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Mountain glaciation and paleoclimate reconstruction in the Picos de Europa (Iberian Peninsula, SW Europe)

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ABSTRACT

Geomorphic mapping and stratigraphic analysis of a lake core document the late Quaternary glacial history of the Central and Eastern Massifs of the Picos de Europa, northwestern Spain. The distribution of glacial deposits indicates that at their most advanced positions glaciers occupied 9.1 km^2, extended as far as 7 km down-valley and had an estimated equilibrium-line altitude (ELA) ranging between 1666 and 1722 m. Radiocarbon dating of sediment deposited in a lake dammed by moraines of this advance show that the maximum glacial extent was prior to 35,280 ± 440 cal yr BP. This advance was followed by two subsequent but less extensive late Pleistocene advances, recorded by multiple moraines flanking both massifs and sedimentary characteristics in the lake deposits. The last recognized glacial episode is the 19th-century maximum extent of small Little Ice Age glaciers in the highest cirques above 2200 m.

Introduction

There is a long tradition of studies into Quaternary glaciations in the Picos de Europa, but there are few absolute ages or studies linking glacial features and environmental evolution. Located in southern Europe, in a maritime environment at the edge of the Atlantic Ocean with altitudes above 2600 m, the Picos de Europa differ from the Mediterranean Iberian Peninsula mountains and is of special interest for the correlation of northern and southern Europe with environmental evolution during the late Pleistocene. In southern Europe there is a great deal of evidence of a widespread glacial phase prior to the last glacial maximum (LGM) (Pérez-Alberti et al., 2004; Woodward et al., 2004; Hughes et al., 2006; Allen et al., 2007; Hughes and Woodward, 2008; García-Ruiz et al., 2010). The LGM is defined as the cold period between 26 and 21 ka and is indicated as the coldest period of the late Quaternary by marine isotope curves (Ehlers et al., 2011). Nevertheless, many of the ages that have now been made for the mountains of the Iberian Peninsula, both in Atlantic and Mediterranean environments, reveal asynchroneity with respect to the north of Europe. They define a "local maximum glacial advance" (LMGA), reflecting the maximum extent of glaciers in the different massifs of Iberian Peninsula relative to the European LGM (Mardones and Jalut, 1983; Andrieu et al., 1988; Vilaplana and Montserrat, 1989; Jalut et al., 1992, 2010; García-Ruíz et al., 2003, 2010; González Sampériz et al., 2006; Calvet, 2008; Moreno et al., 2010).

The glacial footprints of the Picos de Europa were attributed to two Quaternary glaciations, Riss and Würm (Obermaier, 1914), depending on the presence of slope deposits that fossilized till and later remodeling by a new glacial advance. The following authors studying the Picos de Europe glaciations attributed the glacial landforms to a single Quaternary and recent glaciation (Frochoso and Castañón, 1986, 1998; Smart, 1986; Flor and Bailón-Misioné, 1989; Castañón and Frochoso, 1992, 1996; Serrano and González-Trueba, 2002; González-Trueba, 2007a,b; Moreno et al., 2010). The existing ages point to an age between 90 and 17 ka (Frochoso and Castañón, 1998) or between 40 and 35 ka (Moreno et al., 2010). The relative chronology is now known (Gale and Hoare, 1997; Serrano and González-Trueba, 2002; González-Trueba, 2007a,b; González-Trueba and Serrano, 2010) but very few absolute ages exist.

The aim of this study is to establish the glacial evolution of the Picos de Europa in the Central and Eastern Massifs, its chronology, the environmental changes taking place during the maximum glacial advance and the successive phases of glacial equilibrium and retreat, and to evaluate the distinct glacial behavior related to other European locations during Marine Isotope Stage 3 (MIS 3) and Marine Isotope Stage 2 (MIS 2).

Study site

The Picos de Europa are located to the north of the Cantabrian Mountains (43°10'N/4°50'W) just 20 km from the sea. They are split

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into three massifs (the Western, Central and Eastern) separated by deep gorges (Sella, Cares, Duje and Deva) (Fig. 1). It is a mountain range with a marked oceanic influence characterized by abrupt vertical relief, with height differences of over 2300 m within a few kilometers and summits of up to 2700 m (Torre Cerrado, 2648 m a.s.l.). The massif constitutes a succession of thrust faults of south vergence divided by faults. The predominating rocks are limestones of the Carboniferous Age, with alternating slates, calcareous conglomerate, limestones and turbiditic sandstones from the Stephanian Age. The relief is characterized by fluviotorrencial erosion, karst and Quaternary glacial landforms. It is a glacio-karstic landscape with periglacial and nivation processes.

The paleolake Campo Mayor, located in Áliva at 1425 m a.s.l. (43°10'17"N/4°46'13"E) between the Central and Eastern massifs, is 1400 m long, 200 m wide and 20 m deep. It forms a plain deriving from an old moraine-dammed lake generated between the lateral moraine of the Duje glacier and the slope of the Eastern Massif. At the head of the lake to the SE are the nine arches of the Las Salgardas frontal moraine complex (Figs. 1,2A and 3). The lake received proglacial melt waters of high energy and high sedimentary load from the Las Salgardas glacier and generated a proglacial complex dammed by the Duje lateral moraine complex (Lomba de Toro).

Methodology

Mountain lacustrine deposits provide high-resolution records, and the environmental changes identified in them can be extrapolated to the immediate surroundings (Chapron et al., 2007; Ivy-Ochs et al., 2008). To correlate the forms and deposits, a glaciomorphological map was drawn up to form the basis of the morphostratigraphic survey, the Pleistocene Equilibrium Line Altitude (ELA) was reconstructed and a core of the paleolake of Campo Mayor extracted.

The morphostratigraphic correlation of the glacial landforms permits to reconstruct the extension of Quaternary glaciation and its evolution (Lukas, 2006; Hughes, 2010). The morphostratigraphic sequence is based on the distribution of frontal complexes in the cirques and valleys, the number and succession of each morainic complex, the altitudinal position and the altitude of the estimated ELA.

The ELA, the altitude at which the mass balance of a glacier is equal to zero, is a very useful parameter for the environmental characterization of glaciated environments (Porter, 1975; Dahl and Nesje, 1992; Seltzer, 1994; Benn and Ballentyne, 2005). For the reconstruction of the paleo-ELAs (i.e., the ELA of former glaciers), the Accumulation-Area Ratio Method (AAR) was applied based on the relationship between the balance of mass and the percentage of the area of accumulation with respect to its total area, assuming a percentage of the AAR of 0.6 ± 0.05. From the paleo-ELAs, the Mean Equilibrium-Line Altitude (MELA) was estimated, representative of the maximum extension of the ice in a glacial phase with theoretical glacial conditions of equilibrium in one massif, thus permitting regional comparisons (Ohmura et al., 1992; Seltzer, 1994; Benn et al., 2005).

From the reconstruction of the ELAs and the current climatic parameters and following the application of the degree-day model (Brugger, 2006; Allen et al., 2007; Hughes and Braithwaite, 2008), the thermal differences between glacial phases and the present day were estimated. An annual temperature range of 13–16°C and a vertical lapse rate of 0.56°/100 m (González-Trueba, 2007b,a) were used. Present-day temperatures and the ELA allow the estimation of the temperature fall necessary for the development of glaciers at the altitude of the paleo-ELA, with a resolution of less than 2°C for the estimation of Stage 1 and less than 3°C for Stage 3.

