LATE PLEISTOCENE DEGLACIATION IN THE CENTRAL PYRENEES: THE UPPER GÁLLEGO VALLEY

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Abstract

Deglaciation processes in the Upper Gállego Valley, central–southern Pyrenees, were studied using geomorphological mapping and ^{36}Cl cosmogenic dating of moraine and rock glacier boulders, as well as polished bedrock. Although the precise position of the Gállego Glacier during the global Last Glacial Maximum is not known, there is evidence that ice tongues retreated to the headwaters, which caused subdivision of the main glacier into a number of individual glaciers prior to 17 ka BP. A range of ages (16 to 11 ka BP) was found among three tributary valleys within the general trend of deglaciation. The retreat rate to cirque was estimated to be relatively rapid (approximately 5 km per ka). The mapped glacial sedimentology and geomorphology appears to support the occurrence of multiple minor advances and retreats, or periods of stasis during the late deglaciation. Geomorphological and geological differences among the tributary valleys, and error estimates associated with the results obtained, prevented unambiguous correlations of the advances with the Late Pleistocene cold periods. During the latter advances, small glaciers and rock glaciers developed close to the cirque headwalls, and co-occurred under the same climatic conditions. No evidence for Holocene re-advance was found for any of the three tributary valleys.

Keywords: Deglaciation, Cosmogenic dating, Oldest Dryas, Bølling/Allerød, Younger Dryas, Central Pyrenees

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Introduction

The term ‘last deglaciation’ refers to the period between the global Last Glacial Maximum (LGM) and the beginning of the Holocene (11.7 ka BP) (Darnault et al., 2012). The LGM can be defined as the global maximum ice volume recorded in the marine isotope records, and also by sea levels at approximately 23–19 ka BP. Peltier and Fairbanks (2006) dated the LGM at 26 ka, although it probably culminated at approximately 21 ka BP (Yokoyama et al., 2000; Mix et al., 2001). During the deglaciation period, the climate underwent a trend to warming interrupted by various cold, generally dry stadials that affected the extent of ice-sheets and valley glaciers (e.g. Combourieu-Nebout et al., 2009; Ballantyne, 2010; Fletcher et al., 2010). The study of deglaciation has focused on geomorphologically-derived aspects, such as the location and extent of glacial deposits during the various stadials, but also on climate aspects. Since the LGM, climate changes have been defined by their abrupt character, with sudden temperature increases and decreases that caused profound changes in vegetation distribution and landscape features in relatively short time periods (Combourieu-Nebout et al., 2009; Clark et al., 2012a). This highlights the instability of the Earth’s environmental conditions, and the need to investigate paleoclimate shifts to enable detection of early warning signals in the immediate future (Scheffer et al., 2001; Lenton, 2011).

Studies of deglaciation in the northern hemisphere have been carried out in various locations including the Laurentide, Scandinavian and British–Irish ice sheets (Bowen et al., 2002; Scourse et al., 2009; Ballantyne, 2010; Williams et al., 2012; Ballantyne et al., 2013), valley glaciers of the Alps (Ivy-Ochs et al., 2004a, 2006, 2008, 2009; Kerschner and Ivy-Ochs, 2008; Ravazzi et al., 2012; Hippe et al., 2014), the Tatra Mountains and the Carpathians (e.g. Makos et al., 2013), and in Mediterranean mountains (Akçar et al., 2007, 2014; Zahno et al., 2009; Giraudi, 2012). Ivy-Ochs et al. (2004a) reported that the Rhône piedmont glacier collapsed at 21–19.1 ka. By 18 ka more than 80% of the ice volume of the Alpine valley glaciers had disappeared. Deglaciation studies in the Iberian Peninsula have centered on the Sierra Nevada (Gómez-Ortiz et al., 2012), the Cantabrian Mountains (Moreno et al., 2010a, 2010b, 2012; Pellitero et al., 2011; Rodríguez-Rodríguez et al., 2014), the Central Range (Palacios et al., 2011, 2012a, 2012b), and both the Spanish (Jalut et al., 1992; González-Sampériz et al., 2006; Pallàs et al., 2006, 2010; Morellón et al., 2009; Moreno et al., 2012) and French (Bakalowicz et al., 1984; Jalut et al., 1992; Quinif and Maire, 1998;

Delmas, 2005; Delmas et al., 2008, 2011, 2012; Calvet et al., 2011) sides of the Pyrenees. These studies have been based on marine and lake sediment analyses, including high resolution pollen analysis (González-Sampériz et al., 2006), U–Th dating of speleothemes, and exposure dating using cosmogenic isotopes. These multi-proxy approaches have led to relatively detailed knowledge of the various climatic pulses that occurred during the deglaciation period, represented by glacial advances and retreats. Nevertheless, many of the studies have lacked a detailed geomorphological approach, particularly those based on the analysis of marine and lake deposits. For instance, this was the case for the Pyrenees, where distinct cold and warm stages over the last 30,000 years were detected and dated using the Portalet peat-bog (González-Sampériz et al., 2006), for which a chronological model was constructed with the corresponding vegetation model; these stages included the Heinrich Event (HE) 2, LGM, HE1, Oldest Dryas, Bølling, Older Dryas, Allerød, Younger Dryas and the 8.2 event. There is no information on where the glacier fronts were located during the stadials and interstadials, or the rate of glacial retreat, even though geomorphological mapping has shown the distribution of the main tills in the Pyrenees (Chueca et al., 1998; García-Ruiz and Martí-Bono, 2002; García-Ruiz et al., 2011). Surprisingly, for several valleys there is much information on the location and dating of glacier fronts during the local Maximum Ice Extent (MIE) of the last glacial cycle. Amongst these are the Cinca (Lewis et al., 2009), the Gállego (García-Ruiz et al., 2003), the Aragón (García-Ruiz et al., 2013), the Ariège (Delmas et al., 2011), the Têt (Delmas et al., 2008) and the Querol (Pallàs et al., 2010) valleys; the latter two studies included information on deglaciation stadials. Several methods, including optically stimulated luminescence (OSL) dating, cosmogenic exposure ages, U–Th series and ^{14}C , have been used to date deposits (tills and lacustrine sediments), stalagmite growth, and, in the case of cosmogenics, boulders deposited by glaciers and polished surfaces.

Exposure age chronology has been used in dating glacial stages in the northern (Delmas et al., 2008, 2011) and eastern (Pallàs et al., 2010) Pyrenees, where it has contributed to identifying the occurrence of an early local MIE, distinguishing deposits of different ages over very short distance. This dating method has not previously been used in the central–southern Pyrenees, except for the Noguera Ribazgorzana Valley (Pallàs et al., 2006). In this study we dated deglaciation in the Upper Gállego Valley, based on exposure age chronology and geomorphological evidence; this is one of the most important and extensively studied valleys in the Pyrenees (Barrère, 1966; Serrano-

Cañadas, 1991, 1998; Martínez de Pisón and Serrano, 1998; Julián et al., 2000; López-Moreno, 2000; García-Ruiz et al., 2003; Peña et al., 2003; González-Sampériz et al., 2006). Among these studies, mapping of the glacial deposits and landforms corresponding to distinct glacial periods has been conducted; few were dated, but those that were correspond to the local MIE. In this study, surface exposure ages were obtained from 6 moraine boulders, 8 rock glacier and paraglacial boulders and 7 polished bedrock surfaces in small valleys of the Panticosa massif, a granitic batholith located in the northeastern sector of the Upper Gállego Valley (Fig. 1).

The main purpose of this study was to investigate deglaciation processes in the study area using analysis based on cosmogenic exposure dating (CED), including the retreat of glaciers and the occurrence of short advances with the deposition of new relatively recent tills, and to compare the results with those obtained elsewhere in the Pyrenees, the Iberian Peninsula and western Europe.

Local MIE and global LGM in the central–southern Pyrenees

Figure 2 shows the distribution of till deposits in the Upper Gállego Valley, focusing on those belonging to the maximum expansion of the ice tongue. The local MIE is represented by several tills located between Biescas and Sabiñánigo (particularly the presence of dispersed boulders near Sabiñánigo), two small remnants in the mouth of the Aurín River, and the large terminal moraine of Senegüé (Barrère, 1966; Serrano-Cañadas, 1991, 1998; Peña et al., 2003; García-Ruiz et al., 2011). Lateral moraines (2–3) indicate the maximum ice development, with an ice thickness of approximately 400 m in the vicinity of Biescas and a substantial decrease in thickness towards Sabiñánigo. Many other tills representing the MIE are apparent upstream of Biescas. Using OSL dating techniques, Lewis et al. (2009) dated the end tills of Sabiñánigo, Aurín and Senegüé at 85 ± 5 ka, 64 ± 11 ka and 36 ± 3 ka, respectively, and showed good correspondence with the dates of fluvial terraces. González-Sampériz et al. (2006) also dated the MIE to earlier than 32–33 ka, based on sediments from the Portalet paleolake in the Gállego glacier headwalls. These dates are consistent with those obtained recently in the Aragón and Cinca valleys (Lewis et al., 2009; García-Ruiz et al., 2013), and in the eastern Pyrenees (Pallàs et al., 2010; Delmas et al., 2011, 2012), confirming the occurrence of a large glacial expansion during Marine Isotopic Stage (MIS) 4.

There is no clear evidence of the LGM in the Gállego Valley and neighboring Pyrenean valleys, as no tills of the global LGM have been found. Nevertheless, the

LGM has been accurately identified in other Pyrenean valleys, including the Carol (Calvet, 2004; Delmas, 2009), Ariège (Jalut et al., 1992; Delmas, 2009) and Têt (Delmas et al., 2008; Delmas, 2009) valleys. A review by Calvet et al. (2011) includes a map showing the glaciated areas in the Pyrenees during the Würmian period. High-resolution multi-proxy analysis of the Portalet paleolake sediment enabled detection of the occurrence of a cold period involving glacial advance between 22,500 and 18,000 cal yr BP, during the global LGM (González-Sampériz et al., 2006). In addition, the base of a glaciolacustrine filling in a sinkhole near Búbal, 15 km upstream of the Senegüé moraine in the Gállego Valley, provided a ^{14}C age of $20,800 \pm 400$ yr BP (i.e. 25,928–23,182 yr cal. BP) (Jalut et al., 1992), suggesting that the front of the Gállego glacier was located near the sinkhole during the LGM (Delmas, 2009). However, the Gállego glacier had retreated to the headwater by $20,150 \pm 150$ yr BP, as deduced from the occurrence of a large landslide and a dammed paleolake (the Corral de las Mulas peatbog) near the uppermost sector of the Gállego Valley (García-Ruiz et al., 2003).

Indirect evidence of a cold and geomorphologically active period has been found in the fluvial terraces of the Alcanadre River, between the Gállego and the Cinca rivers. Terrace Qt6 yielded an OSL age of 19 ± 2 ka, whereas Qt5 yielded an OSL age of 44 ± 2 ka (Calle et al., 2013). A cold and dry period was detected in a loess deposit in the Cinca Valley, with an OSL age of 20 ± 3 ka, and stratified screes located near the front of the MIE Cinca glacier gave an age of $22,800 \pm 200$ ^{14}C yr BP (27,490 cal yr BP; CALPAL) (García-Ruiz et al., 2001).

The study area

The Upper Gállego Valley drains a large part of the central–southern Pyrenees (northeast Spain), and has a complex drainage area composed of various main and secondary valleys (Fig. 1). The study area is in the northeastern part of the basin, where the largest valleys and the highest peaks are located, including Balaitus ($42^{\circ}46'02$ N, $0^{\circ}15'02$ W, 3151 m), Infierno (3082 m) and Argualas (3046 m). The Aguas Limpias and Caldarés valleys penetrate deeply into the highest reliefs, forming a series of tributaries that were occupied by cirques and glacial tongues. This headwater was selected because of the presence of a variety of tills corresponding to the glacial stades that followed the Würmian MIE. The presence of an extensive granitic batholith was also a factor in the selection of this area, as granite is associated with the occurrence of

well-preserved polished surfaces and boulders, which are useful for cosmogenic sampling and analysis.

The Upper Gállego Valley is composed of two of the main structural units of the southern Pyrenees: (i) the Axial Paleozoic Pyrenees; and (ii) the south Pyrenean alpine fold and thrust belt. The former is composed of Silurian, Devonian, Ordovician and Carboniferous marine sediments, which were folded during the Hercinian tectonics (Carboniferous) and have schist, shale and limestone as the predominant materials. At the end of the Hercinian tectonics, two large granitic batholiths (Panticosa and Cauterets) were inserted through the already folded Paleozoic lithologies, causing the development of contacting metamorphic aureoles around the batholiths. Within the Paleozoic sector, limestone outcrops evolved towards small isolated massifs limited by cliffs, whereas shale outcrops developed large deep-seated landslides (Guerrero et al., 2013) that were related to deglaciation. The relief is characterized by wide and relatively smooth valleys having undulated slopes locally affected by badlands. The granitic batholiths evolved into high and steep massifs, with acute divides characterized by the presence of large, rounded, generally over-deepened glacial cirques occupied by lakes (García-Ruiz et al., 2000). Each valley accounts for several glacial troughs, developed at the confluence of two glacial valleys and delimited downstream by thresholds where the bedrock appears to be polished. Small-scale landforms are, in general, very well conserved.

