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The late Pleistocene and Holocene glaciation in the Pyrenees: A critical review and new evidence from ^{10}Be exposure ages, Noguera Ribagorçana Valley, south-central Pyrenean range

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Abstract

A compilation and a critical assessment of the ^{14}C dataset available show that the chronology of glacial events in the Pyrenees is not well constrained. After reviewing the literature on glacial reconstruction, we suggest a simplified subdivision of the Pyrenean last glacial cycle record into Last Pleniglacial, Deglaciation, and Neoglacial. To improve the numerical glacial chronology, we provide ^{10}Be surface exposure ages for 5 glacial erosion surfaces, 9 moraines and 2 erratics in the Upper Noguera Ribagorçana Valley (south-central Pyrenees). Published corrected ^{14}C data and new ^{10}Be exposure ages indicate that the major phase of moraine building in this valley during the Last Pleniglacial probably occurred after 25 ka BP. This age calls in question the generally accepted hypothesis of a very early deglaciation of the Pyrenees c. 70-40 ka BP, and strongly suggests that the Pyrenees could have been in pleniglacial conditions during the Last Glacial Maximum (LGM). However, we do not exclude the possibility that the maximum glacier extent during the last glacial cycle had taken place much earlier than the LGM, as indicated by some published U-Th, AMS ^{14}C and OSL data. We suggest that pleniglacial conditions could have taken place during a longer ($\gg 30-20$ ka) period than generally assumed, and that the Last Pleniglacial could include several glacier fluctuations recorded irregularly in different valleys, with a last major glacier readvance taking place around the LGM. In addition, the Deglaciation is represented by a series of moraines deposited between c. 13.7 ± 0.9 and 10.1 ± 0.6 ka. This moraine series indicates a highly variable climatic pattern that is partly correlated with Greenland Stadial 1 (the Younger Dryas), and suggests that the Deglaciation could have continued into the early Holocene.

1. Introduction

The complex oceanographic, atmospheric and glacial system in the North Atlantic region is considered to have played a significant role in the rapid and global climate fluctuations experienced during the late Quaternary (e.g. Alley and Clark, 1999). Recent studies clearly demonstrate that the Iberian Peninsula and surrounding offshore areas are highly sensitive to the variability of the North Atlantic system (e.g. Pérez Obiol and Julià, 1994; Cacho *et al.*, 1999, 2000, 2001; Sanchez Goñi *et al.*, 2000, 2002; Combourieu *et al.*, 2002; Moreno *et al.*, 2002). The Pyrenees are located in the north of the Iberian Peninsula, between the Atlantic and the Mediterranean. In this context, the Pyrenean glacial record is a potential source of relevant paleoclimatic data. Despite its relatively low resolution, when correlated and combined with other marine or terrestrial paleoclimate proxies, the glacial record of mountain areas may provide additional constraints on regional precipitation patterns, atmospheric temperature, and on predominant wind regimes.

Current knowledge of the Pyrenean glacial record is based on numerous local geomorphological and sedimentological studies that provide a relative chronology of glacial events valid for individual valleys. Similarities between valleys have given rise to tentative correlations and several valuable regional syntheses (Taillefer, 1969; Bru *et al.*, 1985; Andrieu *et al.*, 1988; Bordonau, 1992; Bordonau *et al.*, 1992; Serrat *et al.*, 1994; García Ruiz and Martí Bono, 1994; Serrano and Martínez de Pisón, 1994; Gómez Ortiz and Salvador, 1994; Peña Monné *et al.*, 1997; Gómez Ortiz *et al.*, 2000; Calvet, 2004). However, numerical chronological data are scarce, and the resulting chronological framework remains largely speculative. The lack of a robust numerical chronology hinders the correlation with other paleoclimate proxies, and constitutes the main obstacle to extracting paleoclimatic information from the glacial record of the Pyrenees.

