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Asynchroneity of maximum glacier advances in the central Spanish Pyrenees

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ABSTRACT: The deglaciation history of the Escarra and Lana Mayor glaciers (Upper Gállego valley, central Spanish Pyrenees) had been reconstructed on the basis of detailed geomorphological studies of glacier deposits, sedimentological and palynological analyses of glacial lake sediments and an accelerator mass spectrometry (AMS) ^{14}C chronology based on minimum ages from glacial lake deposits. The maximum extent of the Pyrenean glaciers during the last glaciation was before 30 000 yr BP and pre-dated the maximum advances of the Scandinavian Ice Sheet and some Alpine glaciers. A later advance occurred during the coldest period (around 20 000 yr BP), synchronous with the maximum global ice extent, but in the Pyrenees it was less extensive than the previous one. Later, there were minor advances followed by a stage of debris-covered glaciers and a phase of moraine formation near cirque backwalls. The deglaciation chronology of the Upper Gállego valley provides more examples of the general asynchroneity between mountain and continental glaciers. The asynchroneity of maximum advances may be explained by different regional responses to climatic forcing and by the southern latitude of the Pyrenees. Copyright © 2002 John Wiley & Sons, Ltd.

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KEYWORDS: Last Glacial Maximum; glaciers; upper Gállego Valley; central Spanish Pyrenees.

Introduction

The last maximum glacial advance in many mountain ranges appears to have pre-dated the last maximum advance of the Laurentide and Scandinavian continental ice-sheets (marine oxygen isotope stage 2, around 20 000 yr BP; Gillespie and Molnar, 1995). The asynchronous advances and retreats of mountain and continental glaciers during the last glaciation have been explained in terms of different responses to similar global climate forcing, the effects of the local climate and the peculiarities of mountain glaciers (Clapperton, 1993). However, the absence of an adequate chronological control of most mountain deglaciation sequences impedes comparison with global chronologies and tests for global synchroneity.

Glacial deposits in the Spanish Pyrenees have been studied since the nineteenth century (see references in Chueca *et al.*, 1998). Most of them correspond to the last glaciation but some isolated moraine deposits are attributed to previous glacial cycles (Vilaplana, 1983; Serrano, 1992; Martí-Bono, 1996; Calvet, 1998). During the past 20 yr, several geomorphological and glacial-geology studies in the Pyrenees have helped to identify and describe the main retreat, stillstand and advance phases after the Last Glacial Maximum (Vilaplana, 1983; Martínez de Pisón, 1989; Bordonau, 1992; Martí-Bono, 1996; Copons and Bordonau, 1996; Serrano, 1998). There are almost no absolute dates available for any of these episodes. Correlations between different valleys can be made using only topo-geomorphological methods and, consequently, remain hypothetical. The timing of the maximum extent of the glaciers and of the main deglaciation events remains one of the most significant problems of Pyrenean Quaternary geology. Several studies (Vilaplana, 1983; Bordonau, 1992; Montserrat, 1992) suggest that the maximum extent of Pyrenean glaciers occurred before 38 000 yr BP, long before the Last Glacial Maximum (LGM) as defined in marine (Ruddiman and McIntyre, 1981; Maslin *et al.*, 1995; Baas *et al.*, 1997) and terrestrial records (Blunier *et al.*, 1998; Petit *et al.*, 1999; Mix *et al.*, 2001). An early deglaciation also has been suggested for several valleys in the northern Pyrenean slopes (Andrieu *et al.*, 1988; Montjuvent and Nicoud, 1988) and other European mountain ranges, such as the French Vosges (Seret *et al.*, 1990) and the Alps (Chapron, 1999; Guiter *et al.*, 2001), and recently in the Cantabrian Mountains (northwest Spain, Ruiz-Zapata *et al.*, 2000; Jiménez-Sánchez and Farias, 2002). Early deglaciation could reflect regional differences in the Alpine domain or relate to geographical location (low latitude) and local factors (southern exposure, local climate).

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Detailed geomorphological studies of glacier retreat phases and absolute dating are needed to solve these uncertainties. The upper Gállego River in the central Spanish Pyrenees provides an excellent study area because it has well-preserved glacial deposits, extending from the outermost moraines to the most spatially restricted retreat phases (Martínez de Pisón and Serrano, 1998), and several glaciolacustrine deposits (Montserrat, 1992; Valero-Garcés and Martí-Bono, 1997; Valero-Garcés and Kelts, 1997). In this paper we present a detailed study of the glacial deposits of the Escarra and Lana Mayor valleys, two tributaries of the upper Gállego River. Several accelerator mass spectrometry (AMS) ^{14}C dates constrain the timing of the maximum glacier extent and the history of deglaciation in the Spanish central Pyrenees (Table 1).

Geographical and climatic setting

The headwaters of the Gállego River are in the most humid sector of the Spanish Pyrenees. The average annual precipitation is around 2000 mm (García-Ruiz *et al.*, 1985), mainly concentrated between October and June, with a slight decrease in January and February. Most of the precipitation reflects movement of fronts from the Atlantic Ocean. The modern snow equilibrium line is at 2805 m. The Pleistocene glaciers in the Gállego valley were the longest in the Spanish western–central Pyrenees (more than 30 km long), descending to 850 m a.s.l. During the Little Ice Age, the snow equilibrium line was at 2618 m a.s.l. (López-Moreno, 2000), reaching 1900 m during the maximum glacier extent of the last glaciation (García-Ruiz *et al.*, 2000).

The Escarra and Lana Mayor valleys are tributaries of the upper Gállego Valley (Fig. 1A). Both valleys are underlain by Devonian and Carboniferous rocks (shales, quartzites, quartzitic sandstones and limestones), and bounded to the south by Cretaceous and Paleocene limestones and sandstones (Fig. 1B). The headwaters of the Gállego River are underlain by Palaeozoic granitic and sedimentary rocks and by Triassic sedimentary rocks. A large number of glacial deposits (moraine ridges, tills, proglacial lacustrine sediments) overlie the headwaters area of the Gállego River.

The Escarra Valley begins in El Rincón de Balsera, in a large cirque with steep backwalls up to 2713 m a.s.l. in the Escarra Peak and 2697 m a.s.l. in the Águila Peak (Fig. 2). The cirque is carved in Cretaceous and Paleocene rocks. Glacial erosion has excavated a typical U-shaped valley in the Palaeozoic materials. The Lana Mayor Valley also has a large cirque with headwalls that reach 2763 m a.s.l.(Pala de Alcañiz Peak). This valley is wide and asymmetric with a strong contrast between the southern slope, formed by vertical cliffs carved in the Cretaceous and Paleocene rocks of Sierra Telera, and the central and northern areas, composed of Palaeozoic quartzites and shales. Small cirques and avalanche channels fed the Lana Mayor Glacier from Sierra Telera. The divide between the Escarra and the Lana Mayor valleys was partially overdeepened by the glacier, resulting in a small basin occupied by a lake (Tramacastilla Lake). After glacier retreat, several lakes formed behind the moraine deposits. Most were very small and filled with sediments very quickly. A few topographically low areas are still occupied by lakes, such as Piedrafita Lake, located behind a late moraine front.