The Alpine Pyrenees is composed of marine Mesozoic and Cenozoic sediments, including Maastrichtien sandstone, and Cretaceous and Eocene limestone, forming a long and narrow ridge oriented from west to east: the so-called Inner Sierras. The Alpine tectonics resulted in stacking of a large south-verging overthrusting anticline, forming a dramatic vertical cliff on the north-facing slope, and complex structural reliefs on the south-facing slope, corresponding to the evolution of the front of the anticline.

The climate of the Upper Gállego Valley is markedly influenced by Atlantic Ocean air masses, although a transition towards Mediterranean influences is evident. The study area receives average annual precipitation of >1200 mm, and >2000 mm above 2000 m a.s.l. The precipitation gradient is 0.94 mm m⁻¹ (de la Riva, 2000). The seasonal maximum precipitation occurs in winter, whereas the minimum occurs in summer. A consistent negative trend in snow accumulation in March and April has been observed since at least the middle of the 20th century (López-Moreno, 2005). The

temperature gradient is $0.37^{\circ}\text{C } 100 \text{ m}^{-1}$ in January and December, and $0.54^{\circ}\text{C } 100 \text{ m}^{-1}$ in August (de la Riva, 2000). The 0°C isotherm in winter is located at 1611m. The mean annual temperature is 6°C at Balneario de Panticosa (1620 m a.s.l.), 8°C at Lanuza (1283 m) and 9°C at Búbal (1150 m). Since the end of the Little Ice Age (LIA) a temperature increase of approximately 0.9°C has been estimated (López-Moreno, 2000).

Methods

A geomorphological survey of glacial forms and deposits was carried out in the Upper Gállego Valley. The resulting geomorphological map was the basis for identifying the most suitable sites to sample for ^{36}Cl dating. Samples were collected (hammer and chisel) from moraine and rock glacier boulders $> 1 \text{ m}$ wide located on stable, gently sloping surfaces. Samples were also taken from areas: (i) of well-preserved glacial polish on bedrock steps, particularly at protruding sites, to reduce the possibility of sediment cover and to minimize the effect of snow cover; (ii) of clear glacial polish, to ensure that the rock had not been eroded since deglaciation; and (iii) located where the former glacier was thick (thus maximizing erosion of the pre-glacial surface, and minimizing the chance of ^{36}Cl inheritance).

The study area is drained by the Aguas Limpias and Caldarés rivers, which are the two main tributaries of the Gállego River in its headwater. The five areas described below were selected for the sampling needed to investigate CED (Fig. 1).

(i) The Respumoso Cirque area, in the Upper Aguas Limpias Valley. This is a wide valley in the headwater (Respumoso Lake), although it incises deeply into the granite downstream of the lake, forming a narrow canyon with some thresholds where polished granite occurs. The northern side of the valley received the ice tongues from the Balaitus massif, where a number of small glaciers remained until 25 years ago.

(ii) The Balneario de Panticosa resort area, in the Upper Caldarés Valley. Between Balneario de Panticosa and Bachimaña Lake the valley is very steep, and includes several glacial troughs where polished and striated granite occurs at several points. No significant glacial tills have been found in this area, which has mainly been dominated by glacial erosion.

(iii) The Lower Bolatica Valley, which is the main tributary of the Caldarés River. This valley contains glacial tills in its lower course. A large till is present on the left side of the valley, at approximately 400 m above the valley bottom. These deposits rest on a steep slope and are being intensively eroded, and so cannot be used to calculate

the CED. Other deposits, located less than 100 m above the valley bottom, belong to a period of glacial advance or stabilization following the LGM, and were deposited by the glacial tongue of the Caldarás Valley. Some of these deposits rest on horizontal surfaces of thresholds and are very stable, and are therefore suitable for CED analysis.

(iv) The Catieras Cirque, in the Upper Bolatica Valley. This is a glacial cirque developed on Devonian shale. The cirque tends to be rounded and remains perched 350 m above the main valley. A lake is located on the flat bottom of the cirque (which also has recent tills and a small rock glacier), far from the activity of the walls.

(v) The Piniecho Cirque, also in the Upper Bolatica Valley. This is also a glacial cirque developed on granite bedrock. It contains a variety of very recent glacial deposits (rock glaciers; end and lateral moraines of different ages) within a small area, suggesting the occurrence of rapid climatic and geomorphological shifts. The moraine ridges and the front of the rock glacier rest on flat steps; they are not affected by the activity of the walls and are suitable for CED dating.

(vi) No suitable blocks for CED dating were found in lateral moraines from the MIE on the lateral slopes of the Gallego River, as the moraines are intensively eroded and/or covered by slope deposits. Only some blocks protrude, but they seem to have been exposed by agricultural activity.

We selected the ^{36}Cl cosmogenic nuclide because our research generally concerned the glacial chronology of different mountain areas, some of which do not have rocks suitable for analysis using other nuclides (e.g. ^{10}Be or ^{26}Al). In addition, other tributaries of the Gállego River are formed on limestone rocks, and the use of ^{36}Cl will enable comparative analyses of results in future studies. In addition, in areas where conditions are similar to those of our study the use of ^{36}Cl has yielded results that are consistent with those derived from ^{10}Be analysis (e.g. Phillips et al. 1997; Brugger, 2007).

The laboratory procedures for ^{36}Cl analysis in whole rock (Zreda et al., 1999; Phillips, 2003) were followed. Whole rock samples were crushed and pulverized using a roller grinder. Then they were sieved to separate the sand size fraction, and leached in deionized water and HNO_3 to remove atmospheric Cl. Next they were dissolved in a hot mixture of hydrofluoric and nitric acids, and AgNO_3 was added to the solution to precipitate AgCl . The isobar ^{36}S was separated by precipitating BaSO_4 . A spike of isotopically enriched ^{35}Cl was added during the dissolution process. This isotope dilution mass spectrometry method enabled the sample Cl content to be determined

from accelerator mass spectrometry (AMS) analysis (Ivy-Ochs et al., 2004b; Desilets et al., 2006). The AMS analysis of the $^{36}\text{Cl}/\text{Cl}$ and $^{37}\text{Cl}/^{35}\text{Cl}$ ratios in the AgCl targets was carried out at the PRIME Laboratory (Purdue University, USA). The ^{36}Cl data is presented in Table 1.

Aliquots of rock, pre-treated (bulk rock) and post-treated (target fraction), were powered and analysed for: (i) major elements, using fusion inductively coupled plasma optical emission spectrometry (ICP-OES); (ii) trace elements, using inductively coupled plasma mass spectrometry (ICP-MS); and (iii) boron, using prompt-gamma neutron activation analysis (PGNAA) at the Activation Laboratories (Ancaster, Canada). The element concentration of bulk rock and target fraction are listed in Table 1.

The exposure ages were calculated using the spreadsheet for in-situ ^{36}Cl exposure age calculations proposed by Schimmelpfennig (2009) and Schimmelpfennig et al. (2009). We used the cosmogenic ^{36}Cl production rates for Ca spallation by Stone et al. (1996) (48.8 ± 3.4 atoms ^{36}Cl (g Ca) $^{-1}$ a $^{-1}$) for K spallation by Schimmelpfennig et al. (2014) (148.1 ± 7.8 atoms ^{36}Cl (g K) $^{-1}$ a $^{-1}$) for Ti spallation by Fink et al. (2000) (13 ± 3 atoms ^{36}Cl (g Ti) $^{-1}$ a $^{-1}$), and for Fe spallation by Stone et al. (2005) (1.9 atoms ^{36}Cl (g Fe) $^{-1}$ a $^{-1}$). The production rate of epithermal neutrons from fast neutrons in the atmosphere at the land/atmosphere interface by Phillips et al. (2001) (626 ± 46 neutrons (g air) $^{-1}$ a $^{-1}$) was applied.

The “in situ” accumulation of ^{36}Cl depends on various factors including latitude, elevation, sample thickness, surrounding topography and snow cover. The elevation–latitude scaling factors for nucleonic and muonic production have been evaluated using CosmoCalc (Vermeesch, 2007), based on the scaling model of Stone et al. (2000). The shielding factor has been calculated using the Topographic Shielding Calculator v1.0 of CRONUS-Earth Project (2014).

Snow cover (thickness and density) reduces cosmogenic nuclide production rates in bedrock by 12–14% (Benson et al., 2004; Schildgen et al., 2005). Recent studies, combining in situ ^{14}C and ^{10}Be dating methods, have demonstrated that partial surface shielding by snow has to be incorporated in the exposure age calculations and in models of deglaciation (Ivy-Ochs et al., 2009; Hippe et al., 2014). In the present study, many samples were collected from the valley bottom near summit areas, where substantial variation in snow cover occurs over very short distances because of factors including slope, aspect, wind redistribution and local topography variability. To evaluate the effect of snow, we calculated the ages without considering the effect of the

snow cover. As an alternative, to minimize the effects of snow cover we calculated the shielding factor, based on the snow cover distribution in the Gállego Valley reported in previous studies (López-Moreno, 2005; López-Moreno et al., 2010, 2013a, 2013b), and applied the equation proposed by Gosse and Phillips (2001). This yielded snow shielding factor values ranging from 0.86 to 0.98 among the samples, depending on the altitude, surface shape and local topography at the sampling location. The snow cover value applied was based on snow conditions at the time of measurement. A factor not considered in the evaluation of our results was the different evolution of snow cover during the Late Pleistocene and Holocene, which were periods of very short-term glacial change.

Results

The cosmogenic exposure results are summarized in Table 2 and Figure 3. All the parameters considered are included in the supplementary material. For cosmogenic dating of moraines corresponding to the maximum MIE (MIS 4) advances of the Upper Gállego Valley glacier, moraine boulders on stable sites were selected for sampling according to the geomorphological map. A number of boulders were found on the oldest glacial deposits, but the surfaces had been affected by proglacial melt-out waters or hillslope processes, and none were undisturbed. However, the results for the boulder samples confirmed the field observations, suggesting that the boulders had been exhumed. For instance, the samples GAVIN-2 (42°36'44.802"N; 0°17'54.83"W) and GAVIN-3 (42°36'44.40"N; 0°17'53.89"W), from the outermost moraine, yielded ages of 5.3 ± 0.3 ka and 3.0 ± 0.4 ka, respectively. Consequently, these results were not included, and suggest that cosmogenic methods may not be suitable for dating the MIE and LGM stages in the Upper Gállego Valley because of redistribution of boulders.

The first evidence of deglaciation was apparent upstream of the Búbal reservoir, where two tills indicated the occurrence of a stage during which the glacier was dissociated into two independent glacial tongues: the Aguas Limpias and the Caldarés glaciers (Serrano-Cañadas, 1991). At that time, only two of the three main valleys in the Upper Gállego Valley (the Aguas Limpias and the Caldarés valleys) were occupied by ice tongues. The third, in the headwater of the Gállego Valley, was almost completely deglaciated because of the low altitude of the divides (< 2300 m a.s.l.) relative to the other two valleys (> 3000 m). The dissociation is demonstrated by the presence of lateral tills located at low altitude (< 100 m above the valley bottom) in Lanuza

(deposited by the Aguas Limpias glacier), and close to Panticosa, deposited by the Caldarés glacier in the lower course of its main tributary, the Bolatica Valley (Fig. 2). The presence of moraine ridges with granite blocks, which are oriented north to south at El Formigal, indicates that they were deposited by a glacier that came from the Aguas Limpias Valley. Consequently, the Gállego glacier was spatially restricted to higher altitudes. The Aguas Limpias glacier penetrated 2 km into the Gállego Valley, leaving the lateral moraines. Thus, the ice tongue of the Aguas Limpias glacier widened markedly, favouring a rapid decrease in thickness and melting of the glacier 3 km downstream of Sallent (Fig. 2).

All these moraines were unsuccessfully searched for boulders for sampling. Tills adjacent to the Lanuza and Búbal reservoirs are intensively disturbed by post-glacial erosion, and cannot be dated by cosmogenic methods. In addition, there are no thresholds having glacial polish, because the limestone and shale outcrops have been highly eroded.

However, in the middle and upper stretches of the Aguas Limpias Valley (Figs. 4 and 5), which is incised on granite, there are several glacial thresholds and troughs in the valley bottom. Three samples were collected from the best polished surfaces and dated: RES-1 (14.6 ± 2.3 ka), located at 1525 m a.s.l.; RES-2 (11.7 ± 1.7 ka), located at 2132 m; and RES-3 (12.3 ± 1.6 ka), located at 2169 m near the cirque wall.

To analyse deglaciation in the tributaries of the Upper Gállego River we collected samples from the Caldarés Valley, which is also on granitic substratum. A stable moraine was found at the confluence of the Caldarés River and its main tributary, the Bolatica River. The two more stable large protruding granite boulders on this moraine yielded a minimum age of 13.9 ± 2.0 ka (PANTI-01) (Fig. 6) and 21.9 ± 2.4 ka (PANTI-02).

The Caldarés Valley has similar characteristics to the Aguas Limpias Valley in having polished granitic thresholds in the valley bottom (Fig. 7 and 8). Three clear polished surfaces were sampled: one at Balneario de Panticosa, located at 1653 m (PANTI-21: 12.2 ± 1.5 ka); one at the front of the Bachimala Cirque, located at 1844 m (PANTI-22: 12.8 ± 1.4 ka); and one at the bottom of the Bachimala Cirque, located at 2218 m near the headwall (PANTI-23: 13.9 ± 1.8 ka).