With the advent of new geochronological techniques such as cosmic ray exposure dating, it is now possible to improve the chronological dataset of the last Pyrenean deglaciation. The Upper Noguera Ribagorçana Valley (UNRV) in the south-central Pyrenees is specially suited to ^{10}Be surface exposure dating because it hosts a well studied and relatively dense and continuous

succession of glacial features such as morainic ridges and glacially eroded rocks with quartz-bearing lithologies (Vilaplana, 1983a,b). In addition, the configuration of the UNRV tributaries allows us to test potential east-to-west asymmetries due to topographic shadow effects and prevailing winds. All these reasons make the UNRV an ideal case on which to base a preliminary chronological reference framework for the deglaciation of the south-central Pyrenees.

The aims of the present paper are 1) to make a critical review of the previously published chronological data on the Pyrenean deglaciation, 2) to provide a first numerical chronology for the glacial phases recorded in the Noguera Ribagorçana Valley based on ^{10}Be surface exposure dating, and 3) to discuss the new ^{10}Be dataset in the frame of the glacial chronology of the Pyrenees. The correlation with other palaeoclimatic proxies as well as the palaeoclimatic implications of the new chronology await data from additional areas in the Pyrenees, and will be discussed elsewhere.

2. Climatological setting of the Pyrenees

The Pyrenees are located between 42° and 43° of latitude N, and reach maximum heights at roughly 3,400 m a.s.l. in their central area (Fig. 1). The mountain range acts as a barrier to atmospheric circulation and determines strong N-S and E-W asymmetries in the precipitation pattern. The north and north-westerly winds from the Atlantic Ocean are the primary source of humidity and provide high precipitation rates on the northern slope of the Pyrenees. In contrast, the drier southern and eastern Pyrenees are under the influence of a Mediterranean type of climate. Superimposed on the general westerly regime, atmospheric depressions in the Mediterranean and their associated south-easterly winds provide a secondary source of humidity. Precipitation associated with this source rarely reaches the central Pyrenees. Present day glaciers are mostly limited to NE-facing cirques, with maximum areas not significantly greater than 1 km² (Serrat and Ventura, 1993, Chueca *et al.*, 2002). The Equilibrium Line Altitude (ELA) is at roughly 3,000 m a.s.l. in the central Pyrenees (Copons and Bordonau, 1994; Chueca *et al.*, 1997).

3. The glacial record in the Pyrenees: Overview

Based on a large number of local studies, several syntheses on the glacial record of the Pyrenees have been published (Barrère, 1963; Taillefer, 1969; Taillefer, 1982; Bru *et al.*, 1985; Hérail *et al.* 1987; Andrieu *et al.*, 1988; Bordonau, 1992; Bordonau *et al.* 1992; Serrat *et al.*, 1994; García Ruiz and Martí Bono, 1994; Serrano and Martínez de Pisón, 1994; Gómez Ortiz and Salvador, 1994; Peña Monné *et al.*, 1997; Gómez Ortiz *et al.*, 2000; Calvet, 2004). Geomorphic evidence indicates that Quaternary glaciers in the northern Pyrenees reached maximum thicknesses of c. 900 m and maximum lengths of c. 65 km (Taillefer, 1969, and references therein). Their termini descended to c. 400 m a.s.l. forming piedmont glaciers in the Aquitanian Basin (the northern foreland) in the Pau and Ossau valleys, where the unconstrained topography favoured deposition of a series of terminal moraines (Taillefer, 1969; Hazera, 1980; Hérail *et al.*, 1987). In contrast, the glaciers in the southern Pyrenees reached maximum thicknesses of c. 600 m and maximum lengths of c. 30 km (Martí Bono and García Ruiz, 1994). As these glaciers never reached the Ebro Basin (the southern foreland), the general narrowness and entrenchment of most valleys did not favour the generation or preservation of terminal moraines. The only exceptions to this are the Querol (a tributary of the upper Segre Valley), the Têt and the Aude valleys when entering into the Cerdanya-Capcir intramontane basins (Viers, 1961; Gourinard, 1971; Hazera, 1980; Calvet, 1997), and the wide Gállego and Aragón valleys (Serrano, 1991; García Ruiz and Martí Bono, 1994; Serrano and Martínez de Pisón, 1994; Martí Bono, 1996; García Ruiz *et al.*, 2003), where there are several terminal and/or lateral moraines at different heights, akin to the north-Pyrenean succession of piedmont moraines.