In the paleolake Campo Mayor, a sedimentary core of 20-m depth and 7.5 cm diameter was extracted using a mobile drilling rigs equipment mounted on a truck, which reached the calcareous substrate. The sedimentary core was photographed and its structures, Munsell color, texture and lithofacies to the cm scale described, with millimetric observations of lakeside laminar structures. The Loss on Ignition (LOI) is an effective technique to estimate the organic content of lakeside sediments due to the close relationship between total organic carbon (TOC) and LOI (Dean, 1974; Heiri et al., 2001). The organic material contained in lakeside sediments reflects the biological activity and environmental conditions of the water and its surroundings, and points to periods of increasing and decreasing glacial activity. In the core, the LOI was applied in 51 samples and the results calculated as a percentage of dry weight (Dean, 1974; Nesje et al., 1991, 2001; Heiri et al., 2001).

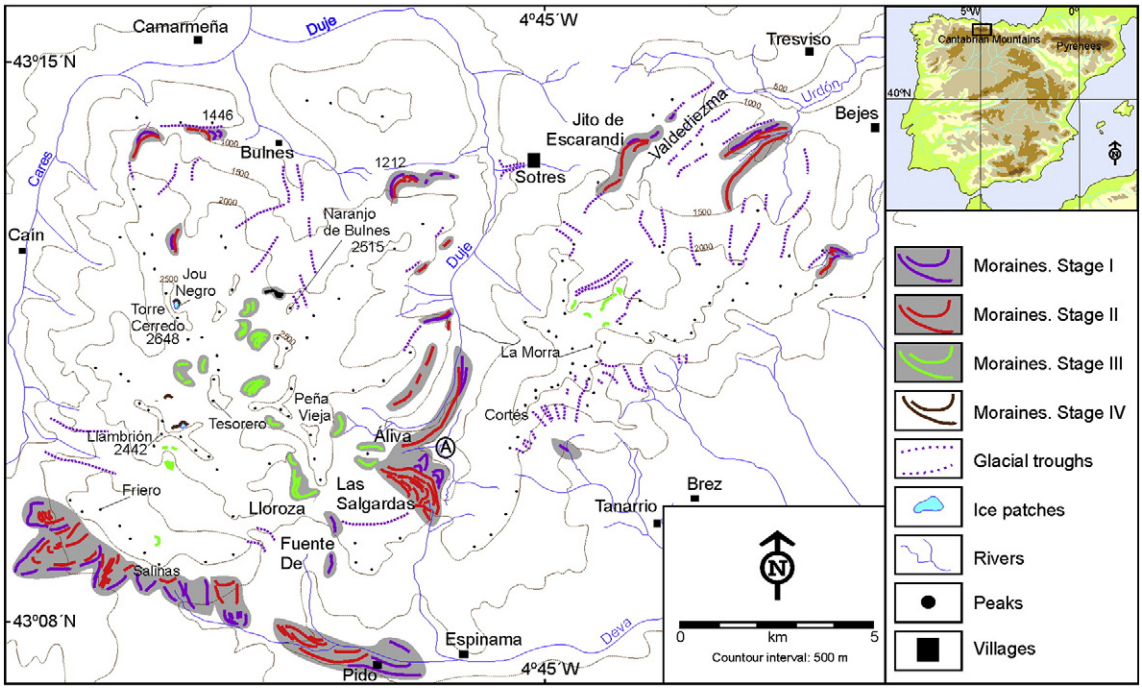

Figure 1. Glaciomorphological sketch and location of Central and Eastern massifs.

Figure 2. Glacial landforms of Picos de Europa. A) Lateral and frontal moraines of Áliva area, located between the Eastern and Central massifs. S1, Location of Campo Mayor sedimentary core. B) Glacier reconstruction of local glacial maximum in the Áliva area. C) Lateral moraine of Jito de Escarandi, Eastern Massif. D) Glacial trough with glaciokarstic depressions of Valdediezma, Eastern Massif. E) Lloroza moraines, Central Massif, built in the high mountain phase, Stage III. White lines follow the moraine crests.

Eight samples were dated by accelerator mass spectrometry (AMS). The extremely low residual concentration of ^{14}C in the age samples prior to 25 ka and the scarcity of data on the quantitative production of cosmogenic ^{14}C during MIS 3 (Bard et al., 2004) involves a greater final error and less chronological precision (approx. 800 yr) than for the more recent ages (Danzeglocke et al., 2009). The ages obtained were calibrated using the software 5.0.2 CALIB (Reimer et al., 2004) for the more recent ages and the software CALPAL (Danzeglocke et al., 2009) for the older ones.

Results

Glacial record and evolution

The glacial landforms of the Picos de Europa are closely related to karstification and the dominant erosion features are glaciokarstic depressions (Fig. 2). The glacial troughs are short and steeply sloped, often of preglacial origin and eroded by glaciation, although there are well configured troughs in northern orientations (Valdediezma, Camburero). The great height differences prevented the development of long glaciers, although their fronts reached very low altitudes (450 m in Dobresengos, 600 m in Bulnes, 800 m in Liébana).

The morphostratigraphic correlation and the altitude of the estimated ELA permit differentiate four main glacial stages in the Picos de Europa (Tables 1 and 4).

1. *Stage of maximum expansion with summit domes (S.I):* Glaciers occupied 9.1 km^2. There were 39 glacial tongues of between 7 km (Duje valley) and 4 km length (Deva and El torno valleys), and large interconnected icefields whose lowest fronts terminated at 700–800 m a.s.l. to the north and 900 m a.s.l. to the south (Serrano and González-Trueba, 2002; González-Trueba, 2007a,b; Gonzalez-Trueba et al., 2008; González-Trueba and Serrano, 2010; Serrano et al., 2012). During this period most of the erosion glacial landforms were shaped and glacial relief elaborated (Figs. 1 and 2a, b and c). The ELA is located at a mean altitude of 1666 m in the Central and 1722 m in the Eastern massifs, in nearly all cases in the glacial cirques.
2. *Stage of alpine glaciers (S.II):* This is a phase characterized by a reduction of length and width of glaciers but with similar proportions in extension to the previous phase and an increase in the