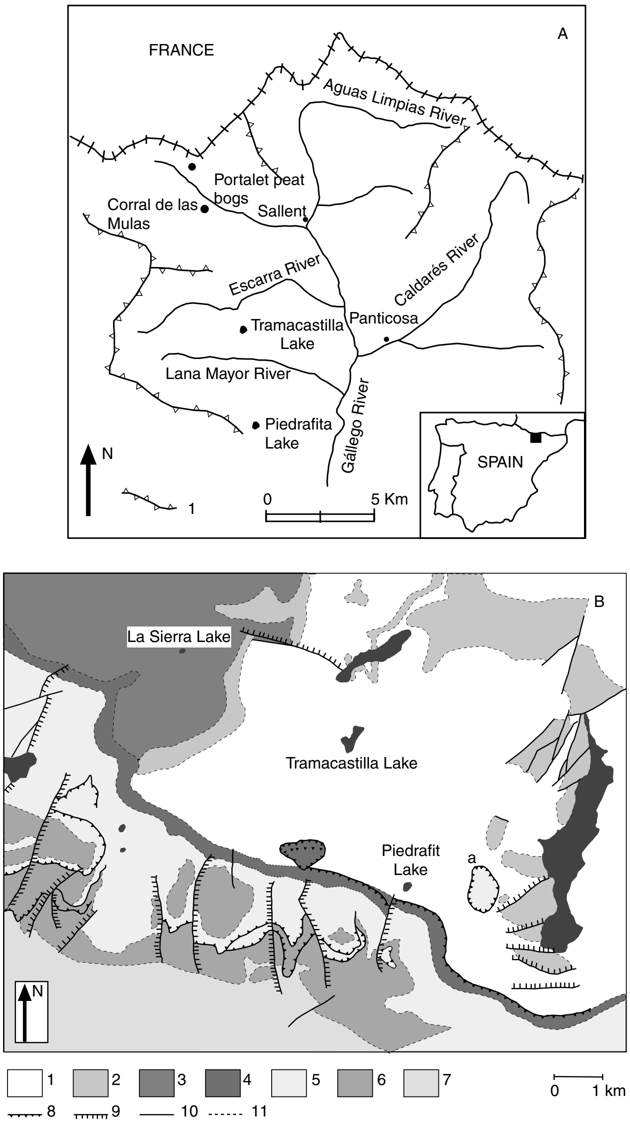

Figure 1 (A) Location map of the Escarra and Lana Mayor valleys within the upper Gállego Valley: 1, main mountain divides. (B) Geological map of the study area (after Ríos *et al.*, 1989): 1, shales (Devonian); 2, limestones (Devonian and Carboniferous); 3, sandstones and shales (Carboniferous Culm facies); 4, limestones and sandy limestones (Cretaceous); 5, sandstones and marly sandstones (Cretaceous); 6, limestones and dolomites (Paleocene); 7, sandstones and marls (flysch facies of the Eocene); 8, thrust; 9, fault; 10, tectonic contact; 11, normal contact

Methods

Mapping of glacial, lacustrine and moraine deposits was based on fieldwork and aerial photograph analysis. Pollen and sediment stratigraphy, ^{14}C dating and the organic matter content of the Tramacastilla Lake core can be found in Montserrat (1992). He dated the sediment record with eleven ^{14}C dates for the lake sequence plus two from the intercalated littoral peat layers. We resampled the core for mineralogy, organic and inorganic carbon and grain-size analyses. Sediment mineralogy was determined by a Siemens D-500 diffractometer. The lacustrine sediment section located north of Tramacastilla Lake was measured, described and sampled.

Three cores, up to 2 m long, were retrieved from Piedrafita Lake, using a modified Livingstone coring apparatus from a floating platform. The cores were described and

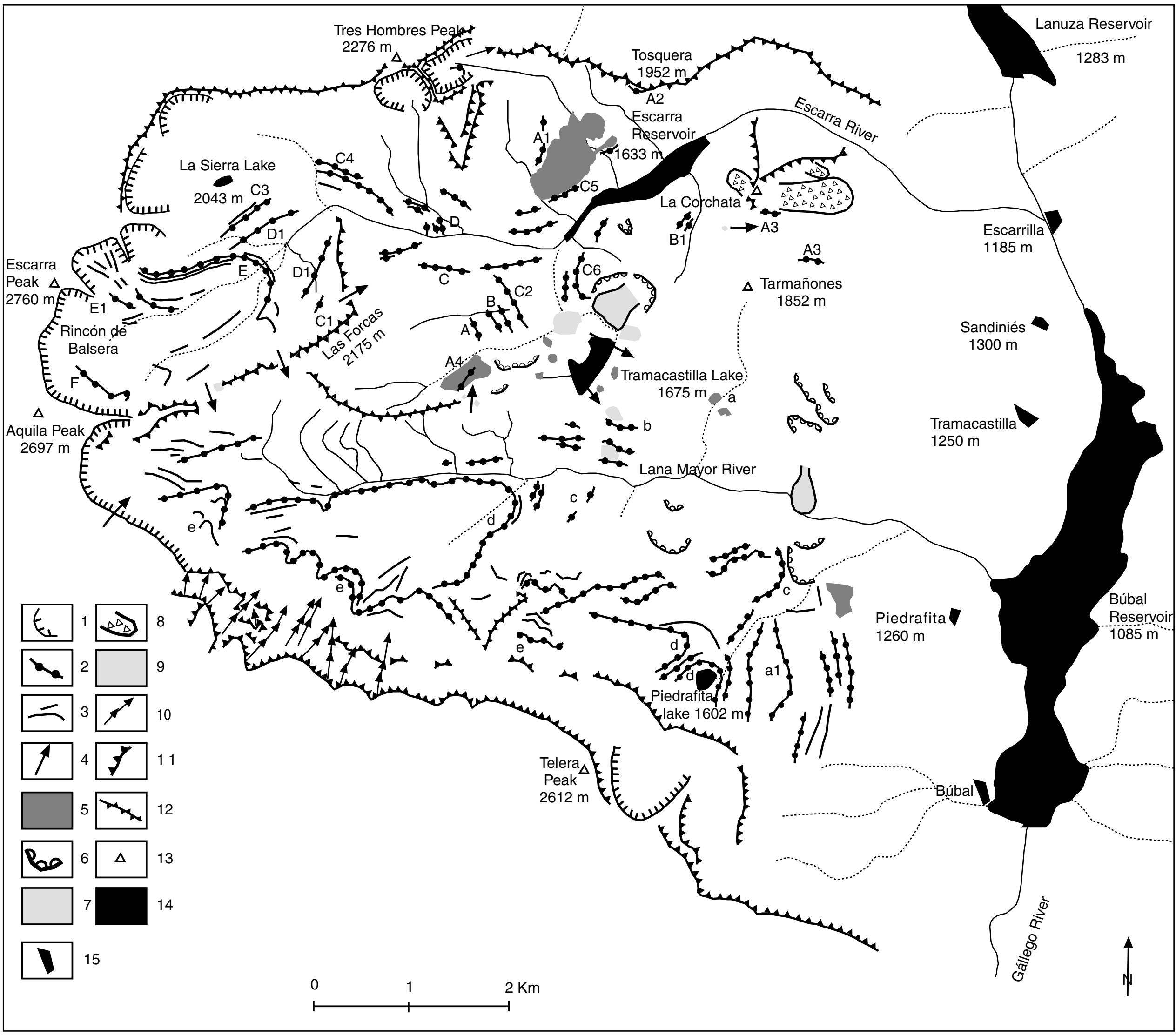

Figure 2 Geomorphological map of the Escarra and Lana Mayor valleys: 1, glacial cirques; 2, main moraine ridges; 3, secondary moraine ridges; 4, ice flow in the transfluence passes; 5, moraine accumulations; 6, scars of large landslides; 7, landslide tongues; 8, large rock avalanches; 9, former glacial lakes, infilled with sediment; 10, avalanche couloirs channels; 11, structural cliffs; 12, divides; 13, main peaks; 14, lakes and reservoirs; 15, villages

correlated using lithological and sedimentological criteria. The sediment sequence was dated by AMS ^{14}C dates of bulk organic matter and a pine fragment sample (Valero-Garcés *et al.*, 1998).

In the headwater of the Gállego River, we cored a small peatbog close to the river (Corral de las Mulas peat bog, <1 m long core) and a large peat bog (Portalet peat bog, 6 m long core) close to the mountain divide (Fig. 1A). The sediment sequence recovered from El Corral de las Mulas was <1 m long and only a basal sample was taken for AMS dating. The 6-m-long sediment core from El Portalet peatbog provides a sequence since deglaciation (González-Sampériz *et al.*, 2001). Pollen was extracted from selected samples from the outcrop profiles and sediment cores by the classic chemical method (Dupré, 1992). *Lycopodium* spores were added to the samples to calculate pollen concentrations (Stockmarr, 1971).