Hubschman (1984) reported a contrast in soil development and degree of weathering between the outer and the inner (fresher) moraines in four main north-Pyrenean valleys, and considered that the terminal complexes must have been deposited during different glaciations. Calvet (1997) applied a similar approach to the terminal moraine complex in the Querol Valley (south-eastern Pyrenees), providing arguments to differentiate the relatively fresh record of the Last Glaciation from deposits of two further glaciations (probably MIS 6, and older). In

addition, Hetu and Gangloff (1989) had reported a till deposit located 3 km beyond the limits of the outermost frontal moraines in the Ossau Valley (a tributary of the Oloron Valley), which probably corresponds to an even older glaciation. Additional indirect evidence based on karst stratigraphy and speleothem U/Th chronologies support the interpretation of several phases of extensive glacier development since 350,000 yr, which may be correlated with the last glaciation, MIS 6, 8 and, with less certainty, with MIS 10 (Sorriaux, 1981; Bakalowicz *et al.*, 1984; Quinif and Maire, 1998). More recently, Peña Monné *et al.* (2004) reported two OSL ages c. 155 ka for a glaciofluvial terrace laterally related to the most external till outcrop in the Gállego Valley, providing numerical evidence to attribute these sediments to the penultimate glaciation (i.e. correlative with MIS 6).

While there is strong evidence that the Pyrenean glacial record includes deposits from several glaciations, the record of the Last Glaciation is the best preserved, showing the freshest forms and the largest volumes of glacial deposits. Despite variations in the morphostratigraphy of different areas, the record of the last glacial cycle in the Pyrenees is consistent with the following evolutive phases.

3.1. The Last Pleniglacial

The term Pleniglacial is used in the literature to refer to the period of maximum and near-maximum glacial extent, irrespective of the age of glaciation (e.g. Taillefer, 1969; Serrano and Martínez de Pisón, 1994). In the present paper we use the term Last Pleniglacial to refer to the same concept, but restricted to the Last Glaciation. Both in the northern and southern Pyrenees this period is recorded by the most prominent morainic suite and by the thickest juxtaglacial successions. According to Bordonau (1992, 1993) and Bordonau *et al.* (1992), these large depositional forms necessitate stability of ice volumes for long periods. Instead of using the term Pleniglacial, these authors defined the following phases: "pre-maximum stabilisation", "maximum", and "post-maximum stabilisation".

There is general consensus on the view that the Pyrenean last glacial maximum took place several thousands of years earlier than the global Last Glacial Maximum, LGM, (Mardones and

