-Sistema Central and SN-Sierra Nevada. (B) Palaeo-glaciers reconstruction for the regional maximum ice extent (MIE) based on a compilation of previous works. Squares indicate the location of the different mountain areas reviewed in this work: 1- Queixa-Invernadoiro; 2A- Sierra del Teleno; 2B- Trevinca Massif; 3- Serra dos Ancares; 4- Somiedo/Alto Sil/Babia and Omaña; 5- Central Cantabrian Mountains; 6- Picos de Europa; 7- Fuentes Carrionas; 8- Peña Sagra and Peña Labra; 9- Castro Valnera; 10- Basque Mountains/Aralar.

(Alonso et al., 1996), the elevation of this alpine landscape varies from 2128 m (Peña Trevinca) in the Trevinca Massif to 1548 m (Aizkorri) in the Basque Mountains, reaching a maximum of 2648 m (Torre Cerredo) in Picos de Europa. Current climate is strongly influenced by the proximity to the Atlantic Ocean in the northern slope of the range where mean annual precipitation increases progressively from 1000 to 1100 mm in the coastline to 1600–2000 mm at the edge of the mountain range, turning to continental climate in the southern slope where mean precipitation is 600–700 mm. Mean annual temperature values range between 17.5 and 2.5 °C (Ninyerola et al., 2005).

The aim of this paper is to set the state-of-the-art in the study of glacial geomorphology and timing of Quaternary glaciations in the Cantabrian Mountains, reviewing the research history on glacial geomorphology and the different methods applied in this region since the 19th century.

2. Methodologies applied in glacial geomorphology

This section briefly addresses the methods that have been applied in northern Iberia to understand the spatial and temporal evolution of past mountain glaciations.

2.1. *Spatial reconstruction of palaeo-glaciers*

The development of geomorphological maps including the distribution of glacial features from a study area is a key step to identify where ice source and terminal zones were placed, to trace ice flow trajectories or to set the spatial extent of minor glacial advances. In Spain, contour lines were incorporated on the geomorphological maps in 1958 when the first national topographic map (1/50,000) was completed by the Instituto Geográfico Nacional using terrestrial photogrammetry (Muro-Morales et al., 2002). The interpretation of aerial photos to complement field observations during the production of geomorphological maps started in Spain with the diffusion of the first national coverage of aerial pictures taken in 1956–57 by the American Army. Nowadays, the geomorphological mapping task is digitally produced using Geographic Information Systems (GIS) designed to store, manage, analyze, and compare quantitatively all kinds of geographical data (e.g. Pellitero, 2009).

Once the glacial evidence is mapped, the local maximum extent can be delineated using the terminal moraines or tills placed at the lowest altitudes, while minor advances or stillstands related to subsequent glacial stages can be deduced from the recessional moraines located inward. The first approach applied in the Cantabrian Mountains to reconstruct the topography of palaeo-glaciers was to use hand-drawn ice contour lines taking modern glaciers as analogues. This empirical approach is now improved or complemented through the use of theoretical glacier surface profiles, which represent steady-state glacier models based on the assumption of perfect plasticity to describe ice rheology (e.g. Schilling and Hollin, 1981; Benn and Hulton, 2010). These methodologies were successfully applied in some areas of the Cantabrian Mountains like the Trevinca Massif (e.g. Cowton et al., 2009; Rodríguez-Rodríguez et al., 2011, 2014). The topography of a former glacier is useful to determine the total ice volume, the thickness distribution, and the palaeo Equilibrium Line Altitude or palaeo-ELA in steady-state conditions that represents the average elevation at which the annual mass balance equals zero for the whole glacier. Initially, palaeo-ELA estimations in the Cantabrian Mountains were mainly based on the maximum elevation of lateral moraines (MELM) and the altitude of the cirque floors (e.g. Nussbaum and Gigax, 1952; Alonso, 1994; Jiménez-Sánchez, 1996; Menéndez-Duarte and Marquínez, 1996). The main disadvantages of these methods are that moraines degrade very fast after glacier retreat and that cirques develop cumulatively over multiple glacial cycles and cannot be assigned to any particular glacial event (Benn and Lehmkuhl, 2000). During the last decade, the methods commonly used to estimate palaeo-ELAs in this region have been the Accumulation-Area-Ratio (AAR) and the Area-Altitude Balance Ratio (AABR) (e.g. Serrano and González-Trueba, 2004; Cowton et al., 2009; Santos-González, 2010; Pellitero, 2012; Serrano et al., 2013a). The AAR method assumes that the accumulation area

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occupies a fixed proportion of the total area of the glacier, while the AABR method takes explicit account of the balance ratio of the glacier (Osmaston, 2005).

2.2. Constraining the timing of the main glacial stages

The chronology of a glacial record is essential to understand landscape and climate evolution. Glacial chronologies can be established by means of relative and numerical dating, giving us the formation sequence of observed glacial features or the numerical age of sampled glacial features (Jull, 2007). Relative chronologies in glacial geomorphology are based on morphostratigraphy, that combines the spatial relationships between glacial landforms and their sedimentological characterization to establish their formation sequence, providing a useful tool to set sampling strategies for numerical dating (Hughes, 2010). The weathering degree of glacial deposits and soil development, which are time-dependent and closely related to local climate and geology, were frequently used to establish relative chronologies in this region (e.g. Hernández-Pacheco, 1957; Llopis, 1957).

The chronological framework of the glacial record preserved in the Cantabrian Mountains was initially established based on the radiocarbon dating method (^{14}C) applied to ice-dammed deposits and glaciolacustrine sequences deposited at former proglacial sites or in glacial over-deepened basins (e.g. Pérez-Alberti and Valcárcel-Diaz, 1998; Jiménez-Sánchez and Farias, 2002; Jalut et al., 2010; Moreno et al., 2010; Serrano et al., 2012). Other numerical techniques, like terrestrial cosmogenic nuclides (TCN) and optically stimulated luminescence (OSL), have been used to constrain the timing of the glacial maximum and subsequent deglaciation, providing results that not always fit to radiocarbon ages (e.g. Vidal-Romaní et al., 1999; Frochoso et al., 2013; Rodríguez-Rodríguez et al., 2014). Finally, the uranium decay series (U/Th) have been applied to secondary carbonate cements developed in tills and other non-glacial deposits attributed to the interglacial periods (Villa et al., 2013), resulting in numerical ages with considerably large errors (Frochoso et al., 2013).

3. The research of past glaciations in the Cantabrian Mountains

This section reviews the glacial evidence and the history of glacial research, following a division of knowledge in 3 stages (Pioneer, Mapping, and Chronological) similar to that proposed before for the Mediterranean region (Pioneer, Mapping and Advanced in Hughes et al., 2006).

3.1. Pioneer stage

This stage represents the starting point of the glacial research in an area and comprises publications that recognize and describe glacial evidence, providing the sequence of formation by means of morphostratigraphy and relative dating. In general, they were accomplished with nonexistent or unfinished topographic information, so the descriptions and interpretations used to be accompanied with field sketches and photographs instead of geomorphological maps. The study of past glaciations in the CM started late in the 19th century with the identification of glacial features in the landscape of Picos de Europa and the Trevinca Massif (Prado, 1852; Fernández-Duro, 1879) (Fig. 1). Early in the 20th century, the fieldtrip memoirs of many geographers and geologists that worked in these areas incorporated descriptions of the most outstanding glacial features (e.g. Carballo, 1911; Taboada, 1913), pointing to the idea that past glaciations were probably generalized in the CM (Hernández-Pacheco, 1914). One of the first monographic works focused directly on the study of past glacial record was done by Obermaier (1914) who described the glacial evidence of the Central and Eastern massifs of Picos de Europa. He suggested that glaciers achieved their longest extent in the northern slope, reaching 4–7 km in length, due to the stronger oceanic influence on local climate and estimated the local palaeo-ELA at about 1400–1500 m altitude. He also argued the superposition of at least two glaciations based on the cross-cut relationships between glacial erosive features and a particular kind of deposits that he called “gonfolitas”, made up of a mix of sharp-edged and rounded cobbles of limestone and sandstone cemented by white or yellowish carbonates originated by fluvial and/or slope processes. He attributed these calcareous cemented breccias to the interglacials because they can be cut by glacial valleys, included in moraines as erratic boulders, or preserved in situ covering glacial polished surfaces.

More clues to understand the scope of past glaciations in the CM were compiled by Stickel (1929). He identified, described, and photographed glacial features at altitudes as low as 1000–1300 m in the Central Cantabrian Mountains, Somiedo/Alto Sil/Babia and Teleno (Fig. 1). He also visited Lago de Sanabria, in the Trevinca Massif, where he tried to improve previous descriptions of the moraine complex, glaciofluvial sediments and fluvial terraces preserved in the vicinity of the lake, evidence that he linked to the Würm glaciation (palaeo-ELA at 1500 m altitude). However, Llopis (1957) interpreted the same sequence as the result of 3 glacial advances during the Mindel, Riss, and Würm glaciations. Similarly, the glacial record from the nearby Queixa-Invernadoiro Massif was described by Hernández-Pacheco (1949, 1957) and interpreted as the superposition of 2 glaciations (Riss and Würm).

In 1949, Nussbaum and Gigax studied the glacial record of the western and central parts of the CM to estimate the regional palaeo-ELA during the Quaternary. They quoted moraines in the Courel and Ancares ranges at altitudes of 1180–1240 m, and gave more details about the location of the glacial fronts in the Somiedo/Alto Sil/Babia area (680–1260 m). Based on the maximum elevations of the different mountain ranges and massifs that compound the CM and the altitude distribution of moraines, they estimated a regional palaeo-ELA ranging between 1400 and 1800 m, rising inland and eastward (Nussbaum and Gigax, 1952). This tendency had been already suggested based on palaeo-ELA estimations made in the main mountain ranges of the Iberian Peninsula (Obermaier and Carandell, 1915).