The lack of an absolute chronology has hindered our understanding of Pyrenean glaciation history. The absence of adequate organic material to date the moraines and the scarcity of lake deposits associated with the main glacial fluctuations were impeded conventional radiocarbon dating. Glacial and fluvial deposits in the upper Cinca Valley (central Pyrenees, east of the Gállego River valley) have been dated using thermoluminescence techniques (Sancho *et al.*, in press) and the preliminary results indicate early deglaciation (>40 ka) in Cinca Valley. Pollen concentrates have provided enough material for AMS dating in organic-poor deposits at several sites in the Pyrenees and the Ebro Basin (Valero-Garcés *et al.*, 2000). To test this possibility, several moraine deposits and lake deposits behind the moraine fronts in the Escarra and Lana Mayor valleys were sampled for pollen content. All of them were sterile. Several larger glacial lakes and peatbogs were cored and the exposed lacustrine sections were sampled in order to obtain basal ages for the lake sequences. No organic macroremains were found. However, the pollen content was sufficient to provide AMS dates. The pollen concentrates were obtained following the same chemical method used to prepare palynological samples. Two separate samples were prepared in each case in order to study the palynological composition and to check for other organic remains that could have contaminated the samples. The validity of the dates is discussed in the corresponding lake section.

Results

The Escarra Valley deglaciation sequence

The Escarra Valley contains several moraine complexes, labelled in upper case letters in Fig. 2. The evolution of the ice masses for the Escarra and Lana Mayor glaciers is shown in Fig. 3. Owing to the absence of absolute dates for the moraine deposits, the proposed glacial sequence summarised in Fig. 3 is the best-fit interpretation of the geomorphological evidence. Based on the geomorphological study of the glacial deposits, we propose the following history as the most plausible for the retreat, advance and stillstand periods.

1. The maximum ice extent is marked by a moraine deposit at 1800 m a.s.l., near Tramacastilla Lake (Fig. 2, A and Fig. 3(1 and 2)). This upper level would correspond to a moraine ridge (1840 m) on the northern margin of the valley (Fig. 2, A1) and to other small till accumulations (Fig. 2, A2). During this period, the ice was 230 m thick over the modern Escarra Reservoir, which resulted in several transfluences towards the Lana Mayor Valley (through the Tramacastilla divide) and towards the Gállego main glacier (Fig. 2, A3). The deposits belonging to the maximum ice extent mainly comprise Palaeozoic rock fragments with an abundant greyish-bluish matrix. Devonian quartzites and sandstones (between 45 and 60%) and black limestones (around 50%) are dominant. Cretaceous and Paleocene limestone and sandstone content is always less than 10%.

   Two periods of glacier stillstand were identified after the maximum: two moraine ridges at 1760 and 1740 m a.s.l., close to Tramacastilla Lake (Fig. 2, B) and two more on the right margin of the Escarra Reservoir, around 1730 m a.s.l. (Fig. 2, B1). Although close proximity does not guarantee similar age, the similar lithology of all these deposits suggests that they are related to the glacial maximum extent. The thinning of the ice did not preclude ice flow over the Tramacastilla divide towards the Lana Mayor Valley. However, the transfluences to the Gállego main glacier were already ice-free.

   A unique deposit also related to the maximum ice extent is located in the Ordecito Ravine (Fig. 2, A4). Almost all the boulders are Cretaceous sandstones (45%) and Cretaceous and Paleocene limestones (45%), whereas Palaeozoic sandstones and quartzites represent less than 10%, and the Devonian black limestone clasts are less than 2%. This deposit was clearly laid down by ice from the Lana Mayor Valley, coming through a transfluence pass.
2. After the glacial maximum extent, the ice retreated a long distance towards the upper part of the valley. Later, a readvance of the Escarra glacier occurred but it was much more spatially restricted than the previous stage. During this advance two lateral moraines were deposited (Fig. 2, C to C6 and Fig. 3(3)). The terminal area was probably located around the middle zone of the Escarra Reservoir. An ice lobe went towards Tramacastilla Lake but it did not pass over the divide.

   The tills deposited during this stage are composed of Palaeozoic sandstones and limestones (70%), shales (11%), Cretaceous sandstones (11%), Cretaceous and Paleocene limestones (4%) and greywackes (4%). The matrix, still very abundant, has the same greyish-bluish colour as the older tills.
3. The third moraine complex is topographically higher, and was deposited when the Escarra glacier developed a 4 km long ice-tongue (Fig. 2, D and Fig. 3(4)). It is composed of three frontal arcs, elongated by well-developed lateral ridges. The most important feature of this moraine complex is the dominance of Cretaceous and Paleocene sandstones and limestones. The fine matrix also has a conspicuous brown colour, distinctly different to the older tills. The three frontal arcs are composed of large, non-striated blocks. These deposits are interpreted to be a readvance from the cirque, where the glacier incorporated the Cretaceous and Paleocene blocks.
4. A large frontal arc is easily identified in the Rincón de Balsera (Fig. 2, E and Fig. 3(5)). It extended upwards, especially on its left margin. This moraine complex is a chaotic mixture of poorly sorted, non-striated blocks with long *a* axes (several metres in some cases). This deposit displays an irregular topography, with many depressions and ridges, and without clear lineations. We interpret this deposit as the remains of a debris-covered glacier that advanced during a period of especially intense rock-fall from the cirque backwalls. During this time, the ice tongue was slightly longer than 2 km, with a maximum thickness of 80–100 m.
5. A large moraine ridge is located very close to the backwall of the Rincón de Balsera cirque (Fig. 2, F). It contains large, angular, sharp, non-striated Cretaceous and Paleocene sandstone and limestone pebbles with a small amount of fine matrix. The arc corresponds to the last glacial stage (represented by a small ice body), partially functioning as a protalus rampart. More recently, the lower part of the cirque backwall was occupied by a scree talus.

The Lana Mayor deglaciation sequence

Figure 2 shows the moraine deposits (lower case letters) from the Lana Mayor Valley and Fig. 3 shows the proposed glacial evolution based on the geomorphological evidence.

1. The maximum extent of the Lana Mayor glacier can be assessed from two transfluence deposits and a large moraine deposit east of Piedrafita Lake (Fig. 2, a1 and Fig 3(1 and 2)). The first transfluence corresponds to the pass of the Lana Mayor ice toward the Escarra Valley, which left a patchy till cover in the headwater area of the Ordecito Creek (Fig. 2, A4). The ice was around 200–250 m thick. The second transfluence corresponds to the pass of the Escarra ice toward the Lana Mayor Valley through the Tramacastilla Lake divide. Here, the Escarra glacier left several small moraine deposits (Fig. 2, a1) that contain Devonian quartzites and limestones, confirming that the Escarra valley was the source area. The ice thickness would have been around 175 m and the glacier was probably connected with the Gállego glacier.

