GLACIAL AND FLUVIAL DEPOSITS IN THE ARAGÓN VALLEY, CENTRAL-WESTERN PYRENEES: CHRONOLOGY OF THE PYRENEAN LATE PLEISTOCENE GLACIERS

JOSÉ M. GARCÍA-RUIZ[1], CARLOS MARTÍ-BONO[1], JOSÉ L. PEÑA-MONNÉ[2],
CARLOS SANCHO[3], EDWARD J. RHODES[4], BLAS VALERO-GARCÉS[1],
PENÉLOPE GONZÁLEZ-SAMPÉRIZ[1] and ANA MORENO[1]

[1]Instituto Pirenaico de Ecología, CSIC, Campus de Aula Dei, Zaragoza, Spain.
[2]Department of Geography, University of Zaragoza, Zaragoza, Spain.
[3]Department of Earth Sciences, Faculty of Sciences, University of Zaragoza, Zaragoza, Spain.
[4]Department of Earth and Space Sciences, University of California, Los Angeles, CA, USA.

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ABSTRACT: The Aragón Valley glacier (Central Western Pyrenees) has been studied since the late 19th century and has become one of the best areas in the Pyrenees to study the occurrence of Pleistocene glaciations and the relationships between moraines and fluvial terraces. New morphological studies and absolute ages for moraines and fluvial terraces in the Aragón Valley allow a correlation with other Pyrenean glaciers and provide solid chronologies about the asynchroneity between global Last Glacial Maximum (LGM) and the Maximum Ice Extent (MIE). Six frontal arcs and three lateral morainic ridges were identified in the Villanúa basin terminal glacial complex. The main moraines (M1 and M2) correspond to two glacial stages (oxygen isotopic stages MIS 6 and MIS 4), dated at 171 ± 22 ka and 68 ± 7 ka, respectively. From a topographical point of view, moraine M1 appears to be linked to the 60 m fluvioglacial terrace, dated in a tributary of the Aragón River at 263 ± 21 ka. The difference in age between M1 moraine and the 60 m fluvioglacial terrace suggests that the latter belongs to an earlier glacial stage (MIS 8). Moraine M2 was clearly linked to the fluvioglacial 20 m terrace. Other minor internal moraines were related to the 7–8 m terrace. The dates obtained for the last glacial cycle (20–18 ka) are similar to other chronologies for Mediterranean mountains, and confirm the occurrence of an early MIE in the Central Pyrenees that does not coincide with the global LGM.

Key Words: glacial stages, moraines-terrace interrelations, terminal glacial complex, Aragón Valley, Pyrenees.

Introduction

The Central Spanish Pyrenees include some of the best-developed and preserved glacial complexes in southern Europe. A frontal glacial complex in the Aragón Valley was already described in the late 19th century (Penck 1883), and several hypotheses concerning the number of glacial periods represented in the terminal area and the ages of the main glacial advances have been the subject of much subsequent discussion. Following Penck’s study in the Central Pyrenees, the main features of the Pyrenean Quaternary glaciers were defined, including their extent. Penck confirmed that glaciers on the northern face of the Pyrenees reached lower altitudes than did those on the southern face (400–600 m a.s.l. and 800–1000 m a.s.l., respectively), and that the former ones were longer. He also noted the presence of various fluvial terrace levels, each corresponding to a cold period in the Quaternary. Panzer (1926) studied the frontal complex in the Aragón River Valley and recognized the presence of two glacial stages (then attributed to the Riss and Würm stages), based on the link between the two main end moraines and two terrace levels (60 and 20 m) in the Aragón River. Studies of the Pyrenean Quaternary glaciers intensified after the Second World War, particularly in the Aragón and Gállego valleys. These studies were carried out by French and Spanish geologists and geographers, including Solé-Sabarís (1941), Llopis-Lladó (1947) and Fontboté (1948), who pursued the arguments of Panzer (1926). However, Barrère (1963) argued that there was evidence for only one glaciation because there was no physical connection between the moraines and terraces. More recent studies have had a regional focus (Calvet 1984; Martí-Bono and García-Ruiz 1994; Martí-Bono 1996; Chueca *et al*. 1998; Serrano 1998; García-Ruiz and Martí-Bono 2011; Calvet *et al*. 2011; García-Ruiz *et al*. 2011; Montserrat-Jiménez *et al*. 2012), and no dates for the Aragón Valley deposits have been reported. Various studies of the Gállego Valley located 15 km east of the Aragón Valley (Montserrat 1992; García-Ruiz *et al*. 2003; Peña *et al*. 2004; González-Sampériz *et al*. 2007; Sancho *et al*. 2008; Lewis *et al*. 2009;

Sancho *et al.* 2011) provided optically stimulated luminescence (OSL) and radiocarbon dates for the glaciolacustrine deposits, terraces and moraines, and concluded that the glacial maximum in the Central Pyrenees occurred earlier (oxygen isotope stages MIS 4 and MIS 3) than in central and northern Europe (MIS 2). Other studies in the Mediterranean mountains based on ^{14}C and OSL dating techniques led to similar conclusions (Mardones and Jalut 1983; Andrieu *et al.* 1988; Jalut *et al.* 1992; Jiménez-Sánchez and Farias 2002; Hughes and Woodward 2008; Jalut *et al.* 2010; Moreno *et al.* 2010). Nevertheless, Pallàs *et al.* (2006) and Delmas *et al.* (2008) proposed a major glacial advance during the LGM in the Noguera Ribagorzana and the Têt valleys, central and eastern Pyrenees, respectively. Recent ^{10}Be exposure ages (Pallás *et al.* 2010) confirmed that the maximum glacial extent in some eastern Pyrenees valleys (the Carol and Malniu valleys) may have occurred during MIS 4.

The main objective of this paper is (i) to provide a global overview of the Late Pleistocene glacial stages in the Pyrenees, and to correlate information from various valleys and dating techniques, including OSL dates from the Aragón Valley; and (ii) to review the chronological position of the Pyrenean late Pleistocene glaciers in the context of the last glacial cycle in the Mediterranean mountain glaciers.

The study area

The Pyrenees is a 440 km long mountain range extending from the Bay of Biscay (Atlantic Ocean) to Cape Creus (Mediterranean Sea). The structure of the Pyrenees is related to Alpine tectonics, although major Paleozoic outcrops are present in many parts of the range. The main peaks occur in the Central Pyrenees in granite or Paleozoic metamorphic rocks (Aneto peak, 3404 m a.s.l.; Posets peak, 3371 m a.s.l.; Infierno, 3177 m a.s.l.), and Alpine calcareous massifs (Monte Perdido, 3355 m a.s.l.). The peaks tend to decrease in height towards the west and the east. Glacial and fluvial valleys incise the range in both the north and the south sides forming deep canyons in the calcareous areas. Glaciers were, in general, of modest size compared with those in the Alps, although excellent examples of cirques, U-shaped valleys, over-excavated basins, tills and moraines can be found up to 400–600 m a.s.l. on the northern slopes and up to 800 m a.s.l. on the southern slopes.

The Aragón Valley is located in the southern slope of the western central Pyrenees (Fig. 1). The valley crosses three east-west trending lithological units:

(i) The uppermost part of the watershed is comporsed of Paleozoic formations (marine limestones, quartzites and shales, and continental sandstones and conglomerates) with some volcanic rocks (andesites). They are intensively folded and faulted by the Variscan and Alpine orogenies. The highest peaks exceed 2400 m a.s.l. (the highest is Anayet peak, 2559 m a.s.l.).

(ii) The Inner Ranges are composed of marine Cretaceous and Eocene limestones and sandstones folded during the Alpine orogeny. They form a series of overthrusting anticlines displaced towards the south, with an abrupt relief on both the north and the south faces, and large glacial cirques (García-Ruiz *et al.* 2000), avalanche chutes and screes, particularly on the northern face. In this sector, the Inner Ranges reach their highest altitude at the Collarada peak (2886 m a.s.l.).

(iii) The Flysch Sector is composed of alternating thin beds of Eocene sandstones and marls, intensively folded by the Alpine orogeny. The relief is smoother, with wide divides that progressively become smaller to the south as the valleys become wider because of the high erodibility of these materials. In general, the major glaciers of the central and western Spanish Pyrenees ended in the Flysch Sector (Fig. 1).

The Aragón glacier was approximately 30 km in length, with an ice thickness exceeding 400 m in some places (Martí-Bono 1996). Other glaciers in the region recorded long distances between the headwater cirques and the terminal fronts, particularly the Aragón Subordán ice tongue (García-Ruiz *et al.* 2011). A variety of tributaries contributed to growth of the main glacier. As a result of differences in the erosion capacities of these small tributaries relative to the Aragón glacier, most of these remain perched 200-400 m above the main valley floor.

The headwater of the Aragón Valley is one of the most humid areas in the southern Pyrenees, with a strong influence from Atlantic Ocean fronts. The ski resort of Candanchú (1600 m a.s.l.) records an average annual precipitation of 1887 mm, and estimates of approximately 2500 mm have been reported for the divides (Del Barrio *et al.* 1990).

Methods

A geomorphological map was developed based on aerial photographs (from 1956 and 1977, at scales of 1:33 000 and 1:18 000, respectively) and detailed field work in the central-western part of the Spanish Pyrenees. The map included the location of cirques, U-shaped valleys, glacial deposits, fluvial deposits (terraces), hillslope deposits and mass movements (García-Ruiz *et al*. 2011). Figure 2 refers to the terminal sector of the Aragón Valley glacier, and only the glacial and fluvial deposits are represented. Field work focused on the relationships between the moraines and terraces.

The flattness and abrasion indices for gravels were obtained in the field from the moraines, terraces and the present fluvial channel of the Aragón River, using the methods of Cailleux and Tricart (1963). For the flatness index: $(L + 1)/2E$, where L is the maximum length of the pebble, l is the maximum width, and E is the thickness, and for the abrasion index: $2000r_1/L$, where r_1 is the minor radius than we can identify in the plane of the pebble.