The glacial evidence preserved in the eastern CM was recognized slightly later than in the central and western sectors (Sáenz, 1935; Gómez de Llarena, 1948). The glacial geomorphology of the Peña Labra Range was described and mapped by Hernández-Pacheco (1944), who distinguished 3 sets of moraines marking glacial front stabilizations at mean altitudes of 1385, 1534, and 1645 m that he assigned to the Mindel, Riss, and Würm glaciations. Further to the East, Lotze (1962) described 2 sets of moraines in the Castro Valnera Massif arranged at different altitudes and showing weathering differences. For Lotze, the oldest set of moraines, placed at 550–600 m altitude, marks a maximum length of 6–11 km for the glacier tongues during the Rissian Glaciation, when the local palaeo-ELA was at 1300–1400 m altitude. In the Aralar Massif, located at the transition between the CM and the western Pyrenees, Gómez de Llarena (1948) described a possible glacial valley in the Arritzaga Valley and quoted poorly defined glacial cirques and moraines at altitudes as low as 1350–1080 m. Therefore, the evidence described at the eastern Castro Valnera and Aralar massifs, suggested that glacial conditions reached extremely low altitudes at the transition between the CM and the Pyrenees, considerably decreasing the palaeo-ELA values estimated previously (Obermaier and Carandell, 1915; Nussbaum and Gigax, 1952).

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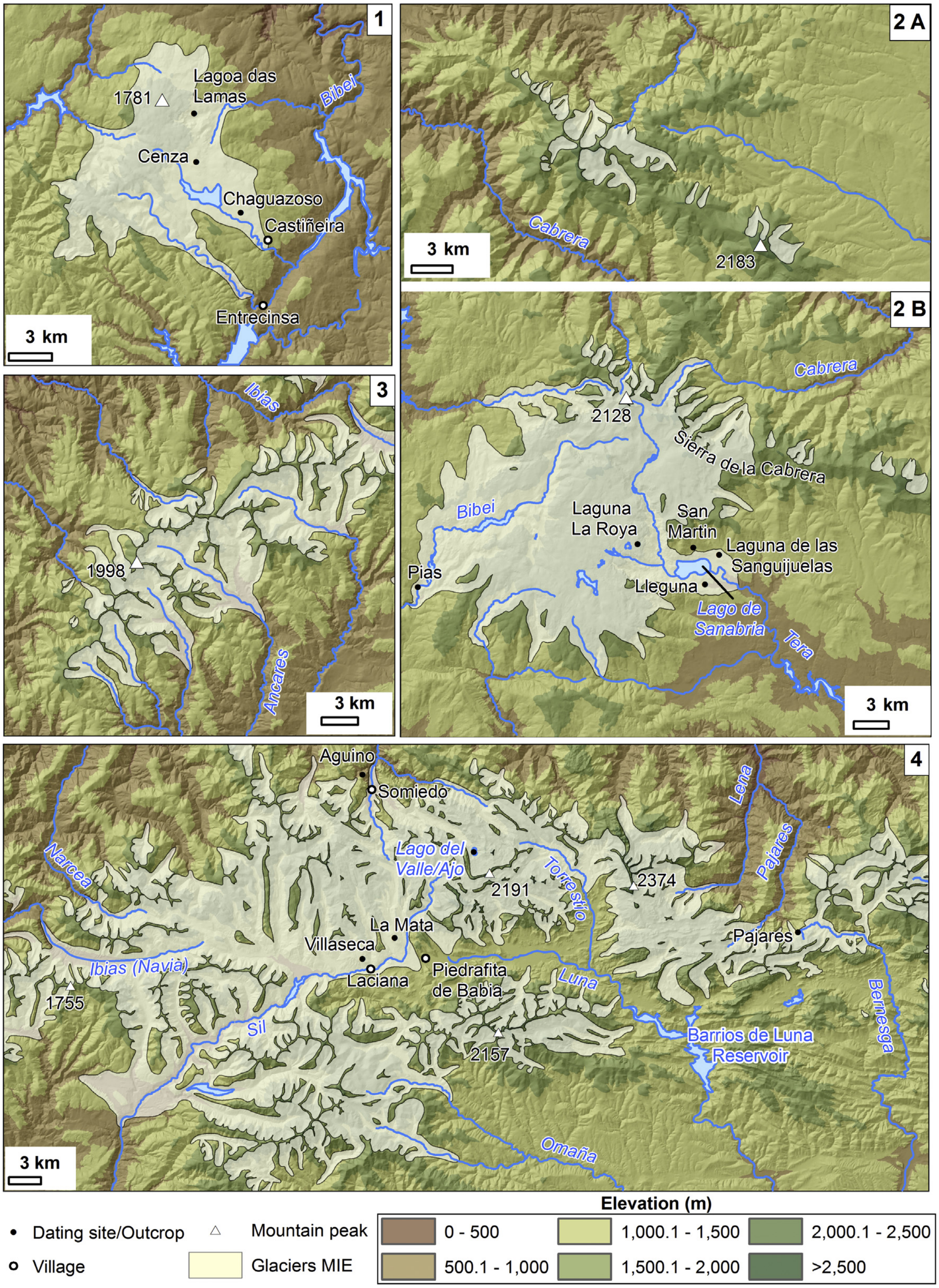

Fig. 2. Maximum ice extent (MIE) recorded by glaciers in the different mountain areas of the Cantabrian Mountains according to current knowledge (see Section 3.2 for more details): 1- Queixa-Invernadoiro; 2A- Sierra del Teleno; 2B- Trevinca Massif; 3- Serra dos Ancares; 4- Somiedo/Alto Sil/Babia and Omaña (see locations in Fig. 1). The elevation of the highest mountain peaks is given in meters; their names are given in the text and/or in Table 1.

3.2. *Mapping stage*

This stage represents an inventory phase crucial to understand the spatial extent of past glaciations in a region. Its beginning in Spain can be set between the late 1950s and early 1960s when the national topographic map coverage was completed. This section summarizes the main contributions to geomorphological maps and glacial reconstructions in the different massifs (Figs. 2 and 3, Table 1).

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Table 1
Compilation table with the dimensions of the longest glacier tongues in the different mountain areas reviewed. Total ice surface estimations are based on the maximum ice extent reconstruction offered in this work (Figs. 2 and 3).

Mountain area	Total ice surface (km^2)	Valley	Headwall altitude (m)	ELA	Glacier surface (km^2)	Glacier front elevation (m)	Glacier length (km)	Aspect	References
Queixa-Invernadoiro	130	Entrecinsa	1781 (Cabeza de Manzaneda)		27	820	6[a]	SE	Vidal-Romaní and Santos-Fidalgo, 1994
Trevinca	475	Tera	2128 (Peña Trevinca)	1687	140	950	8[a]	E	Cowton et al., 2009; Rodríguez-Rodríguez et al., 2011, 2014
Serra dos Ancares	130	Ancares	1998 (Cuiña)	1350	44	700	13	SE	Valcárcel and Pérez-Alberti, 2002a
Somiedo/Alto Sil/Babia	1215	Sil	2191 (Peña Orniz)	1520	490	750	51	S	Santos-González, 2010
Central Cantabrian Mts.	545	Curueño	2141 (Peña Agujas)	1620	50	1120	16	S	Santos-González et al., 2013
Picos de Europa	195	Bulnes	2648 (Torre Cerredo)	1670	10	650	7	N	Serrano et al., 2013a
Fuentes Carrionas	98	Cardaño	2536 (Peña Prieta)	1750	36	1290	15	S	Pellitero, 2012, 2013
Peña Sagra	12	Tánago	2047 (Peña Sagra)		3	850	3	NE	Frochoso and Castañón, 1998
Peña Labra	35	Híjar	2171 (Tres Mares)	1700	14	1300	6	SE	Serrano et al., 2013b
Castro Valnera	77	Trueba	1717 (Castro Valnera)	1190	49	300	15	S	Serrano et al., 2013a,b; Frochoso et al., 2013
Aralar	4	Arritzaga	1430 (Irumugarrieta)		4	800	5	N	Rico-Lozano, 2011

[a] Length of the outlet glacier measure from the main ice cap to the glacier front.

3.2.1. *Queixa-Invernadoiro Massif*

The Queixa-Invernadoiro Massif represents a high plateau of crystalline igneous bedrock with a maximum elevation of 1781 m (Cabeza de Manzaneda) (Fig. 2, box 1). Hernández-Pacheco (1957) published the first geomorphological map of glacial landforms and deposits, complemented by Vidal-Romaní and Santos-Fidalgo (1994), who distinguished a glacial maximum stage followed by 3 deglaciation stages. The glacial maximum stage was characterized by an ice cap (130 km^2) drained by outlet glaciers that showed an asymmetric development along the plateau margins. Glacier outlets attained longer distances and lower elevations in the southeast side of the plateau, with the glacial front of the longest ice tongue (6 km-long) at 820 m while at the opposite side glacier fronts were placed at 1500–1650 m altitude. The first deglaciation stage is indicated by erratic boulders that mark the disjunction of 2 ice domes, and subsequent stages are recorded by moraines at higher elevations.

3.2.2. *Sierra del Teleno and Trevinca Massif*

Sierra del Teleno is a mountain range up to 2183 m altitude (Teleno). Glacial cirques and moraine deposits in its northern slope (Alonso-Otero, 1982; Luengo-Ugidos, 2002), indicate the development of short alpine glaciers during the glacial maximum stage covering a total area of 35 km^2 (Fig. 2, box 2a).