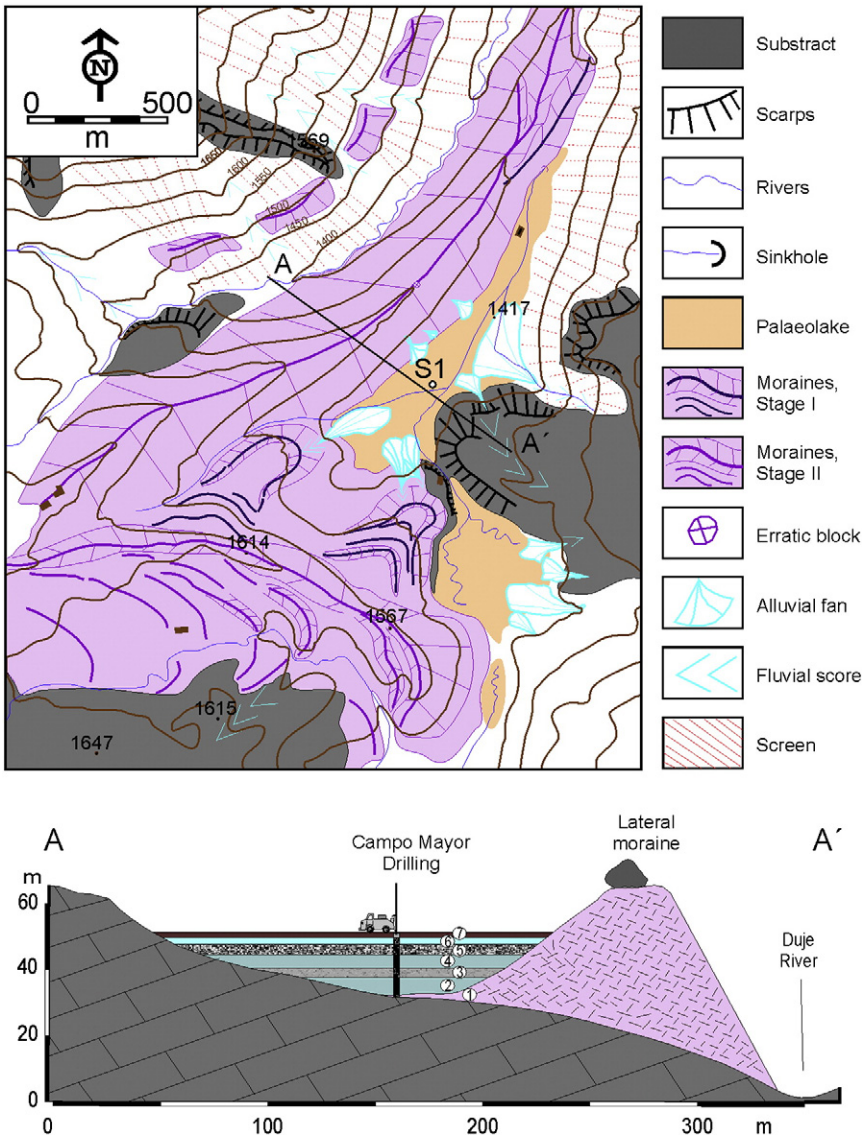

Figure 3. Detailed geomorphological sketch of the high Duje, Campo Mayor and Áliva Paleolake area.

volumes of fronts. In the Eastern Massif, of moderate altitude and extension, glaciers reduced in size by 32%. We ascribe this to a period of retreat, equilibrium and minor advance immediately following Stage I. The advance led to changes in drainage similar to the changes in Las Salgardas, where the main drainage in Stage I (toward the rivers Deva and Duje) altered during Stage II, mainly towards the river Deva.

3. *Stage of cirque glaciers (S.III):* At over 1800–2000 m, the glacial cirques oriented to the north and with walls of 200–250 m of relief present well-conserved morainic complexes (González-Trueba, 2007a,b; Gonzalez-Trueba et al., 2008; González-Trueba and Serrano, 2010). These forms belong to a period of equilibrium and minor advance when the Picos de Europa were practically deglaciated (Fig. 2E). The loss of ice surface with respect to the maximum was 88.4% in the Central and 96.5% in the Eastern massifs. The ELAs are situated at above 2000 m a.s.l. in almost all cases. Glaciers were located at shaded sites and at altitude, and were generated in a period of moderate cooling.
4. *Historical glaciation (S.IV):* There are footprints of historical glaciation in the highest cirques, always oriented to the north (Serrano

Table 1
Pleistocene glacier extent and MELA altitudes in the Eastern and Central massifs of Picos de Europa.

	Stage I			Stage II			Stage III		
	n	ELA Mean (m a.s.l.)	ha	*n*	ELA Mean (m a.s.l.)	ha	*n*	ELA Mean (m a.s.l.)	ha
Central Massif	24	1600	6854.9	24	1670	–	33	2132	790.9
Eastern Massif	15	1722	2338.2	14	1745	1583.3	8	2055	80.4
Total	39	1705	9193.1	38	–	–	41	2094	871.3

n, number of glaciers, Ha, hectares. ELA mean estimated by AAR method.

and González-Trueba, 2002; González-Trueba, 2006; 2007a,b; Gonzalez-Trueba et al., 2008). Glaciation was marginal, favored by topoclimatic effects, characterized by very small glaciers located above 2200 m a.s.l., below the regional climatic ELA and with strong north–south dissymmetry. Glaciers were very small and at their maximum extension the location of their fronts corresponded to the last glacial advance of the first one-third of the 19th century (González-Trueba, 2007a,b; Gonzalez-Trueba et al., 2008).

The infilling of the paleolake of Campo Mayor (Áliva)

The sedimentary core of the paleolake of Campo Mayor presents seven lithostratigraphic units (LU) with five main infilling phases correlated with the glacial evolution in the surroundings of the lake (Figs. 4 and 5;Table 2). The LU1, between soil and 1.3 m depth, is formed by marshy sediments and soils developed in a clogged lake. At between 1.3 and 13.5 m depth, shallow-water lake sediments (LU6, LU3), a foreset complex (LU5) and deep-water lake sediments (LU4) alternate. Finally, between 13.5 and 19 m depth a lacustrine deposit (LU2) rests on the till (LU1).

Dating on the core (Table 3;Fig. 4) point to the first 1.3 m depth (LU7) being of Holocene age (the last 10,000 yr, MIS 1). The Holocene–Pleistocene transition in the deposit of Campo Mayor-Áliva is at about 1.3 m in depth (Table 3). Between 1.3 and 5–6 m depth (LU6, LU5c and 5b) the deposit has an age about 21–17 ka, belong to MIS 2. From about 6–7 m (LU5a, LU4, LU3 and LU2) depth, sediments are older than 21 ka and so belong to MIS 3. The oldest dated age is 35,700–34,850 cal yr BP at 15.5 m depth. The age of the beginning of lacustrine sedimentation on till is before 35 ka.

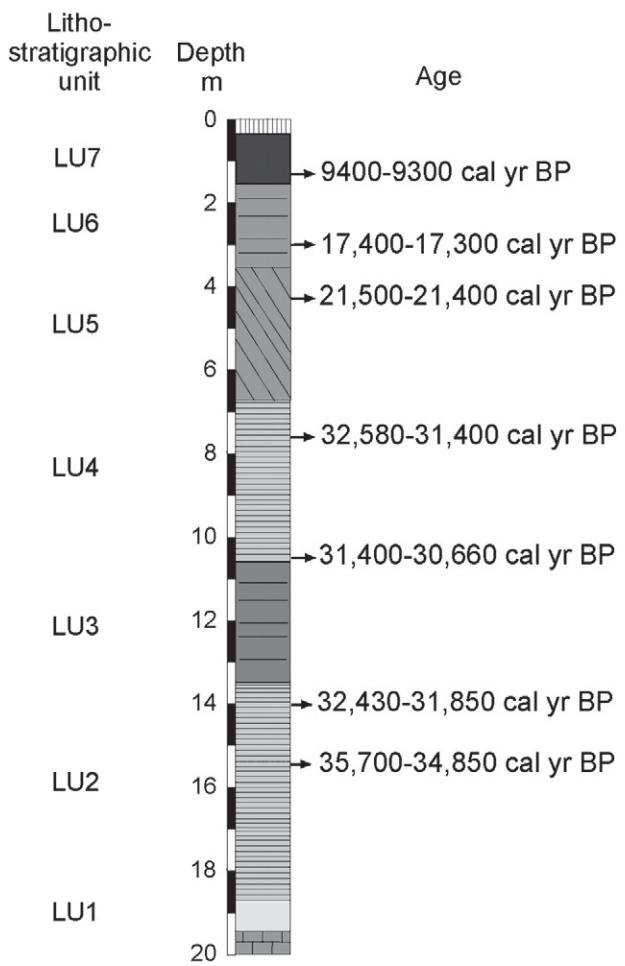

Figure 4. Lithostratigraphical log and chronologies of the Campo Mayor-Áliva core.