   There are two large north–south moraine ridges east of Piedrafita Lake (Fig. 3, a1) culminating at 1677 and 1697 m a.s.l. They are composed exclusively of Cretaceous and Paleocene clasts from the Sierra Telera cliffs.
2. Several ridges located immediately south of the Tramacastilla lake divide represent a secondary maximum stage (Fig. 2, b and Fig. 3(3)). The ridges are well defined and incorporate small depressions containing glaciolacustrine sediments. We were not able to date these sediments owing to their very low pollen concentration. The lithology of the ridges is dominated by Cretaceous and Paleocene sandstones (70%) and limestones (28%). This composition demonstrates that ice moved from the Lana Mayor Valley, and that there was no transfluence from the Escarra Valley through the Tramacastilla divide at that time. During

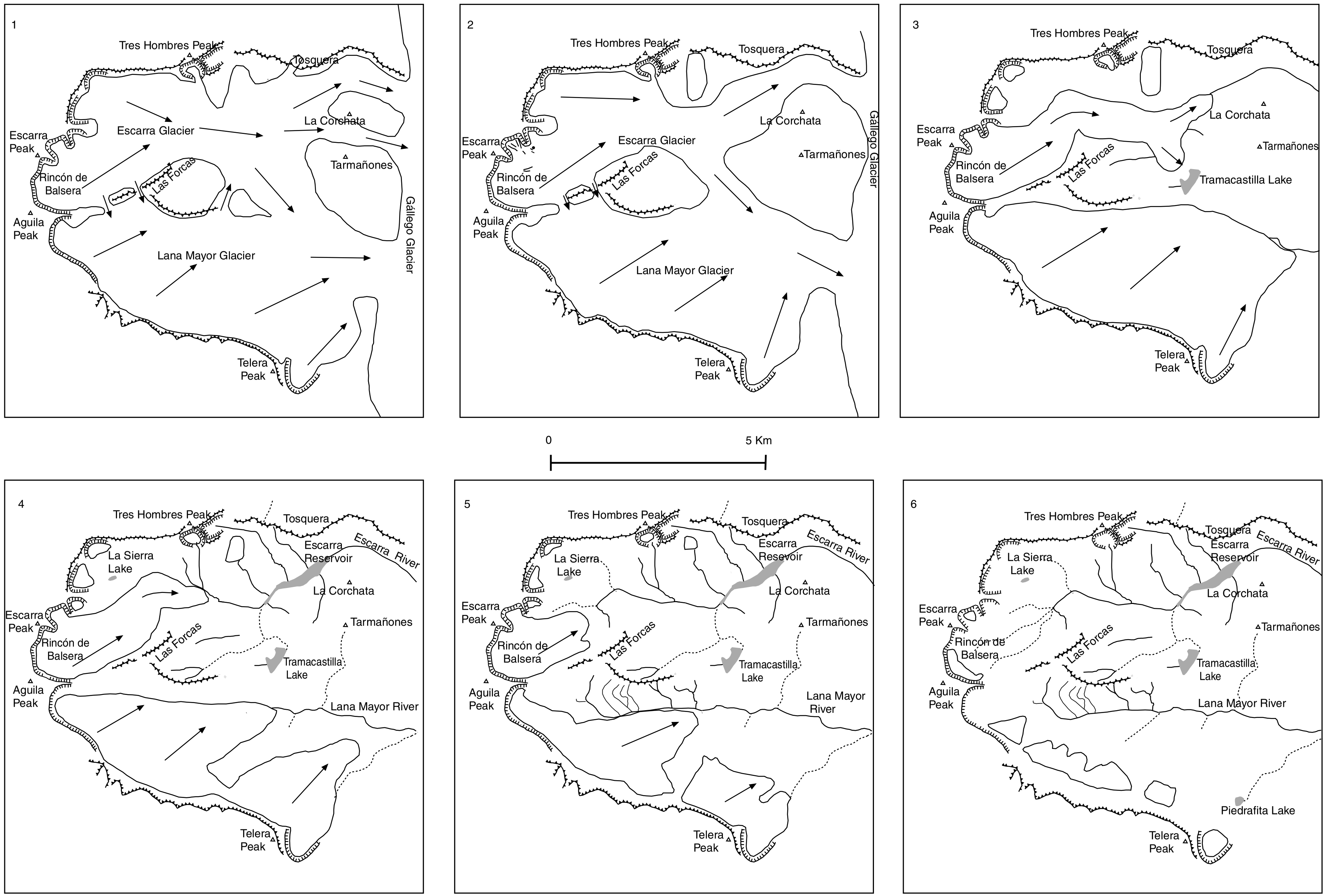

Figure 3 Extent of the Escarra and Lana Mayor glaciers during the different phases identified in this paper. (1) Main maximum ice extent. (2) Secondary maximum ice extent. (3) Valley Glaciers Phase (secondary maximum at the end of the Upper Pleistocene). (4) Upper Valley Glacier Phase. (5) Debris-covered Glaciers Phase (Cirque Glacier Phase). (6) Final Phase (Wall Glaciers Phase or Rock Glaciers Phase)

this period, the Lana Mayor glacier was confined inside the valley, forming one or two thin ice masses towards the north-northeast.

3 Several north–south ridges identified above the previous moraines (Fig. 2, c) suggest that the Lana Mayor glacier was divided into two independent ice masses during this period.

4 There is evidence of two debris-covered glaciers, similar to those described in the Escarra Valley (Fig. 2, d and Fig. 3(5)).

5 The most recent advance corresponds to a series of lobate moraine ridges at the foot of the Sierra Telera cliff (Fig. 2, e and Fig. 3(6)). All apparently were related to small ice bodies fed by avalanche channels. Once the ice disappeared, a scree accumulation developed that remains active today.

The glacial lake records

Tramacastilla and Piedrafita lakes

Tramacastilla Lake is located in a low divide, formerly occupied by a glacial tongue that moved from the Escarra glacier to the Lana Mayor glacier. There are many patchy till deposits close to the lake (Figs 2 and 3). Several moraines in the Escarra Valley near the lake are around 100 m above the divide. Consequently, the maximum ice thickness over the divide is estimated to have been around 100 m. The glacier excavated a small basin in the divide, which was occupied by a lake after its retreat. The Tramacastilla catchment is very small and composed of Devonian sandstones and shales, with only small ephemeral creeks feeding the lake. The Tramacastilla Lake core was described from a palynological and sedimentological point of view by Montserrat (1992). Detailed sedimentological and mineralogical studies performed on the same cores provided more information on the palaeohydrological and palaeolimnological changes in the lake (Valero-Garcés and Martí-Bono, 1997; Valero-Garcés and Kelts, 1997). Figure 4 shows the main vegetational events, the sediment stratigraphy, the total carbon content, the grain-size distribution and the mineralogy of the core.

The lower 4.3 m of the sequence comprises massive fine silts ('blue clays' facies) with low organic matter, relatively low quartz and feldspar and relatively high carbonate contents. The fine grain size, the greyish-bluish colour and the high carbonate content in the 'blue clays' indicates that the sediment source was glacier moraine deposits from valleys with carbonate rocks. The silts were deposited during glacial times when the lake was fed directly by glacier meltwater. Pollen stratigraphy (Jalut *et al.*, 1992; Montserrat, 1992) indicates an *Artemisia*–Chenopodiaceae–Poaceae steppe indicative of a cold and arid continental climate. Montserrat (1992) provided a conventional ^{14}C date on bulk organic matter at 11.8 m depth of 29 400 ± 600 ^{14}C yr BP, which suggests that the ice had retreated to the headwaters of the valleys by 30 ka. The presence of significant amounts of carbonate in the basal