The Trevinca Massif is a plateau of igneous and metamorphic bedrock at 1600–2128 m altitude (Peña Trevinca is the highest peak), slightly tilted southward from Sierra de la Cabrera (Fig. 2, box 2b). Glacial cirques are mainly carved along the northern side of Sierra de la Cabrera and connect downwards into glacial valleys. The plateau highlands are characterized by a smooth topography and over-deepened basins while its margins are interrupted by glacial valleys disposed radially. The main glacial valleys are Bibei and Tera, which run N–S for more than 20 km, defining the west and east limits of the plateau, respectively. The best moraine complex is preserved at 950–1000 m in Lago de Sanabria area and includes: (i) lateral moraines that connect to the front with tills marking the maximum ice extent, (ii) a set of 9 frontal moraines enclosing Lago de Sanabria and (iii) glaciolacustrine and ice-dammed basins formed between moraine ridges or between the lateral moraines and tributary valleys (Rodríguez-Rodríguez et al., 2014). An ice cap (475 km^2) covered the plateau during the glacial maximum stage and was drained by glacier outlets that descended to 950 m, whereas alpine glaciers up to 8 km-long developed on the northern side of Sierra de la Cabrera, flowing down to 1500–1100 m. Initial reconstructions of the glacial maximum stage done by Schmitz (1969) and Pérez-Alberti et al. (2002) were improved using palaeo-ice surface profiles to produce numerical ice surface reconstructions. Cowton et al. (2009) applied the Schilling and Hollin (1981) equation and used the altitude distribution of the calculated ice surface to estimate a mean palaeo-ELA altitude of 1687 m. Rodríguez-Rodríguez et al. (2011, 2014) applied the Benn and Hulton (2010) equation and extended the reconstruction to include the northern side of Sierra de la Cabrera, obtaining maximum ice thickness estimations of 200 m on the plateau and up to 450 m in the Tera and Bibei glacial valleys. The set of frontal moraines enclosing Lago de Sanabria, located inwards respect to the tills that mark the maximum ice extent, were interpreted as recessional moraines formed during the general retreat of the Tera glacial front (Rodríguez-Rodríguez et al., 2011, 2014). Moraine deposits at higher altitudes are generally scarce, and mainly concentrated near the glacial cirques.

3.2.3. *Serra dos Ancares*

This mountain range displays a NE–SW orientation and elevations do not exceed 1998 m (Cuiña). Glacial evidence includes glacial cirques, moraine complexes, tills, and glaciofluvial sediments that allowed reconstruction of several glacial stages (Pérez-Alberti et al., 1992, 1993; Pérez-Alberti and Valcárcel-Diaz, 1998; Valcárcel and Pérez-Alberti, 2002a). The glacial maximum stage was characterized by alpine glaciers reaching lengths of 7–13 km in the southeastern slope and 6–10 km in the northwestern slope and minimum altitudes at the glacial fronts of 825 m and 700 m, respectively (Pérez-Alberti et al., 1992). Glaciers developed asymmetrically during the glacial maximum, with 84% of the total ice surface located in the southeastern side of the range (Fig. 2, box 3). This asymmetry has been related to the gentler gradient of the southeastern slope that let glaciers flow further down valley before ice melted (Pérez-Alberti et al., 1993). The total extent of glaciers was estimated on 130 km^2 and the palaeo-ELA at 1350 m altitude (Valcárcel and Pérez-Alberti, 2002a). Moraine complexes preserved up valley (1400–1800 m) and close to the glacial cirques indicate 2 subsequent glacial stages, recording a general retreat tendency of the glacial fronts, with a surface extent of 41 km^2 and 2 km^2, respectively. Glacial evidence has been also noted at the nearby mountains of Serra do Courel (1641 m), Oribio (1442 m), Rañadoiro (1474 m) and Montes do Cebreiro (1409 m), located 12–30 km southwest of Ancares (Fig. 1). Although elevations do not exceed 1700 m, glacial evidence support the occurrence of alpine and cirque glaciers (up to 1–8 km long) reaching minimum altitudes at their fronts comparable to those in Ancares and pointing to palaeo-

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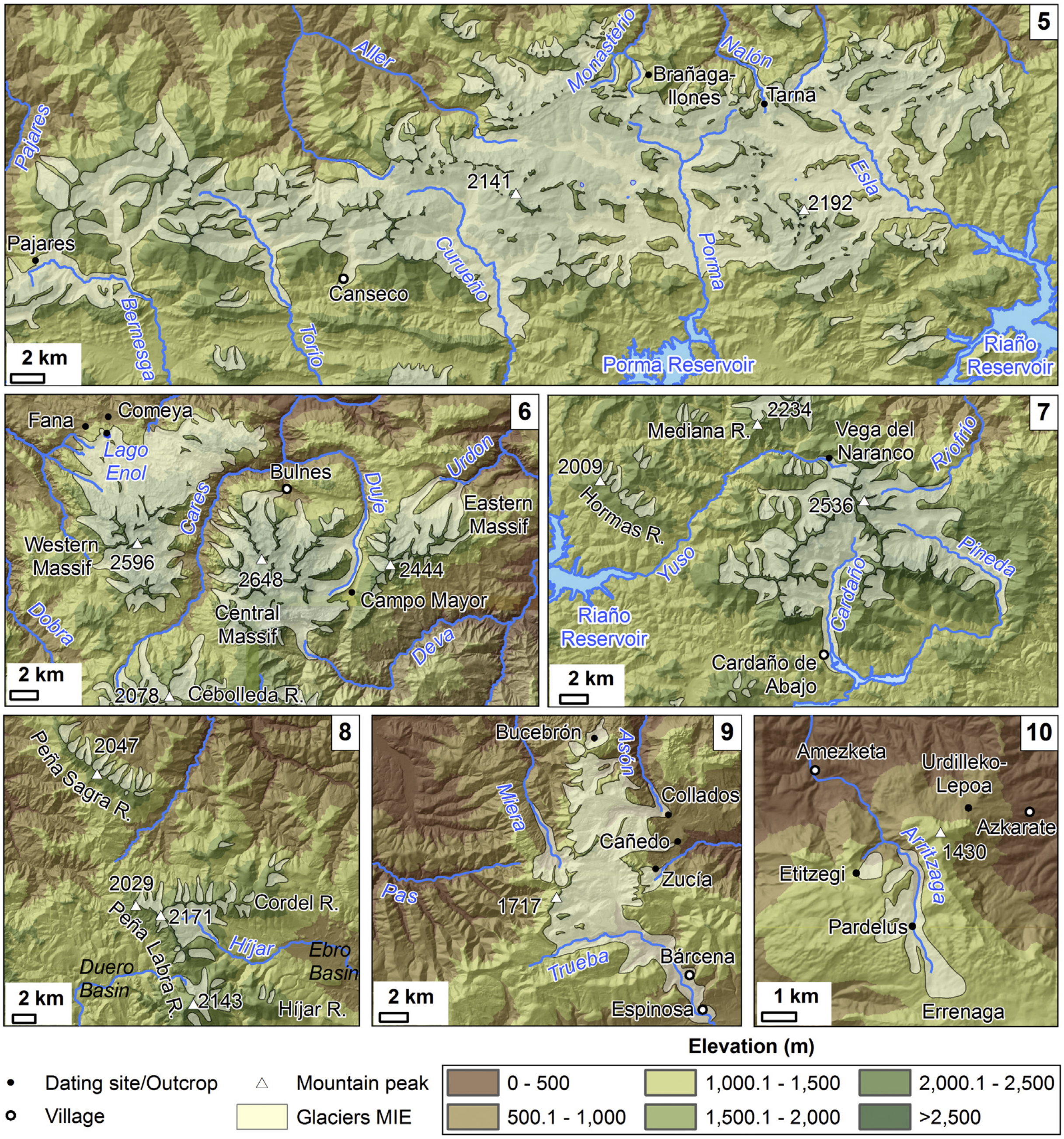

Fig. 3. Maximum ice extent (MIE) recorded by glaciers in the different mountain areas of the Cantabrian Mountains according to current knowledge (see Section 3.2 for more details): 5- Central Cantabrian Mountains; 6- Picos de Europa; 7- Fuentes Carrionas; 8- Peña Sagra and Peña Labra; 9- Castro Valnera; 10- Basque Mountains/Aralar (see locations in Fig. 1). The elevation of the highest mountain peaks is given in meters; their names are given in the text and/or in Table 1.

ELA values below 1300 m during the glacial maximum stage (Pérez-Alberti et al., 1993; Rodríguez-Guitián et al., 1995; Valcárcel and Pérez-Alberti, 2002b).