The sedimentation rates of the Áliva core vary according to sediment types and basin dynamics, showing a decrease from the bottom to the top (Fig. 4). Sedimentation begins with the highest rates (approx. 1 mm yr^{-1}) in the first 8 m (LU2 and LU3) of the lacustrine deposits. In the upper part of the lake, considering the upper lacustrine body (LU4) and the bottom of the foreset (LU5), the sedimentation rate is approximately 0.6 mm yr^{-1}, but on the top of the lacustrine deposits (LU4, 7.5 m depth) the ages are reversed. This has been attributed to chemical modification or possible contamination, as the sediments do not show physical alterations or hiatus. The chronological and physical proximity to the upper and lower ages gives consistency to the overall chronological model, although is not possible to estimate precise sedimentary ranges. In the foreset (LU5) the sedimentation is comparable (approx. 0.6 mm yr^{-1}) to the previous levels if we exclude the 7.5 m depth age. In the LU6 the sedimentation rates lower (approx. 0.3 mm yr^{-1}), consistent with the dynamic of a shallow-water lake and changes in the basin. The moraine (Stage II) closed the drainage toward the Duje valley and the water flowed to the river Deva. The Aliva Campo Mayor Lake thus received less glacial water and this came from the upper lake, which had become a sediment trap. At the top of the core (LU7), during the Holocene, the sedimentation rate is lowest (approx. 0.1 mm yr^{-1}), in accordance with a marshy environment in which glaciers are absent and Las Salgardas drains towards the river Deva. The basin dynamic, sedimentation and chronology seem consistent, so the age–depth model appears reliable if we exclude the ages at 7.8 m depth.

LOI and organic matter content

The biological activity and environmental conditions of the water and its surroundings are revealed by the organic content of lacustrine sediments, with increases during warm periods and decreases during cold periods, the last of these related to glacial advances. The LOI values obtained in the sediments show ranges between 83.5% and 1.48%, though only in the first 40 cm of depth have values over 18.9% been recorded. Relatively high values (17.5% and 18.9%) are also found at the base of the deposit, at more than 19 m depth in the till deposited on the substrate. In the intermediate portion, between 80 cm and 19 m, the values of LOI are between 16.75% for the highest and 1.48% for the lowest.

The values of LOI and organic matter (OM) studied in high mountain environments show values of between 1% and 9% (Matthews et al., 2000; Nesje et al., 2001; Chapron et al., 2007), significantly lower than in Áliva, where values of over 10% make up 52%. The biannual moving means permit the general trend to be tracked and the differentiation of ten significant sections of increase or loss of LOI, four minimums and three maximums of LOI content (Fig. 7), which allow the differentiation of the phases of glacial activity and rhexistasic environments around the lake (phases B), and of phases of glacial retreat with a biostatic tendency in the surroundings of the lake (phases A). A first phase of rhexistasic conditions (B1) is recorded with a gradual rise in LOI, in which two maximums (A1 and A2) are included, culminating in three LOI minimums (B2, B3 and B4). The phases of minimum values may be correlated with the glacial pulsations of Áliva, Duje, Ándara and Deva, all very close to the paleolake, within a few hundreds of meters and 3 km.

The LOI maximums (A1, A2 and A3) reach very similar values, except for one lesser maximum (A4) around 20,000 yr, moderate and very slightly above the mean. Finally, in the last 10,000 yr a continuous rise has begun, culminating in the organic richness of present-day soils.

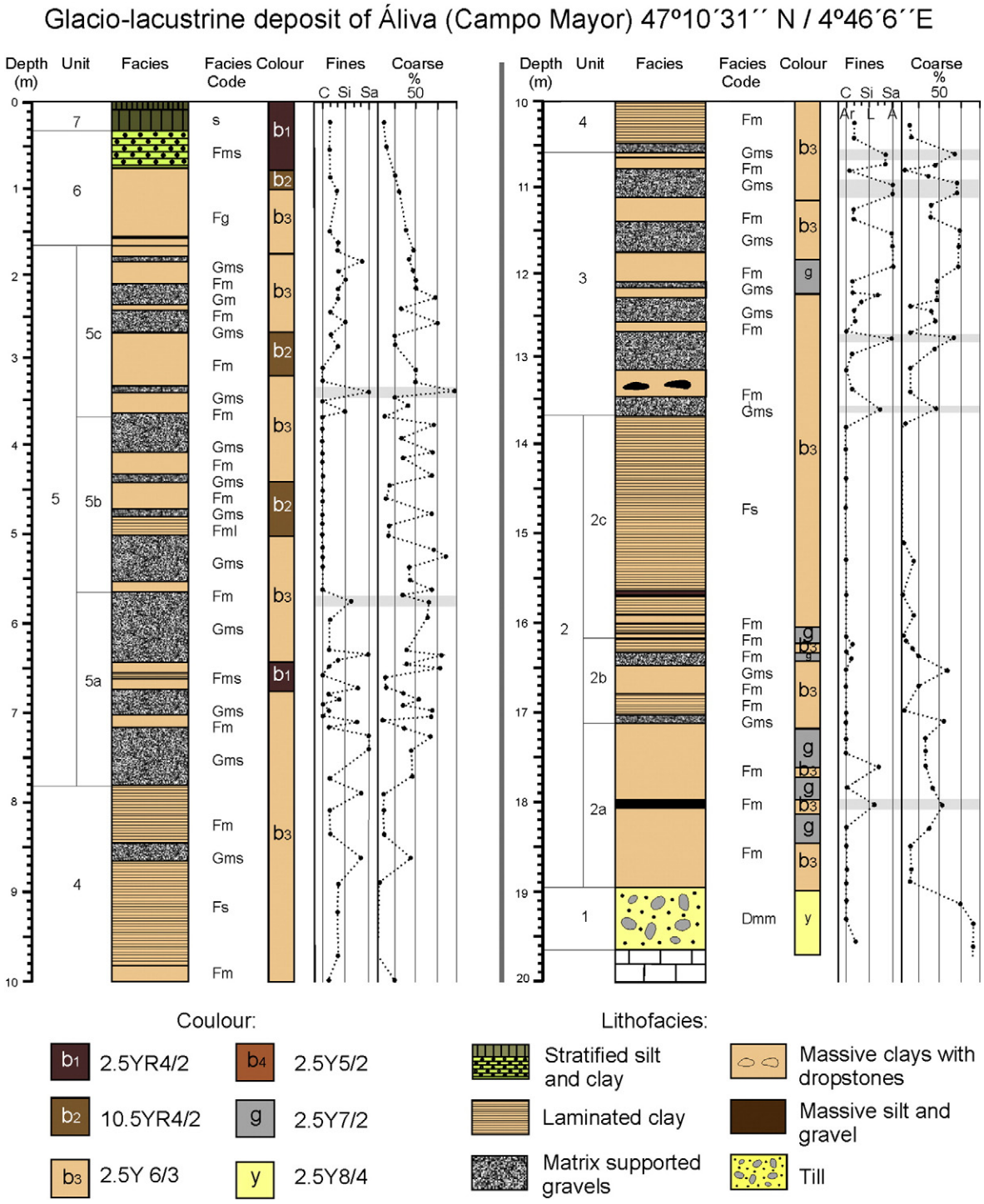

Figure 5. Lithostratigraphic column of Campo Mayor paleolake core (Áliva).