Jalut, 1983; Vilaplana, 1983a,b; Andrieu *et al.*, 1988; Jalut *et al.*, 1988, 1992; Bordonau, 1992; Gillespie and Molnar, 1995; Florineth and Schluchter, 2000; García Ruiz *et al.*, 2003; Calvet, 2004). This idea is suggested by ^{14}C dates from sediments in the basal units of glaciolacustrine successions which, according to their geomorphological location, must have been deposited during or after the Last Pleniglacial period. The most ancient dates come from the work in the Pau Valley (northern Pyrenees) by Mardones and Jalut (1983). They reported an age of 38,400 ^{14}C yr BP for the nearly basal units of the lacustrine succession of Biscaye, deposited inwards from the Last Pleniglacial piedmont moraines. Extrapolating from the oldest dates in this succession, Mardones and Jalut (1983) calculated an age of c. 45 ka BP for the start of the lacustrine deposition and suggested an age between 70 and 50 ka BP for the piedmont moraines. Similarly, the glaciolacustrine succession of Llestui (Noguera Ribagorçana Valley, southern Pyrenees), yielded ^{14}C ages between $\geq 34,000$ and $\geq 31,500$ ^{14}C yr BP (Vilaplana, 1983b). These figures were the main cornerstones on which the widely cited chronological frameworks of Vilaplana (1983a,b), Bordonau *et al.*, (1992) and Bordonau (1992) were built. The glacial maximum was placed between 70-50 ka BP by Vilaplana (1983a,b), around 60 ka BP by Bordonau *et al.* (1992), and was later shifted to 50-45 ka BP by Bordonau (1992) to include the arguments raised by Montserrat (1992). According to Montserrat (1992), independent theoretical criteria suggest that the optimum conditions for the maximum advance of Pyrenean glaciers during the Last Glaciation took place between 50-45 ka BP. This author pointed out that during this period, ablation could have been reduced in the Pyrenees because of a minimum in summer radiation (Berger, 1978), and an increased vertical temperature gradient determined by low CO_2 concentration values in the atmosphere (Barnola *et al.*, 1987). The contrast between the low latitude radiation minimum and the high latitude radiation maximum would have produced a reinforced latent heat flow to the Pyrenean latitudes and an increased precipitation (Montserrat, 1992). A number of additional glaciolacustrine successions across the Pyrenees have yielded radiocarbon dates older than 20 ky BP, as summarized in Tables 1 and 2. These dates are generally accepted as providing minimum ages for the start of the deglaciation and are

often quoted as proof of an early Pyrenean glacial maximum (e.g. Andrieu *et al.* 1988; García Ruiz *et al.*, 2003; Calvet, 2004).

The validity of the oldest radiocarbon dates from glaciolacustrine successions was first questioned by Turner and Hannon (1988), who were reluctant to accept a marked climatic asynchronicity between the Pyrenees and northern Europe. They considered that the oldest part of the palynological succession presented by Mardones and Jalut (1983) was not consistent with the regional evidence and rejected the dates ranging between 29,500 and 38,400 yr BP. According to Turner and Hannon (1988) the basal sediments at Biscaye and probably other sites (see Table 1) were likely to be aged by a hard water effect and/or by presence of old reworked organic matter. Jalut *et al.* (1992) accepted that a hard water effect was likely, but argued that it could only be responsible for an ageing of less than 1.5 ka. However, these authors did not fully discuss the possible ageing due to the mineral carbon effect or the possible input of organic matter reworked from older sediments, and they considered the original dates of Mardones and Jalut (1983) to be roughly correct.

The first attempt to quantify the possible ageing of radiocarbon dates from the Pyrenean deposits was done in the glaciolacustrine succession of Llestui (Noguera Ribagorçana Valley, southern Pyrenees), which had initially yielded ^{14}C ages between $\geq 34,000$ and $\geq 31,500$ ^{14}C yr BP (Vilaplana, 1983a,b). Bordonau *et al.* (1993) resampled the same succession to attempt a separation of the mineral and organic carbon components present in bulk sediment samples. They measured the activity of the CO_2 released by igniting the samples in two steps, at c. 400°C and at c. 900°C. The step at higher temperature should correspond to oxidation of the mineral component and yielded ages about 40,000 yr BP. In contrast, the step at 400°C, which must roughly correspond to the oxidation of the organic component, provided two new dates of 18.2 ± 0.6 ^{14}C ka BP and 21.6 ± 0.9 ^{14}C ka BP (Table 1). Despite the fact that these corrected dates of Bordonau *et al.* (1993) show age inversion and that they display slightly high $\delta^{13}\text{C}$ values, they must be closer to the true ages of the Llestui succession than the former >30 ^{14}C ka BP measured by Vilaplana (1983a,b).