3.2.4. Somiedo/Alto Sil/Babia and Omaña

Somiedo/Alto Sil/Babia refers to the mountain area located at the headwaters of the Lena-Narcea-Navia (northern slope) and Bernesga-Luna-Sil (southern slope) river catchments (Fig. 2, box 4). Maximum elevation is 2374 m (Peña Ubiña) and descends to 1755 m (Pico Faro) westward. Omaña refers to the mountain area located immediately to the other side of the Luna and Sil river valleys, at the headwaters of the Omaña and Sil rivers, with a maximum elevation of 2157 m (Alto de la Cañada). Glacial cirques, glaciated valleys, glacially over-deepened basins, moraine complexes, tills, erratic boulders and glaciofluvial sediments stand out among the best preserved glacial evidence in this region (Muñoz-Jiménez, 1980; Castañón, 1983; Alonso, 1994; Menéndez-Duarte and Marquínez, 1996; Frochoso and Castañón, 1998; Alonso, 1998b; García de Celis and Martínez-Fernández, 2002; Redondo-Vega, 2002; Alonso and Suárez-Rodríguez, 2004; Ruiz-Fernández et al., 2009; Santos-González, 2010). In the northern slope, 3 glacial stages were identified at Somiedo area (Menéndez-Duarte and Marquínez, 1996): (i) a glacial maximum stage characterized by alpine glaciers descending down to 800–850 m altitude (palaeo-ELA at 1500 m), (ii) a second glacial stage with the glacial fronts at 1300–1500 m altitude, and (iii) a third glacial stage with glaciers

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restricted to the highest cirques (fronts at 1500–1700 m altitude). The same work described reddish deposits at Aguino village, intensely weathered and out of place regarding other glacial evidence, which they interpreted as tills deposited during a previous glaciation. Alpine glaciers 18 km-long developed in the Ibias valley during the glacial maximum stage, reaching a minimum altitude of 800 m (Alonso, 1998b). Recent glacial reconstructions carried out in the Babia/Alto Sil area (southern slope) have also identified 3 glacial stages (Santos-González, 2010): (i) a glacial maximum stage characterized by transection glaciers forming the Sil/Laciana/Babia glacial complex (490 km^2 surface; total length of 51 km at the Sil valley where the glacial front reached 750 m; palaeo-ELA at 1520 m altitude); (ii) a second glacial stage characterized by alpine glaciers up to 10–13 km-long (310 km^2 surface; glacial front at 910 m; palaeo-ELA at 1600 m altitude); and (iii) a glacial cirque stage in Omaña preferentially developed in the north-facing cirques at above 1800 m altitude, and some alpine glaciers up to 12 km-long at the south-facing hillslopes of Laciana (95 km^2 surface; glacial fronts at 1210 m; palaeo-ELA at 1750 m altitude). Torrestío and other tributaries of the Luna River located eastward from Piedrafita de Babia show evidence of a glacial maximum stage characterized by alpine glaciers up to 5–9 km-long, with their glacier fronts at 1250–1300 m altitude. The headwaters of the Omaña catchment were characterized by alpine glaciers up to 13–16 km long that flowed down to 1190–1130 m altitude, where 3 subsequent and less extent glacial stages are recognized, marking a general trend of glacier retreat (Redondo-Vega, 2002).

3.2.5. *Central Cantabrian Mountains*

Central Cantabrian Mountains (CCM) refers to the 60 km-long central portion of the CM that extends from Pajares Pass (1378 m) to Picos de Europa, recording a maximum elevation of 2192 m (Mampodre) (Fig. 3, box 5). Glacial evidence includes cirques, overdeepened basins, glacial valleys, tills, glaciofluvial terraces, and ice-dammed deposits (Arenillas and Alonso, 1981; Alonso-Herrero, 1987, 2002; Rodríguez-Pérez, 1995; Jiménez-Sánchez, 1996; Frochoso and Castañón, 1998; González-Gutiérrez, 2002; Rodríguez-Rodríguez et al., 2013). Glacial reconstructions in the Nalón catchment (northern slope) defined 3 glacial stages (Jiménez-Sánchez, 1996): (i) a glacial maximum stage characterized by alpine glaciers up to 5 km-long descending to 950 m (palaeo-ELA at 1550 m altitude); (ii) a second stage with shorter alpine glaciers with their fronts at 1300–1500 m; and (iii) a third glacial stage with glaciers restricted to the highest cirques (1500–1700 m). A similar evolution was proposed for the Curueño, Torío and Canseco valleys (southern slope); with alpine glaciers up to 16 km-long and the glacial fronts at 1120–1280 m altitude during the glacial maximum stage (González-Gutiérrez, 2002). The mean palaeo-ELA altitude estimated for the Curueño glacier during the glacial maximum was 1620 m (Santos-González et al., 2013). In contrast, the glacier evidence of the nearby Esla catchment pointed to only 2 glacial stages (Alonso-Herrero, 1987, 2002): (i) an ice field glaciation with glacier tongues up to 5–6 km-long and (ii) a second stage with glaciers up to 2 km-long preferentially oriented to the N–NE. New research is being developed in the Porma-Esla and Aller-Nalón catchments, where numerical reconstructions based on an updated geomorphological map are revealing significant asymmetry in the extent of glaciers between both slopes, with short alpine glaciers in the northern slope (1–6 km) whereas extensive ice-fields drained by long transection glaciers (20 km) occurred in the southern slope (Rodríguez-Rodríguez et al., 2013). Preliminary palaeo-ELA estimates indicate that this asymmetry is probably closely related to local topography, with gentler slope gradients in the southern side of the range.

3.2.6. *Picos de Europa*

Picos de Europa is a limestone mountain area located 20 km inland from the Cantabrian Sea, broadly elevated above 2000 m. Fluvial incision at the headwater of the Dobra, Cares, Duje and Deva rivers has cut deep gorges trending north in the limestones, distinguishing 3 massifs: Western or Cornión (2596 m, Peña Santa), Central or Urrieles (2648 m, Torre Cerredo) and Eastern or Ándara (2444 m, Morra de Lechugales) (Fig. 3, box 6). Mapping contributions started in the late 1950s, when Hernández-Pacheco mapped the glacial features described by Obermaier in the Central Massif, and continue nowadays in the 3 massifs (Bertrand and Bertrand, 1971; Frochoso, 1980; Castañón and Frochoso, 1986; Frochoso and Castañón, 1986, 1998; Flor and Baylón-Misioné, 1989; Castañón, 1990; Gale and Hoare, 1997; Alonso, 1998a; Marquínez and Adrados, 2000; González-Trueba, 2007; Ruiz-Fernández et al., 2009; Serrano et al., 2012, 2013b). Due to the calcareous character of these mountains, karst processes are widespread, showing interactions with glacial landforms and deposits above 1000 m altitude (Miotke, 1968; Bertrand and Bertrand, 1971). Typical glacial cirque morphologies are commonly masked by glacio-karst closed depressions developed from pre-glacial karst dolines with optimal topo-climatic and geological conditions that favored snow-accumulation and enhanced glacial excavation (Smart, 1986). Moraine complexes are well-preserved in the northern side of the massifs reaching altitudes as low as 650 m in the Central Massif, 850 m in the Eastern Massif and 1000 m in the Western Massif. The latest reconstructions of the glacial maximum stage carried out in the Central and Eastern massifs suggest the occurrence of summit ice fields covering a total extent of 100 km^2, with the mean palaeo-ELA at 1670–1720 m altitude, drained by glacier tongues up to 4–7 km-long flowing northwards (Serrano et al., 2012, 2013b). Glacial evidence described in the Western Massif also supports the development of a summit ice field during the glacial maximum stage covering an extent of ca. 95 km^2 and drained by glacier tongues up to 8 km-long (Fig. 3, box 6). Moraine deposits located at higher altitudes than the terminal moraine complexes are preserved in the 3 massifs, recording subsequent and less extensive glacial stages, being the last one related to the Little Ice Age (González-Trueba et al., 2008). Finally, evidence of previous glaciations was described at Fana (Western Massif), where a weathered till outcrop was noted outside the limits of the fresh terminal moraine complex preserved at Lago Enol area (Gale and Hoare, 1997). The same authors considered the trough-like upper component of the Cares Valley as evidence of a previous glaciation more extensive than the last one, instead of a feature developed during the last glacial maximum stage (Obermaier, 1914).

3.2.7. *Fuentes Carrionas*

Fuentes Carrionas Massif records maximum altitudes of 2536 m (Peña Prieta) and contains evidence of past glaciations (Alonso-Herrero, 1987; Frochoso and Castañón, 1996, 1998; Pellitero, 2009, 2012, 2013; Redondo-Vega and Santos-González, 2013; Serrano et al., 2013b). Pellitero (2012, 2013) reconstructed the contour lines of former glaciers during 4 different glacial stages. According to his models, the glacial maximum stage (palaeo-ELA at 1750 m altitude) was characterized by a set of alpine glaciers up to 15-km long draining radially from Peña Prieta along the headwaters of the current river valleys of Riofrío, Pineda, Cardaño and Yuso, reaching minimum altitudes of 1240–1460 m at the glacial fronts (Fig. 3, box 7). Glaciers covered a total extent of 98 km^2 and recorded maximum thickness of 200–300 m. Extensive frontal moraine complexes such as those preserved at Cardaño and the Naranco

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valley suggest that glacial maximum conditions were long-lasting, and recorded small oscillations in the glacial front positions. Thus, the second glacial stage was characterized by a 300–500 m retreat of the glacial fronts, located at similar altitudes than during the previous glacial maximum stage but recording a 100 m reduction in ice thickness. Moraine deposits located at altitudes of 1600–1800 m and 1900–2000 m (cirque moraines) suggest that subsequent glacial stages were markedly less extensive. Between Fuentes Carrionas, Picos de Europa and Central Cantabrian Mountains, the Mediana (2234 m, Coriscao), Cebolleda (2078 m, Gildar) and Hormas ranges (2009 m, Pandial or Alto Redondo) have glacial cirques and moraines in their northern slopes that clearly indicate the occurrence of alpine glaciers (locally up to 4 km-long) during the glacial maximum stage (Alonso-Herrero, 1987, 2002; Serrano et al., 2013a) (Fig. 3, boxes 6 and 7).

3.2.8. *Peña Sagra and Peña Labra*

Peña Labra is a mountain range with a NW–SE orientation that runs from Peña Labra (2029 m) to Valdecebollas (2143 m) mountain peaks, marking the divide between the Duero and Ebro basins (Fig. 3, box 8). It intersects the Cordel and Híjar ranges at Tres Mares (2171 m) and Valdecebollas (2143 m) mountain peaks. After the pioneer work of Hernández-Pacheco (1944), several authors have worked to better understand the extent and number of glacial stages recorded in this area (Frochoso, 1990; Frochoso and Castañón, 1998; Serrano and Gutiérrez, 2000, 2002; Serrano and González-Trueba, 2004). Recent publications reconstruct 3 glacial stages (Serrano et al., 2013a). First stage corresponds to the glacial maximum advance, characterized by alpine glaciers covering a total area of 35 km^2 and the palaeo-ELA at 1700 m altitude. During this stage the glacier tongues that flowed downslope in the southern side of the Cordel Range attained 6 km in length and minimum altitudes of 1300 m at the glacial fronts, while in the northern side of the Cordel and Híjar ranges glaciers reached maximum lengths of 3 km and altitudes of 1200–1400 m at the glacial fronts. Some valleys contain evidence of a second glacial stage with glacier tongues up to 2.6 km-long. Finally, a cirque stage is preserved in the north-facing glacial cirques located at 1800–2000 m altitude, where cirque moraines indicate that glaciers reached lengths of 150–400 m.