The results obtained from the Aguas Limpias and Caldarés valleys were very homogeneous. The date from the moraine and from the six thresholds can be considered a minimum age. Therefore, the results support the hypothesis that a glacial advance

occurred in the tributary valleys, but the time that this occurred cannot be accurately determined because of the difference between the results for the two boulders in the moraine (PANTI 1 and PANTI 2), and the large error rate. In particular, the age determined for sample PANTI-2 (almost 22 ka) appears excessive considering its context, which could be because of a problem in cosmogenic heritage, as this boulder is located only 2 km from the headwall. Following this advance the valleys were deglaciated, and were completely ice-free at approximately 12–14 ka ago.

The results suggest that the glaciers have not overstepped the base of the headwalls during the last 14 ka. To study the subsequent glacial evolution in these upper mountain areas, exposure ages were obtained in the Piniecho and Catieras glacial cirques, which are in tributaries of the Bolatica River.

The Piniecho cirque is composed of three cirques that had almost independent glacial development during the final deglaciation. It has a large variety of glacial-related deposits associated with valley tongues, small glaciers close to the cirque headwall, rock glaciers and a protalus lobe (Figs. 9, 10, 11 and 12). Figure 9 shows the geomorphological map of the Piniecho cirque, where six types of glacial deposit (described below) have been identified.

(i) The oldest deposit, based on its geomorphological position, is a large lateral moraine. The height of the moraine is 150 m high in the upper part, and this rapidly decreases downstream. The lower part of the moraine has disappeared, although it probably extended a further 350–500 m to the end of the glacier. This glacier would have had a total length of approximately 1500 m from the headwall, occupying two of the cirques and the main stem of the Piniecho Valley. The moraine ridge appears to have been interrupted by minor posterior glacial advances from the headwall. A very large granite block was sampled at 2319 m a.s.l. (PANTI-18), and was found to have a ^{36}Cl exposure age of 15.5 ± 1.8 ka. The advance in the Piniecho Cirque must have been much more limited in extent than in the Aguas Limpias and Caldares valleys, as it was derived from mountains that were 500 m lower in altitude.

(ii) Following retreat of the Piniecho ice tongue, two small tongues developed from the northern and central cirques. The northern tongue was approximately 450–500 m in length, with a clear frontal end cut by a ravine, and the central tongue would have been approximately 700 m in length. No boulders suitable for cosmogenic exposure age analysis were available in any of the moraines, and consequently they have not been dated.

(iii) Two small rock or moraine-derived glaciers developed from the southern slope of the cirque. They are composed of various arcs and vallums. The innermost part of these rock glaciers is occupied by depressions containing small lakes and a chaotic rock avalanche. Two boulders were sampled in the upper part of the arcs in the western rock glacier: PANTI-16 (^{36}Cl exposure age of 13.1 ± 1.8 ka) and PANTI-17 (11.7 ± 1.7 ka). Three boulders were also sampled in the eastern rock glacier: PANTI-10 (16.8 ± 2.4 ka), PANTI-11 (14.7 ± 3.5 ka) and PANTI-12 (11.5 ± 1.5 ka). The differences in age between boulders within each of the rock glaciers may be related to later movement of the boulders. This could have occurred as a result of collapses because of later ice melting that caused displacement of the boulders.

(iv) A glacial advance from the headwall probably occurred contemporaneously with development of the rock glaciers. This advance caused the formation of a wavy moraine corresponding to two small ice tongues. Two boulders were sampled on the ridge of this moraine (PANTI-13: 19.1 ± 2.8 ka; and PANTI-14: 13.5 ± 1.8 ka). Another boulder (PANTI-15: 12.3 ± 1.7 ka) was sampled in a relatively isolated body of the moraine, which apparently developed in a later period. Heritage is possible in the case of PANTI-13, because of its proximity to the headwall.

(v) At the foot of the southern cirque there is a relatively complex lobate protalus lobe related to rock avalanches; this has various ridges that show an initial trend towards a rock glacier. Three boulders were sampled at this site: PANTI-7 (11.1 ± 1.3 ka), PANTI-8 (14.3 ± 1.7 ka) and PANTI-9 (12.9 ± 2.4 ka).

(vi) A rock glacier developed in the western sector of the Piniecho Cirque area, and has several arcs composed of large boulders. The rock glacier is derived directly from a scarp in the valley wall, and probably formed following retreat of the main ice tongue of the Piniecho cirque. Two boulders were sampled on the ridges: PANTI-19 (12.6 ± 1.6 ka) and PANTI-20 (14.8 ± 1.9 ka).

There are other deposits within the Piniecho cirque. For instance, an alluvial fan and a large debris flow are present in the northern part of the cirque, perhaps related to the collapse of a moraine ridge. The headwall of the central cirque is affected by numerous debris flows and their corresponding levees, and the cirque and valley walls are covered with screes that are still active.

There are fewer glacial features in the Catieras Cirque (Fig. 13 and 14). A small rock glacier 200-m in length is derived from the western headwall. A block sampled in the front of the glacier (PANTI-4) yielded a ^{36}Cl minimum exposure age of 12.5 ± 1.3

ka, indicating that it is similar in age to the rock glaciers in the Piniecho Cirque. A block of small moraine close to the rock glacier (PANTI-5) yielded a ^{36}Cl minimum exposure age of 10.9 ± 1.2 ka. A rocky threshold with a well-preserved glacial polish (PANTI-6), located 100 m below the rock glacier yielded an age of 18 ± 1.9 ka.

In summary, the glacial dates obtained from the Piniecho and Catieras cirques are consistent with those obtained from the Aguas Limpias and Caldarés valleys. The moraines that delimited this advance appear to be somewhat younger than the thresholds, probably because of the time involved in the moraine reaching complete stabilization. A later retreat culminated at approximately 14 ka ago, and there were subsequent small local advances near the cirque headwall. These glacial advances were contemporaneous with the development of rock glaciers. The minimum ages determined for these moraines were approximately 11 ka. No evidence of new glacial advances or rock glacier development since 11 ka has been found, except for some cases related to the LIA.

Discussion

A number of studies have revealed the location of most of the end and lateral moraines in the main valleys of the central–southern Pyrenees, particularly the Aragón (García-Ruiz et al., 2013), Aragón Subordán (García-Ruiz and Martí-Bono, 2011), Cinca (Lewis et al., 2009), Gállego (Barrère, 1966; Peña et al., 2003; Lewis et al., 2009; García-Ruiz et al., 2011), and Noguera Ribagorzana and Carol (Pallàs et al., 2006, 2010) valleys. It is noteworthy that the MIE end moraines and their corresponding fluvial terraces have been dated as belonging to the MIS 4 and MIS 3. Similar findings have been reported for other localities in northern Spain, particularly the Cantabrian Range (Moreno et al., 2010b; Frochoso et al., 2013; Jiménez-Sánchez et al., 2013; Serrano et al., 2013). This is consistent with other chronologies reported for certain Mediterranean mountains (Hughes et al., 2006; Hughes and Woodward, 2008). In the case of the central-southern Pyrenees, few clear manifestations of the global LGM have been found, although some indirect results obtained from fluvial terraces, stratified screes and glacio-lacustrine sediments confirm a glacial advance at approximately 20–22 ka, but of consistently lesser extent than the local MIE.

This study focused on deglaciation processes in the Upper Gállego Valley, using exposure ages from granitic moraine boulders and polished bedrock. The results highlight the occurrence of several climatic pulses since the global LGM, and the

sensitivity of small glaciers to climate variability. The dating method used enabled us to detect distinct groups of glacial deposits and thresholds, and to identify some of the main glacial events during the complex period of deglaciation.

Cosmogenic dating methods, based on the cosmogenic isotope ^{10}Be , have previously been used in the study of glacial evolution in the Pyrenees, including in other valleys of the central–southern sector (Pallàs et al., 2006), in the southeastern sector (Delmas et al., 2008; Pallàs et al., 2010) and in the northeastern sector (Delmas et al., 2011). The main difficulty in comparing the results of these studies with those of the present study lies in differences in the snow cover depth and duration: in some cases in the earlier studies an absence of snow cover was assumed, even for samples taken near the summit (Pallàs et al., 2006, 2010), and in other cases a uniform snow cover was assumed (50 cm during 6 months), regardless of the altitude (Delmas et al., 2008, 2011). This is important because the ages obtained from exposure to cosmogenic radiation can vary up to 15% based on the snow cover conditions assumed (Benson et al., 2004; Schildgen et al., 2005; Ivy-Ochs et al., 2009; Böhlert et al., 2011; Stroeve et al., 2011; Hippe et al., 2014). In spite of these limitations, our results are consistent with others based on cosmogenic methods in the Pyrenees.

The interpretation of the results of this work was limited by the large error rate. We considered all factors that could affect the results, except large post-glacial erosion and cosmogenic heritage. Both these factors were minimized by use of the polished thresholds, which supported high erosion rates at the bottom of the valleys and preserved the glacial surfaces. However, these factors could be important in morainic blocks, particularly those at the bottom of valleys, including the Bolatica Valley (samples PANTI-1 and PANTI-2), which have been subject to extensive post-glacial erosion. In addition, it is necessary to add the time involved in moraine stabilization (Putkonen and O’Neal, 2006; Houmark-Nielsen et al., 2012) in estimating absolute ages. Based on its geomorphological position, the same age could be expected for the Lanuza moraine, in the Aguas Limpias Glacier, and based on the threshold ages we assume that by approximately 18–16 ka the ice tongues from the Aguas Limpias and Caldarés valleys had already separated (Fig. 2). This has been referred to as the “disjunction phase” in the glacial evolution of the Upper Gállego Valley (Barrère, 1966; Serrano-Cañadas, 1991) or “break up stage” in the eastern and northern Pyrenees (Delmas et al., 2008, 2011).

Similarly, the Gállego Glacier (highest divide not exceeding 2300 m) had retreated to the headwater, and was probably reduced to small ice masses in the cirques (González-Sampériz et al., 2006). For this reason the Aguas Limpias Glacier penetrated into the Gállego Valley, leaving at least two lateral moraine ridges. Previous studies have reported an early deglaciation in the Gállego Valley, particularly the occurrence of deep-seated landslides as a consequence of glacial retreat, which occurred as early as 20,120 ¹⁴C yr BP (García-Ruiz et al., 2003).

As indicated by indirect evidence, this suggests that the Gállego Glacier expanded during the global LGM, then retreated to the headwater. A new cold period could have represent an advance of 10–12 km for each individual glacier. This left tills at Lanuza and in the Lower Caldarés Valley, although the advance was not so great as to result in a new glacial junction. It is noteworthy that evidence of this glacial push has also been detected in the Piniecho Cirque. Using minimum ages for mid valley sites, the rate of retreat to the cirque was relatively rapid (estimated to be approximately 5 km per ka).

The diversity of results and the large error rate make it difficult to relate this advance to a specific Late Pleistocene cold period. Based on correlations with other proxies and the results found, one hypothesis worthy of testing in future research based on expanded sampling is that this period of glacial re-advance is related to the Oldest Dryas (Heinrich Event 1, the Gschnitz Stadial in the Alps, and the “Mystery Interval”; Denton et al., 2006). This was an extremely cold and dry period between approximately 18 and 14.5 ka, when vegetation returned to its glacial state (Clark et al., 2012a), and represents a clear period of glacial advance following several millennia of retreat. This advance coincided with a very cold and dry period reported for the Mediterranean basin (Dormoy et al., 2009; Fletcher et al., 2010), the Iberian Peninsula (Morellón et al., 2009; González-Sampériz et al., 2013) in lacustrine sediments in the pre-Pyrenees and the Iberian Range, and the Cantabrian Mountains (Pellitero et al., 2011), where rock glaciers developed. In the Alps, precipitation was 1/3 of current levels, and the summer temperature was 10° lower than now (Ivy-Ochs et al., 2006).

A similar advance during the Oldest Dryas has been reported for southern–central, eastern and northern Pyrenean valleys (Pallàs et al., 2006; Delmas et al., 2008, 2011). Moraines of this period have also been dated in the central (Palacios et al., 2011, 2012a, 2012b) and northwestern Iberian Peninsula (Rodríguez-Rodríguez et al., 2014). The Oldest Dryas moraines are common in many other Mediterranean mountains,

including in the Anatolian Peninsula (Sarıkaya et al., 2008; Zahno et al., 2010; Akçar et al., 2014), the Balkans (Kuhle et al., 2013), the Apennines (Giraudi, 2012) and the Italian Maritime Alps (Federici et al., 2012). In the central Alps the moraines of the Gschnitz Stadial glaciers were formed between 17–16 ka and 15.5 ka (Ivy-Ochs et al., 2006, 2008). Major advances also occurred in this period in the Tatra Mountains (Makos et al., 2013), and almost reached the LGM position in the Scandinavian Ice Sheet (Rinterknecht et al., 2012; Lasberg and Kalm, 2013).