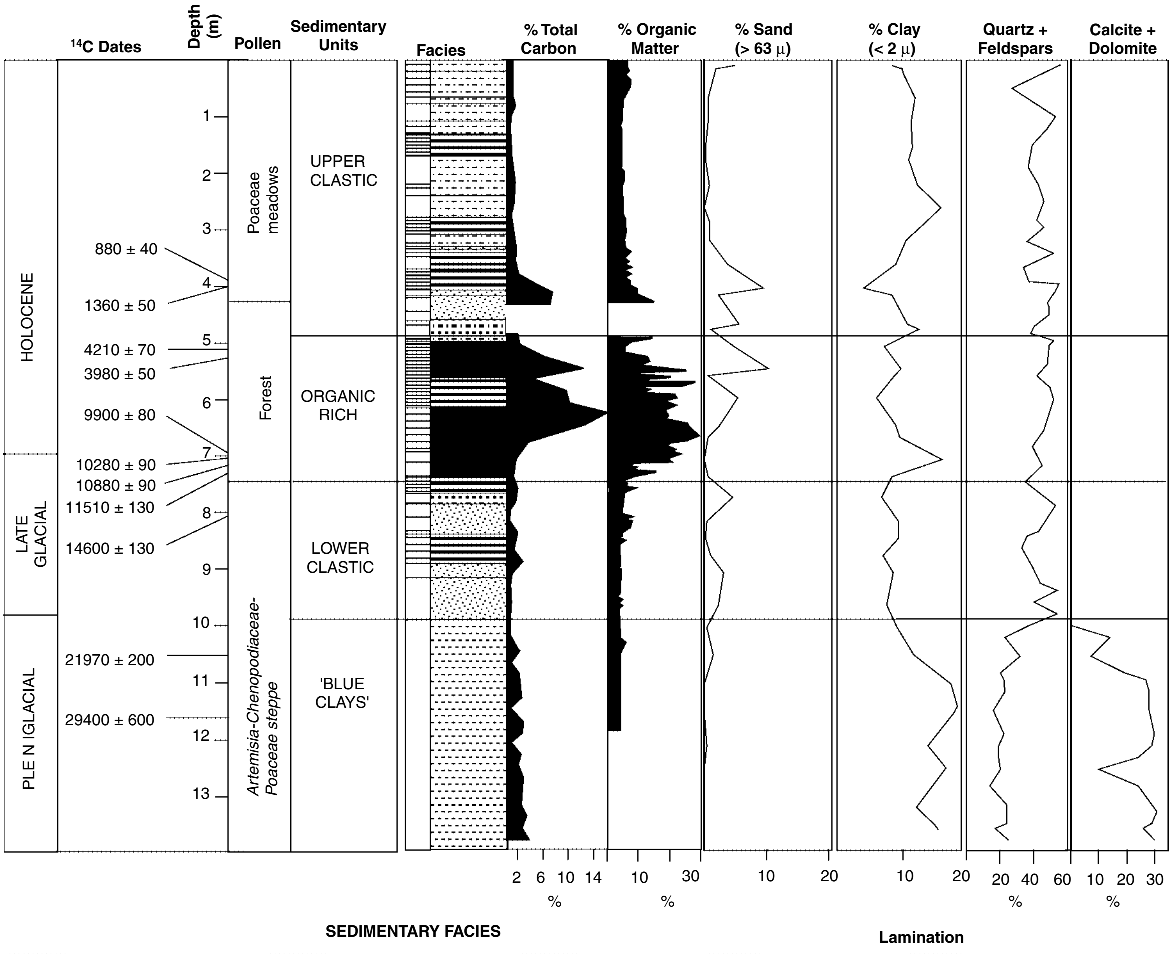

Figure 4 Summary of the sedimentological and palynological record of the Tramacastilla Lake (Montserrat, 1992; Valero-Garcés *et al.*, 1998b)

sediments raises the possibility of hard-water effects and contamination by 'old carbon'. In order to test the hypothesis of an early glacial maximum, other glacial lakes in the area were cored and the results are presented in the following sections.

There was an abrupt change in the sediment mineralogy at the onset of the deposition of the lower clastic unit, around 20 000 yr BP (Fig. 4). The coarser silt–sand rhythmites and laminated black silts of the lower clastic unit are devoid of carbonates and their quartz and feldspar content is much higher. Detailed mapping of glacial features suggested that a change in the surface hydrology was responsible for this lithological change. Originally, the creek that drained to the lake (Tramacastilla Ravine) had a larger basin (130 ha), covered by a thick moraine deposit composed of Cretaceous and Paleocene limestone and calcareous sandstone. These moraines were deposited by the Lana Mayor glacier through a transfluence pass. The Ordecito Ravine captured the headwater of the Tramacastilla Ravine after a large landslide (Fig. 5), reducing the catchment of the Tramacastilla Lake to 16 ha, and blocking any source of carbonate material to the lake. As a result of these changes, the watershed reduced to the surrounding Devonian shales and sandstones, and the sediments deposited in the lake became coarser. The age of the landslide should coincide with the disappearance of carbonate sediments in the Tramacastilla lake record (around 20 000 ^{14}C yr BP). The occurrence of a landslide in this area also indicates that the glacier had retreated further up the valley on that time.

Cores from Piedrafita Lake provide information only about the past 4000 yr (Valero-Garcés *et al.*, 1998a). Sandy layers prevent further penetration and the substrate was not reached. The 1.5 m long sequence contains carbonate-rich mud, clastic silt and sand, and thin peat layers. The intercalated peat layer in the upper part of the sequence could be a reflection of lower lake-levels during the Little Ice Age.

The northern Tramacastilla Lake sequence

Lacustrine sediments crop out on the northern slope of the Escarra–Lana Mayor divide. They were deposited in a glacial lake that was drained and partially eroded. The former basin of the lake was dammed to the north by several small, rounded hills. These small hills are not moraine deposits but outcrops of Palaeozoic shales. They are part of the landslide that changed the course of the Ordecito Creek (Fig. 5). The changes in the surface hydrology induced by this landslide around 20 000 yr BP apparently were responsible for both the origin of this small lake basin and the changes in sedimentary conditions in Tramacastilla Lake.

The stratigraphical section of this deposit is shown in Fig. 6. The lower part of the 4 m thick section is composed of decimetre-thick sets of poorly sorted, coarse gravel, overlain by upward-fining sequences of gravel–sand–silt. The middle part is composed of fine silt. The upper part includes gravel and 1 m of upward-fining silts. These sediments were deposited in a lacustrine environment influenced by fluvial–deltaic conditions. Two sediment samples were taken at 350 and 275 cm depth for pollen analyses and AMS ^{14}C dating of the pollen concentrates. The first one was sterile and the latter had very low pollen concentrations (around 3000 grains g^{-1}). The pollen spectrum indicates a cold steppe dominated by non-arboreal taxa (75%) with Poaceae, *Helianthemum* and other taxa typical of open vegetation, such as Chenopodiaceae, Carduaceae,*Artemisia* and *Centaurea*. There is less than 5% of some meso-thermophylous taxa (*Abies*, *Corylus*, *Alnus*, *Fraxinus*, *Quercus* type *faginea-pubescens* and type- *ilex*). The presence of similar small amounts of such thermophilous pollen grains is common in many Pyrenean sites, and it has been considered either as evidence for long-distance transport (Mardones, 1982) or for contamination from older sediments (Reille, 1990; Andrieu, 1991). Long-distance transport (more than 1500 km) of pollen taxa such as *Pinus*, but also other mesophilous taxa such as *Tilia*, *Quercus* and *Alnus*, has been described in modern tundra environments in Canada (Lichti-Federovich and Ritchie, 1968; Ritchie *et al.*, 1987). The similar preservation of all the pollen grains and the absence of any indication of secondary reworking are considered evidence for long-distance transport (Diot, 1991). The AMS ^{14}C date from the pollen concentrate at this level was 20 600 ± 170 yr BP (AZ-35870). A hard-water effect is unlikely, because of