Palynological and dating studies also indicate that ^{14}C dates obtained from glaciolacustrine successions in the Pyrenees must be taken with caution. Reille and Lowe (1993), and Reille and Andrieu (1995) show that radiocarbon dates from lacustrine sediments are often inconsistent with the biostratigraphical correlations between neighbouring sites found at similar altitudes. Hence, in agreement with Turner and Hannon (1988), Reille and Andrieu (1995, page 18) conclude that the ages between 38,400 and 31,900 ^{14}C ka BP for the basal succession of Biscaye are too old, and suggest an alternative age of less than 25 ka BP. Redating of the same succession by Reille and Andrieu (1995) provided an age of 12,480 ^{14}C yr BP for sediments found at greater depth than those dated by Mardones and Jalut (1983) as 29,500 ^{14}C yr BP (see Table 1). In addition, the same authors suggest that most of the dates given by Andrieu (1987, 1991) and Jalut *et al.* (1988) from the successions of Barbazan, Estarrès and Castet may be considered too old (Table 1).

More recently, additional dates from glaciolacustrine sediments and bog deposits in the southern Pyrenees have been made available. Some of these are AMS ^{14}C dates from pollen concentrates which, in principle, should not be affected by the mineral carbon ageing. The oldest date comes from the glaciolacustrine juxtaglacial sediments of Linás de Broto that yielded an age of 30,380 ^{14}C yr BP (González Sampériz, 2004). This succession was emplaced when large lateral moraines were being built and when the Ara Valley must have been extensively glaciated (Last Pleniglacial), with an ice tongue about 30 km long (Martí Bono and García Ruiz, 1993; Serrano and Martínez de Pisón, 1994; Peña Monné *et al.*, 1997). Another interesting date from the neighbouring valley to the west (Gállego Valley, Fig. 1) is taken from the basal sediments of the El Portalet peat bog, which yielded an age of 28,300 ^{14}C yr BP (García Ruiz *et al.*, 2003; González-Sampériz *et al.*, 2004, *in press* 2006). This site is located at the bottom of a glacial cirque and the basal sediments are interpreted as the result of deposition in a proglacial lake. Since the site is at high altitude and close to the glacial divide, the date obtained was interpreted by García Ruiz *et al.* (2003) as evidence of an early age for deglaciation. However, according to González-Sampériz *et al.*, (2004; *in press* 2006), the

sedimentological and palynological record in the El Portalet succession suggests a later glacier readvance overriding this site around the LGM.

Bakalowicz *et al.* (1984) interpreted that clastic deposition in the Niaux-Lombrives caves (Ariege Valley) took place when the entrances of the cave system were glaciated. Based on U-Th dating of speleothems, these authors established that the last period of clastic deposition, and hence local glaciation took place between 90 and 19 ka. This means that the Ariege Valley must have been extensively glaciated with a >40 km-long glacier during the whole period. This glacier extent corresponds to >75% of the maximum Ariege glacier length suggested for the last glacial cycle (Taillefer, 1985).

Preliminary optically stimulated luminescence (OSL) dates by Sancho *et al.* (2002) suggest a correlation between the lowermost till outcrop in the Cinca Valley (2 dates yielding 49.5 ± 3.9 and 62.7 ± 6.2 ka) and a fluvial terrace (6 dates from different localities ranging from 53.8 ± 3.8 to 65.1 ± 4.5 ka). According to these authors, the OSL dates suggest a glacial outwash origin for the dated terrace and an age greater than 50 ka for the maximum glacial extent. Similarly, Peña Monné *et al.* (2004) sampled proximal and distal glaciofluvial deposits related to the lowermost till outcrop in the Gállego Valley, yielding OSL dates of 85 ± 5 and 67 ± 8 ka, respectively. In addition, for waterlain sediments included in a well preserved frontal moraine located c. 2 km upvalley, they provide two OSL ages of 35 ± 3 and 36 ± 2 ka. Although all published OSL dates from the southern Pyrenees may correspond to depositional ages, no detailed discussion is yet available about the possibility of partial bleaching prior to deposition, and an ageing effect cannot be completely ruled out.