The results appear to indicate that the deglaciation process accelerated at approximately 14 ka, and may be related to Bølling and Allerød interstadials (between approximately 15 and 13.5 ka). This was a period of wetter and warmer climate, which enabled forest expansion in the western Mediterranean (Fletcher et al., 2010). In the study area the polished thresholds were ice-free in the Caldarés Valley upstream of Balneario de Panticosa approximately 12–14 ka. In the Aguas Limpias Valley the ice tongue disappeared from the Respumoso Lake approximately 12 ka, and only small glaciers remained in the headwalls of the divides. Thus, glaciers may have completely disappeared from the cirques, or were reduced to residual ice patches in the headwall, as occurred in the eastern Pyrenees (Delmas et al., 2008, 2011), other northern mountains of the Iberian Peninsula (Fernández-Mosquera et al., 2000; Cowton et al., 2009; Rodríguez-Rodríguez et al., 2011), in the Central Range in central Spain (Palacios et al., 2011, 2012a, 2012b), and in Sierra Nevada, southern Spain (Gómez-Ortiz et al., 2012). In Sierra Nevada the melting of ice masses during the Bølling/Allerød period resulted in the development of rock glaciers that survived until the early Holocene (Palade et al., 2011; Gómez-Ortiz et al., 2012). Marked downwasting of the Alpine glaciers occurred between 14.7 and 12.9 ka (Ivy-Ochs et al., 2006, 2008; Hippe et al., 2014): a similar situation occurred in the Tatra Mountains (Makos et al., 2013) and the Alps (Dielforder and Hetzel, 2014). The Scandinavian Ice Sheet retreated between 14.2 and 13.3 ka (Lasberg and Kalm, 2013), the British-Irish Ice Sheet almost disappeared after 15 ka (Ballantyne, 2010; Clark et al., 2012b; Ballantyne et al., 2013), and the Iceland Ice Sheet broke up catastrophically (Geirsdóttir et al., 2009). In general, there is little information on deglaciation in this period for most Mediterranean mountains, because most attention has been focused on dating moraine blocks, and not polished thresholds. In the Pyrenees, this warm period was characterized by a decrease in the salinity of lakes (Morellón et al., 2009). Nevertheless, the occurrence of a short glacial re-advance in the Piniecho cirque cannot be ruled out. This would be evident through the presence

of moraines and rock glaciers, but the age of these could not be determined in this study because of the large error rate. Such a re-advance would correspond to a decline in temperature centered at 14.0 ka, during the Older Dryas. The small rock glaciers in the Piniecho and Catieras valley, which yielded exposure minimum age of 14–13 ka, could belong to the final stage of the Oldest Dryas rather than to the Bølling-Allerød interstadials, or to the short crisis of the Older Dryas.

After the benign period of the Allerød, a relatively sudden temperature decrease (cooling of approximately 5°C; Clark et al., 2012a) and a 30% decline in precipitation (Ivy-Ochs et al., 2006, 2008) resulted in the onset of the Younger Dryas, between approximately 12.9 and 11.7 ka. Glacial advances during the Younger Dryas have also been recorded for other Pyrenean valleys (Pallàs et al., 2006; Delmas et al., 2008, 2011), and for other Mediterranean mountain regions including the Anatolian Peninsula (Akçar et al., 2007, 2014; Zahno et al., 2010), Greek mountains (Hughes et al., 2006), the Balkans (Hughes and Woodward, 2008; Hughes et al., 2010), the Carpathians (Rinterknecht et al., 2012), the Maritime Alps (Federici et al., 2012), and the Atlas of Morocco (Hughes et al., 2011). This period was represented by the Egesen Stadial moraines in the Alps (Ivy-Ochs et al., 2006, 2009; Hippe et al., 2014), and by generalized moraine development in many mountain regions and the British-Irish (Ballantyne, 2010) and Scandinavian ice sheets (Rinterknecht et al., 2012; Lasberg and Kalm, 2013).

Nevertheless, in some mountains that were glaciated during most of the Late Pleistocene there is no evidence of Younger Dryas moraines (e.g. the Central Ranges, Spain; Palacios et al., 2011, 2012a, 2012b), suggesting that mountains in central Spain were significantly drier than mountains elsewhere in Europe. In some Pyrenean massifs the glacial re-advance was of very limited spatial extent. This occurred for the Marboré Cirque (central–southern Pyrenees), where the Marboré lake was already deglaciated at 12.7 ka (Oliva-Urcia et al., 2013), despite having a north-facing exposure and being at the foot of a massif exceeding 3200 m a.s.l. Ivy-Ochs et al. (2008) reported that the Younger Dryas was a climatically unstable period, and this perhaps explains the occurrence of several deposits in the Piniecho Cirque, including new moraines and the development of rock glaciers. During the Younger Dryas, glaciers in the Aguas Limpias Valley were confined to ice tongues up to 2 km in length, and these had begun to retreat by approximately the end of this period (11.7 ka).

The occurrence of a small deposit at the foot of the southern cirque in the Piniecho Valley suggests the occurrence of a late cool event that ended approximately 11 ka ago, resulting in the development of a protalus lobe built by rock avalanches. It comprises large blocks and boulders arranged in a chaotic manner with no fine matrix, and thus its structure is very different from the other deposits in the area. The presence of arcs indicates an incipient trend towards a rock glacier, suggesting that it could be the last manifestation of the Younger Dryas. The position and characteristics of the deposit are similar to that of many other glacial deposits located close to cirque headwalls throughout the central–southern Pyrenees; these are usually attributed to the Younger Dryas or to the last cooling of the Late Pleistocene (Serrano-Cañadas, 1995, 1998; García-Ruiz et al., 2011). Up to now there has been no evidence of glacial activity during the so-called 10.8 event, which is a short cold period detected in the Alps, and represents the earliest Holocene (Ivy-Ochs et al., 2009).

The results of this study demonstrate that glacial advances and the development of rock glaciers ceased at the end of the Younger Dryas. In the Aguas Limpias Valley the threshold that deglaciated at the end of this period (11.7 ka) is located near the LIA moraines. In the Piniecho and Cateras cirques, the most recent moraine deposits are dated at 11 ka. No new glacial activity has been recorded in the Upper Gállego Valley until the LIA.

Conclusions

The current study of deglaciation in the Upper Gállego Valley provides the first information for this area on the main stages of glacial advance and retreat between the LGM and the beginning of the Holocene. The results indicate that the sequence of events during deglaciation was similar to that recorded since the LGM in other European mountains. Most previous studies have focused on the location and dating of glacial deposits related to the local MIE and the global LGM. This study has demonstrated:

(i) The rapidity of glacial retreat since the LGM. Although the exact location of the end moraines and the maximum extent of the Gállego Glacier during the LGM were not determined, the occurrence of the LGM was deduced from analysis of glaciolacustrine and periglacial deposits. The glacier later retreated towards the headwater prior to several re-advances and retreats during the Late Glacial period.

(ii) The sensitivity of small glaciers to climate variability. Mapping and dating of Late Glacial deposits in the Upper Gállego Valley confirmed that the ice tongues reacted rapidly and extensively to any climate change, causing the deposition of a variety of tills. The spatial distribution and dating of moraines over a short distance within the Piniecho Cirque suggests the occurrence of distinct stages of glacial advance and retreat between 16 and 11 ka, covering the Oldest Dryas and the Younger Dryas periods.

(iii) The occurrence of several climate and glacial reversals from cirque rockwalls or stillstands within a general scenario of deglaciation following the LGM.

(iv) Glacial retreat following the LGM represented the dissociation of ice tongues in the Upper Gállego Valley. A new advance occurred before approximately 17 ka, which represented a clear period of glacial expansion involving the deposition of tills in the Aguas Limpias and Caldarés valleys, although they were not again in contact. The Gállego Glacier remained in the headwater. The large error rate associated with the results precludes correlation of this advance with a specific glacial period, but one hypothesis is that it is related to the Oldest Dryas.

(v) Glaciers seem to have advanced again at approximately 14–11.7 ka, although the large error rates prevent greater specificity; one hypothesis is that this period is correlated to the Older and Younger Dryas periods. No evidence of glacial re-advances from the Holocene until the Little Ice Age has been found in this area.

(vi) Using minimum ages for mid valley sites, the rate of retreat to cirque headwalls was estimated to be relatively rapid (approximately 5 km per ka).

(vii) During the late glacial advances, small glaciers and rock glaciers developed close to the cirque headwalls, and co-occurred under the same climatic conditions; many of the rock glaciers represent the last phase of glacial decay.

Future studies should focus on locating the end position of the glaciers during the global LGM, which will enable the significance of glacial retreat prior to the onset of the Mystery Interval to be assessed. Detailed mapping and dating of glacial deposits close to the cirques will provide more precise information on glacial reversals during the Oldest and Younger Dryas, and the possibility that re-advance occurred during the Older Dryas.

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TABLE CAPTIONS

Table 1. Field and analytical data for ^{36}Cl samples from Gallego valley, Pyrenees, Spain.

Table 2. ^{36}Cl exposure ages, sample type and sample location. Ages are reported for 0 mm/ka erosion rate. Errors correspond to the analytical uncertainty of the AMS ^{36}Cl determination (one standard deviation). Ages are also reported for snow shielding and 0 mm/ka erosion rate and snow shielding and 3 mm/ka erosion rate.

FIGURE CAPTIONS

Figure 1. A: Location of the study area and main rivers cited in the text. B: The Alto Gállego Valley map, showing the main lithological outcrops and the valleys, cirques and peaks cited in the text. 1: Fluvial network. 2: Lakes and reservoirs. 3: Settlements. 4: Granites. 5: Paleozoic rocks. 6: Cenozoic limestone and sandstone. 7: Eocene flysch. 8: Eocene marl. 9: Oligocene sandstone and clay. 10: Quaternary.

Figure 2. The extent of the Gállego Valley glacier during the MIE and associated moraines, and the Aguas Limpias and Caldarés glaciers and associated moraines, with the cosmogenic results. 1: Moraines from the MIE. 2: Extent of the Gállego Glacier during the MIE. 3: Moraines from the readvance (Oldest Dryas?). 4: Maximum extent of the glaciers during this readvance. 5: Fluvial network. 6: Lakes and reservoirs. 7: Settlements.

Figure 3. Cosmogenic exposure results and their distribution in relation to distance from the head of the valley. A.1) Caldarés and Bolatica valley; A.2) Aguas Limpias valley; B.1) Catieras cirque; B.2) Piniecho cirque.

Figure 4. The Aguas Limpias Valley transect and the distribution of cosmogenic exposure results on polished bedrock surfaces.

Figure 5. Location and dates of the samples RES-1, -3 and -4, obtained from polished bedrock surfaces in the Aguas Limpias Valley and the Respumoso Cirque.

Figure 6. Penetration of the Caldarés Oldest Dryas lateral moraine into the Bolatica Valley, and the boulder corresponding to the PANTI-1 sampling point.

Figure 7. The Caldarés Valley transect, showing the cosmogenic exposure dates for polished bedrock surfaces.

Figure 8. Location and ages for the samples PANTI-21, -22 and -23, from polished bedrock surfaces in the Caldarés Valley.

Figure 9. Glacial deposits and other geomorphological features of the Piniecho Cirque. 1-5: Moraine deposits, ordered from the oldest (1) to the youngest (5); 6: Rock glacier; 7: Rock avalanche; 8: Alluvial fan; 9: Debris flows; 10: Glacial cirque; 11: Scree; 12: Rock avalanches; 13: Sampling points; 14: Fluvial network; 15: Sediment

1107 accumulation, most likely corresponding to a large hydrological event. 16: Lakes.
1108 Distance between contour lines: 20 m.
1109 Figure 10. The Piniecho Cirque transect and the location of the main samples and their
1110 cosmogenic exposure ages on various landforms.
1111 Figure 11. Small moraines and rock glaciers of the Piniecho Cirque, showing the
1112 location of the sampled boulders and their cosmogenic exposure ages.
1113 Figure 12. The older Piniecho moraine and the sampled boulder (PANTI-18), showing
1114 surrounding younger moraines and rock glaciers.
1115 Figure 13. The Catieras Cirque transect, showing the location of the rock glacier,
1116 moraine and polished bedrock.
1117 Figure 14. The Catieras Cirque, showing the location of the sampling points and their
1118 cosmogenic exposure ages.
1119

COMMENTS TO REVISION

Ms. Ref. No YQRES-D-14-00025 Title: Rapid Late Pleistocene Deglaciation in Central Pyrenees: The Upper Gállego Valley Quaternary Research

Associate Editor comments:

OVERVIEW

This is a good paper with a good set of exposure ages in an otherwise difficult and complex glacial terrain. The paper is fully detailed and perhaps in some sections particularly the discussion section is too long. The figures and photos are very helpful and the table of data complete but contain errors.

After reviewing the manuscript, we are aware of these defects and we have shorted the manuscript and corrected and changed completely the tables.

However the paper requires a major revision in both organization, quantity and more importantly in the scientific conclusions it draws from the data set and the mapping. There are numerous passage which could be improved and some typos etc. a restructure is required, plus a more objective evaluation and interpretation of the exp ages, with less speculation with regards to inferring millennial scale correlations (ie synchrony) of glacial climate events from this small data set to continental European glacial changes from LGM to Holocene. The cherry picking of single samples from one valley across to another valley that have equal ages to support a climate based conclusion needs to be tempered with the fact that geologic scatter dominates this data set and prevents any millennial scale conclusion that these ages demonstrate a bimodal H1 and YD structure. They simply do not show this.

We have restructured the manuscript, exposed the objective data and being much less speculative

The following summarizes the important issues I have with the paper in its present form.

1) overall structure.

A) Section at line 189 (MIE and LGM) needs to precede section at line 111.

Done

B) Methods section should be split into two - one for sampling philosophy, strategy and site complications re: exposure dating as a lead in to geologic scatter (as exemplified by GAVIN ages) such as snow cover, erosion rates, exhumation etc. moraine degradation, whilst the second is for methods and formalism specific to calculating exp ages. The latter needs all factors including prod rates used for Ca K Ti Fe etc., scaling etc , spread of snow cover effect, e-rates and best estimate to show shift in ages. My guess is that at 3 mm/ka over 14 ka, you could underestimate age by maybe 5-6%.in addition the real uncertainty in extrapolating today's effective mean annual snow shielding back to 14ka plus the topographic selectivity of snow preservation is so uncertain as to make this correction invalid. The authors calculate a range in ages resulting from snow packing correction of about +/- 8%. Hence overall the calculable geologic variation could easily be as high as 10-15%. These issues need to be presented.