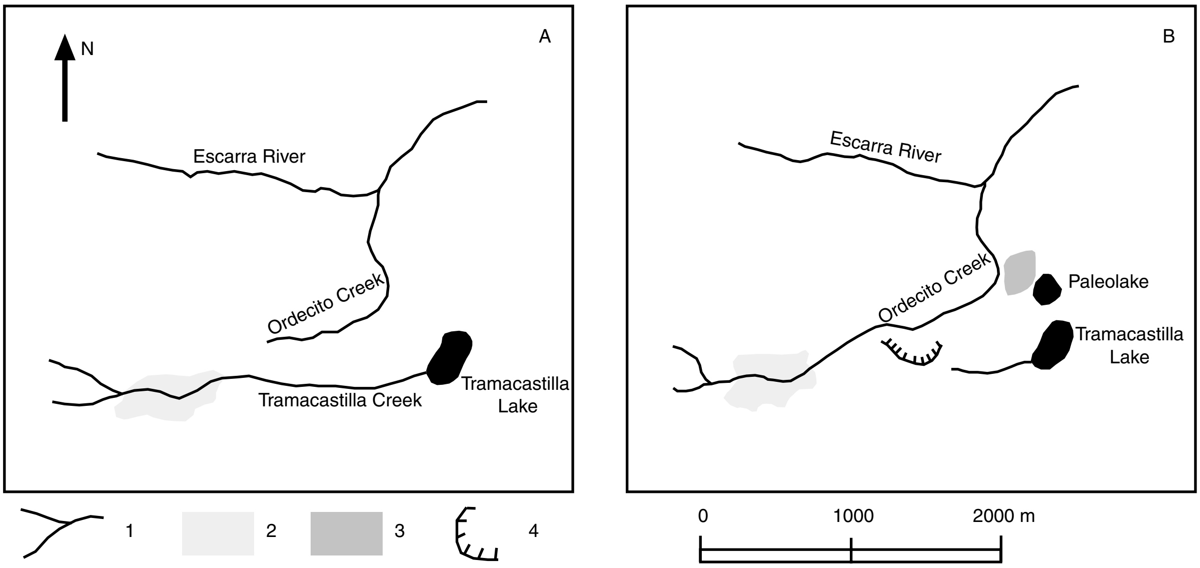

Figure 5 The capture of the Ordecito Ravine at about 20 000 ^{14}C yr BP. (A) Pre-landslide situation; the Tramacastilla Creek directly fed the Tramacastilla Lake. (B) Post-landslide situation; the upper reach of the Tramacastilla creek is captured by the Ordecito Ravine and the lower reach is isolated from the headwaters. Other landslides north of Tramacastilla lake block the outlet from this lake and create another lake (the northern Tramacastilla palaeolake): 1, fluvial network; 2, moraines with limestone clasts; 3, landslide accumulation; 4, Ordecito landslide scar

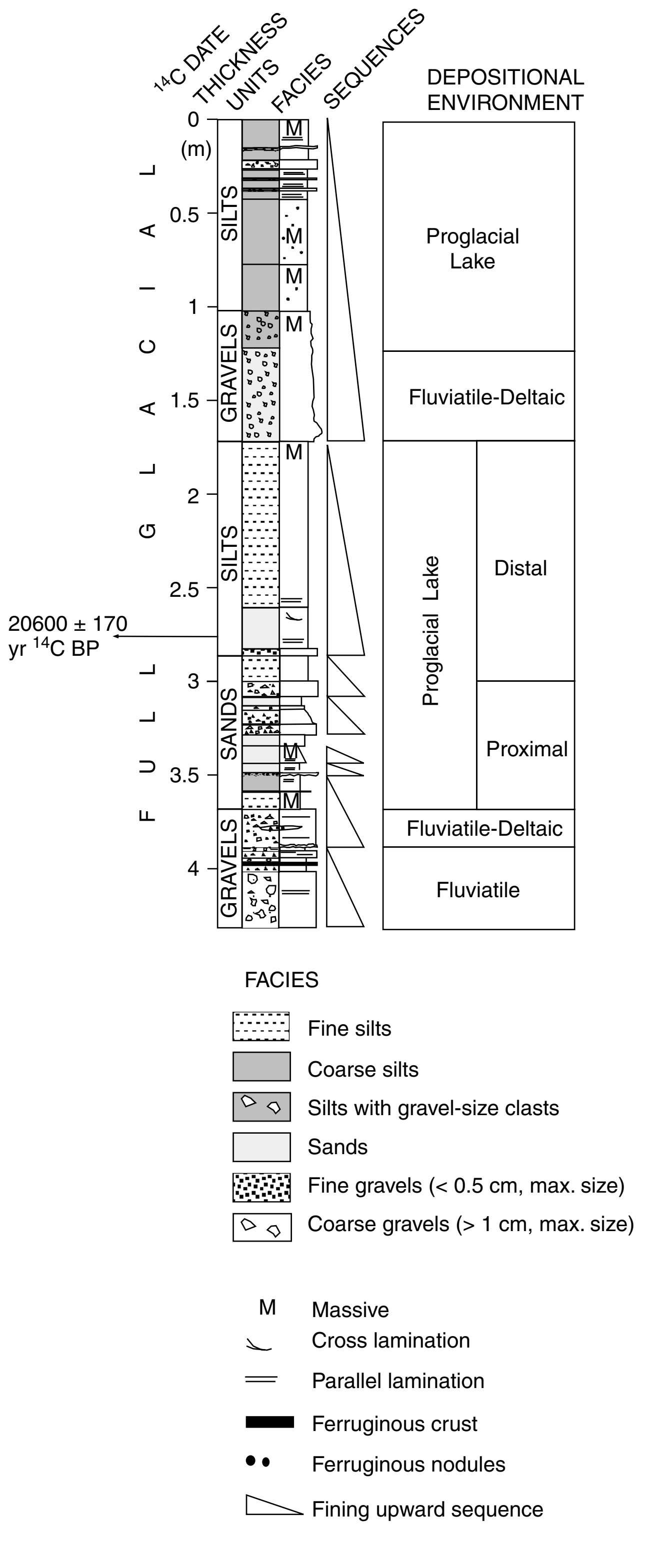

Figure 6 The sedimentological record of the northern Tramacastilla Lake sequence

the absence of any pollen from aquatic plants, and the non-carbonate nature of the sediments, On the other hand, the scarcity of thermophilous pollen grains and the absence of evidence for reworking suggest that all the pollen grains were synchronous with deposition and favour the validity of this age.

The Gállego River valley lake deposits

Montserrat (1992) reported a lacustrine sequence in a doline about 20 km up-valley of the maximum extent of the Gállego glacier. Although hard-water effects are possible in this environment, the basal date at this site suggests that the area was deglaciated by 20 800 ^{14}C yr BP. By that time, the glacier had almost disappeared even from some of its source areas. This is the case in the Formigal area, where the age of basal sediments deposited in a lake dammed by a large landslide (Corral de las Mulas peatbog) is 20 150 ± 150 yr BP (AZ-35867). The sediments are also carbonate-poor. Pollen concentration is about 32 000 grains/g^{-1}. The pollen spectrum indicates a cold steppe environment similar to the northern Tramacastilla sequence, and dominated by non-arboreal taxa (70%) such as Poaceae and *Helianthemum*, with the presence of other taxa typical of open vegetation, such as Chenopodiaceae, Carduaceae,*Artemisia* and *Centaurea*. The arboreal pollen assemblage is dominated by *Pinus* (20%) and *Juniperus* (5%). The remaining 5% of arboreal pollen is composed mostly of meso-thermophilous taxa (*Corylus, Ulmus, Fraxinus* and *Populus*). As with the basal sample from the northern Tramacastilla sequence, these pollen grains probably have been transported from known glacial refuges in the Pre-Pyrenees and the Ebro valley (Sanchez-Goñi and Hannon, 1999; Valero-Garcés *et al.*, 2000).

Finally, the Portalet peatbog located in the upper part of the Gállego River basin (1980 m a.s.l.) within a small glacial cirque, provides another minimum age for deglaciation (Fig. 7). The basal age of the lacustrine section from a 6.40 m long core that reached the underlying glacial till gave an age of >28 300 ± 370 yr BP (NSRL-11969). Sediments are also carbonate-poor. Pollen data from the basal samples showed typical glacial assemblages characterised by low pollen concentrations (1950 grains g^{-1}), high percentages of *Artemisia* (up to 30%) and low arboreal pollen contents (20%) dominated by *Pinus* and *Juniperus*. The *Artemisia–Chenopodiaceae–Poaceae-Helianthemum-Ephedra dystachia* type steppe suggests a cold and arid continental climate. No mesophilous taxa or aquatic plants were present in these samples, and consequently the ages are considered valid.