Glacial evolution and environmental reconstruction

The paleolake is a particularly suitable location for the correlation between glacial evolution and infilling, due to the location of the lake between the two massifs and very close to the best preserved lateral and frontal complexes. During the lake infill, lake waters varied greatly in depth depending on glacial evolution. When glaciers advanced, the ice and moraines dammed water and thus lacustrine sediments were dominant. When glaciers retreated, water was released and debris slope and torrential deposits occupied the basin.

The morphostratigraphy, lithostratigraphy, LOI and ages allow the reconstruction of the evolution and environmental changes in the different glacial periods. The glaciomorphological stages (four in total) can be correlated with the phases of lacustrine infilling, the increase and decrease in LOI content, lithostratigraphic units, and ages (Figs. 6 and 7; Table 4).

Glacial Stage I. Glacial maximum

The frontal and lateral complexes, as well as the erosional landforms, indicate the maximum expansion of the glaciers in the Picos de Europa. The reconstructed ELAs would be located at 1600–1700 m a.s.l. and the glaciers would have tongues with lengths of between 5 and 8 km for the largest, whose fronts reached elevations of between 490 and 1850 m a.s.l. This wide variability of sizes and altitudes is in accordance

Table 2
Sedimentary, morphological and environmental interpretation.

Unit	Lake	Morphogenesis	Stage	
LU1	Till	Glacial expansion	Glacial advance and equilibrium	**1**
LU2a	Initial waterlogging, basal lacustrine deposit.	Phase of glacial equilibrium. Lateral moraine building. Very cold and dry environment.		
LU2b	Shallow water lake, waters from the front of Las Salgardas and its proglacial cones.	Possible small advances related to colder and drier periods with slope debris supply.	Glacial retreat and equilibrium Less cold environment.	**2**
LU2c	Deep water lake and calm sedimentation.	Retreat and glacial pulsations.		
LU3	Lake of little depth, fed by waters from the slopes.	Alternating glacial advances and retreat in a cold dry environment.	Glacial advance and equilibrium	**3**
LU4 lower	Increase in the depth and continuous infilling.	Greater hydric availability by access of melt waters in a warming environment.	Warming, frequently glacial advances and retreat.	**4**
LU4 medium	High energy sediments and coarse supply.	Hydric availability decline.		
LU4 superior	Calm water lakeside sedimentation	Glacial retreat, gradual warming in cold mountain environment.		
LU5a	Swift infilling, prograde deltaic environment.	Gradual warming, hydric availability and clogged lake with a well drained basin. Retreat and melt of glaciers.	Warmest and wettest period. Temperate high mountain environment.	**5**
LU5b	High energy coarse sediments supply.			
LU6	Fluviolacustrine and marsh sedimentation. Calm water currents, clogged basin	Temperate mountain environment with hydric availability.		
LU7	Soils	Clogging of the lake and pedogenesis. Wet temperate environment.		

with a massif of moderate altitude and considerable N–S contrasts, both morphostructural and thermal, and in precipitation.

In this period the Las Salgardas tongue drained toward the Duje valley, dammed by the lateral moraine of Duje glacier, the lake of Campo Mayor was generated and the sedimentation of the lacustrine basin began. The LOI values are very low (Fig. 7), pointing to a rhexistasic period with a glacial advance capable of building up the frontal and lateral moraines. The proximity of the glaciers to the lake (400 m from the fronts and 300 m from the tongue of Duje) implied a very cold environment in which there was practically no vegetation, and clasts and mineral supply predominate. This is an maritime glaciation, defined by high snowfall and moderately cold mean annual temperatures (MAAT = −3° to −5°C). The access of cold wet fronts from the N and NW deposited large quantities of snow on the summits and generated coalescent glacial domes and cirques characteristic of cold maritime environments. The intense snowfall and the low summer sunlight due to the frequency of cloud cover deriving from the proximity of the sea favored snow accumulation and the development of glacial tongues that, despite the moderate altitudes of the mountain, reached very low altitudes (500–800 m) below the upper limit of the treeline.

The estimates of ELAs allow the extrapolation of temperatures. The degree-day model estimates these at between −10 and −12°C, significantly higher by between −2.5 and −3°C than those estimated from the ELA (González-Trueba, 2007a,b). The Picos de Europa are not an exception, and as in other mountains of the Cantabrian Mountains with moderate altitudes and located windward from oceanic fronts, glaciers also reached altitudes of between 425 and 600 m. Only in the western oceanic part of the Pyrenees did glaciers reach similar altitudes, whereas to the east, with altitudes similar to the Picos de Europa, the fronts were at higher altitude.

Table 3
AMS dates in Campo Mayor palaeolake (Áliva, Picos de Europa).

Depth (m)	Lab. Code	^{14}C yr BP	cal yr BP
1	Beta-269555	6660 ± 40	6720–6640
1.33	Beta-264113	8310 ± 50	9400–9300
3	Beta-269556	17300 ± 100	17,400–17,300
5.50	Beta-26557	21390 ± 100	21,500–21,400
7.80	Beta-264115	27570 ± 320	32,580–31,900
10.55	Beta-264116	26090 ± 240	31,400–30,660
14.10	Beta-264117	27460 ± 300	32,430–31,850
15.50	Beta-264118	31200 ± 440	35,700–34,850

Dating of the paleolake of Campo Mayor-Áliva reveal that the last glacial maximum was prior to 35,700–34,850 cal yr BP. Below the dated sample (at 15.5 m depth), 3.5 m of lacustrine deposit (LU 2) develops. Assuming a constant rate of sedimentation during the formation of LU2 and given the rate of sedimentation of the 2 m above (0.41 mm yr^{-1}), the age of the base of the LU2 in contact with the till is about 43.7 ka. Although it may be older than MIS 3, as has been found in other mountains of southern Europe (Hughes et al., 2011), it is a minimum age and so we judge that the present-day data on the rate of sedimentation and the good conservation of landforms do not indicate a very old glacial stage. This period coincides with the LMGA in the Picos de Europa, when the lateral moraine of Áliva and the frontal moraines of Las Salgardas were shaped, the lateral moraine formed a dam and generated the lake before 35 ka. Thus, the maximum glacial expansion in the Picos de Europa belongs to MIS 3 (59–28 ka).