The objective was to define the morphometric relationships among the various deposits, and to assess the fluvioglacial or torrential character of the terraces. Only the red sandstone clasts from the Permian formations were used, because they are easily identified and came from the headwater of the valley. The size of the selected clasts (one hundred from each sample) was 4–8 cm.

OSL techniques were used to date quartz from sand lenses within the glacial till, and well sorted fluvial sands within massive gravel deposits (fluvial terraces). Standard sampling techniques involving plastic and metal tubes were used for poorly lithified materials. Sample preparation and OSL measurements were carried out at the Luminescence Dating Laboratory of the Research Laboratory for Archaeology and the History of Art (University of Oxford, UK; http://www.rlaha.ox.ac.uk). Sand-sized quartz was extracted based upon the method described by Rhodes (1988). This involved sieving, concentrated hydrofluoric acid treatment (with additional hydrochloric acid present), and density separation of heavy minerals using sodium polytungstate solution. OSL dating was based on the single aliquot regenerative-dose (SAR) protocol (Murray and Wintle 2000), using a Riso TL-DA-15 automated luminescence reader. The gamma dose rate was based on in-situ gamma ray spectrometry, while neutron activation analysis (NAA) of the U, Th and K concentrations were used to estimate the beta dose rate for each sample. Based on in-situ samples, a water content value of 15 ± 5% was used in age calculations. All OSL dates are presented with a 1 sigma uncertainty.

Results

Glacial records

The terminal area of the Aragón Valley glacier, also termed the Villanúa basin, is located in the Flysch Sector of the Central Pyrenees, where the valley widens considerably (Fig. 2). The best examples of morainic deposits in the Aragón Valley and arguably the entire southern Pyrenees are located between Villanúa and Castiello de Jaca.

The terminal area is flanked by lateral moraines that progressively descend in height toward the valley floor, indicating a thinning of the ice tongue because of enlargement of the valley and acceleration of melting processes. On the right margin three lateral morainic ridges are at the same altitude as the village of Aratorés (Fig. 2). Two of the ridges run parallel and close to each other. They block the outlet of the tributary ravine and a temporary lake that was filled with sediment (glaciolacustrine deposits). The third ridge is more external, close to the valley wall, with no topographic evidence and only marked by the presence of scattered boulders of morainic-origin.

The lateral morainic ridges on the left margin are larger and more continuous than those on the right margin. The outer ridge is the biggest and forms a large hill that extends toward the south-southwest, and culminates at 1082 m a.s.l. (i.e., approximately 160 m above the valley floor). At a lower altitude and in an internal position, another lateral moraine turns toward the axis of the valley, where it connects with minor frontal deposits. As on the right margin of the valley, some remnants of glacial tills (sub-rounded boulders) are scattered close to the valley wall.

At the bottom of the terminal area there are up to six frontal arcs within a distance of 3 km; these were originally identified by Panzer (1926). Llopis-Lladó (1947) differentiated these as large (M1, M2) and small (m1, m2, m3, m4) frontal arcs.

The outermost arc (M1) connects topographically with the 60 m terrace of the Aragón River (Fig. 3), where the village of Castiello de Jaca is located (921 m a.s.l.). The moraine extends approximately 80 m above the current Aragón River channel, and forms an impressive hill almost transverse to the valley direction. The second arc (m1), 0.5 km upstream, rises only 10 m above the 15–20 m terrace of the Aragón River.

The third arc (M2) has a similar relief to that of M1 (Fig. 3). M2 is an arched hill transverse to the direction of the Aragón Valley, and up to 80 m high above the Aragón river channel. This arc links with the 15–20 m terrace level of the Aragón River.

Approximately 1 km upstream of M2 the three minor transverse frontal arcs (m2, m3 and m4) are cut by the main highway and rail road (Fig. 4).

The outermost moraine (M1) clearly links with the lateral, scattered remnants located against the valley walls, particularly on the right side. The thick moraine M2 appears to connect to the two inner moraine ridges of Aratorés (right margin), and is also apparently a continuation of the large, intermediate ridge on the left margin. The inner and lower ridge on the left margin links relatively well to the innermost frontal arcs (m2–m4). These internal arcs connect with a lower terrace level (7–8 m), suggesting a new advance rather than a retreat.

Figure 5 shows the accumulated curves of the abrasion index of Permotriasic sandstones in four of the frontal tills (M1, M2, m2 and m3). The separation of M1 and M2 from m2 and m3 is evident, with the latter two arcs more eroded or rounded. The average abrasion indices for M1 and M2 were 70 and 50, respectively, whereas the indices for m2 and m3 were 155 and 135, respectively. This suggests a glacier retreat after M2 was deposited, and a new advance during a later glacial stage when m2, m3, and m4 were deposited. During this new advance relatively rounded clasts from fluvial deposits where incorporated into the till. The internal structure of these minor moraines is very simple, with a nucleus of lodgement till and a cover of ablation till. The morphology of the moraine ridges is rounded, showing the effect of a degradation and considerable lowering, that is typical in unconsolidated Quaternary deposits on steeply sloping landforms (Putkonen and O’Neal, 2006).

Upstream, the lateral morainic ridges continue on both the right and left margins. On the right margin, at the Lierde ravine confluence, a thick moraine can be followed toward the south for several hundred meters. The partial dismantling of this moraine resulted in an alluvial fan that occupies part of the alluvial plain of the Aragón River. On the left margin, the lateral ridges blocked the Villanúa ravine and formed a lateral lake filled with glaciolacustrine sediments. Many other tills are scattered in the headwater of the valley, particularly in some of the tributary valley glaciers (e.g., the Izas Valley).

Moraines and terraces

One of the most significant problems in the study of glacier development in the Aragón Valley is the relationship between moraines and fluvial terraces. Figure 6 shows this relationship in the terminal area of the Aragón glacier, and indicates that: (i) moraines m2, m3 and m4 are related to the 7–8 m terrace; (ii) the 20 m terrace is fluvioglacial, given its sedimentological characteristics (see below) and the connection with moraines m1 and M2; and (iii) the 60 m terrace is thick (approximately 25 m) at Castiello de Jaca, but thins to 5–10 m at Jaca, 10 km downstream.

The 60 m terrace shows three different units: (a) a basal unit (5–7 m thick) with well-rounded gravels (median size of the largest gravels, 28 cm); (b) a middle sandy unit (less than 1 m thick), probably corresponding to a fluvial marginal position within a braided stream. This layer was eroded before 1996 because of the retreat of the terrace scarp; and (c) an upper unit (almost 20 m in depth) composed of coarse gravels (median size of the largest gravels greater than 75 cm).

In order to identify depositional environments (fluvial and glacial), a morphometric analysis of the clasts in the 20 m and 60 m terraces and in the moraines was conducted.. The samples came from: (i) the current bed of the Aragón River, at the headwaters (Candanchú, 1420 m a.s.l.), in Castiello de Jaca (i.e., at 850 m a.s.l.,18 km downstream from Candanchú), and in Santa Cilia (650 m a.s.l., 45 km from the headwaters); (ii) the 20 m and 60 m terraces in the terminal glacial complex of Villanúa. For the 60 m terrace, morphometric analyses were performed in the lower and upper units; and (iii) tills of the M1, M2, m2, and m3 moraines.

Figure 7 shows the flatness and abrasion indices. With respect to flatness, current fluvial deposits and the lower unit of the 60 m terrace group together (index values approximately 2.2–2.5). The moraines, the 20 m and the upper unit of the 60 m terraces have flatness indices of approximately 1.8–1.9, indicative of less intense reworking during transport. The lowest indices are, in general, typical of pebbles transported by the ice. The increment of pebble flatness only occurs after a long fluvial transport.

The abrasion index shows greater variation. In the case of the current Aragón River, the index progressively increases from the headwater (index value = 200) to Santa Cilia (index value = 285). The index value for the lower part of the 60 m terrace (255) and the Aragón River at Castiello de Jaca (260) are similar. The abrasion index for the 20 m and 60 m (upper unit) terraces are higher than those for the moraines, particularly in the case of M1 and M2.

Geomorphological relationships and flatness and abrasion values indicate that the 20 m terrace is of fluvioglacial origin. The 60 m terrace was formed during a period of progression and stabilization of the glacier. The glacier front was initially located far upstream, and the basal sediments were deposited in a fluvial environment. As the glacier front advanced, the gravel size increased significantly, and both glacial and fluvial processes were responsible for deposition of the terrace (Höllermann 1971; Martí-Bono 1973).

Chronological data

Three OSL dates were obtained in the terminal area of the Aragón Valley glacier, two from moraine sediments and one from a terrace (see Figs. 2 and 4 for the location, and Table 1). It was not possible to sample more material for more OSL dates because of the lack of well-sorted fluvial sands and the difficulty to identify them within the glacial till covered with dense vegetation. Moraine M1 was sampled in a trench recently created during construction of a new forest road, and provided and age of 171 ± 22 ka. The age of the 20 m terrace, sampled at a scarp eroded by the Aragón River near Castiello de Jaca, was 68 ± 7 ka, and consequently moraine M2 is of similar age. Finally, moraine m2 (Fig. 8) was sampled at a new scarp created by gravel quarry, and gave an age of 51 ± 4 ka, that should be younger than M2, given its more internal position,

A 60 m terrace level in a tributary of the Aragón River (the Aragón Subordán River) was sampled at Javierregay (Fig. 9) and dated with OSL methods. Both, the similar height and the soil characteristics (a red soil) suggest that the Javierregay terrace is comparable to Castiello de Jaca terrace. This possibility had been suggested by several authors that provided a regional perspective of the Quaternary deposits in the Upper Aragón Valley and its tributaries (Barrère 1963; García-Ruiz *et al.* 2011). Nevertheless, it is noteworthy that the 60 m terrace of Javierregay is located more than 15 km downstream of the glacial front, so the relative elevations of the two terraces cannot be compared without uncertainties. The OSL age of the Javierregay terrace is 263 ± 21 ka (Table 1).