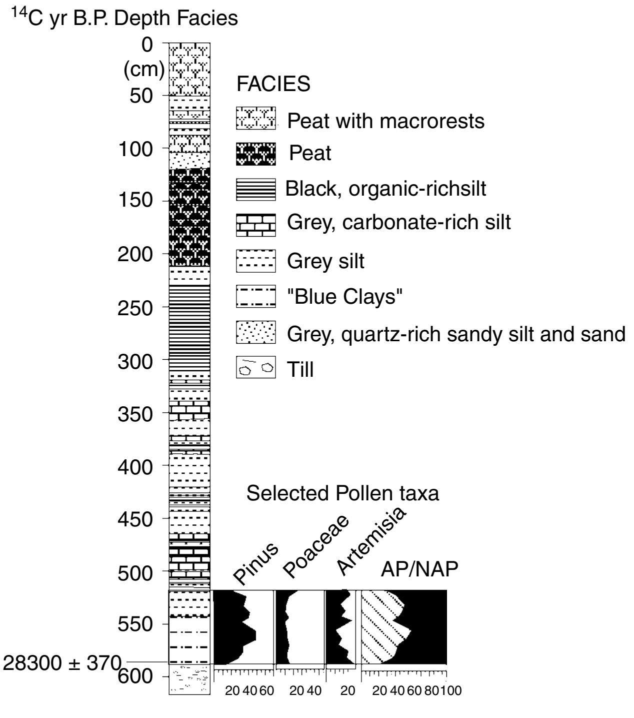

Figure 7 The sedimentological record of the Portalet peatbog core and the palynological record for the basal lacustrine deposits

Table 1 Radiocarbon dates from basal lake deposits associated with moraines

Sample	Laboratory number	Material	δ^{13}C (per thousand PDB[a])	Fraction of modern ^{14}C	^{14}C age (yr BP)	Age error (yr)
Tramacastilla paleolake	AZ- 35870	Pollen concentrate	−26.1	0.0770	20 600	170
Tramacastilla Lake	GIF-8239	Bulk organic matter	—	—	29 400	600
Formigal	AZ-35867	Pollen concentrate	−24.6	0.0817	20 120	150
Portalet peatbog	NSRL-11969	Pollen concentrate	−22.7	0.02936	28 300	370
Piedrafita Lake	WHOI 17539	Wood	—	0.6304	3710	60

[a] Standard based on belemnite from the Pee Dee Formation.

Discussion: a >30 000 yr BP maximum glacier advance and a smaller LGM readvance in the central Spanish Pyrenees

The occurrence of a large number of moraines and glaciolacustrine deposits in the Escarra and Lana Mayor valleys provides an excellent case-study for glacial geology and also the opportunity to establish a relative sequence of glacial advance and retreat stages, from the maximum glacial extent to final phases during the Little Ice Age.

During the maximum glacial extent, ice covered most of the area in both valleys with many transfluences between them, and it also extended to the Gállego Valley. Ice depth exceeded 200 m in the middle Escarra Valley. The maximum extent moraine complex included two lower stillstand or minor re-advance episodes (Fig. 3(1)).

This pattern is similar to other Pyrenean valley deglaciation sequences. There are three lateral moraine ridges in the Gállego (García-Ruiz and Martí-Bono, 1994; Martí-Bono, 1996; Serrano, 1998), Ésera (Martínez de Pisón, 1989; García-Ruiz *et al.*, 1992), Hecho (Martí-Bono, 1996) and Ara (García-Ruiz and Martí-Bono, 1994) valleys associated with the maximum glacial extent. The terminal basin of the Aragón Valley (Martí-Bono, 1996) also has several frontal arcs. Several episodes related to the maximum extent of the glaciers also can be found in other Spanish mountains (Martínez de Pisón and Alonso, 1992).

The timing of the maximum ice extent in the Pyrenees is still under debate. Dates from the glaciolacustrine sequence of Biscaye (French Pyrenees; Mardonès and Jalut, 1983) indicate than the maximum must be before 38 000 yr BP. Bordonau (1992) suggests 45 000–50 000 yr BP and Vilaplana and Montserrat (1989) suggest between 70 000 and 50 000 yr BP. In the case of the Escarra and Lana Mayor valleys the best evidence comes from the basal date of the Tramacastilla sequence (29 400 ± 600 ^{14}C yr BP; Montserrat,1992). Obviously, the maximum extent of the glaciers had to be somewhat earlier because the moraines related to the maximum were around 100 m beyond the Tramacastilla Lake divide. The possibility of hard-water effects cannot be ruled out and the validity of this date remains under discussion. However, new ages from other deposits presented here also support early deglaciation (Table 1). According to the basal age of the Portalet peatbog sequence, the headwaters of the Gállego River were deglaciated and small proglacial lakes had developed at altitudes up to 2000 m prior to 20 ka. Preliminary thermoluminescence dates from glacial and fluvial deposits in the upper Cinca Valley (east of the Gállego river valley) also support early deglaciation (>40 ka) in this valley (Sancho *et al.*, in press).

This early age for the maximum extent of Pyrenean glaciers does not coincide with the evolution of the Scandinavian Ice Sheet. Although the maximum extent of the Scandinavian and British ice sheets at ca. 20 k yr BP has been challenged by Sejrup *et al.* (1994), most studies indicate that both the maximum cold and extent occurred around 20 000 yr BP (Mangerud, 1991; Andersen and Borns, 1994). The maximum advance of the Jura glaciers and some of the large Alpine Swiss and Italian glaciers (Magny, 1995) also occurred during the Upper Würm (marine oxygen isotope stage 2). However, the maximum extent of many other Alpine glaciers was during the Middle Würm (marine oxygen isotope stage 3) before 38 000 yr BP (Chapron, 1999). These data correlate well with results from other moraine sequences in the Massif Central (Etlicher and De Goer de Herve, 1988), Vosges (Seret *et al.*, 1990) and Pyrenees (Andrieu *et al.*, 1988). Several valleys have evidence of early glacial retreat along the northern slopes of the Pyrenees, including Gave de Pau, Gave d' Ossau and the Garonne valley (Andrieu *et al.*, 1988). All these dates indicate that the farthest advance of glaciers in the Pyrenees preceded 38 000–27 000 ^{14}C yr BP.

A secondary glacial advance in the Escarra and Lana Mayor valleys is delimited by some lateral moraines at the margins of relatively small glacial tongues (Fig. 3(3)). A similar secondary stage has been found in most Pyrenean glacial sequences (Vilaplana, 1983; Bordonau, 1992; Martí-Bono, 1996) and it has been called the 'Valley Glaciers Phase' (Bordonau, 1992). During this time, the Escarra and Lana Mayor ice tongues were not connected with the Gállego glacier. Although few absolute dates are available in the Pyrenean region, the advance is considered to have occurred around 20 000 to 25 000 yr BP, coinciding with the coldest period of the last glaciation (marine oxygen isotope stage 2). By that time, the glaciers were also at higher elevation in the French Pyrenees (Andrieu *et al.*, 1988, 1993). According to our new dates from the Escarra Valley, the second glacial advance terminated before 20 000 ^{14}C yr BP. The occurrence of laminated lacustrine clays at the base of the northern Tramacastilla Lake sequence indicates that the glacier front was located farther up-valley at about 20 600 ^{14}C yr BP.

Three later minor stages of glacier advance have been identified in the Escarra and Lana Mayor valleys and they can be correlated with three similar stages in other Pyrenean glacial sequences. The geomorphological study suggests that the glaciers of these last three stages advanced from the cirque backwalls and that the short periods between stages represented almost complete melting of the ice masses. Although the absence of absolute dates for the moraine deposits in most Pyrenean valleys makes the proposed correlation somewhat speculative, it is the best-fit interpretation of the geomorphological evidence and the limited absolute ages available. During the first phase of this later glacial advance, the glacier in the Escarra Valley was longer than 4 km, and the Lana Mayor glacier was subdivided into two small ice masses (Fig. 3(4)). This stage can be correlated geomorphologically with the 'Upper Valley Glaciers Phase' defined by Bordonau (1992) and dated between 16 000 and 15 000 yr BP (end of the last pleniglacial). A cooling episode at this time is clearly recorded in the Antarctic and Greenland ice cores (Blunier *et al.*, 1998; Petit *et al.*, 1999) and in the ocean records (Maslin *et al.*, 1995; Baas *et al.*, 1997). However, the Pyrenean dates are not calibrated, and therefore it is difficult to establish an accurate comparison with the calibrated ages from the ice cores.