In the Cantabrian Mountains there are dates on the maximum extension of glaciers in Redes of 29 ka (Jiménez and Farias, 2002); Sil valley, ca. 44 ka; Trueba valley, prior to 29,149–28,572 cal a BP (Serrano et al., 2012); and Picos de Europa, prior to 17–20 ka in Duje valley (Castañón and Frochoso, 1996) and 40 ka in Enol lake (Moreno et al., 2010). The ages of Campo Mayor-Áliva are in accordance with those obtained in the Western Massif of the Picos de Europa and high Sil Valley (Jalut et al., 2010; Moreno et al., 2010) and confirm a glacial period prior to the Pleistocene glacial maximum of the north and northeast of Europe.

The dates established for the Iberian Peninsula show a maximum advance of glaciers coming prior to the LGM (MIS 2), with an early retreat of the glaciers at around 30 ka and a minor phase of glacial equilibrium from 18 ka (Mardones and Jalut, 1983; Andrieu et al., 1988; Jalut et al., 1992, 2010; García-Ruíz et al., 2003, 2010; González Sampériz et al., 2006; Pallás et al., 2006; Delmas et al., 2008; Pérez-Alberti et al., 2011). Nevertheless, dates based on methods other than ^{14}C are more aligned with the northern European chronologies in the Pyrenees and the Central System (Jiménez and Farias, 2002; Pallás et al., 2006; Hughes and Woodward, 2008; Pérez Alberti et al., 2011; Lewis et al., 2009; Palacios et al., 2011). Although there is now broad discussion on the explanation and certainty of this glaciation chronology (Pallás et al., 2006; Calvet, 2008; Delmas et al., 2008; Hughes and Woodward, 2008; García-Ruiz et al. 2010), the dating of Picos de Europa seems to corroborate the existence of a glacial advance that was prior to the European LGM and occurred during MIS3.

The asynchroneity between the LGM and the LMGA in Southern Europe has been attributed to the proximity to the north of the Iberian

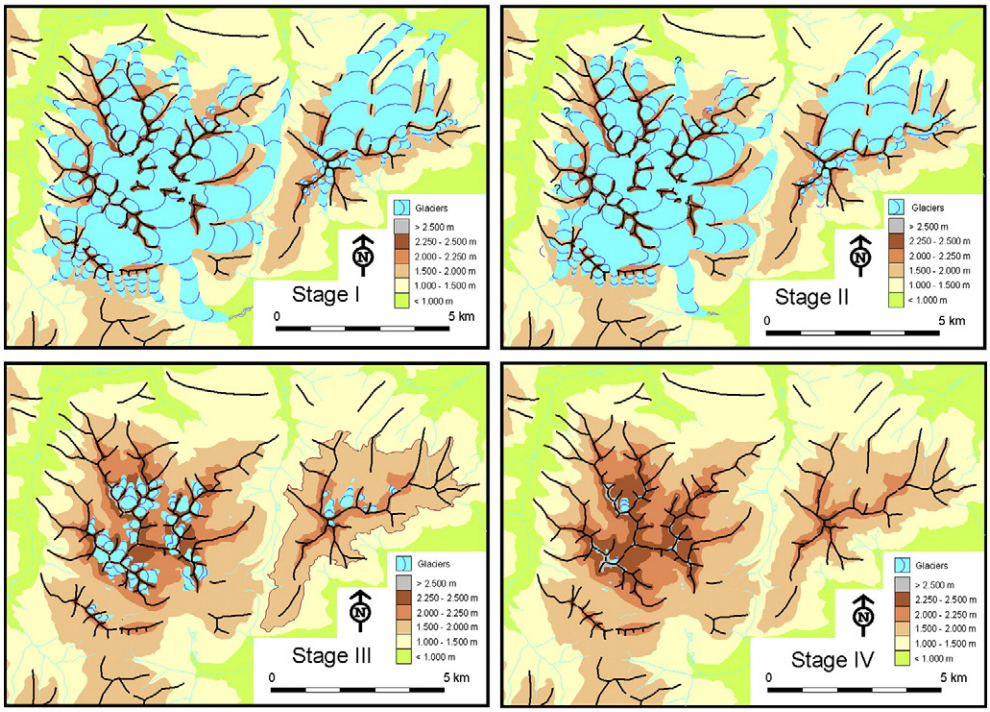

Figure 6. Glacial evolution of the Central and Eastern massifs. 1. Stage 1, local maximum glacial advance (LGMA). 2, Stage 2, minor advance. 3, Stage III, high mountain phase. 4, Stage IV, Little Ice Age.

Peninsula, and the polar front of the North Atlantic situated more to the south during this time (Ruddimann and McYntire, 1981; Florineth and Schlüchter, 2000). The greater frequency of access of air masses from the south led to the increase in snowfall in the mountains of SW Europe to which the mountain glaciers swiftly responded.

Following this glacial advance, a period of less cold conditions is recorded, characterized by the gradual increase of the LOI and coarse sediment supplies until reaching the first LOI maximum (A1). Internal fluctuations are always characterized by LOI values above the mean, with a new pronounced maximum (A2) prior to 31,850–32,430 cal yr

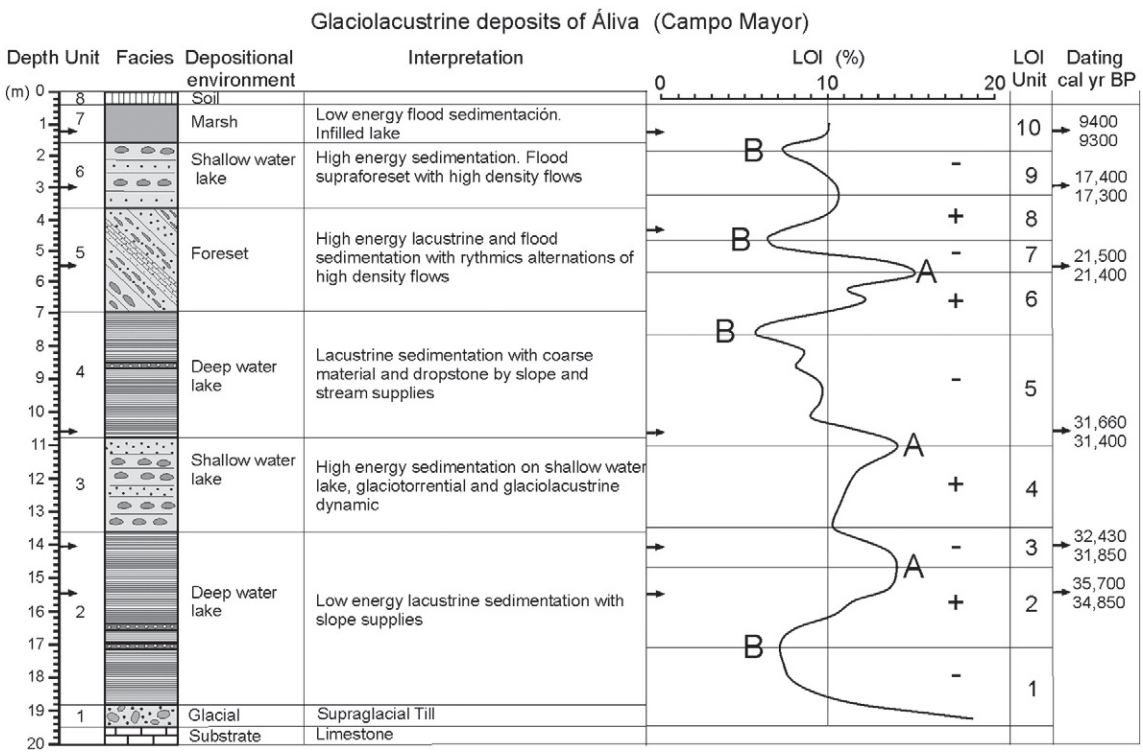

Figure 7. Synthetic and interpretative column and LOI evolution of Campo Mayor paleolake core (Áliva). A, maximum LOI. B, minimum LOI. Arrows indicate the dating level in the stratigraphic column.