Discussion

Glacial stages in the Aragón Valley

We report here new dates for the glacial stages in one of the major valleys in the Pyrenees, with a complex terminal basin including frontal, and lateral moraines, and various terrace levels in close proximity. Although relatively few dates were obtained, these are consistent with other chronologies for both the Spanish and the French sides of the Central Pyrenees.

Following Panzer (1926), various studies suggested that two glaciations (Riss and Würm, according to the Alpine terminology) were represented in this glacial terminal complex. This was consistent with the apparent link between the outermost moraine (M1) and the 60 m fluvial terrace, whereas m1 and M2 were related to the 20 m terrace. However, Barrère (1963) considered that the M1 moraine was leaning against the scarp of the 60 m terrace, and rejected the suggestion of a link between the two sedimentary bodies. Barrère (1963) also argued that in the neighbouring Gállego Valley, the 60 m terrace was completely disconnected from the glacial deposits. However, no absolute dating was available to solve these conflicting hypotheses.

Morphometric analysis of tills and terraces, and OSL dating identifies at least two main glacial stages in the Villanúa/Castiello de Jaca terminal area:

(i) The M2 moraine corresponds to the maximum ice extent (MIE) of the glacier during the last glacial cycle, dated at approximately 68 ± 7 ka (MIS 4), as this is the age of the 20 m terrace connected to the moraine. The m1 moraine should have the same age.

(ii) The M1 moraine does not correspond to the same glacial stage as M2, given the very different OSL dates obtained. The 171 ± 22 ka age of the M1 moraine suggests that it was deposited during an older glaciation (MIS 6)

(iii) Moraines m2, m3 and m4 are associated with the 7–8 m terrace, and represent a new advance following the retreat of the glacial ice after the formation of M2. Their abrasion index was higher than for M2, suggesting that fluvial sediments were incorporated into the glacial till. Only the m2 moraine could be dated and gave an age of 51 ± 4 ka.

The relationship between the M1 moraine and the 60 m terrace remains unclear. It is evident that the terrace formed during a progression of the ice tongue, because the sediment coarsens progressively from the bottom (where fluvial processes were dominant) to the top (where fluvioglacial features are evident). However, our results indicate that the 60 m terrace formed during a period of progression and stabilization of the glacier.

The age of the 60 m terrace obtained in a tributary of the Aragón River (263 ± 21 ka) is much older than the M1 moraine (171 ± 22 ka) and suggests that the terrace may correspond to a previous glacial stage (MIS 8), and that the M1 moraine leaned against the pre-existing terrace, as suggested by Barrère (1963). Nevertheless, it is important to note that the distance between the terrace of the tributary of the Aragón River and the deposits at the front of the Aragón glacier makes difficult to establish a clear correlation among them. Surprisingly, a study of the extent of weathering of

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sediments in terraces and moraines of the Aragón Valley revealed that the development of soil in the 60 m terrace occurred prior to the construction of moraines and that, as a consequence, there was no connection between these sedimentary bodies (Vidal-Bardán and Sánchez-Carpintero, 1990). However, other factors may be responsible for different soil development in the different topographic conditions occurring on a flat terrace or a moraine slope where erosion is able to rejuvenate the soil. It is important to notice that, the 50–60 m terraces in the Gállego and Cinca valleys (also in the Central Pyrenees) have been dated at 178 ± 21 ka to 151 ± 11 ka (Lewis *et al.*, 2009), which is similar to the date obtained for the M1 moraine, but younger than the 60 m terrace in the Aragón River. A different behavior of western (Aragón glacier) relative to eastern (Gállego and Cinca) glaciers during previous glacial cycles, or inaccuracies in that particular date, should not be ruled out until more dates are available.

The chronology of the Last Glacial Cycle in the Pyrenees and the Mediterranean mountains

The new dates from moraines and terraces in the Aragón Valley, though few in number, are consistent with most chronologies from the Pyrenees and other Mediterranean mountains (García-Ruiz *et al.* 2003; Woodward *et al.* 2004; Hughes *et al.* 2006; Hughes and Woodward 2008; García-Ruiz *et al.* 2010; Montserrat-Jiménez *et al.* 2012). Radiocarbon, OSL and cosmogenic surface exposure dating increasingly document an asynchroneity between the Scandinavian ice cap and the small glaciers in southern Europe (Calvet *et al.* 2011, 2012). In the 1980s, studies by Etlicher and De Goer de Hervé (1988) in the French Massif Central, and Seret *et al.* (1990) in the Vosges Mountains raised the possibility that the Würmian MIE did not occur at the same time globally, although the global Last Glacial Maximum occurred between 19 and 24 ka (Mix *et al.* 2001; Yokoyama *et al.* 2000). These hypotheses were based on ^{14}C dates older than 30 000 yr BP obtained in glacier-related sediments. Mardones and Jalut (1983) dated a lacustrine sequence at the morainic front of the Pau Valley (near Lourdes, French Pyrenees) as 38 400 uncal. yr BP, and extrapolated to an age of 45 ka for the bottom of the deposit. They also attributed an age of 50–70 ka to the moraines that blocked the valley and created the glacial lake. The base of the glaciolacustrine deposit of Tramacastilla located in a divide between the Escarra and Lana Mayor valleys in the Gállego Valley was dated as 29 400 ± 600 ^{14}C yr BP (Montserrat 1992), when the divide was ice-free. Lateral moraines located approximately 100 m above the

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However, several recent studies have shown similar results than the 1980s and 1990s studies. Thus, González-Sampériz *et al*. (2006) studied the sedimentary and palynological characteristics of the glaciolacustrine deposit of El Portalet in the upper Gállego Valley, and obtained an age of 32 183–33 773 cal yr BP (calibrated with CALPAL, 2004) for the beginning of sedimentation following the glacial retreat. A hiatus in the lacustrine sequence at 19 250 ± 120 ^{14}C yr BP was interpreted as the consequence of erosion caused by re-advance of the glacier. Near El Portalet a peat-bog associated with a large, deep-seated landslide that temporarily blocked the Gállego River was dated at 20 120 ± 150 yr BP, indicating that the Gállego glacier was spatially restricted to areas in the headwater (García-Ruiz *et al*. 2003). These dates were obtained by radiocarbon dating of discrete organic matter fragments or concentrated pollen, thus minimizing a possible hard-water effect.

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These dates are consistent with recent OSL dates from the Gállego and Cinca valleys. In the Gállego Valley, Peña *et al*. (2004) dated the end moraine of Aurín at 85 ± 5 ka, and at Senegüé (6 km upstream) as 35 ± 3 and 36 ± 2 ka. The date of the end moraine at Aurín has been re-evaluated because the proglacial terrace associated to the moraine was deposited at 69 ± 8 ka, and the same terrace level was dated as 66 ± 4 ka about 20 km downstream. For these reasons, Peña *et al*. (2004) argued that the age of the end moraine at Aurín is 66-69 ka (MIS 4). In the Cinca Valley, Sancho *et al*. (2003) and Lewis *et al.* (2009) dated fluvioglacial sands in the till corresponding to the MIE of the Cinca glacier at 62.7 ± 3.9 ka., consistent with the related terrace in the Cinca River (average age of 64.4 ± 4 ka) (Sancho *et al*. 2003). New OSL dates provided by Sancho *et al*. (2011) for a glaciolacustrine deposit and a lateral moraine in the Ara Valley, located between the Gállego and the Cinca valleys are also coherent with an older MIE. The Linás de Broto glaciolacustrine deposit corresponds to a lake developed in a tributary valley (the Sorrosal stream) of the Ara Valley, dammed by the lateral moraine of the main glacier. Three samples from the glaciolacustrine deposit (55 ± 9, 82 ± 6 and 49 ± 11 ka, respectively) and one sample from the lateral moraine at Viu (49 ± 8 ka) confirmed the occurrence of a cold period during MIS 4.

Evidence for LGM glacial-related deposition in the Pyrenees is scarce. Loess deposits and the development of stratified screes in the Cinca Valley at approximately 20 ± 3 ka (Lewis *et al*. 2009) and 22 800 ± 200 cal yr BP (García-Ruiz *et al*. 2001 b), respectively, are indicative of colder conditions during the global LGM. Lateral moraines representing a glacial re-advance in the Gállego (García-Ruiz *et al.* 2003) and Aragón Subordán (García-Ruiz and Martí-Bono 2011) valleys, occur several kilometers upstream of the MIE.

Radiocarbon dates for the MIE similar to those reported for the Pyrenees have also been obtained in other Iberian mountains, particularly in the Cantabrian Range, where Jiménez-Sánchez and Farias (2002) reported a 34 177 ± 516 yr BP minimum age for a glacio-lacustrine deposit in the Redes Natural Park. Also in the Cantabrian Range, proglacial deposits in the Comella basin (Picos de Europa) were dated as 40 480 ± 820 cal yr BP, and in Enol Lake as 38 000 ± 820 cal. yr BP (CALPAL 2004) (Moreno *et al.*, 2010). In a nearby peat bog at Cuetos (Trueba Valley) the MIE occurred at 29 149–28 752 cal yr BP; and a new re-advance of minor extent, occurred later, perhaps corresponding to the LGM (Serrano *et al*. 2011). In the Sil valley, Jalut *et al.* (2010) estimated that deglaciation occurred between approximately 48 and 32 ka.