3.2. The Deglaciation

Separated by more than 10 km from the Last Pleniglacial features, minor recessional moraines or push moraines are commonly found at increasing heights along the valley axes. These features are not equally distributed or distinguishable in all valleys, but they are consistent with a general deglaciation trend, punctuated by a few relatively short stabilisations

or glacial readvances (Taillefer, 1969; Bordonau, 1992; Martí Bono and García Ruiz, 1994; Peña Monné *et al.*, 1997; García Ruiz *et al.*, 2003).

An early "valley glacier phase" was distinguished by Bordonau *et al.* (1992) and Bordonau (1992) including two deposits (the Seminari de Vilaller frontal moraine in the Noguera Ribagorçana Valley, and La Masana glaciolacustrine complex in the Valira Valley), which had previously been attributed to a "post maximum stabilisation" by Vilaplana (1983b, 1985). Bordonau (1992) tentatively assigned an age $>26,000$ ^{14}C yr BP to his "valley glacier phase" by correlating it with the Barbazan-Coumanié-Labroquère glacial episode (Garonne Valley, northern Pyrenees). The age is based on the interpretations and near-basal date of the proglacial glacio-lacustrine sequence at Barbazan obtained by Andrieu *et al.* (1988), and Andrieu (1989, 1991).

A much more distinctive and widespread feature of the deglaciation is a group of tills and moraines restricted to high mountain areas (Taillefer, 1969; Martí Bono and García Ruiz, 1994; Peña Monné *et al.*, 1997; García Ruiz, *et al.*, 2003). They are clearly distinguishable from the Last Pleniglacial moraines because they are found tens of km upvalley, and are morphologically fresher. These moraines formed after disconnection of the main glacial tributary system, and result from stabilisation or readvance of single ice tongues measuring several km in length. The period of deposition of these moraines has been referred to as the "disjunction stage" by Taillefer (1969), and as the "mountain glacier phase" by Mardones and Jalut (1983). The latter authors associated this phase with a cold period, according to their interpretation of the palynological and sedimentary record of the glaciolacustrine sequence in Biscaye (northern Pyrenees). They assigned an age between c. 24,000 and 13,250 ^{14}C yr BP to this glacial phase based on interpolation of their single bulk sediment radiocarbon dates (Table 1). Partly based on the same data and following a similar terminology, Bordonau (1992) distinguished an "altitude glacier phase" which comprises from older to younger, an "altitude valley glacier episode" and a "cirque glacier episode". Following the interpretations and using the dates from the north-Pyrenean glaciolacustrine and bog successions of Freichinede, Balcère and Laurenti studied by Jalut *et al.* (1982) and Andrieu *et al.* (1988), Bordonau (1992) considered that the glacial fronts

had already receded to high mountain areas by 16 ¹⁴C ka BP. Hence, he suggested an age of about 16 to 13 ¹⁴C ka BP for his "altitude glacier phase". Similarly, Reille and Lowe (1993, p. 74), conclude that the upper valleys in the Pyrenees were mostly deglaciated prior to 15 ¹⁴C ka BP. A minimum age for deglaciation of some cirque areas c. 13.5 ¹⁴C ka BP is deduced from lake Redó d'Aigüestortes in the Tor Valley (Copons and Bordonau, 1996), and c. 16.5 ¹⁴C ka BP from la Grave peat bog in the Têt Valley (Delmas, 2005) (Table 2).