We have followed all these suggestions. The Methods section is now divided into two parts, one with a detailed samples strategy and site complications, and the other for exposure age calculator, where all the indicated items are included.

The editor warnings about the effect of snow shielding have been attended. Samples were collected in an altitudinal range of 1000 m and with an actual difference in the snow cover of over six months, which must, now and in the past, influence the rate of nuclide production. However, we are not sure of the correct solution, as the effect of the snow shielding is still under scientific discussion, and we have decided to eliminate the effect of snow in the main dating results, assuming that this variable is part of the margins of error of the results. In any case, we have also included the effect of snow shielding in a secondary results, applying criteria obtained from the literature, not from our own research, to show which could be the difference.

C) The discussion section contains information that should be removed to the introduction.. The discussion cannot introduce major new ideas or material relevant to aid in interpretation.

Done. Information on Pyrenean glacial studies has been moved to the introduction section, so of all new information that was included in the discussion in the old version of the manuscript

2) the objectives and major conclusions listed in the abstract must be addressed and altered to reflect the data.

Basically there is no evidence for LGM to Holocene rapid deglaciation and no strong evidence for two separate glacial advances commensurate with H1 and YD.. The ages simply range from 16.5 to 11.0 ka.. there is no consistent trend of younging from distal to proximal positions for all the 3 valley and cirque sites sampled.

My suggestion here is a scenario as (or similar) a) down valley LGM limits were abandoned sometime between LGM and 17ka

b) glacial retreat from mid valley and upper valley cirque locations occurred between 16 to 11 ka

c) this covers the H1 and BA and YD periods but the geologic spread of ages precludes a linking of moraine positions to these chronozones across the 3 valleys studied.

d) minor readvances from cirque rock walls or stillstands during the retreat occurred in this period.

e) using min ages for mid valley sites, retreat rate to cirque is estimated to be relatively fast at about 5 km per ka.

e) no Holocene readvance was observed

Broadly, we have followed all the suggestions of the editor (lines 21-31)

3) ^{36}Cl

I presume the CHLOE program is used as the exp ages were done at PRIME lab but more serious is the fact that the authors cite Chloe 3-2003. It is unclear what prod rates for Ca K Ti Fe etc are used. And it is uncertain what was used for the neutron flux modelling relating to ^{35}Cl thermal neutron capture calculations to ^{36}Cl .. And some of the samples have high Cl content and it would be instructive to see what fraction of ^{36}Cl comes from ^{35}Cl . In the past few years there have been real progress in improving ^{36}Cl PRs. The more relevant point here is that Schimmelpfenning has published 3 excellent papers on ^{36}Cl with much improved prod rates based on single target data. And it includes a excel type calculator. I strongly request that either ages be redone using the new prod rates from Schimmelpfenning, and/or list explicitly the PRs used in Chloe or discuss any differences between PRs(Ca) and PR(K) from more recent evaluations compared to what was used for table 2. This is all the more critical as your

samples are bulk rock granites and their mixtures of Ca and K elevates the error in prod rates compared to say using K-feldspars or limestone etc . This also begs the question why mineral separates we not used and not a more direct and simpler method of extracting quartz from the granites for ^{10}Be .

We followed the suggestions of the editor and we have recalculated the dates with the Age calculator of Schimmelpfenning et al. 2009. We have had the invaluable help of Irene Schimmelpfenning to apply correctly this AC, what is recorded in the acknowledgments. We have expanded the laboratory tests necessary to complete all the requirements of the table, which has considerably delayed the correction of the manuscript. Indeed, there are signs of a high content of natural Cl in some samples, but now this uncertainty is reflected in the margins of error of the results. The fact of using ^{36}Cl for dating is an initial research strategy, to use the same isotope in different geological environments, as it is explained in the methodology, but we let open the possibility to compare in the near future the results with ^{10}Be . Other tributary valleys of Gallego river are situated in limestone rocks and we thought that could be better to use in the future research the same isotope.

We have included now new samples that have been analyzed during the revision of the manuscript

A second point re : ^{36}Cl ages. I See no value in reporting erosion corrected exp ages for $e=1, 3$ and for 5.. . Given that there is marginal increase in exp ages in the range of $\sim 15\text{ka}$ for $e=1$ to 5 mm/ ka , I make two suggestions for table 1; Present ages without any corrections other than for horizon and sample thickness shldg and for zero erosion, then add sample specific snow shldg to these ages and then add erosion corrected ages for say 3 mm/ka . This would be far more instructive than that currently presented.

We have followed strictly this suggestion in table 1

4) reviewer 1 points out that the authors have erroneously equated exp age dating in glacial studies that bedrock ages measure retreat and boulders on moraines measure advance. I fully agree with reviewer 1. The description given in the text is naive and basically wrong. I suggest it be fully deleted. I understand very well that if inheritance is truly zero then bedrock ages proxy retreat. Then boulders should also if moraine stabilisation is negligible and erosion zero. But these are ideal scenarios. Moraines

predominately form by alpine valley type glaciers at climate reversals or hiatuses or still stands and not during advances necessarily.

The new version of the manuscript has changed the focus of the analysis of the results completely, following the principle in this suggestion of the editor and reviewer 1.

5) Pyrenees glacial cosmogenic review:

the authors state they have made or attempt some type of regional review of late glacial to interglacial transition period (25-10 ka). The paper has a good literature review of the Pyrenees area plus some citing for Central Europe. I have no problems with this though I think such a review requires a dedicated paper. Reviewer 1 suggests a summary table of some sort to provide the reader with a regional overview that can be readily understood in comparison to multiple lines of text. An excellent idea but would require some work to tabulate. However I hesitate to expand this outside the Pyrenees mountain belt. As it stands the paper is long and additions re: a regional summary would need to be carefully interwoven with a reduced text length.

The review of the literature concerning the Pyrenees glacial evolution has reduced drastically to the results related directly to work, removing everything else. The objective is not therefore make a review of this topic, which would be the subject of a specific work. Thus, we believe that there is no point in developing the general table, but to shorten the text and cite only those papers that are directly related to our work.

Comments re: reviewers 1 and 2

I agree with nearly all of the comments and remarks made by Reviewers 1 and 2 (R1 , R2). R2 review is very generous in his evaluation. In contrast R1 is more exacting and provides an excellent assessment with respect to the regional glacial geochronology and geomorphology. I recommend that all edits and suggestions by R1 be followed thru apart from one dealing with estimating ELAs . I think this request given the current state of data exp age interpretation would not be valid and moreover the data set is too small and variable to make accurate evolutions of time transgressive ice thickness and ice length conclusions for the relevant period.

We followed the suggestions of the editor and we have included the requirements of R2

Taken all together the manuscript is worthy of publication. It adds to the body of data emerging from a sensitive west - east mountain transect in Southern Europe.. However as it stands it requires major readjustment principally with respect to an objective interpretation of the set of ^{36}Cl ages (regardless of which prod rates are used). there is an absence of well preserved recessional cross valley moraine sequences from distal to proximal to provide chrono stratigraphic constraint with multiple samples per moraine to asses the impact and magnitude of geologic variability.

Finally, in order to reduce text length, the full sample description and elemental data sheets given in tables and summary details of constants used in the exp age calculations can be placed in a on-line supplementary section.

We followed the suggestion of the editor and we have changed to the supplementary section the tables with all the inputs of the AC.

The following section relates to some text figure and table corrections and also connects back to comments made above.

TITLE

We have changed it according to editor suggestion and to the present manuscript criteria.

ABSTRACT

LINE 17

Last Glacial Max

Done (line 17)

LINE 17

There is no solid evidence as pointed out by reviewer 1 that the deglaciation was rapid. There is support for an extensive ice volume loss with retreat of a few kms over a few ka but I don't think we can securely quantify the retreat rate from LGM to YD to be rapid.

Done (line 17)

LINE 19

This is one of two major reasons that due to the absence of LGM positions that rate of retreat from LGM thru the deglaciation cannot be defined.

We agree and we have changed the text (line 19)

LINE 21

There is no two clear climate reversals at H1 and YD.. There is simply a population of ages which rather spreads across the 16 to 11 ka period and shows no 2 stage max in prob distribution based on stratigraphic correlation for distal to proximal locations of sites in each valley. According to table 1, there are on average 4 samples for each unit kilo year starting from 11-12 to 15-16. Basically the data set is too small, the geographic spread too large and prevents any millennial scale conclusions..the mapped glacial sedimentology and geomorphology appears to support multiple minor advances and retreats or a set of still stands during the late deglaciation. But that is as far as I would stretch the exp ages.

We have changed completely the second part of the abstract, following these indications (lines 21 to 31)

Line 66: the 1:1 correspondence of warm equates to glacial retreat is too simplistic. It negates the influence of precipitation limited glacial environments such as in Tibet. Edit text.

We have changed the sentence, following this indication.

Line74: delete conversely.. It doesn't fit here .

We have changed the sentence, following this indication.

Line99: moraine boulders. Change all occurrences of morainic to moraine

It has been done in all the cases

Lines101-105: delete

Done

Line128: lithologies , delete materials

Done

Line 257: the impact of snow cover is totally site specific and I cannot see how it's defined to be 12-14%. Such a reduction in prod rate is excessive. For a reasonable example for this elevation and latitude at a density of 0.3, a thickness of say 60 cm for 6

months per year, you would be at most correcting 10be PRs at 3-4% . For Cl it will be similar other than the impact of fast neutron moderation by H atoms in water molecules of the snow. Two samples exemplify the complications of snow correction - pant-7 and pant-8. Both at identical locations with a 8% difference in snow shldg correction. These two samples must be receiving the same snow fall amount and the only way to explain this is via surface slope. In the absence of any snow correction the disparity in age between these co-located samples would increase from 10% to ~18%.. This shifting of ages is obscure to the reader and more details re: snow shldg needs to be given. Moreover given their co-location they surely must have the same horizon shldg but the final total shldg factors are equal despite a 2cm diff (~2%) in thick and 8% in snow shldg. If there is no mistake, then I can only predict that the horizon or self shielding for Pant-8 is 6-7% whilst for pant-7 it is 0%

As we have explained previously, we have considered no-snow shielding in the main results. We have exposed also the effect of the possible snow shielding as a secondary option of the results, according to criteria obtained from the literature, not from our research.

Line 282: the fact that mid last glacial cycle boulders ie MIS 2-4 give apparent exp ages of ONLY 3-5ka attests to the on-going geological modification and resetting of boulders throughout the valley glacial system regardless of true age.

We agree and now this idea is included in the new version of the manuscript

Line 287 : substitute 2nd 'evident' to ,present'

Done

Line 315 : delete rapid

Done

Line 328 : I don't agree that the survival of striations equates to an 'absolute age'. In this work all ages in my opinion should be classified as minimum ages.

Yes, we have incorporated the concept of minimum ages along the analysis of the results in the new version of the manuscript

Line 332 : delete new

Done

Line 335 : delete relatively high resolution

Done

Line 346 : what is melting sector ?

We want to say "end sector". It has been changed in the text.

Line 352 : the comparison between these two samples from possibly two different ice sources at a difference in elevation of ~800 m is not valid.

We have deleted the final part of the sentence

Line 382: the 'relatively small difference in age' amounts to 10% - this is not small and as the authors acknowledge, but do not openly discuss, maybe caused by miscalculations in snow shldg or unknown factors.

We have deleted "relatively small"

Line 408 : I see no statistical support for two age groups in the data set regardless of how you group the ages. Delete

Done

Edits for figs and tables:

Table 1: Why are analytical errors for stable element and for AMs CI not included. Perhaps it would be very instructive to list approx distances of each sample from its parent cirque head wall.

Erosion corrected ages at 1, 3 and 5 mm/ky must increase in age compared to those based on zero erosion.

We have followed all the suggestions of the editor for this table along the comments. We have also included the distance of each sample from its headwall

Table 2:

List all correction factors - horizon shldg, snow shldg, thickness etc and then finally total geometric PR correction factor

Un spiked or pre- spiked

Units for $^{36}\text{Cl}/\text{Cl}$ should be written as ($\times 10^{-15}$) or (x1E-15). Conc spike solution is irrelevant if mass of ^{35}Cl spike added to sample is given.

Effective fast neutron atten length should be I think effective thermal neutron atten length

We have followed all the suggestions of the editor for the table 2 and introduced the results of extent analysis.

Fig2 : expand to show only the top left hand quadrant or top half of map. This will improve the overall geographic relationship of site to site context.

I sample pant-7 is missing

We have maintained the whole area of the main valley to have a reference of the tributary valleys and to introduce the location of Gavin 1 and 2, according with R-1, but we have included an extension of the main study area and located all the samples, to follow the indications of the editor.

Fig3 : in its current form this figure is useless as it does not distinguish which groups of samples belong to a common valley glacier. Ie Aguas limpias, caldares, piniecho. Suggest that the 3 different valleys are grouped into their own graph but with common y-axis and own x-axis ie as columns joined.

We have followed this criteria and now it is a new version of this figure

Fig 4 ok

Fig 7 delete comment for panti- 1. I see no justification for altering the measured 15 ka to 17 ka

Done

Fig 9: this figure exemplifies the issue of modified moraine amplifying geologic variability. Brown#2 is inferred to be older than yellow#5. However they are statistically the same population.