However, recent studies in the Pyrenees based on ^{10}Be exposure ages have provided younger dates, and re-opened the debate about the maximum extent of the Pyrenean glaciers. The analysis of 25 erosive surfaces and granodiorite blocks in the Upper Noguera Ribagorzana Valley (Central-Eastern Pyrenees) showed that the maximum extent of the ice tongue occurred *c*. 21 000 ± 4400 ka (based on an erratic boulder), whereas the dates for other inner surfaces and deposits were 16 000–11 000 ka (Pallàs *et al*. 2006; Rodés *et al*. 2008). Further east, the results from the morainic complex of the Têt Valley (Delmas *et al*. 2008) indicated a LGM (MIS 2) ice re-advance (between 21.4 ± 3.7 and 24.9 ± 4.4 ^{10}Be ka) of similar magnitude that advances during MIS 5, MIS 4 and MIS 3. Other cosmogenic surface exposure ages have provided ages more coherent with an early MIE in the Pyrenees. For instance, Pallàs *et al*. (2010) studied a small basin (Malniu) in the Querol Valley and estimated the occurrence of the MIE at a minimum of 49.2 ± 1.3 ^{10}Be ka, and an almost similar advance during the global LGM. An older date of 76.5 ± 2 ^{10}Be ka was considered as inherited. The largest moraine in the Malniu complex gave an age of 21.3 ± 0.6 ^{10} Be ka. In a study of the Ariège Valley, Delmas *et al.* (2011, 2012) concluded that the Würmian MIE occurred in the Pyrenees much earlier than the global LGM, with ice advances at 79.9 ± 14.3 and 35.3 ± 8.6 ka BP; the global LGM front was located approximately 7 km upstream of the MIE. In the Andorra Valley, where most of the data are still unpublished (Calvet *et al.* 2011), the ice-marginal lake sediment sequence at La Massana, developed after the two main ice tongues separated, returned AMS radiocarbon dates between 20.2 and 29.0 cal BP, with an indirectly deduced age of at least 41 ka on the basis of sedimentation rate estimations.

Pre-Würmian glacial deposits have been described and dated in the Pyrenees.. Older glacial deposits were found by Martí-Bono (1996) and Serrano (1998) in a lateral valley of the Gállego glacier, several km from the Würmian deposits. In the Gállego Valley, the Sabiñánigo fluvioglacial terrace associated to some scattered till on the left side of the valley had OSL ages of 155 ± 24 and 156 ± 10 ka BP (Peña *et al.*, 2004). Delmas *et al.* (2011) dated a deposit in the Ariège Valley at 122 ka BP exposure age, suggesting that the most extensive glaciation occurred during MIS 6 (190–130 ka BP). In northwest Spain (Queixa and Gêrez ranges), ^{21}Ne and ^{10}Be cosmogenic isotope analysis of glacier-polished bedrock surfaces and push-moraine boulders provided ages older than 232 ± 48 ka (MIS 8) and 135 ± 31 ka (MIS 6) (Fernández-Mosquera *et al.*, 2000). In the coastal mountains of the Adriatic Sea, extensive glaciations occurred during the Middle Pleistocene (i.e. MIS 12 and MIS 6) (Hughes *et al.* 2010, 2011).

Chronological uncertainty about the MIE and the LGM persists in many southern European mountains also, partially associated to the different dating techniques. Thus, in the Campo Imperatore Valley (Central Apenines), Giraudi and Frezzotti (1997) dated the maximum extent of the glacier between 34 770 ± 638 cal yr BP and 26 239 ± 789 cal yr BP. In the mountains of Greece, Woodward *et al.* (2004) and Hughes *et al.* (2006 a) applied Uranium series dating methods in the Voidomatis basin (southern side of the Tymphi peak) and identified three glacial stages: (i) 80–70 ka, (ii) 53 ± 4 ka, and (iii) 28.2–24.3 ka. In the Pindus Mountains the last local glacier maximum coincides with a fluvial aggradation phase in the Voidomatis River between 30 and 24 ka (Hughes *et al.* 2000b). In the Turkish mountains the MIE coincided approximately with the global LGM (Akçar *et al.* 2007; Sarikaya *et al.* 2008).

Three issues have to be discussed to evaluate these chronological differences:

(i) The dating procedures. Every dating technique has limitation due to sampling problems or possible contamination. Radiocarbon ages from aquatic organic matter samples could be affected by ageing because of reservoir effects in carbonate watersheds, contamination with old carbon recycled from the watershed or older lake deposits. In the case of exposure dates, the choice of surface for analysis is critical because the original surface must have been preserved and subjected to continuous exposure since the ice retreat (in the case of eroded surfaces) or the moment of deposition (for erratic blocks or moraine ridges). The occurrence of such conditions is difficult to establish, which can cast doubts on the results.

The congruency of dates obtained from different techniques increases the reliability of the chronological models. The coherence of OSL dates from moraines and terraces within the same morphostratigraphic context in the Gállego and Cinca valleys and the agreement of eight dates from the same terrace in the Cinca River at different locations (Lewis *et a*l. 2009) strongly increases the reliability of those OSL dates, and consequently, of similar radiocarbon dates in those valleys. Until the most recent dates obtained from exposure ages (cosmogenics) (Pallàs *et al*. 2010; Delmas *et al*. 2011, 2012), some authors (García-Ruiz *et al*. 2010) argued that radiocarbon and OSL dates would correspond to early advances, whereas exposure ages provided dates mostly from the global LGM. Nevertheless, recent exposure dates obtained from the Central-Eastern and Eastern Pyrenees tend to confirm the occurrence of the MIE earlier than the global LGM (Pallàs *et al*. 2010; Delmas *et al*. 2011, 2012).

(ii) The glacio-morphological context of the samples. The deposits, surfaces and erratic blocks corresponding to the maximum advance of the glaciers are difficult to distinguish in some valleys, In the Gállego Valley, for example, the most extensive advance was identified by two minor tills, with almost no topographic significance (García-Ruiz *et al*. 2011). In most of the Pyrenean valleys the front of the maximum advance is difficult to distinguish.

(iii) Regional response variability. The response to climate fluctuations during the last glacial cycle may have been different among the world's glaciers. Latitude, exposure to wet winds, location on northern or southern slopes may result in marked response differences. Small glaciers also react more rapidly than large glaciers, with almost immediate expansion or contraction of the ice mass as a consequence of changes in precipitation and/or temperature (Delmas *et al*. 2008). This rapid advance of small glaciers occurred during the Little Ice Age in the Pyrenees, the Cantabrian Range and the Balkans (Chueca *et al*. 2002; González-Trueba *et al*. 2008; Hughes 2010), and in recent years in a small glacier of the Durmitor massif, Montenegro (Hughes 2008). Thus, sustained growth of the Scandinavian ice cap and valley glaciers may have occurred between 80 000 and 50 000 yr. The greater inertia of the Scandinavian ice cap during MIS 3 could explain the stabilization or slower growth of the ice mass, during some of the abrupt changes (Dansgaard *et al*. 1993), whereas the Mediterranean valley glaciers would have undergone a retreat during the warm periods (i.e., interstadials 8 and 12, dated at 37 and 45 ka, respectively), because of their greater sensitivity to climate fluctuations. Hughes et al. (2006) suggest that the most favourable factors for glaciation in some Mediterranean regions would have occurred during intermediate conditions, under sufficient moisture supply and relatively cold summer temperatures, when the climate was characterized by less extreme conditions than during the global LGM. These conditions would have happened between 30 and 25 ka BP in the Pindus Mountains, and 33 and 27 ka in the Apennines (Giraudi 2012),

A decline in air temperature of 8–11ºC caused the maximum extent of the Scandinavian ice cap to be reached approximately 20–18 ka. The valley glaciers in the Mediterranean mountains grew during the global LGM, in some cases to a lesser extent than during the previous expansion (García-Ruiz *et al*. 2003), and in other cases to an extent similar to the previous MIE (Pallàs *et al*. 2010). The available paleoclimatic records in southern Europe suggest very cold conditions during the LGM (with an associated major expansion of steppe plants and a large reduction in trees), whereas the temperatures were less cold during the Lower Pleniglacial (about 75–45 ka BP), during which a succession of alternating relatively wet and cold stages occurred (Antoine *et al.* 2001; Guiter *et al*. 2003). Some glacial deposits in the Central Pyrenees have been attributed to this stage (MIS 2), including lateral moraines in the Escarra Valley (García-Ruiz *et al*. 2001, 2003) and Aragón Subordán (García-Ruiz and Martí-Bono 2011) valleys, and other deposits and glacial-eroded surfaces in the Eastern Pyrenees (Delmas *et al*. 2010; Pallàs *et al*. 2010) and the Central Range of the Iberian Peninsula (Palacios *et al*. 2012).

Florineth and Schlüchter (2000) argued that during the MIS 4 and 3 the Polar Front was located at approximately 46ºN and favoured meridian circulation and, consequently, the growth of glaciers in western Scandinavia, the Pyrenees, the Vosges and the northern Alps, although the main Alpine ice cover was during MIS 2. Ivy-Ochs *et al*. (2008) and Preuser *et al*. (2007) proposed a similar explanation for the western

Alps. After 30 000 yr BP the climatic conditions were increasingly dry, and consequently the re-advance of glaciers in southern Europe did not reach the same extent as during MIS 4 and 3. By the LGM (MIS 2) the Pyrenean glaciers had grown again, although their maximum extent remained upstream of the position of the glaciers during MIS 4 and 3.

Regional responses during the LGM have also been suggested for the Pyrenees. Delmas *et al*. (2011) documented that in the eastern Pyrenees the Würmian MIE and LGM ice front reached similar positions, whereas in the central Pyrenees the LGM ice fronts would remain far behind the Würmian MIE. These authors suggested that such differences during the global LGM could be explained because of a west–east gradient in the Pyrenees. A possible mechanism would involve differences in sea-surface temperatures between the Western Mediterranean and the Atlantic Ocean (Bay of Biscay) and the strengthening of the Mediterranean low pressure systems, enhancing precipitation in the eastern Pyrenees and, consequently, glacier growth.