Cirque-floors are commonly occupied by conspicuous rockglaciers (Serrano *et al.*, 1991, Lampre *et al.*, 1997; Serrano and Agudo, 1998). Rockglaciers are especially abundant towards the eastern Pyrenees but are present all along the mountain range. Serrat (1979) argued that the rockglacier dynamics would have been favoured by a period of cold and dry climatic conditions and suggested that there would have been a period of preferred development of rockglaciers towards the end or after the main deglaciation. He acknowledged the coexistence of cirque glaciers during the development of rockglaciers but suggested that this major period of rockglacier development could be correlated with the cold and dry conditions of the Lateglacial period, as deduced from palynological records (e.g. Jalut, 1974), and from sedimentological arguments (Vilaplana *et al.*, 1983, 1989). Based on these considerations, Bordonau (1992) formally defined a "rockglacier phase" taking place after the deglaciation. He suggested that the correlation made by Serrat (1979) could be restricted to the Younger Dryas, and assigned an age of 11,000 to 10,000 ¹⁴C yr BP to the "rockglacier phase". Such restrictive chronology for the major phase of rockglacier activity was rejected by García Ruíz and Martí Bono (1994), and Serrano and Martínez de Pisón (1994). They consider that during a general shift from glacial to periglacial dynamics, rockglaciers can activate asynchronously depending on local factors. Hence, they suggest that rockglaciers in different areas may have been active at different times since the deglaciation to the Holocene, including reactivations during cold historical fluctuations. These ideas are in agreement with the observation of present-day active rockglaciers (Lampre *et al.*, 1997; Serrano and Agudo, 1998; Chueca *et al.* 1994; Chueca and Julián, 2005; Serrano *et al.*, 1991, 1999, 2006).

3.3. *The Neoglacial*

Apart from rockglaciers, most cirques display single or several glacial moraines. Taillefer (1969) distinguished a "neoglacial stage" during which cirque moraines would have been formed after a period of complete or almost complete deglaciation. In contrast, Bordonau (1992) interpreted most of the cirque moraines as part of the main deglaciation, and included them in his late "altitude glacier phase" (the so called "cirque glacier episode"). However, he implicitly recognised that part of them could have been generated in later (Holocene) periods. Although geomorphic data do not allow a clear separation of Lateglacial and Holocene glacial features, it is generally assumed that some of the cirque moraines were deposited during the Holocene (Taillefer, 1969; Bordonau *et al.*, 1992; García Ruiz and Martí Bono, 1994; Serrano and Martínez de Pisón, 1994). Existence of early Holocene glacial advances is supported by Gellatly *et al.* (1992), who inferred glacial phases by conventional ^{14}C dating of a bog succession located between two morainic arcs in the Cirque de Troumouse (northern Pyrenees, Table 2). They distinguished a probable Holocene phase which occurred earlier than 5,190 ^{14}C yr BP, and another phase of moraine construction, which they correlated with a shift towards inorganic sedimentation in the bog between 5,190 and 4,654 ^{14}C yr BP. According to Gellatly *et al.* (1992), there have been at least two further Holocene advances involving moraine construction. Julián and Chueca (2002) also indicate some morainic remnants found at high altitude in cirque areas which they attribute to pre-Little Ice Age times (perhaps corresponding to the Lateglacial) based on lichenometric dating.

In addition, historical glacial phases have been documented. The few present-day glaciers in the Central Pyrenees are bordered by a series of fresh morainic ridges. According to descriptions and engravings made during the 18th and 19th centuries (Martínez de Pisón, 1989; Martínez de Pisón and Arenillas, 1988), and according to lichenometric dating (Chueca and Julián, 1996), these moraines mark the location of the glacial margins during historical times. Together with other equally fresh moraines found in completely deglaciated valleys, these were attributed to the Little Ice Age (Martí Bono *et al.*, 1978; Martínez de Pisón, 1989; Bordonau *et al.*, 1992; Martí Bono and García-Ruiz, 1994). Copons and Bordonau (1994) described two

moraine generations in the Maladeta Massif (Central Pyrenees), which indicate two episodes of glacier advance in the Little Ice Age. Based on correlation with the fluctuations established in the Alps, on dendroclimatological data from the central Pyrenees, and on a discussion on the possible causes of the Little Ice Age, the first episode was considered to have occurred during the 18th century (probably coinciding with the Maunder Minimum), while the second episode was assigned to the 1820s, with a possible causal link with the Tambora volcanic eruption (Copons and Bordonau, 1994). Similarly, based on lichenometric dating, Chueca and Julián (1996) identified two phases of glacier readvance attributable to the Little Ice Age (1600-1620 AD and 1820-1830 AD).