The debris-covered glaciers represent a subsequent, short advance with a large debris input from the cirque backwalls (Fig. 3(5)). This stage ('Debris-covered Glaciers Phase' or 'Cirque Glaciers Phase') occurred between 14 000 and 13 000 yr BP in other Pyrenean valleys (Bordonau, 1992; Copons and Bordonau, 1996, 1997).

The last stage represented by large moraines close to the cirque backwalls (Fig. 3(6)) could be ascribed to the 'Rock Glacier Phase' (Serrat, 1979; Bordonau, 1992). The relationship of this phase with the Younger Dryas cooling episode remains speculative owing to the lack of absolute dates.

Several hypotheses have been put forward to explain the asynchronous maximum advances in Pyrenean mountains and continental glaciers. The coldest phases of the last glacial period, the Dansgaard–Oeschger stadials, were very dry in central and southern Iberia (Sánchez-Goñi *et al.*, 2000, 2002). No detailed Dansgaard–Oeschger palaeoclimate records from northern Iberia are available, but because of the strong Mediterranean influence in the southern central Pyrenees, it is likely that these stadials also were dry, which could limit the expansion of the Pyrenean glaciers. During these periods the North Atlantic Ocean was frozen at relatively low latitudes, reducing the humidity content of the air masses and fronts that affected the Iberian Peninsula (Mix *et al.*, 2001). Consequently, it is possible that a cold period that caused an expansion of the glaciers in northern Europe, produced a more modest expansion in the low-latitude glaciers, such as those in the Pyrenees.

There are few records in the Iberian Peninsula that span beyond the LGM, and, consequently, moisture and temperature reconstructions, and the pattern of regional variability are not conclusive (see references in Sánchez-Goñi *et al.*, 2000, 2002; Valero-Garcés *et al.*, 2000). Most of the Iberian records document several humid and arid periods since the LGM. Some sequences point to a period of increased effective moisture in the Iberian Peninsula immediately after the Last Glacial Maximum. Deep-water sedimentary facies and a large negative δ^{18}O excursion in the Banyoles Lake core suggest a large hydrological change in the lake immediately after the LGM—dated at 22 890 ± 310 ^{14}C yr BP and 18 000 ka (U/Th)—that could be related to a period of increased effective moisture in northeastern Spain (Valero-Garcés *et al.*, 1998b). Similarly, the sea-surface temperature (SST) reconstructions based on cores offshore Portugal suggest relatively mild surface temperature (only about 5 °C lower than modern SST) during the LGM in the strictest sense (21 000 ± 2000 cal. yr BP) (Bard *et al.*, 2000). Oxygen isotopes and dinoflagellate cyst records from a nearby core (Boessenkool *et al.*, 2001) also show a distinct warm episode around the Last Glacial Maximum. These data are consistent with other interpretations from regional marine cores (Bard *et al.*, 1987). However, pollen records from marine cores show evidence for increased precipitation—but not for temperature changes—during the LGM (Turon *et al.*, in press). Pollen records from marine cores offshore Portugal show an alternation of deciduous and evergreen *Quercus* woodland with open vegetation, which reflects a succession of temperate and cold environments in Iberia during the period 50 000–30 000 yr BP (Sánchez-Goñi *et al.*, 2000). They correspond with Heinrich events and with most of the Dansgaard–Oeschger oscillations. Polar water advances during the last interglacial complex, correlate with increased steppe-like vegetation in Iberia (Sánchez-Goñi *et al.*, 1999, 2000, 2002). Most pollen records in Spain suggest increased aridity during the Late-glacial cold events (Pons and Reille, 1988; Jalut *et al.*, 1992; Pérez-Obiol and Julià, 1994; Peñalba *et al.*,1997). However, there are some significant differences among Heinrich events during the last glacial cycle in southwestern Europe, and on land, the last glacial period seems to have been progressively cooler towards the LGM. Cold and arid conditions in Iberia during the H3 event seem to be related more to a combined response of the melting of the European ice-sheet and a decrease in insolation than to large iceberg surges from the Laurentide ice-sheet (Sánchez-Goñi *et al.*, 2000).

Changes in global atmospheric circulation patterns also may have had an impact on mountain glacier fluctuations. Clapperton (1993) suggests that some glaciers in South America were less extensive around 20 000 yr BP because of reduced precipitation. The shifting of the storm tracks, the reduced available moisture owing to colder seas in higher latitudes and the lowered sea-level would have had a synergic effect in reducing the precipitation over the continents. In North America, global circulation models indicate that the Laurentide ice-sheet split the circumpolar jet stream at the peak of the last glaciation (around 20 000 yr BP) and changed the amount of moisture available to the southern arm of the storm track affecting the mountain glaciers of the southern Rocky Mountains. In Europe, the LGM jet stream was shifted equatorward and passed over the Pyrenees and south of the Alps, although it was farther north earlier in the glacial cycle (marine oxygen isotope stages 3 and 4) (Ruddiman and McIntyre, 1981; Maslin *et al.*, 1995). However, the dynamics of the jet stream are much more complex than previously thought (Mix *et al.*, 2001). The extreme cooling and dryness during Heinrich events 5 and 4 in the Mediterranean region have been attributed to the development and persistence of both Scandinavian and Atlantic mobile polar highs over southwestern Europe (Sánchez-Goñi *et al.*, 2002). Precipitation gradients between the more humid Atlantic and the drier Mediterranean sides of the Iberian Peninsula have occurred during the glacial cycle, but they intensified during Heinrich events 4 and 5. It is therefore possible that there were large fluctuations in moisture in the Pyrenees and the Alps and it is reasonable to expect that the local glacial maximum (and maximum ice extent) could have occurred at different times in different mountain ranges. Andrieu *et al.* (1988) report that increased aridity in western Europe during the LGM is the main reason for a smaller advance of mountain glaciers. However, in the Swiss and Austrian Alps the maximum advance seems to occur later and closer to the global LGM. The emerging picture of an E–W gradient, with the largest glaciers occurring earlier in the west and later in the east, needs to be tested with detailed chronologies.

Conclusions

The study of the former extent of glaciation in Escarra and Lana Mayor catchments and the upper parts of the Gállego River Basin provides further evidence for a maximum ice extent in the Pyrenees earlier than for the Scandinavian ice-sheet (>30 000 yr BP). Similar conclusions have been drawn for several valleys along the northern Pyrenean slopes (Andrieu *et al.*, 1988; Montjuvent and Nicoud, 1988), the French Vosges (Seret *et al.*, 1990), the eastern Pyrenees (Sancho *et al.*, in press), the Alps (Chapron, 1999; Guiter *et al.*, 2001), and the Cantabrian Mountains (northwest Spain; Ruiz-Zapata *et al.*, 2000; Jiménez-Sánchez and Farias, 2002). The global Last Glacial Maximum corresponding with the maximum global ice volume (around 20 000 yr BP) was synchronous with an increase in precipitation over central and southern Iberia, along with the increase in the sea surface temperature of the Iberian margin (Sánchez-Goñi *et al.*, 1999; Turon, in press). This global LGM coincided with a glacial readvance, which did not reach the extent of the earlier maximum ice extent in the mountain glaciers. Comparison with other Pyrenean valleys demonstrates that five glacial stages can be identified for the whole Pyrenean domain. More sedimentological and palynological studies and absolute dates are needed in order to establish a chronological framework for the main deglaciation events. They will provide a test for the non-synchronous timing of the Scandinavian ice-sheet expansions and those of the Pyrenean glaciers.

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