Peña Sagra is a 16 km-long mountain range located 8 km northwestward from Peña Labra that trends NW–SE and stands a maximum elevation of 2047 m (Peña Sagra). Glacial evidence includes glacial cirques and moraine deposits preserved in the northeastern slope of the range (Castañón and Frochoso, 1986; Frochoso, 1990; Frochoso and Castañón, 1998), indicating that the glacial maximum stage was characterized by alpine glaciers up to 3 km-long, covering a total surface of 12 km^2 and reaching minimum altitudes of 850 m at the glacial fronts (Fig. 3, box 8).

3.2.9. *Castro Valnera*

The Castro Valnera Massif (or Pas Mountains) shows a smooth landscape with a maximum elevation of 1717 m (Castro Valnera). After the first mapping contributions (Lotze, 1962), several authors have studied the glacial record to reconstruct former glaciations (Serrano, 1996; Frochoso and Castañón, 1998; Serrano and Gutiérrez, 2002; Pellitero, 2012; Frochoso et al., 2013; Serrano et al., 2013a,b). The main glacial evidence includes isolated glacial cirques preferentially oriented to the N–NE, glacial featuring of the Miera, Asón and Trueba valleys and important sets of lateral and frontal moraines at Los Collados (600 m), Cañedo (1050–600 m), Zucía (1150–1020 m), Espinosa (760 m), Bárcena (870 m), Bucebrón (900 m) and along the Miera Valley (620–1100 m). Based on the altitudinal distribution of the moraine complexes, the glacial maximum advance stage has been reconstructed as an asymmetrically developed ice cap with a total surface of 77 km^2 and the mean palaeo-ELA at 1190 m altitude (Fig. 3, box 9). The ice cap was drained by glacier outlets 5 to 15 km-long with their glacial fronts at minimum altitudes of 300 m and 760 m in the Asón and Trueba valleys respectively (Frochoso et al., 2013; Serrano et al., 2013a,b). The occurrence of 5 ridges at the Espinosa and Los Collados moraine complexes suggests that the glacial maximum was a long-lasting and pulsatile stage with minor episodes of glacier advance and retreat. Two subsequent and less extensive glacial stages are indicated by moraine complexes located at Bárcena (870 m), Bucebrón (900 m), Zucía (1150–1020 m) and the head of the Miera Valley (1000–1100 m) (Serrano et al., 2013a,b).

3.2.10. *Basque Mountains*

Geomorphological research in the Basque Mountains was intensified since the 1960s with the acceptance of a glacial origin for the Arritzaga Valley and the occurrence of till deposits near Urdilleko-Lepoa, Azkarate and Etitzegi (Kopp, 1965; Duvernois et al., 1972) (Fig. 3, box 10). Past glacial conditions were also suggested for the Gorbea Range (Schmidt-Tomé, 1973), while periglacial talus scree deposits were described at Aralar and Aizkorri massifs (Ugarte, 1985; González et al., 1988) (Fig. 1). The main difficulties in the identification of glacial features in the Basque Mountains are the low altitude of the region (<1600 m), the superposition of karst and fluvial processes and the dense vegetation cover. Some authors noted the lack of detailed research to confirm past glaciations in the region, raising doubts on glacial attributions made by previous works (Martínez de Pisón and Arenillas, 1984). Further publications have established and characterized the glacial features in the Aralar Massif, a coastal range 25 km-long with a maximum elevation of 1430 m (Irumugarrieta) (González-Amuschástegui, 2000; Rico-Lozano, 2011). The north-facing Arritzaga valley extends from Errenaga (1282 m) to Amezketa village (200 m), showing an U-shaped profile down to Fuente Pardelus (1020 m) where it turns to a V-shape fluvial profile (Fig. 3, box 10). Glacial cirques are located at 1300–1420 m altitude; preferentially oriented to the NE. Subglacial tills and lateral moraines were identified by means of sedimentological analysis and morphostratigraphy (Bordonau et al., 1992; Rico-Lozano, 2011). These features suggest the existence of a valley glacier that flowed from Errenaga to the north, reaching 5 km in length and 70–100 m in thickness during the glacial maximum stage, when the glacial front reached 800 m altitude. A second glacial equilibrium stage was recorded by lateral moraines preserved at higher altitudes (1050 m) suggesting a decrease in snow precipitation. Therefore, glacial conditions in the Basque Mountains were controlled by topo-climatic factors that favored conditions of low insolation and high snowfall rate in the hillslopes with NE orientation (Rico-Lozano, 2011).

3.3. *Chronological stage*

The employment of numerical dating methods to study the age of the glacial record started at the beginning of the 21st century (Vidal-Romaní et al., 1999; Jiménez-Sánchez and Farias, 2002) and has been the aim of a growing number of recent research papers (Jalut et al., 2010; Moreno et al., 2010; Pérez-Alberti et al., 2011; Rodríguez-Rodríguez et al., 2011, 2014; Serrano et al., 2012, 2013b; Frochoso et al., 2013; Jiménez-Sánchez et al., 2013; Villa et al., 2013). A compilation of numerical ages obtained in glacial and ice related deposits along the CM until date is explained ahead and compiled in Table 2 (see Figs. 2 and 3 for dating site locations).

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Table 2

Compilation of geochronological datasets available for the study area (see sample locations in Figs. 2 and 3). Original radiocarbon ages were calibrated using CalPal v.1.5 Software (www.calpal-online.de/index.html; accessed on March 2014) and Calpal 2007_Hulu curve (Weninger and Jöris, 2008). Lab references TER-MAR, SAN, TET and SAU refer to different moraines of the Sanabria moraine complex; each ^{10}Be age represents the error-weighed mean of the exposure ages obtained from 3 different moraine boulders.

Location	Site	Elevation (m)	Lab reference	Depth (cm)	Material	^{14}C age yr BP	^{14}C age cal yr BP	1σ (68% range)	TCN age (ka)	OSL age (ka)	U/Th age (ka)	Reference
Queixa	Lagoa das Lamas	1360	β-49284	765–770	Bulk sediment	12,790 ± 150	15,269 ± 404	14,864–45,673				Maldonado, 1994
Invernadoiro	Castiñeiras moraine	1210	Q-2		Granite				126.1 ± 13.2^{21}Ne			Vidal-Romaní et al., 1999
Massif	Chaguazoso drumlin	1294	Q-3		Granite				21.6 ± 16.9^{21}Ne			
	Cenza drumlin	1340	Q-4		Quartz				15.4 ± 6.9^{21}Ne			
Trevinca	La Roya	1608	12,618	770–774	Bryophytes	12,940 ± 60	15,740 ± 398	15,342–16,138				Allen et al., 1996
Massif	Lleguna	1050	GrN-22750	767.5-770	Bulk sediment	12,130 ± 130	14,171 ± 285	13,886–14,456				Muñoz-Sobrino et al., 2004
	Laguna Sanguijuelas	1080	GrN-22759	245–250	Bulk sediment	14,780 ± 190	18,060 ± 360	17,700–18,420				
	Lago de Sanabria core	1000	Poz-20095	728	Plant remains (basal unit top)	12,330 ± 60	14,494 ± 347	14,147–14,841				Rodríguez-Rodríguez et al., 2011
			Poz-12367	891	Bulk sediment (basal unit bottom)	21,460 ± 140	25,584 ± 374	25,210–25,958				
	San Martín core	1203	Poz-30103	1097	Peat	18,090 ± 90	21,833 ± 358	21,474–22,191				
	Sanabria moraine complex	1731–1382	TER-MAR		Quartz veins/ granodiorite				19.2 ± 1.8^{10}Be			Rodríguez-Rodríguez et al., 2014
		1002	SAN		Granodiorite/gneiss				17.7 ± 1.7^{10}Be			
		1673–1698	TET		Quartz veins				17.2 ± 1.6^{10}Be			
		1006–1009	SAU		Granodiorite				15.7 ± 1.5^{10}Be			
	Pias	1020	PIAS 1	300	Glaciofluvial sands					27 ± 2		Pérez-Alberti et al., 2011
		1020	PIAS 4	500	Glaciofluvial sands					33 ± 3		
		1012	PIAS 8	700	Glaciofluvial sands					31 ± 3		
Serra do Courel	Lagoa da Lucenza	1375	GrA-4888	525–530	Bulk sediment	17,320 ± 250	20,776 ± 389	20,386–21,165				Muñoz-Sobrino et al., 2001
			GrA-5095	525–530	Bulk sediment	17,390 ± 90	20,841 ± 302	20,539–21,143				Pérez-Alberti and Valcárcel-Díaz, 1998
Somiedo	Lago del Valle/ Ajo	1570	9740	2655–2665[a]	Bulk sediment	14,270 ± 180	17,474 ± 282	17,191–17,756				Allen et al., 1996
Laciana	Laguna del Castro (Villaseca)	1317	Poz-11226	270–272	Pollen concentrate	33,440 ± 480	38,663 ± 1553	37,109–40,216				Jalut et al., 2010
			ANUA31506/ GifA50031	325–330	Clay	33,570 ± 770	38,653 ± 1623	37,030–40,276				
			ANUA31509/ GifA50034	343–353	Clay	31,800 ± 630	36,125 ± 1004	35,121–37,129				
			Poz-11228	373–374	Pollen concentrate	39,500 ± 900	43,500 ± 754	42,746–44,254				
			ANUA31508/ GifA50033	377.5–388.5	Sandy clay	32,990 ± 720	37,570 ± 1101	36,469–38,671				
			ANUA31507/ GifA30035	470–478	Sandy clay	32,710 ± 920	37,288 ± 1282	36,006–38,570				
			Poz-11251	532–534	Pollen concentrate	31,000 ± 300	35,070 ± 388	34,682–35,458				
			ANUA31513/ GifA50031	589–592	Sandy clay	33,910 ± 760	38,961 ± 1457	37,504–40,418				
			Poz-11252	671–672	Pollen concentrate	31,900 ± 400	36,051 ± 690	35,360–36,741				
			Poz-11253	781–782	Pollen concentrate	39,300 ± 1000	43,398 ± 792	42,605–44,190				
			Gif9150	885–893	Sandy clay	34,000 ± 1400	38,683 ± 1840	36,843–40,523				
	Laguna del Miro (La Mata)	1500	Gif9151	522–530	Clay	>35,000						