Conclusions

The Villanúa basin complex, in the Aragón Valley (Central-Western Pyrenees) is one of the largest glacier terminal basins in the Pyrenees. Six frontal arcs and three lateral morainic ridges were identified on the sides of the valley, and the new OSL dates are consistent with most Pyrenees, Iberian and Mediterranean mountains. The main moraines (M1 and M2) correspond to two glacial stages (Rissian and Würmian), dated at 171 ± 22 ka BP and 68 ± 7 ka, respectively. Other minor frontal arcs correspond to new advances during the last glacial cycle. M1 is apparently linked to the 60 m fluvioglacial terrace, dated in a tributary of the Aragón River as 263 ± 21 ka. The difference in age between M1 (171 ± 22 ka BP) and the 60 m terrace (263 ± 21 ka) suggests that the terrace may belong to a previous glacial stage, although the distance between the moraine M1 and the sampling site in the 60 m terrace makes this conclusion less certain. Moraine M2 was clearly linked to the 20 m fluvioglacial terrace, The minor moraines were related to the 7–8 m terrace.

These new dates confirm that the Villanúa-Castiello de Jaca complex was formed during at least two main glacial stages, and perhaps three if the M1 terrace and the 60 m terrace were not connected.

The dates for the last glacial cycle are consistent with an early maximum advance in the Central Pyrenees, as previously demonstrated in the Gállego and Cinca valleys, the north face of the Pyrenees, the Cantabrian Ranges, and other Mediterranean mountains. New cosmogenic dates from boulders and polished surfaces in the Pyrenees confirm the asynchroneity between the MIE and the global LGM, and a minor advance during the global LGM. The occurrence of asynchroneity between the Mediterranean mountains and the Scandinavian ice field can be explained by regional climate differences and the rapid response of small valley glaciers to rapid climatic changes during the Upper Pleistocene.

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José M. García-Ruiz, Carlos Martí-Bono, Blas Valero-Garcés, Penélope González-Sampériz, Ana Moreno, Instituto Pirenaico de Ecología, CSIC, Campus de Aula Dei, P.O. Box 13034, 50080-Zaragoza, Spain.
E-mail: humberto@ipe.csic.es
José L. Peña-Monné, Department of Geography, University of Zaragoza, 50009-Zaragoza, Spain.
E-mail: jlpena@unizar.es
Carlos Sancho, Department of Earth Sciences, Faculty of Sciences, University of Zaragoza, 50009-Zaragoza, Spain.
E-mail: csancho@unizar.es
Edward J. Rhodes, Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095, USA.

References

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Akçar, N., Yavuz, N., Ivy-Ochs, S., Kubik, P.W., Vardar, M., and Schlüchter, C., 2007. Paleoglacial records from Kavron Valley, NE Turkey: field and cosmogenic exposure dating evidence. *Quaternary International*, 164–165, 170–183.

Andrieu, V., Hubschman, J., Jalut, G., and Herail, G., 1988. Chronologie de la déglaciation des Pyrénés françaises. Dynamique de sedimentation et contenu pollinique des paleolacs: application à l'interprétation du retrait glaciaire [Chronologie of deglaciation in the French Pyrenees. Dynamics of sedimentation and pollen content of paleolakes: application to the interpretation of glacial retreat]. *Bulletin de l'Association Française pour l'Étude du Quaternaire [Bulletin of the French Association for Quaternary Studies]*, 2/3, 55–67. [In French]

Antoine, P., Rousseau, D., Soller, L., Lang, A., Munaut, A., Hatté, V., and Fontugne, M., 2001. High resolution record of the last interglacial cycle in the Nussloch loess palaeosol sequences. Upper Rhine area, Germany. *Quaternary International*, 76–77, 211–229.

Barrère, P., 1963. La période glaciaire dans l'Ouest des Pyrénées centrals franco-espagnoles [The glacial period in the French-Spanish Western-Central Pyrenees]. *Bulletin de la Société Géologique de France [Bulletin of the French Geological Society]*, 7, 516–526. [In French]

Cailleux, A. and Tricart, J., 1963. *Initiation à l'Étude des Sables et des Galets [Introduction to the Study of Sands and Pebbles]*. Centre de Documentation Universitaire, Paris. [In French]

Calvet, M., 1984. The Quaternary glaciation of the Pyrenees, and attempt of synthesis. In Ehlers, J. and Gibbard, P.L. (eds), *Quaternary glaciations, extent and chronology, Part I: Europe*, Developments in Quaternary Science, vol. 2a, Elsevier, Amsterdam. 119–128.

Calvet, M., Delmas, M., Gunnell, Y., Braucher, R., and Bourlès, D., 2011. Recent advances in research on Quaternary glaciations in the Pyrenees. *Developments in Quaternary Science*, 15, doi: 10.1016/B978-0-444-53447-7.00011-8

Chueca, J., Julian, A., and Peña, J.L., 2002. Comparación de la situación de los glaciares del Pirineo español entre el final de la Pequeña Edad del Hielo y la actualidad [Comparing the state of the Spanish Pyrenean glaciers between the end of the Little Ice Age and today]. *Boletín Glaciológico Aragonés [Aragonese Glaciological Bulletin]*, 3, 13–41. [In Spanish]

Chueca, J., Peña, J.L., Lampre, F., García-Ruiz, J.M., and Martí-Bono, C., 1998. *Los Glaciares del Pirineo Aragonés: Estudio de su Evolución y Extensión Actual [Glaciers in the Aragón Pyrenees: Study of their Evolution and Present Extent]*. Universidad de Zaragoza, Zaragoza. [In Spanish]

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbiörnnsdóttir, A.E., Jouzel, J., and Bond, G., 1993. Evidence for general instability of past climate from a 250-Kyr ice-core record. *Nature,* 364, 218–220.

Del Barrio, G., Creus, J., and Puigdefábregas, J., 1990. Thermal seasonality of the high mountain belts of the Pyrenees. *Mountain Research and Development*, 10, 227–233.

Delmas, M., Gunnell, Y., Braucher, R., Calvet, M., and Bourlès, D., 2008. Exposure age chronology of the last glaciation in the eastern Pyrenees. *Quaternary Research*, 69, 231–241.

Delmas, M., Calvet, M., Gunnell, Y., Braucher, R., and Bourlès, D., 2011. Palaeogeography and ^{10}Be exposure age chronology of Middle and Late Pleistocene glacier systems in the northern Pyrenees: Implications for reconstructing regional palaeoclimates. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 305, 109–122.

Delmas, M., Calvet, M., Gunnell, Y., Braucher, R., and Bourlès, D., 2012. Les glaciations quaternaires dans les Pyrénées Ariégeoises: Approche historiographique, donnés paleogéographiques et chronologiques nouvelles [Quaternary glaciations in the Ariege Pyrenees: Historical approach, paleogeographical data and new dates]. *Quaternaire [Quaternary],* 23, 61–81. [In French]

Etlicher, B. and De Goer de Hervé, A., 1988. La déglaciation würmienne dans le Massif Central Français: Le point de travaux récents [Würmian deglaciation in the French Central Massif: recent works]. *Bulletin de l’Association Française pour l’Étude du Quaternaire [Bulletin of the French Association for Quaternary Studies],* 34–35, 103–110. [In French]

Fernández-Mosquera, D., Martí, K., Vidal-Romaní, J.R., and Weigel, A., 2000. Late Pleistocene deglaciation chronology in the NW of the Iberian Peninsula using cosmic-ray produced ^{21}Ne in quartz. *Nuclear Instruments and Methods in Physics Research B,* 172, 832–837.

Florineth, D. and Schlüchter, C., 2000. Alpine evidence for atmospheric circulation patterns in Europe during the Last Glacial Maximum. *Quaternary Research,* 54, 295–308.

Fontboté, J.M.. 1948. La Ribera de Biescas [The Biescas Riverside]. *Pirineos [Pyrenees]*, 7, 39–88. [In Spanish]

García-Ruiz, J.M. and Martí-Bono, C., 2011. Los depósitos glaciares del valle del Aragón Subordán, Pirineo Centro-occidental español [Glacial deposits in the Aragón Subordán Valley, Spanish Central-Western Pyrenees]. *Cuaternario y Geomorfología [Quaternary and Geomorphology]*, 25 (1–2), 57–81. [In Spanish]

García-Ruiz, J.M., Ortigosa, L., Gómez-Villar, A., and Martí-Bono, C., 2000. Morphometry of glacial cirques in the Spanish Pyrenees. *Geografiska Annaler: Series A, Physical Geography* 82, 433–442.

García-Ruiz, J.M., Martí-Bono, C., Valero, B., and González-Sampériz, P., 2001a. La evolución de los glaciares del Pleistoceno Superior en el Pirineo Central español. El ejemplo de los glaciares de Escarra y Lana Mayor, Alto Valle del Gállego [The evolution of the Late Pleistocene glaciers in the Central Spanish Pyrenees. The example of the Escarra and Lana Mayor glaciers, Upper Gállego Valley]. *Cuaternario y Geomorfología [Quaternary and Geomorphology]*, 15, 103–120. [In Spanish]

García-Ruiz, J.M., Valero-Garcés, B.L., Martí-Bono, C., and González-Sampériz, P., 2003. Asynchroneity of maximum glacier advances in the central Spanish Pyrenees. *Journal of Quaternary Science*, 18, 61–72.