Table 4
Correlation between morphostratigraphical and lacustrine data at the Campo Mayor Palaeolake (Áliva, Picos de Europa).

Glacial stage	Lake infill phase infill	LOI Phases	LOI Max and min	LU	MIS	Age (cal yr BP)
4 LIA	--	10	A4	--	MIS1	
						6720-6640
	9			8		9400-9300
	8			7		
3	7	9/10		6	MIS2	
		8/9				17,400-17,300
2b	6	7/8	B3	5b		21,500-21,400
		6/7	A3	5a		
2	5	5/6	B2	4b		
	4	4/5		4a	MIS3	
1	3	3/4	A2	3		31,400-30,660
	2	2/3	A1	2c		32,430-31,850
				2b		35,700-34,850
	1	1/2	B1	2a		
				1		40 ka*

LU, lithostratigraphic unit. *, estimated age, not cal yr BP.

BP. This is a period of glacial retreat, with glacier fronts far from the lake and vegetation in their surroundings. These less cold conditions are characteristic of the end of MIS 3, defined from marine sediments and ice cores by a complex climatic pattern characterized by the cold and a brief warming of between 33 and 28 ka (Zachos et al., 2001; NGRIP, 2004).

Glacial Stage II. Glacial equilibrium

The lateral and frontal moraines close to the outer complexes denote a new period of glacial equilibrium. This moraine complex is related to the multiple advances and retreats represented by the moraines of Las Salgardas and Torno (frontal moraines), and Duje and Escarandi (lateral moraines).

The Las Salgardas frontal complex culminates in a last continuous and well-modeled morainic arch, with a different direction of drainage to the ones of Stage I. The drainage of proglacial waters was toward the Deva River during this time, and waters could reach the Campo Mayor lake by first crossing a lake located between the glacier and Campo Mayor lake. In the frontal moraines of Las Salgardas and the lateral moraine of Duje (Stage I), the external arches delimit the maximum extension indicating a longer and thinner glacier than the internal arches (Stage II). The last of these indicates the glaciers were shorter but the voluminous moraines reached greater altitude, indicating glaciers that were thicker and shorter than the glaciers of the previous stage. This is also visible in the Eastern Massif and the neighbouring Cantabrian mountains and Central System. Thus, these are glaciers of greater size, though they are not as long as those of Stage I.

The ELAs of this period were very close to the previous ones, at between 1690 and 1745 m a.s.l., and the glaciers had tongues with lengths and frontal sittings very similar to those of the previous phase.

The minimum LOI (B2), the lowest of the entire core, confirmed the presence of a cold phase with the most rigorous rhexistasic conditions of the entire deposit. This minimum LOI was between 31,400–30,660 cal yr BP and 21,500–21,400 cal yr BP in the LU5a. Considering a homogeneous rate of sedimentation for the LU5, this would be at around 24 ka. To this period (B2) or immediately afterwards, the formation of the moraine complexes of Stage II would correspond now to MIS2. In the Cantabrian Mountains a period of glacial equilibrium posterior to the maximum advance of glaciers in the Alto Nalón has been dated at 20.6 ka (Jiménez and Farias, 2002) and between 20 and 18 ka a second phase of deglaciation in Enol lake (Moreno et al., 2010). These moraines would still be prior to the maximum expansion of glaciers in the N and NW of Europe when the Polar Front was at the same latitude as it was in the Iberian Peninsula. Jalut et al. point to a glacial retreat in the Pyrenees to 32 ka (Jalut et al., 2010), a cold and dry period. MIS2 is characterized by intense cold and the maximum expansion of the icefields, defining the LGM in Europe (Ehlers and Gibbard, 2003; Muttoni et al., 2003; Böse, 2005; Ehlers et al., 2006, 2011).

In Las Salgardas the coincidence of the greatest volume of ice and the low altitude reached by the glaciers indicates the persistence of a cold oceanic environment. Nevertheless, the most rigorous rhexistasic conditions and the shortening of glaciers permit the interpretation of a fall in precipitations with respect to the previous phase. The reconstruction of temperatures from the ELA points to thermal conditions very similar to the previous period, of between −12°C and −11.4°C of cooling, and MAAT also between −4.4 and −5.2°C. The difference is so low (0.2°C, in the range of error) that we may rule out any sharp thermal differences with respect to the previous stage. The glacial expansion would respond to a small increase in cold, which reaches conditions similar to the SI and a relative fall in humidity with respect to the previous glaciation. This fall in precipitation may derive from the access of the oceanic fronts and air masses from the SE together with the decrease in latitude of the frozen sea, the ice pack (Ruddimann and McYntire, 1981; Florineth and Schlüchter, 2000), which favors the access of cold but very dry airflow during the winter.

Between 21,500–21,400 cal yr BP and 17,400–17,300 cal yr BP there was a new minimum LOI in LU5b, preceded by a maximum (A3). It denotes a phase with brief variations and rapid transitions from bisotasic to rhexistasic conditions (B2). It is a period of environmental characteristics similar to those of Stage 2, with highly active glacial fronts characterized by small advances and retreats related to the succession of morainic arches. This all belongs to MIS 2, with the last phase (2b) close in time to the Global LGM. If we consider the rates of sedimentation of the LU5b and 5c (0.62 mm yr^{-1}), the approximate age of this phase would be 19 ka, in accordance with the periods of equilibrium and advance dated in Redes and Enol (Jiménez and Farias, 2002; Moreno et al., 2010).

These data confirm an asynchronicity of the maximum extent of glaciers between North and Central Europe and Cantabrian Mountain. The maximum extent of glaciers in Cantabrian Mountain was about 20 ka, before those in Central Europe because of the glacier response to the different thermal and precipitation regimes and climate conditions. The distinct behavior of glaciers shows a MIS 3 final period characterized by cold and wet conditions generating a glacial advance with thinner glaciers reaching the farthest and lowest glaciated areas. The cold and dry conditions during the LGM, early MIS 2, with sea frozen closed to the Cantabrian coast imply thicker but less extensive glaciers.

Glacial Stage III. Last retreat

In the frontal complexes of the cirques of the high mountain the ELA is found at around 2050–2130 m a.s.l., far from the complexes of the previous phases. The glaciers are mainly in cirques, with only three glaciers in the Central Massif having incipient tongues that reach 1 km in length. The fronts are located within a range of 500 m of height difference. In the Central Massif the orientation is not significant (45% glaciers oriented to the N), but in the Eastern Massif, with summits 300 m lower, 88% of the glaciers are oriented to the north. Therefore, at low altitudes with summits of less than 2500 m a.s.l. the topoclimatic factors are of fundamental importance. In the Eastern Massif, with the disappearance of the glaciers of this phase glacial activity came to an end, as there are no signs of Holocene glaciation.