Fig 10 is missing locations of pant-15 to pant-7. When included they will show that there is no true age difference of old and young as stated in the caption.. The glacial mapping may well hint at an age differences BUT the cosmogenic technique in this instance is not capable of verifying this.

Yes we agree and now this idea is clear in the text.

David Fink

AE, QR

Reviewer #1: The manuscript "Rapid Late Pleistocene Deglaciation in Central Pyrenees: The Upper Gállego Valley" by Palacios et al. deals with Lateglacial fluctuations of ice extent in upper Gallego catchment. Authors bear new geomorphological and chronological data which are consistent to each other's and match very well with the timing of Lateglacial climatic changes. New cosmogenic datings are numerous (21) and of high quality although it is surprising to date by ^{36}Cl surfaces sampled on granitic bedrock. The geomorphological approach improves substantially, compared to previous studies, the cartography of glacial deposits in this area. On these bases, authors provide a detailed reconstruction of the MIE and post-MIE glacial stades, the first one at whole catchment scale.

I will begin my review with some general comments, and then list some more specific suggestions.

Generals comments:

All my general comments concern the structure of the paper, in particular how the background, the geomorphological setting and the methodological informations are divided up in the text.

1- The references list on Pleistocene glacial fluctuations is large and relatively exhaustive but the background developed in the introduction could be specified. The content of some references is imperfectly explained and several references cited later in the text does not appear in the background when they should be mentioned (see below for details).

Moreover, I suggest compiling in the same section (i.e. introduction) all data relative to the background on chronology of Pleistocene glaciation in Pyrenees and others glaciated area in Western Europe. Currently, this seems scattered in several sections (see "Local and global MIE LGM in the central-southern Pyrenees").

We have considered this recommendation, as we explained previously to the editor.

2- The study area section details widely the geological and climatic setting. Both items are undeniably useful but could be presented more briefly. Conversely, geomorphological and chronological data previously published about Gallego

catchment should be exposed in this section. This is correctly done for Gallego MIE stadial (location of deposits and datings) but that can be completed for the upper part of the Gallego catchment. This clarification is important to help readers to better distinguish new data bore by this paper and data previously established.

This is solved in the new version of the manuscript, since the section "Local and global MIE LGM in the central-southern Pyrenees" has changed in position, previous to the study area, following the recommendation of one of the reviewers. This section has been also shortened and focused on the work topics and with new data about the Gállego catchment.

3- The methodology focuses only on cosmogenic dating whereas it should include elements related to the geomorphological approach. Authors should describe the facies of the mapped deposits. They also should express more clearly the genetic significance of "rock glaciers" and "protalus rampart". Looking at the figure 11, I wonder if deposits called "rock glaciers" in the paper are ablation till deposited on the margin of a small cirque glacier rather than rock glaciers. Often, small cirque glaciers build ablation moraines containing a large proportion of large and angular blocks because the ice is confined at the bottom of high and rocky cirque headwalls. If the shapes on figure 11 are really rock glaciers, then these deposits cannot be used to delimit paleoglacier margins because a rock glacier is a periglacial form, generally backed by scree. So this shape occurs only when the cirque glaciers have completely disappeared from cirques floors or upper valleys.

Concerning the datings, I suggest the methodological section include not only the analytical procedure but also the sampling strategy. I think you should explain how the sampling sites have been selected, in particular their location in relation to the post-MIE glacial deposits. Readers also want to see in this section what criteria are used to select the surfaces sampled on boulder as on polished bedrocks. Some of these informations are in the paper (but not all) and there are scattered in several sections of the text.

We agree with most of these comments of R2. We have introduced in the methodology a section with the specific research strategy and sampling. Some important aspects are related to specific literature, which describes the strategy that we have followed, in order to not overextend the text. But we do not agree with the comments of R2 on rock glaciers. When we have identified accumulations of blocks as a rock glacier deposit, we have followed a purely morphological

criteria, not genetic. According to the literature on rock glaciers, their origin is still under discussion. For many authors, rock glaciers with glacial origin are authentic rock glaciers. This problem is not the object of this work, so we stick to classify them according to their rock glacier morphology.

Detailed comments :

Lines 16 and 17: "including (i) rapid deglaciation following the Late Glacial Maximum (LGM)

Because the terminal position of the Gallego glacier during the Global LGM is unknown, you cannot estimate the rate of the post-LGM deglaciation. I think you'd better say that this study documents the extent and the chronology of Gallego glacial fluctuations during the Lateglacial.

Done as previously explained

Lines 35 and 36: "Keywords: Deglaciation, Oldest Dryas, Bølling/Allerød, Younger Dryas, Central Pyrenees".

I suggest you insert "cosmogenic dating"

Done (line 33)

Lines 39: "global Last Glacial Maximum (LGM: approximately 25-19 ka BP)"

The Global LGM concept is defined as the time of the most recent and largest globally integrated ice volume. It prevailed between 23 ka cal. BP and 19 ka cal. BP, perhaps culminating ca. 21 ka cal. BP (Yokoyama et al., 2000; Mix et al., 2001).

We have changed the sentence and have incorporated these references (line 42).

Lines 58 and 62 : « Deglaciation studies in the Iberian Peninsula have centered on the Sierra Nevada (Gómez-Ortiz et al., 2012), the Cantabrian Mountains (Moreno et al., 2010a, 2010b, 2012; Pellitero et al., 2011), the Central Range (Palacios et al., 2011, 2012a, 2012b) and the Pyrenees (González-Sampériz et al., 2006; Morellón et al., 2009; Pallàs, 2010; Moreno et al., 2012) ». Rodriguez-Rodriguez et al., 2014 and Pallas et al. 2006 are cited later in the text but they should also be cited here. Moreover, the presentation of the Pyrenean background is too centred on Spanish authors. This leads authors to consider only the Spanish Pyrenean valleys forgetting to cite, in this section of the text, papers concerning the French part of the south and the north side of the

range. Note that U-Th data cited just below are located on the north side of the range (Bakalowicz et al. 1984; Quinif et al., 1998).

We have done all the changes suggested (lines 68 and 70)

Line 78 to 82 : Surprisingly, for several valleys there is much information on the location and dating of glacier fronts during the local Maximum Ice Extent (MIE) of the last glacial cycle. Amongst these are the Cinca (Lewis et al., 2009), the Gállego (García-Ruiz et al., 2003), the Aragón (García-Ruiz et al., 2013), the Ariège (Delmas et al., 2011), the Têt (Delmas et al., 2008) and the Querol (Pallàs et al., 2010) valleys. Pallas et al. and Delmas et al.'s papers focus not only on the MIE glacial stade, they also deal with post-MIE (i.e. deglaciation) stadials.

Now it is clear

Lines 87 and 88: Exposure age chronology has been used in dating glacial stages in the northern (Delmas et al., 2011) and eastern (Pallàs et al., 2010) Pyrenees. Concerning exposure age chronology obtained in the eastern Pyrenees, you can also cite Delmas et al., 2008

Now it is included (line 96)

Lines 90 and 91: This dating method has not in the past been used in the central-southern Pyrenees. This is incorrect. Pallas et al. (2006) produced cosmogenic ages for the Noguera Ribagorçana valley.

It is now corrected (lines 98-102)

Lines 101 to 105: Exposure ages determined from 4 bedrock surfaces enable periods of glacial retreat (interstadials) to be identified, and in some cases the rate at which this occurred, whereas exposure ages from boulders provide information on short glacial advances (stadials) within a general trend of deglaciation. This passage would be better located in the methodology section. Moreover, I'm not sure that cosmogenic ages on boulders date glacial advances. Frontal and lateral moraines build up during glacial advances but what is the significance of exposure duration obtained on a boulder located on a frontal or a lateral moraine? That should be discussed more persuasively.

The sentence has been finally deleted and the topics included in the discussion

Later in the text you write lines 465-467: "it would be necessary to add the time needed for moraine stabilization (Putkonen and O'Neal, 2006; Houmark-Nielsen et al., 2012)" I

agree with that. It seems obvious that frontal or lateral moraines are stabilized when glaciers that have built the ablation moraines have retreated up-valley and ceased to feed boulders to the moraine. The stabilization can even occur later when vegetation covers the slopes of the moraine.

So, two things have to be untangled. (i) Frontal and lateral ablation moraines are constructed when the glacier is advancing. (ii) Cosmogenic data indicate the time when the moraine has stabilized because supply of boulders from the ice margin has ceased and sufficient vegetation covers the till to stabilize the slope.

This idea has been incorporated along the text and cosmogenic results are always exposed as minimum ages

Line 108 and 109: "to compare the results with those obtained elsewhere in the Pyrenees, the Iberian Peninsula and western Europe". The review proposed is interesting and based on a large panel of references. I suggest compiling all references cited in a table that overviews the timing of post-MIE deglaciation in the different areas concerned.

We have previously answered to the editor about this possible table, which it is not the objective of this work.

Line 119 and 120: "corresponding to the post-global LGM, enabling detailed study of the deglaciation process" Here, I suggest writing "corresponding to the glacial stades that followed the Würmian MIE" because there are no accurate data about the terminal position of the Gallego glacier during the Global LGM.

We have followed this suggestion (line 169-170)

Line 124-125: "main structural units of the southern Pyrenees: (i) the Axial Paleozoic Pyrenees; and (ii) the Alpine Pyrenees." I think you'd better call the second structural unit "south pyrenean fold and thrust belt"

We have followed this suggestion (line 175)

Lines 161 to 163: "The five areas described below were selected for the sampling needed to investigate surface exposure ages (Fig. 1)".

This presentation of sampled areas would be better located in the methodological section. In my opinion, this is part of the sampling strategy.

We have followed this suggestion and moved the presentation of sampled areas to the method section

Line 176-177: "and corresponds to a moment close to the local MIE".

You should clarify the concept of MIE. Does it correspond to the Pleistocene maximum extent of the ice in the Gallego valley? Does it correspond to the maximum extent of the ice reached during the last (würmian) glacial cycle.

We considered that this sentence was confused and we have deleted it.

Line 194: "the large end moraine of Senegüé" I suggest "terminal moraine" rather than "end moraine"

We have followed this suggestion

Line 197: "a rapid decrease in thickness towards Sabinánigo"

I suggest "a substantial decrease in thickness" rather than a "rapid decrease" because you have no evidence of the speed.

We have followed this suggestion

Lines 203 and 204: "These dates are consistent with those obtained recently in the Aragón and Cinca valleys"

These ages are also consistent with data obtained in the eastern Pyrenees (Pallas et al., 2010 ; Delmas et al., 2011; Delmas et al., 2012).

This references has been now included to reinforce the sentence

Lines 204-205: "There is no clear evidence of the LGM in the Gállego Valley, as no tills of the global LGM have been found, and the same applies in neighbouring Pyrenean valleys".

Certainly, the terminal position of glaciers is not well established in the neighbouring valleys but it is accurately located in others Pyrenean valleys. It seems useful to indicate which valleys. cf Calvet et al., 2011 for a review of the terminal position of Pyrenean glaciers during the Global LGM in respect to the terminal position of the MIE Pyrenean glaciers.

We have added some sentences, indicating the Pyrenean valleys where the position of the LGM is well known, following the synthesis of Calvet et al. 2011.

Lines 209-211: "High-resolution multi-proxy analysis of the Portalet paleolake sediment enabled detection of the occurrence of a cold period involving glacial advance between 22,500 and 18,000 cal yr BP, during the global LGM (González-Sampériz et al., 2006)."

Authors can also indicate a ^{14}C age obtained at the base of the glaciolacustrine filling of Bubal: 20800 ± 400 yrs BP (i.e. 25928 to 23182 yrs cal. BP). Bubal filling is located in a sink hole deepened on a bedrock step located just above the Gallego canyon. The deglaciation of this section of valley permitted the installation of the lake in the sink hole. The supply of the lake was possible only when the terminal position of the Gallego glacier was enough close to the canyon to pour meltwater in the Bubal Lake. This ^{14}C dating is published by Jalut et al. (1992). Delmas (2009) used this age to locate approximately the extent of the Gallego glacier during the Global LGM. Calvet et al., 2011 wrote : "The position of the Gallego ice front in MIS 2 is difficult to establish, but the 20.8 ^{14}C ka BP (i.e. 24.217 ka cal. BP) radiocarbon age obtained from the base of the Bubal lake deposits (Jalut et al., 1992) suggests that the LGM glacier front was stationed as much as 15 km up-valley from Senegue."

The reference to the Búbal sinkhole has been included, together with the cites of the papers from Jalut et al. (1992) and Calvet et al. (2011).

Lines 231-237: "use of the ^{36}Cl cosmogenic nuclide facilitated comparisons among these areas" What areas are these? Areas previously studied by authors or those reviewed in this paper? The sentence is unclear.

We considered that this sentence was confused and we have deleted it.

Line 276-277: "the maximum Lower Pleistocene advances". I suppose « maximum Lower Pleistocene advances » here means MIE (i.e. MIS 4). Caution because Lower (Early) Pleistocene spans the time between 2.5 and 0.8 Ma.

Yes, it is was a mistake. We referred to MIE and have changed it.

Lines 282-283: "the samples GAVIN-2 ($42^{\circ}36'44.802''\text{N}$; $0^{\circ}17'54.83''\text{W}$) and GAVIN-3 ($42^{\circ}36'44.40''\text{N}$; $0^{\circ}17'53.89''\text{W}$)" I think it would useful to locate these samples on Figure 2.