García-Ruiz, J.M., Moreno, P., González-Sampériz, P., Valero-Garcés, B., and Martí-Bono, C., 2010. La cronología del ultimo ciclo glaciar en las montañas del sur de Europa. Una revisión [Chronology of the last glacial cycle in the southern European mountains. A review]. *Cuaternario y Geomorfología [Quaternary and Geomorphology]*, 24 (1–2), 35–56. [In Spanish]

García-Ruiz, J.M., Valero, B., González, P., Lorente, A., Martí-Bono, C., Beguería, S., and Edwards, L., 2001b. Stratified scree in the Central Spanish Pyrenees: Paleoenvironmental implications. *Permafrost and Periglacial Processes,* 12, 233–242.

García-Ruiz, J.M., Peña-Monné, J.L., Martí-Bono, C., Gómez-Villar, A., Constante-Orrios, A., and Espinalt-Brillas, M., 2011. *El relieve del Alto Aragón Occidental. Cartografía y síntesis geomorfológica [The relief of the High Western Aragón.*

Geomorphological mapping and synthesis]. Publicaciones del Consejo de Protección de la Naturaleza de Aragón, Zaragoza. [In Spanish]

Giraudi, C., 2012. The Campo Felice Late Pleistocene Glaciation (Apennines, Central Italy). *Journal of Quaternary Science,* 27, 432–440.

González-Sampériz, P., Valero-Garcés, B.L., Moreno, A., Jalut, G., García-Ruiz, J.M., Martí-Bono, C., Delgado-Huertas, A., Navas, A., Otto, T., and Dedoubat, J.J., 2006. Climate variability in the Spanish Pyrenees during the last 30,000 yr revealed by the El Portalet sequence. *Quaternary Research,* 66, 38–52.

González-Trueba, J.J., Martín-Moreno, R., Martínez de Pisón, E., and Serrano, E., 2008. Little Ice Age' glaciation and current glaciers in the Iberian Peninsula. *The Holocene* 18, 551–568.

Guiter, F., Andrieu-Ponel, V., De Beaulieu, J.L., Cheddadi, R., Clavez, M., Ponel, P., Reille, M., Séller, T., and Goeury, C., 2003. The last climate cycles in Western Europe: a comparison between long continuous lacustrine sequences from France and other terrestrial records. *Quaternary International,* 111, 59–74.

Höllermann, P., 1971. Zurundungsmessungen an Ablangerungen im Hochgebirge [Measurement of pebbles in high mountain deposits]. *Zeitschrift für Geomorphologie N.F. [Annals of Geomorphology]*, 12, 205–237. [In German]

Hughes, P.D., 2008. Response of a Montenegro glacier to extreme summer heatwawes in 2003 and 2007. *Geografiska Annaler: Series A, Physical Geography* 90, 259–267.

Hughes, P.D., 2010. Little Ice Age glaciers in the Balkans: low altitude glaciation enabled by cooler temperatures and local topoclimatic controls. *Earth Surface Processes and Landforms,* 35, 229–241.

Hughes, P.D. and Woodward, J.C., 2008. Timing of glaciation in the Mediterranean mountains during the last cold stage. *Journal of Quaternary Science,* 23, 575–588.

Hughes, P.D., Woodward, J.C., and Gibbard, P.L., 2006a. Glacial history of the Mediterranean mountains. *Progress in Physical Geography,* 30, 334–364.

Hughes, P.D., Woodward, J.C., and Gibbard, P.L., 2006b. Late Pleistocene glaciers and climate in the Mediterranean. *Global and Planetary Change,* 50, 83–98.

Hughes, P.D., Woodward, J.C., Van Calsteren, P.C., and Thomas, L.E., 2011. The glacial history of the Dinaric Alps, Montenegro. *Quaternary Science Reviews,* 30, 3393–3412.

Hughes, P.D., Woodward, J.C., Van Calsteren, P.C., Thomas, L.E., and Adamson, K.R., 2010. Pleistocene ice caps in the coastal mountains of the Adriatic Sea. *Quaternary Science Reviews,* 29, 3690–3708.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W., and Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. *Journal of Quaternary Science,* 23, 559–573.

Jalut, G., Montserrat, J., Fontugne, M., Delibrias, G., Vilaplana, J., and Juliá, R., 1992. Glacial to interglacial vegetation changes in the northern and southern Pyrenees: deglaciation, vegetation cover and chronology. *Quaternary Science Reviews*, 11, 449–480.

Jalut, G., Turu, I., Michels, V., Dedoubat, J.J., Otto, T., Ezquerra, J., Fontugne, M., Belet, J.M., Bonnet, L., García de Celis, A., Redondo-Vega, J.M., Vidal-Romaní, J.R., and Santos, L., 2010. Palaeoenvironmental studies in NW Iberia (Cantabrian Range): Vegetation history and synthetic approach of the last deglaciation phases in the Western Mediterranean. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 297, 330–350.

Jiménez-Sánchez, M. and Farias, P., 2002. New radiometric and geomorphological evidence of Last Glacial Maximum older than 18 ka in SW European mountains: The example of Redes Natural Park (Cantabrian Mountains, NW Spain). *Geodinamica Acta*, 15, 93–101.

Jiménez-Sánchez, M., Rodríguez-Rodríguez, L., García-Ruiz, J.M., Domínguez-Cuesta, M.J., Farias, P., Valero-Garcés, B., Moreno, A., and Valcárcel, M., 2012. A review of glacial geomorphology and chronology in northern Spain: Timing and regional variability during the last glacial cycle. *Geomorphology,* doi:10.1016/j.geomorph.2012.06.009

Lewis, C.J., McDonald, E.V., Sancho, C., Peña, J.L., and Rhodes, E.J., 2009. Climatic implications of correlated Upper Pleistocene glacial and fluvial deposits on the Cinca and Gállego Rivers (NE Spain) based on OSL dating and soil stratigraphy. *Global and Planetary Change*, 61, 300-312. doi: 10.1016/j.gloplacha.2009.01.001

Llopis-Lladó, N., 1947. El relieve del Alto Aragón [The relief of the Upper Aragón Valley]. *Pirineos [Pyrenees]*, 5, 81–166.

Mardones, M. and Jalut, G., 1983: La tourbière de Biscaye (alt. 409 m, Hautes Pyrénées): approche paleoécologique des 45,000 dernières années [The Biscay peat-

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bog (409 m a.s.l., High Pyrenees): paleoecological approach of the last 45,000 years]. *Pollen et Spores [Pollen and Spores],* 25, 163–212. [In French]

Martí-Bono, C., 1973. Nota sobre los sedimentos morenicos del río Aragón [Note on the morainic sediment of the Aragón River]. *Pirineos [Pyrenees],* 107, 39–46. [In Spainish]

Martí-Bono, C., 1996. *El glaciarismo Cuaternario en el Alto Aragón Occidental [Quaternary glaciers in the High Western Aragón]*. Ph.D. diss., Universitat de Barcelona, Barcelona. [In Spanish]

Martí-Bono, C. and García-Ruiz, J.M. (eds), 1994: *El Glaciarismo Surpirenaico: Nuevas Aportaciones [The South Pyrenean Glaciers: New Contributions]*. Geoforma Ediciones, Logroño.

Mix, A.C., Bard, E., and Schneider, R., 2001. Environmental processes of the ice age: land, oceans, glaciers (EPILOG). *Quaternary Science Reviews,* 20, 627–657.

Montserrat, J., 1992. *Evolución Glaciar y Postglaciar del Clima y la Vegetación en la Vertiente Sur del Pirineo: Estudio Palinológico [Glacial and Postglacial Climate and Plant Cover Evolution in the Southern Versant of the Pyrenees: Palynological Study]*. Instituto Pirenaico de Ecología, Zaragoza. [In Spanish]

Moreno, A., Valero-Garcés, B.L., Jiménez-Sánchez, M., Domínguez, M.J., Mata, P., Navas, A., González-Sampériz, P., Stoll, H., Farias, P., Morellón, M., Corella, P., and Rico, M., 2010. The last deglaciation in the Picos de Europa National Park (Cantabrian Mountains, Northern Spain). *Journal of Quaternary Science*, 25 (7), 1076–1091.

Murray, A.S. and Wintle, A.G., 2000. Luminiscence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurement*, 32, 57–73.

Palacios, D., De Andrés, N., De Marcos, J., and Vázquez-Selem, L., 2012. Glacial landforms and their paleoclimatic significance in the Sierra de Guadarrama, Central Iberian Peninsula. *Geomorphology,* 139–140, 67–78.

Pallàs, R., Rodés, A., Braucher, R., Bourlès, D., Delmas, M., Calvet, M., and Gunnell, Y., 2010. Small, isolated glacial catchments as priority targets for cosmogenic surface exposure dating of Pleistocene climate fluctuations, southeastern Pyrenees. *Geology,* 38 (10), 891–894.

Pallás, R., Rodés, A., Braucher, R., Carcailler, J., Ortuño, M., Bordonau, J., Bourlés, D., Vilaplana, J.M., Masana, E., and Santanach, P., 2006. Late Pleistocene and Holocene glaciation in the Pyrenees: a critical review and new evidence from ^{10}Be exposure ages, south-central Pyrenees. *Quaternary Science Reviews*, 25, 2937–2963.

Panzer, W., 1926. Talentwicklung und Eiszeitklima im nordostlichen Spanien [Evolution of glacial valleys and climate in northeast Spain]. *Abhandlungen der Seckenbergischen Naturforschenden Gesellschaft [Monographs of the Seckenberg Society of Nature Research]*, 33, 1–155. [In German]

Penck, A., 1883. Die Eiszeit in den Pyrenaen. *Mitt. Ver. Erdk.*, Leipzig (Translated to French as "La période glaciaire dans les Pyrénées" [The glacial period in the Pyrenees]. *Bulletin de la Société d'Histoire Naturelle de Toulouse [Bulletin of the Society of Natural History of Toulouse]*, 19, 105–200). [In French]

Peña, J.L., Sancho, C., Lewis, C., McDonald, E., and Rhodes, E., 2004. Datos cronológicos de las morrenas terminales del glaciar del Gállego y su relación con las terrazas fluvioglaciares (Pirineo de Huesca) [Chronological data of the end moraines in the Gállego glacier and their relationships with the fluvioglacial terraces (Pyrenees of Huesca)]. In Peña, J.L., Longares, L.A., and Sánchez, M. (eds), *Geografía Física de Aragón. Aspectos generales y temáticos*, Universidad de Zaragoza e Institución Fernando El Católico, Zaragoza. 71–84. [In Spanish]

Prescott, J.R. and Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long term time variations. *Radiation Measurement*, 23, 497–500.