The lacustrine sediments of Campo Mayor-Áliva record a minimum LOI (B4) pointing out a rhexistasic period, but the LOI values

are higher than the previous LOI minimums. This is the last record of an increase in cold before biostatic conditions definitively began. The glaciers disappeared from the environment of Áliva, but they would still have existed in the massif, with its singularly cold conditions. The temperature estimates from the ELAs point to a thermal fall of between −1.6 and −9.3°C with respect to the present day and temperatures between 3°C and 4.6°C higher than in the SI. The estimate of the MAAT is −5.6 to −4°C at 2100 m a.s.l. The heavy snowfall resulting from the oceanic environment and the topoclimatic factors promote a glacial development, with moderately cold conditions compared to the earlier stages. The minimum LOI B4 is at 2 m depth at the top of the LU5c, between 9400 and 9300 cal yr BP and 17,400–17,300 cal yr BP. An estimate from the rhythm of sedimentation of the LU5 indicates an approximate age of 13.9 ka. This glacial phase may be related to the late glacial (14–10 ka), a cold period of transition towards the Holocene. At the end of MIS 2, between 11 and 10 ka in the Younger Dryas or Dryas III, glaciers advanced in the mountains of Europe (Ehlers et al., 2006) in relation to the increase in cold or humidity, the latter resulting from the access of masses of cold humid air.

In the Cantabrian Mountains in Redes (Alto Nalón), Pleistocene cooling periods have not been detected posterior to the LGM, though a Holocene equilibrium is detected at 5740 ± 50 ^{14}C yr BP (Jiménez and Farias, 2002). In Enol, on the other hand, from an equilibrium in Ca content, a cooling period is interpreted between 14.5 and 13.5 ka (Moreno et al., 2010). This phase may coincide, therefore, with the chronology put forward for Enol, as the glacial remnants located in the high mountain may be attributed to this date. For the range of the Picos de Europa the possible correlation of this latter Pleistocene glacial episode with the late glacial has already been described in morphostratigraphic studies (Serrano and González-Trueba, 2002; Gonzalez Trueba, 2007a,b; Serrano et al., 2012). The presence of small glaciers at altitude cirques is common in many massifs of the Cantabrian Mountains with summits higher than 2000 m, as in Ancares, Alto Nalón, Alto Campoo and the Mountains of Palencia. It is, therefore, a general fact of the highest of the Cantabrian Mountains, where a cold period at the end of the Pleistocene was capable of generating small glaciers in favorable locations.

Glacial Stage IV. Historical advance of the Little Ice Age

The last glacial advance in the Cantabrian Mountains is not detected in lacustrine sediments, but there was a final glacial advance in the Central Massif of Picos de Europa as indicated by the geomorphological features alone. Whereas Holocene glacier stages have not been detected in Picos de Europa, they have in the Cantabrian Mountains (Jiménez et al., 2002). The glacial advance developed in the highest cirques above 2200 m a.s.l. have been attributed to the Little Ice Age (LIA), between the 14th and 19th centuries, and their maximum extension in the Picos de Europa corresponded to the last glacial advance of the first third of the 19th century (González-Trueba, 2006; 2007a,b; Gonzalez-Trueba et al., 2008; Serrano et al., 2011). Picos de Europa is the only mountain group of the Cantabrian Mountains with historical glaciers. Historical records indicate that there were at least four glaciers until the end of the 19th century, confirmed by voluminous and well preserved moraines and internal deformation structures (ice folds and faults) in the present-day ice patches.

At present four ice patches occupying a total of 61,850 m^2 exist in the Picos de Europa. The ELA during the maximum advance of the LIA has been estimated by the AAR method at 2287 ± 15 m a.s.l. in Jou Negro cirque, and the temperature decrease has been estimated at 1°C (González-Trueba, 2007a,b). Topoclimatic factors, appearance, topographical features and snow overaccumulation determine glacial development. These are located only at favorable places with strict topoclimatic conditions, always below summits of over 2600 m a.s.l. Thus, in the Eastern Massif, with summits below 2500 m a.s.l., glaciers did not develop during the LIA.

Conclusions

The core of the paleolake of Campo Mayor-Áliva in the Picos de Europa has allowed the environmental reconstruction of the period of infilling of the lake from the dating of eight levels and the analysis of the LOI, together with the micromorphological and textural analyses of the lacustrine succession. Absolute ages in the lacustrine deposits of the moraine-dammed lake are correlated to the adjacent lateral and frontal moraines.

The LOI variations permit the correlation of glacial sedimentation and environmental changes. For MIS 3 they point to a period characterized by small swift advances and retreats with rapid changes between temperate and cold phases, the former dominating. The sharp dynamic changes were colder each time, and after reaching the maximum began a gradual warming. The environmental and morphological changes allow the appreciation of how the glacial maximum advance of this period did not correspond to the greater volume of ice. A first expansive stage (S-I) of lobated fronts and widespread glaciers with little volume was followed by a stage with more voluminous but less extensive glaciers (S-II), correlated with the LGM. A later cold stage (S-III) defined by altitude moraines is located in the Lateglacial. Finally, the LIA glacial advance (S-IV) is not detected in the lacustrine sediments.

The absolute chronology shows a maximum glacial expansion prior to 35,700–34,850 cal yr BP, a period in which the lateral moraine of the Duje glacier dammed the proglacial waters from Las Salgardas glacier and began the infilling of the lakeside basin. It may have been prior to MIS 3 because it is only a minimum age, but the data point to the beginning of the lake as being close to the date indicated. The lake shows rapid infilling during MIS 3, to which the first 11.5 m belong. This reveals a great annual resolution, appropriate to a swift rate of infilling. The MIS 2 and MIS 1 sedimentary levels have low resolution and very slow infilling rates. During this period the lake was partially clogged and had a marsh dynamic, not receiving glacial supplies.

This chronological succession, with the local glacial maximum advance of the Picos de Europa at around 43 ka during the last phases of MIS 3, is in accordance with studies previously carried out in the Cantabrian Mountains, which place the local glacial maximum as being prior to that of the north of Europe. In the Picos de Europa the maximum extent of glaciers took place at about 30 ka, before that of Northern Europe, during a glacial period different to the LGM. The maximum extent corresponds to the late MIS 3, when glaciers were longer but thinner than during the LGM.

The LGM correspond to a glacial advance in the Picos de Europa, and LOI indicate the coldest phase of the last 40 ka, but glaciers were shorter and thicker than during Stage I (MIS 3). The differential behavior of glaciers could be related to a wetter environment during MIS 3, with access of cold and wet airflow to the Southern Europe, with cold but dry airflow reaching the Cantabrian Mountains during LGM.

The present study demonstrates the interest of lakeside studies in order to reconstruct the paleoenvironmental and paleoclimatic characteristics of the Picos de Europa. In Campo Mayor, a more detailed analysis of the upper levels in the first 4 m may lead to a more precise deciphering of the changes and chronology taking place during the LGM and late glacial (MIS 2) and the Holocene (MIS 1).

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