Now they are located on fig.2

Lines 294-297: "The dissociation is demonstrated by the presence of lateral tills located at low altitude (< 100 m above the valley bottom) in Lanuza (deposited by the Aguas Limpias glacier), and close to Panticosa, deposited by the Caldarés glacier in the lower course of its main tributary, the Bolatica Valley (Fig. 2)." It would be interesting to indicate the ELA ascribed to each of these post-MIE ice tongues. This would help to correlate each others glacial deposits located in glacial catchments. Moreover, this would enhance the review proposed in this paper of Lateglacial data in Western European glaciated areas (see Ivy-Ochs et al., 2006 for variations of ELA in the Alps).

This is not the objective of this work. It must be a specific aim for another work.

Line 327-328: "The date from the moraine (PANTI-01, 15.2 ± 0.4 ka; Fig. 6) can be considered a minimum age, whereas dating of the six thresholds yielded absolute ages" Because cosmogenic ages are exposure times, data on boulders as on bedrock steps are minimum ages. See my comment above about boulders. Concerning bedrock steps, we hope to capture the time when sampled surfaces have been free of ice, but we are never sure of that because till may also have covered the sampled surfaces for a unknown duration after deglaciation of the bedrock step.

We have followed this suggestion and now it is considered as minimum ages

Line 338: "during the last stages of deglaciation" The notion of « glacial stage » is ambiguous because, by definition, frontal and lateral moraines are built when valley glaciers advance.

We have followed this suggestion

Line 339-340: "small glaciers close to the cirque headwall, rock glaciers and a protalus lobe (Figs. 9, 10, 11 and 12" The shapes on figure 11 seem ablation till built on margin of cirques glaciers rather than rock glaciers.

We have changed the photo, for another clearer.

Line 340 : « Figure98 shows » Typing error ?

Yes, it is a typing mistake, it corresponds to figure 9

Line 343-348: "(i) The oldest deposit, based on its geomorphological position, is a large lateral moraine. The height of the moraine is 150 m high in the upper part, and this rapidly decreases downstream. The lower part of the moraine has disappeared, although it probably extended a further 350-500 m to the melting sector of the glacier. This

glacier would have had a total length of approximately 1500 m from the headwall, occupying two of the cirques and the main stem of the Piniecho Valley". The figure does not show explicitly the extent of ice for each stade noted here.

The length of the main (oldest) glacier in the piniecho cirque is rather speculative, according to the decreasing height of the lateral moraine.

Line 362: "from the south versant of the cirque" I suggest "southern slope of the cirque" rather than "south versant"

It has been changed

Lines 439-443: "in the snow cover depth and duration: in some cases in the earlier studies an absence of snow cover was assumed, even for samples taken near the summit (Pallàs et al., 2006, 2010), and in other cases a uniform snow cover was assumed (50 cm during 6 months), regardless of the altitude (Delmas et al., 2008, 2011)." You could correct the data already published to correct them considering some snow duration. Moreover, it would be interesting to discuss to what extent snow duration influences the cosmogenic data.

It has been explained in the methodology and exposed previously to the editor.

Line 446-448: Furthermore, previous cosmogenic studies in the Pyrenees have mainly focused on dating the MIE, and have paid less attention to deglaciation processes. This assertion is untrue. All studies using cosmogenic dating in Pyrenean valleys focus not only on MIE chronology but also on the timing of the post-MIE stadials. This concerns the data obtained in Noguera Ribagorçana (Pallas et al., 2006), the Têt Valley (Delmas et al., 2008), The Carol and Malniu valleys (Pallas et al., 2010) and the Ariège Valley (Delmas et al., 2011). Moreover, the authors point this out later in the text (cf. lines 499-501).

Note that in the cases of Têt and Ariège valley, the extent of each post-MIE stadial is accurately reconstructed on the basis of a detailed map of glacial deposits (geomorphological data published in Delmas, 2005 and Delmas et al., 2012).

The sentence has been deleted to avoid the erroneous assertion.

Line 450-456: "Extensive deglaciation processes that commenced approximately 19-21 ka have been reported in various regions of Europe, including the British-Irish Ice Sheet (Bowen et al., 2002), the Alpine piedmont glaciers (Hippe et al., 2014), the Appennines

(Giraudi, 2012), the Tatra Mountains (Makos et al., 2013) and the Mediterranean mountains (i.e. Pallàs et al., 2010; Palacios et al., 2011, 2012b). Ivy-Ochs et al. (2004) reported that the Rhône piedmont glacier collapsed at 21-19.1 ka. By 18 ka more than 80% of the ice volume of the Alpine valley glaciers had disappeared." Sharp and early deglaciation is found also in the eastern Pyrenees (Delmas et al. 2008 ; Delmas et al. 2011).

These references has been now included.

Line 465-467: it would be necessary to add the time needed for moraine stabilization (Putkonen and O'Neal, 2006; Houmark-Nielsen et al., 2012) This is in agreement with the idea that cosmogenic data on boulders give a minimum age for the ice advance that built the frontal or lateral moraine on which the sampled boulders are located (see comment above).

Now the text refers always to the results as minimum ages.

Line 499-501: A similar advance during the Oldest Dryas has been reported for southern-central, eastern and northern Pyrenean valleys (Pallàs et al., 2006; Delmas et al., 2008,2011). It would be interesting to compare the Oldest Dryas ELA in several Pyrenean, indeed European, glaciated catchments (See Ivy-Ochs et al., 2006).

The purpose of this paper was not to estimate the ELA position in the Gállego valley, nor to compare it with that of the European mountains.

Line 510: Rinterknecht et al., 2012 Rinterknecht

Corrected

Line 540: type ii moraines?????

Corrected

Line 597-598: Therefore, they appear to represent finiglacial rather than periglacial activity, as also occurred in the southern Iberian Peninsula (Gómez-Ortiz et al., 2012). This sentence introduces a big ambiguity about what are rock glaciers according to the authors (see comments above)

The sentence has been re-written according with the suggestion

Line 621-623: whereas a rapid process of glacial melting occurred between the LGM and the onset of the Mystery Interval (ca 19-17 ka), This has already been reported for the Pyrenees (see 14C dating in Tet Valley, Delmas, 2005).

This corresponds to the Conclusions section, where not any cite has been included. The conclusions refer exclusively to the results obtained in this paper. The paper from Delmas et al. (2005) has been cited previously.

I hope these comments will help you to better highlight the interesting and consistent data contained in this paper.

Magali Delmas

References cited in the review, not in the paper:

Most of these cites has been incorporated into the text.

Bakalowicz, M., Sorriaux, P., Ford, D.C., 1984. Quaternary glacial events in the Pyrenees from U-series dating of speleothems in the Niaux-Lombrives-Sabart caves, Ariège, France. *Norsk Geografisk Tidsskrift*, 38, 193-197.

Calvet, M., Delmas, M., Gunnell, Y., Braucher, R., Bourlès, D., 2011. Recent advances in research on Quaternary glaciations in the Pyrenees. In: Ehlers, J., Gibbard, P.L., Hughes, P. (Eds.), *Quaternary Glaciations, Extent and Chronology, A Closer Look Part IV*. Elsevier, Amsterdam, pp. 127-139.

Delmas, M., 2005. La déglaciation dans le massif du Carlit (Pyrénées orientales): approches géomorphologique et géochronologique nouvelles. *Quaternaire* 16, 45-55.

Delmas, M., 2009. Chronologie et impact géomorphologique des glaciations quaternaires dans l'est des Pyrénées. (PhD thesis) Université Paris 1 Panthéon-Sorbonne (529 pp.).

Delmas, M., Calvet, M., Gunnell, Y., Braucher, R., Bourlès, D., 2012. Les glaciations quaternaires dans les Pyrénées ariégeoises: approche historiographique, données paléogéographiques et chronologiques nouvelles. *Quaternaire* 23, 61-85.

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

Ivy-Ochs, S., Kerschner, H., Reuther, A., Maich, M., Sailer, R., Schaefer, J., Kubik, P.W., Synal, H.A., Schlüchter, C., 2006. The timing of glacier advances in the northern European Alps based on surface exposure dating with cosmogenics ^{10}Be , ^{26}Al , ^{36}Cl , and ^{21}Ne . *Geological Society of America Special Paper* 415, 43-60.

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

Quinif Y., Maire R. (1998) - Pleistocene Deposits in Pierre Saint-Martin Cave, French Pyrenees. *Quaternary Research*, 49, 37-50.

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

Reviewer #2: This a very good contribution to the glacial history of the Pyrenees. The paper presents a large sample of ^{36}Cl ages and these make an important story for the deglacial history of this area. I think that this is clearly a paper suitable for *Quaternary Research* and it is certainly well worth publishing. I have very few comments to make as this paper is very well written already and there is little to improve upon. I think that the definition of the LGM could be improved. For example you should mention what the LGM is: it is the global record of maximum ice volume recorded in the marine isotope records and also by sea levels. Peltier and Fairbanks 2006 put this at 26 ka whereas Mix et al 2001 put it centred on 21 ka. Furthermore, a recent paper (*Earth-Science Reviews* 125 (2013) 171-198; <http://dx.doi.org/10.1016/j.earscirev.2013.07.003>) notes that whilst the LGM is often a significant advance in many areas, the largest glacier advances sometimes occurred before the global LGM. In the Pyrenees, especially, this seems to be the case with an 'early' ice maximum (Pallas et al. 2010) as you note in your paper.

The definition of LGM has been changed

You note that in central Spain the Younger Dryas is often not represented by glacier advances. This is interesting and you should compare with the more northerly areas on a similar longitude, i.e Britain and Ireland, where Younger Dryas is clearly recorded. It might mean that Spain was significantly drier than these areas during the YD. Note also that rock glaciers are absent from the British Isles during the Younger Dryas. see Harrison, S., Whalley, B. and Anderson, E. 2007. Relict rock glaciers and proglacial lobes in the British Isles: implications for Late Pleistocene mountain geomorphology and palaeoclimate. *J. Quaternary Sci.*, Vol. 23 pp. 287-304.

A new sentence has been added, incorporating these topics

Whilst I agree that the rock glaciers are rock glaciers, you need to provide some more defence of their geomorphological interpretation. Recent work in Morocco (Hughes, Fink, Fletcher & Hannah. *Geog Soc America, Bulletin*) has shown that not all debris accumulations near headwalls are necessarily rock glaciers and some are rock avalanches. It might be worth a brief note to show that you are aware of the issues in separating rock glaciers from rock avalanches and that your Pyrenees features are definitely rock glaciers. Have you dated rock glaciers in the Pyrenees or central Spain?

We suggested in the text that the innermost deposits in the Piniecho cirque were built by rock avalanches

Please provide a reference for the term 'Mystery Interval'.

We have already included this reference.

Table 1

Table 1

Sample ID	Thickness (cm)	Sample mass (g)	Mass of ³⁵ Cl spike solution (mg)	Analytical isotope ratio (³⁵ Cl/(³⁵ Cl+ ³⁷ Cl))	stable	Analytical ratio (³⁶ Cl/10 ¹⁵ Cl)	³⁶ Cl/Cl	Measured concentration (10 ⁵ atoms ³⁶ Cl g ⁻¹)	³⁶ Cl	Production rate (*) (atoms ³⁶ Cl g ⁻¹ a ⁻¹)
PANTI-1	1.5	28.45	1.161	3.67 ± 0.0050		134.62 ± 3.48		74.0 ± 2.9		46.5
PANTI-2	5.5	29.97	1.008	4.29 ± 0.0140		166.42 ± 6.63		40.2 ± 1.8		17.5
PANTI-3	2.0	31.36	1.048	5.16 ± 0.0150		249.29 ± 20.20		39.9 ± 3.5		29.7
PANTI-4	3.0	30.72	1.082	4.73 ± 0.0210		267.16 ± 6.39		54.9 ± 1.9		39.3
PANTI-5	3.5	30.70	1.026	4.64 ± 0.0230		248.08 ± 13.03		49.4 ± 2.8		38.2
PANTI-6	3.0	30.17	1.097	7.76 ± 0.0170		315.23 ± 12.92		35.5 ± 2.1		17.2
PANTI-7	2.5	30.29	1.071	4.00 ± 0.0120		210.93 ± 4.71		69.2 ± 2.3		55.4
PANTI-8	5.0	30.41	1.030	4.03 ± 0.0150		254.85 ± 6.21		78.1 ± 2.8		48.1
PANTI-9	2.5	30.01	1.058	3.66 ± 0.0080		195.75 ± 5.33		97.4 ± 3.9		65.7
PANTI-10	5.0	30.18	1.047	3.77 ± 0.0100		194.02 ± 4.27		79.9 ± 2.6		43.4
PANTI-11	6.0	29.97	1.058	3.57 ± 0.0630		176.28 ± 8.58		105.0 ± 14.7		64.8
PANTI-12	5.0	31.61	1.037	3.99 ± 0.0160		193.51 ± 5.42		59.2 ± 2.4		45.8
PANTI-13	4.0	31.90	1.118	3.82 ± 0.0240		237.24 ± 10.85		95.4 ± 5.4		45.1
PANTI-14	4.0	31.12	1.025	3.83 ± 0.0100		226.14 ± 5.70		83.0 ± 3.1		54.2
PANTI-15	5.5	30.03	1.024	3.99 ± 0.0100		224.15 ± 5.68		71.3 ± 2.6		50.2
PANTI-16	4.0	30.07	1.018	3.82 ± 0.0010		174.95 ± 5.01		65.9 ± 2.8		46.3
PANTI-17	2.5	30.05	1.022	3.84 ± 0.0300		170.86 ± 5.55		63.1 ± 3.0		48.9
PANTI-18	3.5	31.57	1.080	4.23 ± 0.0090		279.04 ± 8.72		73.9 ± 3.3		43.1
PANTI-19	5.0	30.46	1.010	4.20 ± 0.0190		222.17 ± 5.86		57.6 ± 2.2		40.4
PANTI-20	5.0	30.27	1.124	4.21 ± 0.0100		248.65 ± 6.49		72.4 ± 2.8		44.1
PANTI-21	1.5	31.29	1.033	4.11 ± 0.0140		172.76 ± 4.39		47.3 ± 1.8		32.8
PANTI-22	3.5	30.57	1.029	4.73 ± 0.0160		235.19 ± 5.72		45.9 ± 1.6		32.2
PANTI-23	3.0	32.06	1.134	3.87 ± 0.0180		239.71 ± 5.73		90.2 ± 3.2		57.6
RES-1	1.5	30.02	1.041	7.59 ± 0.0550		87.67 ± 3.13		8.6 ± 0.5		5.5
RES-3	2.5	30.19	1.035	3.92 ± 0.0160		192.69 ± 5.42		65.1 ± 2.8		47.1
RES-4	2.0	30.17	1.044	4.12 ± 0.0190		211.81 ± 4.93		60.8 ± 2.2		44.1