Preusser, F., Blei, A., Graf, H., and Schlüchter, C., 2007. Luminiscence dating of Würmian (Weichselian) proglacial sediments from Switzerland: methodological aspects and stratigraphical conclusions. *Boreas*, 36, 130–142.

Putkonen, J. and O'Neal, M., 2006. Degraded unconsolidated Quaternary landforms in the western North America. *Geomorphology*, 75, 408–419.

Rodés, A., Pallàs, R., Braucher, R., and Bourlès, D., 2008. La última deglaciación en los Pirineos a partir de la datación de superficies de exposición mediante ^{10}Be [The last deglaciation in the Pyrenees dated from ^{10}Be exposure ages]. *Geo-Temas [Geo-Themes]*, 10, 755–758. [In Spanish]

Sancho, C., Peña, J.L., Lewis, C., McDonald, E., and Rhodes, E., 2008. Actividad glaciar y desarrollo de terrazas durante el Pleistoceo Superior en Pirineos – Cuenca del Ebro [Glacial activity and terrace development during the Late Pleistocene in the Pyrenees – the Ebro basin]. *Geo-Temas [Geo-Themes]*, 10, 763–766. [In Spanish]

Sancho, C., Peña-Monné, J.L., Rhodes, E., Arenas, C., Pardo, G., García-Ruiz, J.M., and Martí-Bono, C.E., 2011. El registro glaciolacustre de Linás de Broto (Valle del Ara, Pirineo Central, Huesca): Nuevas aportaciones [The glaciolacustrine record of Linás de Broto (Ara Valley, Central Pyrenees, Huesca): New contributions]. In *El Cuaternario en España y áreas afines, avances en 2011*, Fundación Henri Chevalier, Andorra. 11–14. [In Spanish]

Sarikaya, M.A., Zreda, M., Çiner, A., and Zweck, C., 2008. Cold and wet Last Glacial Maximum on Mount Sandiras, SW Turkey, inferred from cosmogenic dating and glacier modelling. *Quaternary Science Reviews*, 27, 769–780.

Seret, G., Dricot, J., and Wansard, G., 1990. Evidence for an early glacial maximum in the French Vosgues during the last glacial cycle. *Nature*, 346, 453–456.

Serrano, E., 1998. *Geomorfología del Alto Gállego, Pirineo Aragonés [Geomorphology of the Upper Gállego Valley, Aragón Pyrenees]*. Institución Fernando El Católico, Zaragoza. [In Spanish]

Serrano, E., González-Trueba, J.J., Turu, V., and Ros, X., 2011. Cronología glaciar pleistocena en el valle de Trueba (Cordillera Cantábrica): Primeras dataciones [Pleistocene glacial chronology in the Trueba Valley (Cantabrian Range): First dating]. In *El Cuaternario en España y áreas afines, avances en 2011*, Fundación Henri Chevalier, Andorra. 3–6. [In Spanish]

Solé-Sabarís, L., 1941. La Canal de Berdún [The Berdún Corridor]. *Primera Reunión de Estudios Geográficos [First Meeting of Geographical Studies]*, Instituto Juan Sebastián Elcano, Madrid; 113–160. [In Spanish]

Turner, C. and Hannon, G.E., 1988. Vegetational evidence for late Quaternary climate changes in southwest Europe in relation to the influence of the North Atlantic Ocean. *Philosophical Transactions of the Royal Society, London,* B318, 451–485.

Vidal-Bardán, M. and Sánchez-Carpintero, I., 1990. Análisis e interpretación de algunas cuestiones que plantea el complejo de morrenas y terrazas del río Aragón (Huesca) [Analysis and interpretation of the moraines and terraces complex of the Aragón River (Huesca)]. *Cuaternario y Geomorfología [Quaternary and Geomorphology]*, 4, 107–118. [In Spanish]

Woodward, J.C., Macklin, M.G., and Smith, G.R., 2004. Pleistocene glaciation in the mountains of Greece. In Ehlers, J. and Gibbard, J. (eds), *Quaternary glaciations: extent and chronology, Part I, Europe.* Elsevier, Amsterdam. 155–173.

Yokoyama, Y., Lambeck, K., De Deckker, P., Johnston, P., and Fifield, L.K., 2000. Timing of the Last Glacial Maximum from observed sea-level minima. *Nature*, 406, 713–716.

FIGURE CAPTIONS

Figure 1. The Aragón Valley glacier and other main glacial valleys in the Central-Western Pyrenees during the Maximum Ice Extent (MIE), coinciding most probably with MIS 4. In grey, the maximum extent of the ice tongues. Heavy black lines represent the main moraines. The box corresponds to the area represented in Figure 2.

Figure 2. The terminal complex of the Aragón Valley glacier. Sections A–B and C–D are shown in Figure 6.

Figure 3. Downstream perspective of the Villanúa glacial basin, showing the main end moraines (M1 and M2, and the 60 m terrace related to M1).

Figure 4. Moraines m2 and m3, forming small transverse hills at the bottom of the Villanúa glacial basin. The ice flow was from left to right.

Figure 5. Abrasion indexes of the Permian sandstone clasts in four frontal moraines of the Villanúa basin complex. 1: moraine M2. 2: moraine M1. 3: moraine m3. 4: moraine m2. Source: Martí-Bono (1973).

Figure 6. Relationships between glacial deposits and fluvial terraces in the terminal area of the Aragón Valley glacier. The location of the section is shown in Figure 2. Black dots represent the sampling sites for OSL dating.

Figure 7. Relationships between the flatness and abrasion indexes in fluvial, fluvioglacial and till deposits of the Aragón Valley. Source: Martí-Bono (1973).

Figure 8. Cross section in the moraine m2, where a sample for OSL was taken.

Figure 9. A trench in the 60 m terrace at Javierregay, showing a sandy outcrop where a sample for OSL dating was taken.