(*continued on next page*)

Table 2 (*continued*)

Location	Site	Elevation (m)	Lab reference	Depth (cm)	Material	^{14}C age yr BP	^{14}C age cal yr BP	1σ (68% range)	TCN age (ka)	OSL age (ka)	U/Th age (ka)	Reference
Redes Natural Park	Brañagallones	1200–1250	Beta-129359	3560–3550	Bulk sediment	28,990 ± 230	33,485 ± 362	33,123–33,847				Jiménez-Sánchez and Farias, 2002
			MAD-5598SDA		Moraine silt-sand sediments					24.0 ± 1.8		Jiménez-Sánchez et al., 2013
	Tarna	1415	Beta-132819	230	Bulk sediment	20,640 ± 300	24,579 ± 421	24,158–25,000				Jiménez-Sánchez and Farias, 2002
			MAD-5594SDA		Landslide silt sediments					23.0 ± 2.3		Jiménez-Sánchez et al., 2013
Picos de Europa National Park	Comeya	800–850	Beta-93164	3550	Bulk sediment	40,480 ± 820	44,118 ± 885	43,232–45,003				Jiménez-Sánchez and Farias, 2002
			MAD-5560SDA	4260–4280	Glaciofluvial sands					45.0 ± 3.3		Jiménez-Sánchez et al., 2013
	Lago Enol (Unit 3)	1070	Poz-18456	347	Bulk sediment	32,400 ± 700	36,896 ± 1059	35,836–37,955				Moreno et al., 2010
			Poz-12251	386	Bulk sediment	31,700 ± 500	35,785 ± 723	35,061–36,508				
			Poz-12252	585	Bulk sediment	32,600 ± 500	37,110 ± 852	36,257–37,962				
			Poz-18457	439	Bulk sediment	36,200 ± 1100	40,726 ± 1255	39,470–41,981				
			Poz-18458	530	Bulk sediment	32,500 ± 500	37,015 ± 878	36,137–37,893				
	Duje Valley (Campo Mayor)	1417	Beta-264115	780	Clay	27,570 ± 320	32,222 ± 329	31,892–32,551				Serrano et al., 2012
			Beta-264116	1055	Clay	26,090 ± 240	31,016 ± 368	30,648–31,384				
			Beta-264117	1410	Clay	27,460 ± 300	32,117 ± 284	31,833–32,401				
			Beta-264118	1550	Clay	31,200 ± 440	35,251 ± 487	34,764–35,738				
	Duje Valley		DUJE-2		Cemented breccia						276.3 ± 22.8	Villa et al., 2013
			DUJE-5		Cemented breccia						394.1 ± 50. 7	Pellitero, 2013
Fuentes Carrionas Massif	Vega del Naranco	1530	UBA-15736	240	Lacustrine rhythmites	25,591 ± 141	30,624 ± 337	30,287–30,961				Serrano et al., 2013a
			UBA-15735	270	Lacustrine rhythmites	15,614 ± 70	18,890 ± 222	18,668–19,112				
		1470	MAD-5980SDA	40	Moraine					36.0 ± 2.4		
	Cardaño de Abajo	1340	UBA-15734	2050	lacustrine rhythmites	14,275 ± 49	17,472 ± 251	17,221–17,723				
Castro Valnera Massif	Espinosa	759	UBA-15876	100	Peat bog	26,082 ± 118	31,012 ± 336	30,676–31,348				Frochoso et al., 2013
	Bárcena	870	UBA-15879	160	Clay	10,467 ± 42	12,403 ± 168	12,234–12,571				
	Los Collados	690	MAD-5677BIN	250	Fine silt and clay					40.4 ± 5.1		
			MAD-5678BIN	500	Fine silt and clay					64.6 ± 5.1		
			MAD-5680BIN	650	Fine silt and clay					75.1 ± 5.2		
			MAD-5679BIN	950	Fine silt and clay					78.5 ± 7.2		
	Cañedo	1050–600	MAD-5498rBIN	300	Fine silt and clay					41.6 ± 2.4		
			MAD-5499rBIN	350	Fine silt and clay					45.0 ± 2.4		
			MAD-5514BIN	300	Fine silt and clay					44.5 ± 2.4		
	Zucía	1150–1020	MAD-5893rSDA	50	Fine silt and clay					13.4 ± 1.2		
			SEV-ZUC	50	Moraine, secondary carbonates						6.3 ± 0.6	
	Bucebrón	900	SEV-BUCInf	350	Moraine, secondary carbonates						7.1 ± 0.9	
			SEV-BUC1	450	Moraine, secondary carbonates						4.3 ± 0.1	

[a] Depth measured from water surface.

3.3.1. *Queixa-Invernadoiro Massif*

The local glacial maximum in the Queixa-Invernadoiro Massif was dated using stable TCN ^{21}Ne (Vidal-Romaní et al., 1999). A sample taken on a moraine boulder surface in the Cenza palaeoglacier front (Castiñeiras moraine) provided a surface exposure age of 126 ± 13 ka ^{21}Ne. Two other samples taken from two drumlins placed progressively up valley (Chaguazoso and Cenza drumlins) provided ages of 22 ± 17 and 15 ± 7 ka ^{21}Ne, indicating that they were exposed to daylight during the last deglaciation. The authors found these ages coherent with previous ^{14}C results obtained from palynological research developed at Lagoa das Lamas (Queixa-Invernadoiro Massif) and Lagoa da Lucenza (Serra do Courel), which indicated that lacustrine sedimentation started at 15.3 ± 0.4 cal ka BP (Maldonado, 1994) and at 20.8 ± 0.3 cal ka BP (Pérez-Alberti and Valcárcel-Diaz, 1998; Muñoz-Sobrino et al., 2001), respectively.

3.3.2. *Trevinca Massif*

The glacial record of this massif has been studied by means of ^{14}C, OSL and TCN methods. In the western side of the massif, 3 OSL samples taken from glaciofluvial sands overlying a basal till unit in the proglacial site of Pias (Bibei Valley) revealed minimum ages for the local glacial maximum between 27 ± 2 and 33 ± 3 ka (Pérez-Alberti et al., 2011). The results are similar to ^{14}C ages obtained close to the base of the glaciolacustrine unit of Lago de Sanabria (Tera Valley) and the nearby ice-dammed deposit of San Martín, deposited behind the outermost north lateral moraine, which yielded minimum ages of 25.6 ± 0.4 cal ka BP and 21.8 ± 0.4 cal ka BP respectively (Rodríguez-Rodríguez et al., 2011). Both studies support glacial retreat conditions between 25.6 and 33 ka, whereas previous ^{14}C analysis linked to palynological research in small ponds in the vicinity of Lago de Sanabria (Lleguna and Laguna de las Sanguijuelas) and the Trevinca Massif highlands (Laguna La Roya) show that their sedimentation started at 14.2 ± 0.3 cal ka BP, 18.1 ± 0.4 cal ka BP and 15.7 ± 0.4 cal ka BP (Allen et al., 1996; Muñoz-Sobrino et al., 2004), suggesting a glacial advance coeval with the global Last Glacial Maximum or LGM (Cowton et al., 2009). The ^{10}Be dataset recently published for the Sanabria moraine complex (Rodríguez-Rodríguez et al., 2014) indicates that glacier retreated from the lateral moraine that marks the glacial maximum at a minimum age of 19.2 ± 1.8 ka (TER-MAR moraine) and formed a set of recessional moraines with minimum ages between 17.7 ± 1.7 and 15.7 ± 1.5 ka (SAN, TET and SAU moraines). Therefore, geochronological and geomorphological evidence in this valley supports the idea of a glacier advance during the global LGM of Marine Isotope Stage 2 (MIS 2) reaching a spatial extent comparable to the previous local glacial maximum, which occurred prior to 33 ka (Rodríguez-Rodríguez et al., 2014).

3.3.3. *Alto Sil/Babia and Central Cantabrian Mountains*

The palaeoenvironmental studies carried out in 2 lacustrine sequences at Laciana gave minimum ages for the local glacial maximum in the Sil catchment. Together, the Villaseca (Laguna del Castro) and La Mata (Laguna del Miro) cores provided 12 ^{14}C ages between 35.1 ± 0.4 and 43.4 ± 0.8 cal ka BP, suggesting that the local glacial maximum was prior to 43 ka (Jalut et al., 2010). Their results are coherent with the ^{14}C ages obtained at the base of the Lago del Valle (or Lago de Ajo), located at a glacial cirque in the Somiedo valley, which yielded 17.5 ± 0.3 cal ka BP (Allen et al., 1996).