(*) Scaled total sample specific ³⁶Cl production rate without radiogenic

Table 1 (continued)

Sample ID	Major elements concentration in bulk rock										Trace elements concentration in bulk rock					
	CaO (wt %)	K ₂ O (wt %)	TiO ₂ (wt %)	Fe ₂ O ₃ (wt %)	SiO ₂ (wt %)	Na ₂ O (wt %)	MgO (wt %)	Al ₂ O ₃ (wt %)	MnO (wt %)	P ₂ O ₅ (wt %)	B (ppm)	Sm (ppm)	Gd (ppm)	Th (ppm)	U (ppm)	Cl (ppm)
PANTI-1	4.95	3.72	0.64	5.79	60.69	2.56	4.49	14.72	0.10	0.12	6.50	5.30	4.20	11.00	1.70	305.05
PANTI-2	3.11	3.87	0.45	3.87	67.46	2.61	2.07	14.72	0.06	0.13	44.20	4.70	3.50	11.10	1.90	110.70
PANTI-3	4.44	2.68	0.77	5.96	66.10	0.84	1.98	14.74	0.16	0.12	23.70	10.30	7.80	20.80	3.10	59.40
PANTI-4	7.44	1.65	0.57	3.48	69.91	0.61	0.92	12.94	0.07	0.11	23.90	6.80	5.50	12.50	2.00	89.80
PANTI-5	9.03	2.08	0.98	5.03	63.43	0.51	1.57	14.51	0.17	0.13	31.00	14.00	10.70	31.80	5.00	82.50
PANTI-6	0.53	3.82	0.95	6.94	56.99	1.16	1.46	22.56	0.07	0.16	84.20	12.10	8.80	22.50	3.00	31.76
PANTI-7	5.14	2.96	0.67	5.67	60.98	2.30	3.31	15.44	0.09	0.10	19.30	5.50	4.20	7.00	1.50	165.72
PANTI-8	4.31	3.00	0.65	4.73	63.09	2.36	2.65	15.50	0.08	0.09	29.80	4.60	3.30	13.30	2.00	152.47
PANTI-9	3.41	3.10	0.70	5.65	61.16	3.36	3.05	15.44	0.08	0.10	10.80	4.50	3.60	10.10	2.20	269.51
PANTI-10	5.62	2.11	0.60	6.19	58.12	2.64	4.56	16.03	0.11	0.08	25.40	4.20	3.10	6.90	1.20	218.37
PANTI-11	7.44	0.64	0.72	6.19	57.10	2.56	3.40	17.52	0.11	0.18	12.90	5.40	4.10	7.60	1.70	317.00
PANTI-12	6.19	1.75	0.60	5.95	59.89	2.52	4.15	17.16	0.11	0.13	36.00	5.10	3.70	7.70	1.80	155.60
PANTI-13	4.61	2.68	0.65	5.50	61.61	2.41	3.28	15.21	0.09	0.11	19.40	5.90	4.40	12.30	1.10	200.80
PANTI-14	4.96	2.79	0.68	5.67	62.94	2.36	3.26	15.46	0.09	0.12	18.80	5.10	4.20	12.10	2.00	190.91
PANTI-15	4.92	2.39	0.78	6.35	61.53	2.83	3.79	15.02	0.10	0.13	11.90	6.50	4.90	12.20	3.10	160.31
PANTI-16	6.25	2.17	0.51	5.44	62.58	2.42	3.75	15.39	0.09	0.14	44.20	4.90	3.70	8.00	1.30	199.27
PANTI-17	7.35	1.86	0.58	6.36	58.99	2.31	4.45	16.71	0.11	0.10	22.50	4.70	3.80	7.00	1.60	195.09
PANTI-18	4.70	2.97	0.71	5.80	61.15	2.34	3.42	15.23	0.09	0.11	27.60	4.90	3.70	10.20	2.70	126.45
PANTI-19	5.31	2.05	0.65	6.14	60.58	2.38	3.75	16.62	0.11	0.11	11.80	6.50	4.80	11.90	2.00	125.72
PANTI-20	4.89	2.80	0.60	5.35	62.47	2.29	3.08	15.43	0.09	0.08	10.60	5.70	4.30	12.10	1.30	140.23
PANTI-21	3.19	3.76	0.51	4.47	67.49	2.30	2.51	14.06	0.07	0.11	5.90	3.80	3.40	11.70	5.20	136.97
PANTI-22	1.90	4.29	0.22	2.31	71.86	2.90	0.86	14.27	0.05	0.11	7.20	3.50	2.70	10.50	2.80	85.71
PANTI-23	4.09	3.41	0.63	5.52	62.94	2.56	3.30	15.64	0.09	0.14	8.10	5.90	4.20	13.30	1.90	193.71
RES-1	1.48	0.30	0.42	3.13	83.34	0.76	0.60	4.26	0.05	0.06	17.60	4.10	3.10	7.00	1.60	31.48
RES-3	3.47	2.77	0.42	3.57	66.50	3.23	1.49	15.89	0.06	0.12	5.50	4.60	2.90	8.30	3.20	175.12
RES-4	10.02	0.68	0.71	5.75	54.60	2.54	2.55	19.06	0.08	0.12	4.60	3.30	2.80	5.80	1.80	142.66

Table 1 (continued)

Sample ID	Element concentration in target fraction				
	CaO (wt %)	K ₂ O (wt %)	TiO ₂ (wt %)	Fe ₂ O ₃ (wt %)	Cl (ppm)
PANTI-1	4.86	3.79	0.62	5.67	305.05
PANTI-2	3.13	3.73	0.36	3.00	110.70
PANTI-3	4.28	2.74	0.82	6.03	59.40
PANTI-4	7.44	1.67	0.59	3.39	89.80
PANTI-5	8.64	2.09	0.97	4.70	82.50
PANTI-6	0.40	3.88	1.00	6.94	31.76
PANTI-7	5.62	2.75	0.52	4.73	165.72
PANTI-8	4.16	2.99	0.59	4.29	152.47
PANTI-9	1.26	3.16	0.69	5.50	269.51
PANTI-10	5.63	2.19	0.60	6.03	218.37
PANTI-11	7.21	0.66	0.71	5.99	317.00
PANTI-12	6.20	1.61	0.51	5.45	155.60
PANTI-13	4.86	2.44	0.50	4.56	200.80
PANTI-14	5.08	2.59	0.52	4.52	190.91
PANTI-15	4.47	2.28	0.70	5.56	160.31
PANTI-16	6.50	1.83	0.37	4.55	199.27
PANTI-17	7.84	1.28	0.36	4.80	195.09
PANTI-18	4.69	2.95	0.67	5.37	126.45
PANTI-19	5.14	2.02	0.57	5.51	125.72
PANTI-20	5.09	2.70	0.51	4.63	140.23
PANTI-21	3.22	3.53	0.45	3.89	136.97
PANTI-22	1.74	3.98	0.19	1.88	85.71
PANTI-23	3.91	3.40	0.64	5.19	193.71
RES-1	0.96	0.30	0.43	3.16	31.48
RES-3	3.50	2.80	0.40	3.37	175.12
RES-4	9.87	0.69	0.69	5.73	142.66

Table 2

Sample	Sample type	Distance from the headwall	Latitude	Longitude	Elevation	Topographic y correction factor	Zero erosion age	Snow correction factor	Age with snow correction and zero erosion	Age with snow correction and 3 mm ka ⁻¹ erosion
ID		(m)	°N (DD)	°W (DD)	(m)	(unitless)	(ka)	(unitless)	(ka)	(ka)
PANTI-1	moraine boulder	11800	42.7218	0.2462	1519	0.93	13.9 ± 2.0	0.98	14.1 ± 2.1	13.0 ± 2.1
PANTI-2	moraine boulder	11700	42.7235	0.2606	1442	0.67	21.9 ± 2.4	0.98	22.2 ± 2.4	22.0 ± 2.4
PANTI-3	rock glacier boulder	450	42.7221	0.1973	2308	0.86	11.6 ± 1.4	0.87	12.9 ± 1.6	12.8 ± 1.6
PANTI-4	rock glacier boulder	430	42.7228	0.1975	2322	0.99	12.5 ± 1.3	0.87	13.6 ± 1.5	13.2 ± 1.5
PANTI-5	moraine boulder	670	42.7230	0.1993	2337	0.91	10.9 ± 1.2	0.87	12.1 ± 1.3	12.0 ± 1.3
PANTI-6	polished bedrock	800	42.7189	0.1971	2295	0.67	18.0 ± 1.9	0.87	20.8 ± 2.2	20.8 ± 2.2
PANTI-7	rock glacier boulder	395	42.7284	0.2082	2434	0.96	11.1 ± 1.3	0.85	12.1 ± 1.5	11.6 ± 1.5
PANTI-8	rock glacier boulder	395	42.7284	0.2082	2429	0.89	14.3 ± 1.7	0.85	15.6 ± 2.0	15.1 ± 2.0
PANTI-9	rock glacier boulder	405	42.7288	0.2081	2425	0.93	12.9 ± 2.1	0.85	13.7 ± 2.3	12.7 ± 2.3
PANTI-10	moraine boulder	600	42.7286	0.2120	2374	0.70	16.8 ± 2.4	0.86	17.9 ± 2.7	16.9 ± 2.7
PANTI-11	moraine boulder	635	42.7299	0.2112	2356	0.82	14.7 ± 3.5	0.86	15.2 ± 3.7	14.1 ± 3.7
PANTI-12	moraine boulder	600	42.7295	0.2111	2353	0.99	11.5 ± 1.5	0.86	12.4 ± 1.7	12.0 ± 1.7
PANTI-13	moraine boulder	570	42.7297	0.2100	2370	0.76	19.1 ± 2.8	0.86	20.5 ± 3.2	19.1 ± 3.2
PANTI-14	moraine boulder	530	42.7304	0.2090	2397	0.90	13.5 ± 1.8	0.86	14.5 ± 2.1	13.8 ± 2.1
PANTI-15	moraine boulder	555	42.7311	0.2093	2382	0.94	12.3 ± 1.7	0.86	13.1 ± 1.9	12.6 ± 1.9
PANTI-16	rock glacier boulder	405	42.7303	0.2138	2273	0.91	13.1 ± 1.8	0.89	13.8 ± 1.9	13.3 ± 1.9
PANTI-17	rock glacier boulder	415	42.7298	0.2150	2291	0.92	11.7 ± 1.7	0.89	12.3 ± 1.8	11.3 ± 1.8
PANTI-18	moraine boulder	940	42.7311	0.2118	2319	0.90	15.5 ± 1.8	0.89	16.7 ± 2.0	16.2 ± 2.0
PANTI-19	rock glacier boulder	530	42.7319	0.2181	2209	0.95	12.6 ± 1.6	0.89	13.4 ± 1.8	12.9 ± 1.8
PANTI-20	rock glacier boulder	555	42.7321	0.2182	2212	0.89	14.8 ± 1.9	0.89	15.7 ± 2.1	15.0 ± 2.1
PANTI-21	polished bedrock	7300	42.7550	0.2397	1653	0.93	12.2 ± 1.5	0.98	12.3 ± 1.5	11.7 ± 1.5
PANTI-22	polished bedrock	6000	42.7671	0.2305	1844	0.96	12.8 ± 1.4	0.93	13.4 ± 1.5	13.0 ± 1.5
PANTI-23	polished bedrock	3075	42.7890	0.2308	2218	0.98	13.9 ± 1.8	0.89	14.7 ± 2.0	13.8 ± 2.0
RES-1	polished bedrock	8600	42.8090	0.3391	1525	0.92	14.6 ± 2.3	0.98	14.8 ± 2.3	13.6 ± 2.3
RES-3	polished bedrock	2600	42.8167	0.2957	2132	0.93	11.7 ± 1.7	0.87	12.4 ± 1.9	11.6 ± 1.9
RES-4	polished bedrock	2400	42.8139	0.2785	2169	0.97	12.3 ± 1.6	0.87	13.1 ± 1.8	12.3 ± 1.8

Figure 1
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Figure 2
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Figure 3a
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A)

A.1) Caldarés-Bolatica valley

A.2) Aguas Limpias valley

Figure 3b
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PINIECHO CIRQUE

NW S

Figure 11
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Figure 12
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