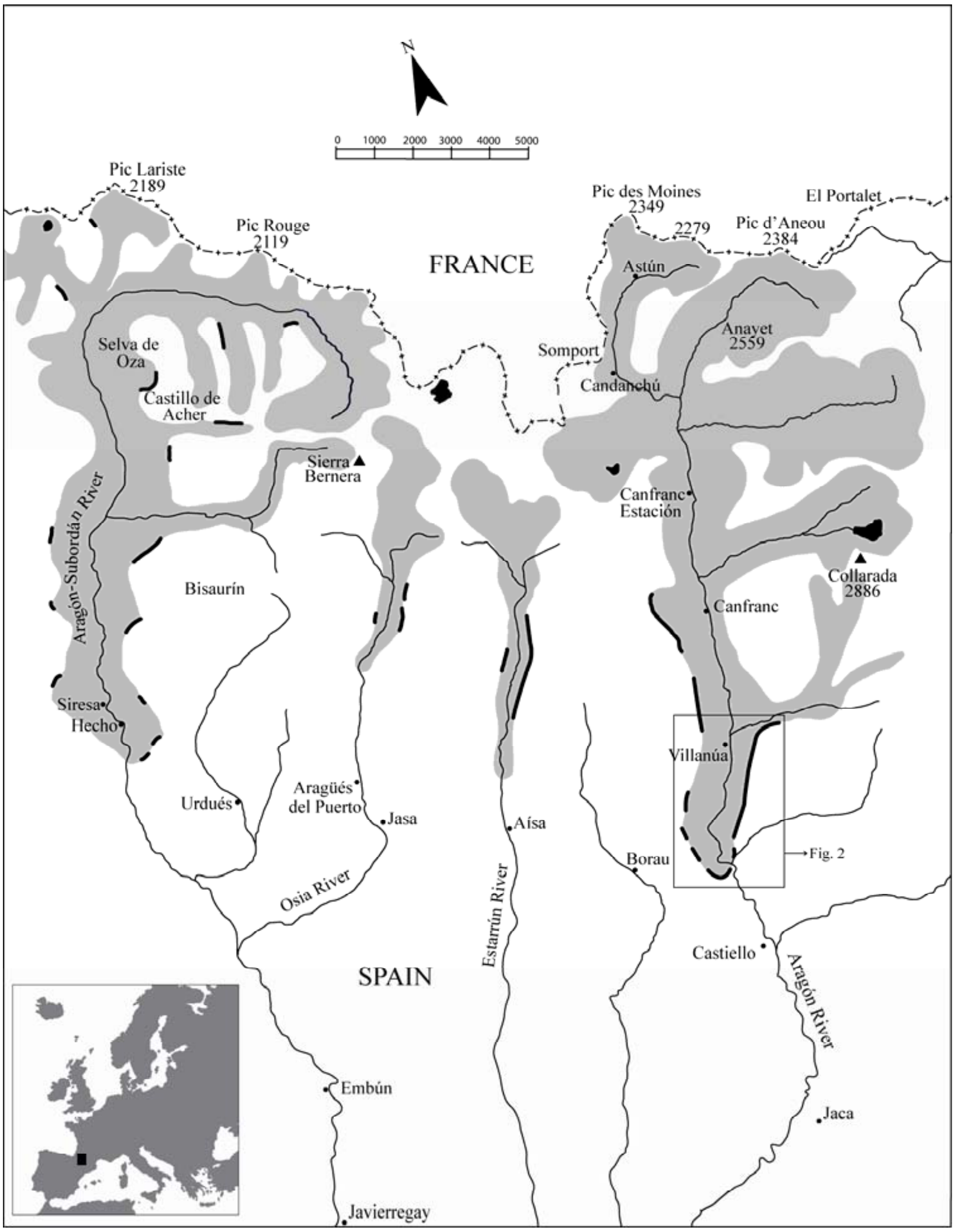
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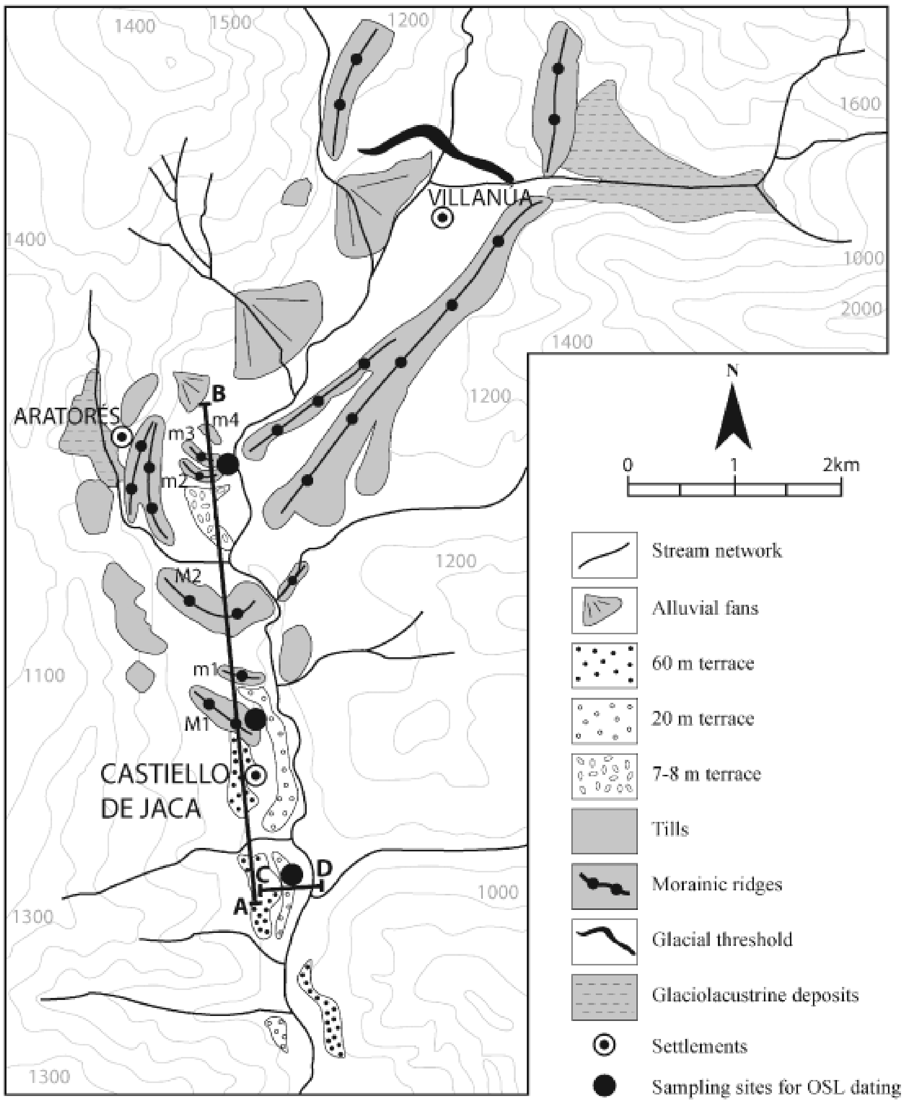
FIG.1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Stream network
Alluvial fans
60 m terrace
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Tills
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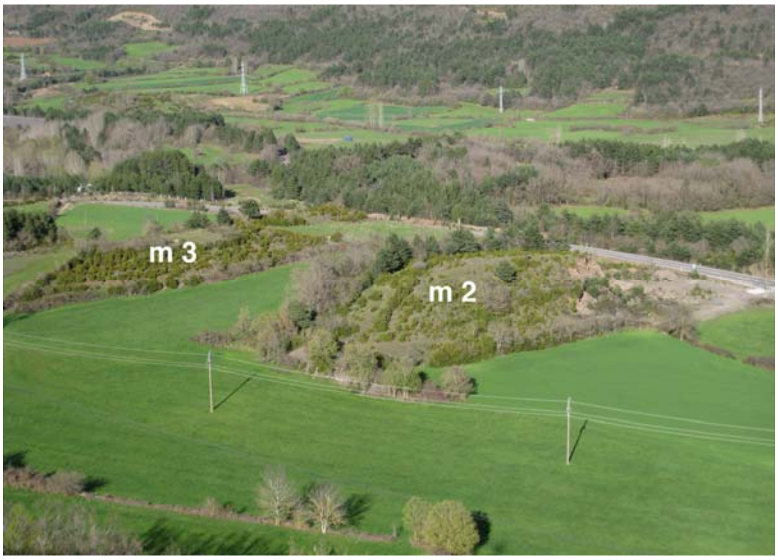
Glacial threshold
Glaciolacustrine deposits
Settlements
Sampling sites for OSL dating

Fig.2

Fig.3



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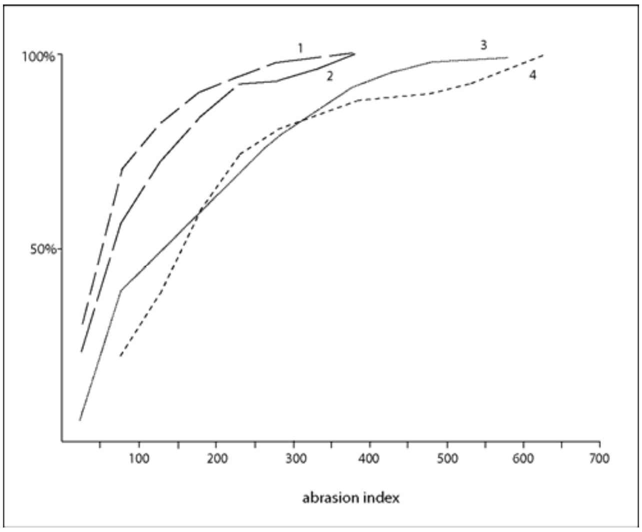
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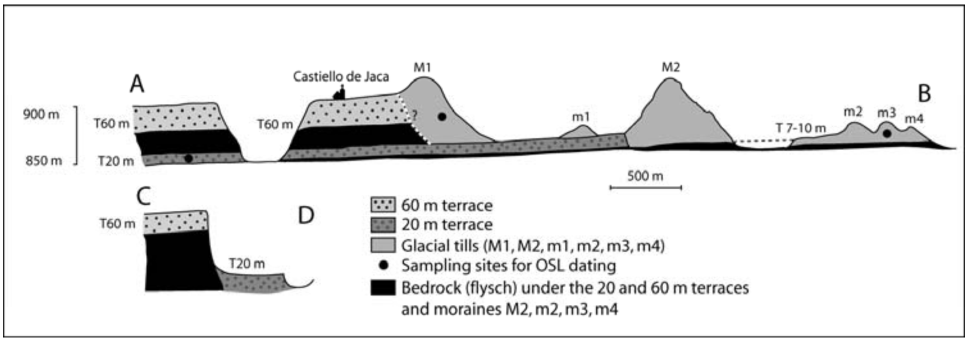
Fig. 5


A
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C
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Castiello de Jaca
M1
M2
m1
m2
m3
m4
900 m
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T 7-10 m
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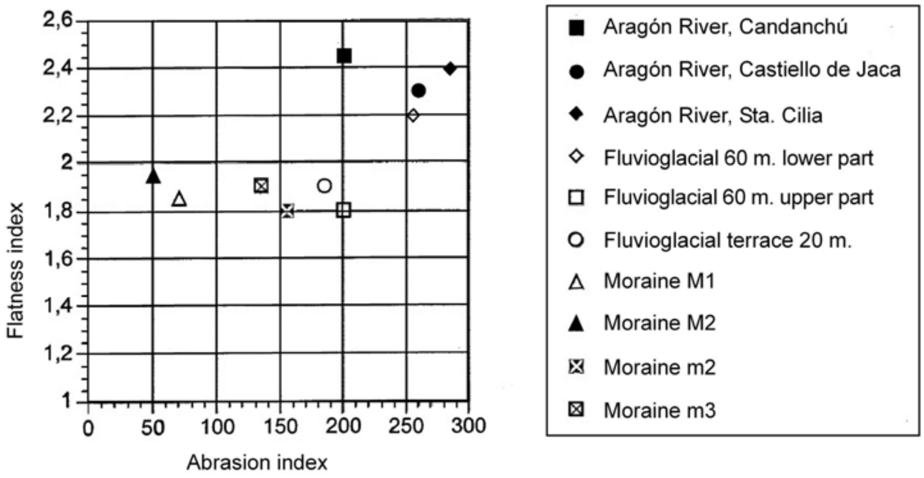
500 m
T60 m
T20 m
60 m terrace
20 m terrace
Glacial tills (M1, M2, m1, m2, m3, m4)
Sampling sites for OSL dating
Bedrock (flysch) under the 20 and 60 m terraces and moraines M2, m2, m3, m4

Fig. 6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250
300
Abrasion index
■ Aragón River, Candanchú
● Aragón River, Castiello de Jaca
◆ Aragón River, Sta. Cilia
◇ Fluvioglacial 60 m. lower part
□ Fluvioglacial 60 m. upper part
○ Fluvioglacial terrace 20 m.
△ Moraine M1
▲ Moraine M2
☒ Moraine m2
☒ Moraine m3

Fig. 7

Fig. 8

Fig. 9