The glacial maximum recorded in the CCM was dated by means of ^{14}C analysis applied to bulk sediment samples taken from drill cores of ice-dammed and postglacial lacustrine deposits (Jiménez-Sánchez and Farias, 2002). The basal age of the Brañagallones ice-dammed deposit in the Monasterio Valley, located outwards from a set of 5 lateral moraines, yielded a minimum age of 33.5 ± 0.4 cal ka BP for the local glacial maximum. The same work provides time constrain for a subsequent glacial stage close to the divide in the nearby Tarna Pass, where the basal age of a core drilled in a glacial valley bottom-infill provided a minimum age of 24.6 ± 0.4 cal ka BP. Further studies have strengthened this chronological framework by applying OSL to other features of these sedimentary sequences (Jiménez-Sánchez et al., 2013). Two samples from the Brañagallones lateral moraine complex and a postglacial debuttresing landslide in the Tarna Valley provided OSL ages of 24 ± 1.8 and 23 ± 2.3 ka respectively. The moraine age corresponds to a moraine ridge located inwards of the outermost lateral moraine, suggesting that the glacier tongue that flowed along the Monasterio Valley recorded a similar position at 24 ka as before, when the outermost moraine dammed the valley side tributary (prior to 33.5 ka). Whereas, 7 km eastward, the ages of the landslide and the glacial valley bottom infill near the former ice divide suggest ice free conditions in the Tarna Valley at 24 ka BP.

3.3.4. *Picos de Europa*

A sample taken close to the base of the Comeya sequence, a karst polje that occupied a proglacial site during the local glacial maximum stage in the Western Massif of Picos de Europa, yielded a minimum radiocarbon age of 44.1 ± 0.9 cal ka BP (Jiménez-Sánchez and Farias, 2002). Up valley, the Enol Lake occupies a glacial depression that was carved when the glacial front was located at 1030 m altitude, feeding the Comeya polje with its meltwaters. Its basal glaciolacustrine unit, studied from 2 different drill cores, provided 5 ^{14}C ages ranging from 35.8 ± 0.7 to 40.7 ± 1.3 cal ka BP that were used to estimate an age of 38 cal ka BP for the onset of the Enol glacio-lacustrine sedimentation (Moreno et al., 2010). Additionally, an independent age for the Comeya sequence was recently obtained using OSL on a glaciofluvial sandy level slightly below the lowest ^{14}C sample, which provided an age of 45 ± 3.3 ka (Jiménez-Sánchez et al., 2013).

Geochronological contributions in the Central Massif of Picos de Europa are based on ^{14}C and U/Th analysis carried out on palaeolake and cemented calcareous breccias in the Alto Duje Valley. The Campo Mayor palaeolake is an ice-dammed deposit located between the lateral moraine of the Duje Valley (Llomba del Toro moraine) and the western slope of the Eastern Massif of Picos de Europa. Radiocarbon analysis of a 20 m-long core provided a minimum age of 35.3 ± 0.5 cal ka BP for the local glacial maximum (Serrano et al., 2012). At the other side of this moraine, an outcrop of cemented breccias is cut by the Duje glacial valley and overlies a former glacial polished surface. U/Th analysis of 2 samples of calcareous coatings from these breccias gave ages of 394.1 ± 51 and 276.3 ± 22.8 ka for the cementation process, interpreted as a consequence of the interglacial episode that followed the MIS 12 glaciation (Villa et al., 2013). Evidence of a glacial stage even older than this was suggested before by Gale and Hoare (1997), who estimated the age of the U-shaped component in the upper part of the Cares cross profile as formed at 850 ka (MIS 22), using the fluvial incision rate of 0.3 m ky^{-1} estimated by Smart (1986) in the Urdon river gorge (Eastern Massif) and the depth of the fluvial gorge carved at the floor of the glacial upper profile of the Cares Valley (255 m).

3.3.5. *Fuentes Carrionas*

The glacial record preserved at Fuentes Carrionas Massif has been studied through ^{14}C and OSL (Pellitero, 2013; Serrano et al., 2013a). An OSL sample of supraglacial till taken at the outermost frontal moraine of the Vega del Naranco terminal complex, in the northern slope of the massif, gave a minimum age of 36.0 ± 2.4 ka for the local glacial maximum. In the same valley, sedimentation at

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a palaeolake deposit dammed by the Vega del Naranco moraine complex started at a minimum age of 18.9 ± 0.2 cal ka BP. In the southern side of the massif, a minimum age of 17.5 ± 0.3 cal ka BP was obtained for the ice-dammed deposit developed behind the moraine that marks the local glacial maximum at Cardaño de Abajo (Serrano et al., 2013a).

3.3.6. *Castro Valnera*

The chronological studies focused on the glacial record of the Castro Valnera Massif have applied ^{14}C, OSL, and U/Th methods to study the moraine complexes and related lacustrine sedimentation. In the south-facing Trueba Valley, ^{14}C analysis conducted at the base of 2 peat bogs deposited between the ridges of the Espinosa and Bárcena moraine complexes gave minimum ages for the glacial maximum of 31.0 ± 0.3 cal ka BP and 12.4 ± 0.2 cal ka BP (Serrano et al., 2013a). OSL analysis carried out on till samples taken from Los Collados and Cañedo moraine complexes, in the Asón Valley, also yielded minimum ages for the local glacial maximum between 40.4 ± 5 and 78.5 ± 7 ka, as the analysis did not involve the bottom of the till sequence (Frochoso et al., 2013). These authors combined OSL and U/Th analysis to date the Zucía and Bucebrón moraine complexes and found that U/Th analysis carried out on calcareous cements precipitated in tills provided results that were too young to constrain the age of the different glacial stages recorded.

4. Discussion and conclusions

As previously shown, evidence of Quaternary glaciations is widespread in the coastal mountains of north Iberia. Based on a compilation of published works, we have estimated a total area of 3150 km^2 covered by glaciers at the glacial maximum stage, which means that the CM constituted the most important mountain glaciation in Iberia after the Pyrenees (Fig. 1b). Glaciers developed asymmetrically in both slopes, showing less surface extent and attaining shorter glacier tongues in the northern side of the CM (3–11 km) where they reached lower elevations at their glacial

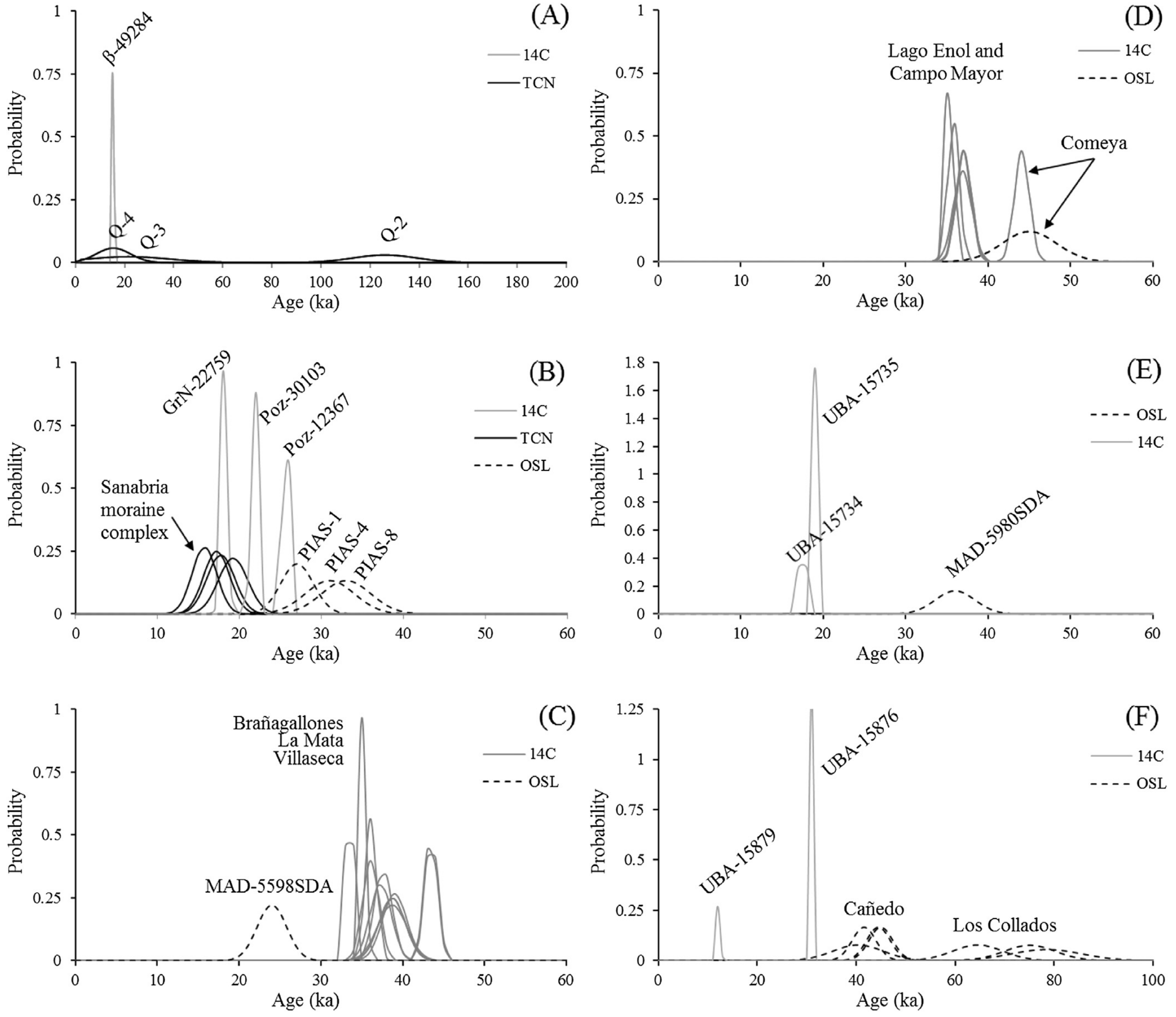

Fig. 4. Probability density functions (PDFs) of the single numerical ages and their random uncertainties ($x \pm \sigma$) obtained for the glacial maximum stage recorded in the different massifs of the Cantabrian Mountains through radiocarbon (^{14}C), terrestrial cosmogenic nuclides (TCN) and optically stimulated luminescence (OSL). (A) Queixa-Invernadoiro; (B) Trevinca; (C) Alto Sil/Babia and Central Cantabrian Mountains; (D) Picos de Europa; (E) Fuentes Carrionas; (F) Castro Valnera.

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fronts (300–1200 m) than in the southern side (6–51 km; 760–1300 m) (Table 1). This asymmetry in glacier development was probably closely related to topographic and climate factors. Nowadays, the northern side of the range receives greater moisture supply than the southern side but displays steeper slope gradients, a factor that could have avoided the formation of long ice tongues towards the north. In some areas such as Picos de Europa, Aralar, Peña Sagra, and Rañadoiro, glaciers inverted this tendency and covered broader land areas in the northern slope and developed longer glacier tongues than in the southern slope favored by the gentler slope gradients and/or low insolation conditions in this side of the range. Santos-González et al. (2013) estimated that regional palaeo-ELA varied between 1100 and 2000 m during the glacial maximum, increasing inland and from the western (1300 m) and eastern (1100 m) ends of the range towards its center and southern side, showing a similar distribution pattern than current mean winter precipitation and summer temperature values. They concluded that the influence of the range on regional climate was similar to present during glacial times and that differences in moisture supply rather than temperatures were responsible for the palaeo-ELA variations along the range. Therefore, a combination of topographic configuration and moisture supply were the main factors that controlled the asymmetry of glaciers between mountain slopes, especially in the case of mountain ranges where maximum elevations barely reach 1400–1700 m (Aralar, Courel, Oribio, Rañadoiro). Moraines at higher elevations than those corresponding to the glacial maximum are preserved along the range, defining 3 to 4 subsequent and less extensive glacial advances.

Available numerical ages for the glacial maximum stage have been plotted as probability density functions of the single dates (PDFs) to illustrate age differences noted between the minimum ages obtained for the glacial maximum stage in the different massifs of the CM, arranged from the Queixa-Invernadoiro Massif (Fig. 4A) to the Castro Valnera Massif (Fig. 4F). A comparison between the glacial stages identified and the Greenland ice core GISP 2 is provided as well (Fig. 5). The minimum ages obtained on tills and glaciolacustrine samples from the mountain areas of Alto Sil/Babia/CCM, Picos de Europa and Fuentes Carrionas suggest that the local glacial maximum took place at a minimum age of 36–45 ka BP (MIS 3) and was followed by glacial retreat conditions (Jiménez-Sánchez and Farias, 2002; Jalut et al., 2010; Moreno et al., 2010; Serrano et al., 2012; Jiménez-Sánchez et al., 2013; Pellitero, 2013) (Fig. 4, plots C–F). This episode of deglaciation was also recorded in the Trevinca Massif; where numerical ages obtained for glaciofluvial and glaciolacustrine samples suggest that the glacial maximum stage took place prior to 33 ka BP (Pérez-Alberti et al., 2011; Rodríguez-Rodríguez et al., 2011) (Fig. 4B). A glacial advance during MIS 3 was also reported for the Castro Valnera Massif, where till samples have reported burial ages of 40–45 ka. However, 3 till samples from Los Collados gave numerical ages of 65–78 ka, suggesting that the local glacial maximum stage was coeval with MIS 4 (Frochoso et al., 2013) (Fig. 4F).

The minimum exposure ages obtained for the sequence of recessional moraines preserved in the Trevinca Massif support a second advance of the Tera glacier front coeval with the global LGM of MIS 2, attaining a similar ice tongue length than during the previous glacial maximum (Rodríguez-Rodríguez et al., 2014). In the CCM, an inner moraine of the Brañagallones lateral moraine complex provided a burial age of 24 ka BP that also suggest a glacial advance coeval with the global LGM of MIS 2 (Jiménez-Sánchez et al., 2013). The palaeolake sequence deposited inside the limits of the terminal moraine in Vega del Naranco, Fuentes Carrionas, gave a minimum age of 19 ka BP for the beginning of the sedimentation process, when a receding glacier was feeding the lake with meltwaters (Pellitero, 2013). This numerical age agrees with the minimum age of 17.4 ka BP obtained for the Cardaño de Abajo palaeolake in the southern side of the same massif (Serrano et al., 2013a) (Fig. 4E). In Castro Valnera, the ages obtained from 2 peat bog samples deposited between the moraine ridges of the Espinosa and Bárcena moraine complexes (Trueba Valley) gave minimum ages of 31 and 12 ka BP for their formation (Serrano et al., 2012) (Fig. 4F). Thus, the Espinosa terminal moraine complex could correspond to the MIS 3 glacier advance recorded in almost all the massifs of the CM while the Bárcena moraine complex could

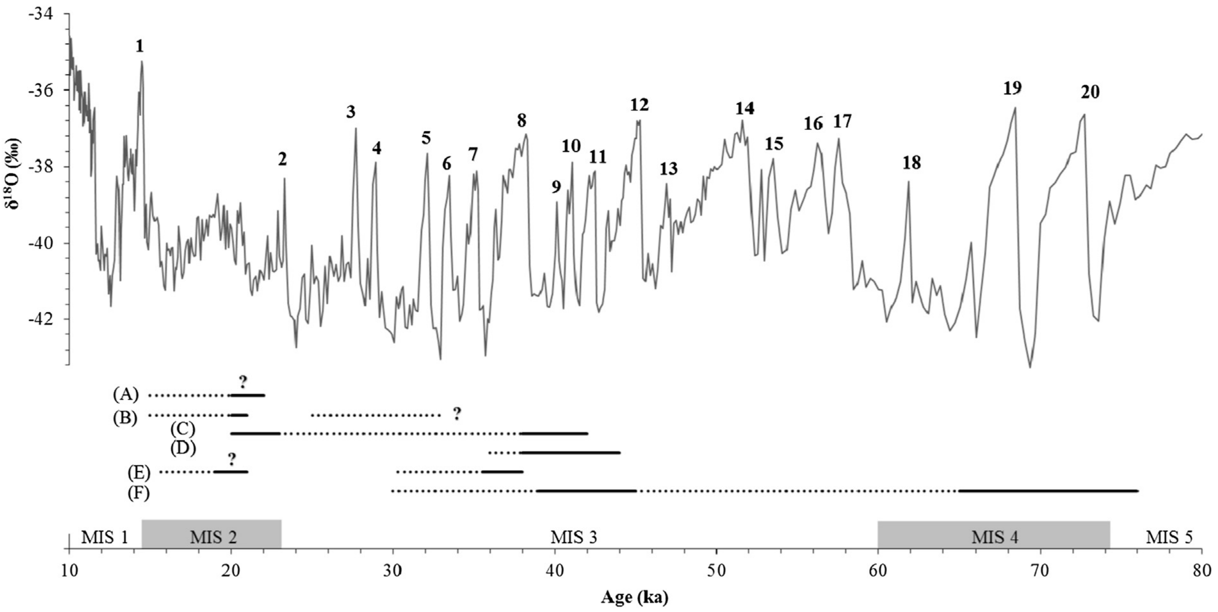

Fig. 5. Comparison between the glacial chronology of the Cantabrian Mountains and the oxygen isotope record of the Greenland ice core GISP 2 (Grootes et al., 1993). Numbers indicate warm periods associated to the Dansgaard/Oeschger events (D/O). Continuous lines represent the timing of glacial advances (question marks indicate those deduced from post-glacial numerical ages) while dashed lines represent glacier retreat periods in the different massifs of the Cantabrian Mountains: (A) Queixa-Invernadoiro; (B) Trevinca; (C) Alto Sil/Babia and Central Cantabrian Mountains; (D) Picos de Europa; (E) Fuentes Carrionas; and (F) Castro Valnera.

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correspond to the MIS 2 glacial advance. In Queixa-Invernadoiro, the exposure ages of 2 drumlins and a glaciolacustrine deposit located up valley from the terminal moraine indicate that the last deglaciation was taking place coevally with the global LGM. However, only 1 exposure age obtained from the terminal moraine at Entrecinsa suggests that the local glacial maximum stage ended at 126 ka, matching the end of MIS 6 (Vidal-Romaní et al., 1999) (Fig. 4A).

Thus, the available chronology for the glacial record of the CM clearly suggests the occurrence of 2 glacial advances during the Last Glacial Cycle (Fig. 5): (i) a glacial maximum stage between 36 and 45 ka BP (MIS 3) coeval with the general cooling trend recorded between Dansgaard/Oeschger (D/O) events 12 and 8 in the Greenland ice core GISP 2 (Grootes et al., 1993) and (ii) a subsequent glacial advance at 19–23 ka BP coeval with the global LGM of MIS 2. This second advance was recorded in all the massifs and, at least in some valleys, the glacier tongues were comparable in extent to the previous glacial maximum. Only the glacial evidence dated in Queixa-Invernadoiro and Castro Valnera massifs suggests the occurrence of a glacial maximum stage older than MIS 3. Additional chronological studies are required to test if these previous glacial advances were recorded in other parts of the Cantabrian Mountains, especially in those mountain areas where: (i) the oldest glacial deposits have not been directly dated yet, (ii) there are a small number of numerical ages and/or available ages show low reliability, and (iii) the timing of the glacial maximum stage is mainly based on the results provided by the ^{14}C method. Similarly, some features have been interpreted as remnants of ancient glaciations and correlated with cold conditions of MIS 12 and MIS 22 on the basis of U/Th ages obtained from stalagmites and cemented breccias (Gale and Hoare, 1997; Villa et al., 2013). Further studies are required to confirm these glaciations based on new geomorphological and geochronological evidence.

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