4. The glacial record in the Upper Noguera Ribagorçana Valley

The study area is located in the UNRV between 3,240 and 900 m altitude (Fig. 2). The geological, geomorphological and sedimentological record of the UNRV was studied in detail by Vilaplana (1983a,b), Vilaplana *et al.* (1989) and Vilaplana and Bordonau (1989). In this section we summarise the most relevant data on glacial reconstruction, with especial emphasis on the geomorphological features suitable for surface cosmic ray exposure dating. The information included in this section is taken from Vilaplana (1983a) and from additional aerial photointerpretation and fieldwork carried out in 2003.

Paleozoic granodiorites of the Maladeta batholith crop out in the northern UNRV (Fig. 2). South of the Maladeta batholith, bedrock is largely composed of quartz-poor sedimentary paleozoic units including limestones, slates and sandy slates (Mey, 1965). However, granodioritic blocks are pervasive in tills and moraines cropping out in the study area, both in areas of granodioritic and sedimentary bedrock.

About 9 km south of Vilaller the valley is relatively narrow and shows no signs of glacial erosion. Associated with a widening of the Noguera Ribagorçana Valley at the convergence with the Noguera de Tor Valley there are a few terrace remnants at c. 15-20 m above the present-day talweg (Vilaplana, 1983a). Some of these deposits have been interpreted as

glaciofluvial in origin, but since they have no contact with glacial sediments, they can hardly be situated in the relative chronological framework (Vilaplana, 1983a,b).

The lowest till outcrops in the valley are found about two km south of Vilaller (c. 940 m a.s.l., Fig. 2). They correspond to the Sant Antoni subglacial till, whose surface displays abundant rounded to subangular granodiorite boulders of metric size (Vilaplana, 1983a,b). The present day Noguera Ribagorçana river incised this deposit by c. 20 m. These subglacial tills were deposited when the Noguera Ribagorçana glacier was more than 30 km-long, close to its assumed maximum extent (Vilaplana, 1983a,b).

The volumetrically most important glacial deposits in the UNRV correspond to a left lateral moraine whose remnants and associated juxtaglacial obturation terraces can be traced discontinuously for >10 km along the eastern valley flank (Figs. 2, 3). These moraine remnants gradually descend from about 1,700 m a.s.l. near Artigalonga (600 m above the valley floor), to about 1,280 near Tinabre (250 m above the valley floor). At the opposite (western) valley side, the remnants corresponding to this major moraine building episode are well preserved in the tributary valley of Llauset where a well developed left lateral moraine exists. Associated with this lateral moraine is the juxtaglacial glaciolacustrine complex of Llestui, produced by the obstruction of two small tributary fluvio-torrential basins. The excellent exposure of the Llestui complex indicates synchronous construction of the moraine, with sedimentation of glaciolacustrine rhythmites and alluvial fan progradation (Vilaplana, 1983a,b; Vilaplana and Bordonau, 1989). The glaciolacustrine rhythmites of Llestui were ^{14}C dated by Vilaplana (1983a,b), and the dates were later corrected by Bordonau *et al.* (1993) to c. 18-20 ka BP (see the present paper section 3.1., for details). Bordonau (1992) attributed the lateral moraines of Artigalonga and Llestui together with their associated juxtaglacial deposits and terraces (termed the Artigalonga-Llestui moraine system in the present paper) to the "post-maximum stabilisation phase" (Fig. 4).

About 2-3 km north of Vilaller, and at slightly higher (up to c. 20 m) elevations than the Artigalonga-Llestui moraine system, the Noguera Ribagorçana Valley-flanks display sparse

granodioritic erratic boulders. These erratics mark an earlier period of slightly more extensive glaciation than the period of deposition of the Artigalonga-Llesui moraine system.

Despite the large deposits of the Artigalonga-Llestui moraine system, there is no frontal moraine which can clearly be considered a correlative. The only possible candidate is the Seminari de Vilaller moraine (Vilaplana, 1983a,b) located 1 km north of Vilaller and at c. 990 m a.s.l. (Fig. 2). This is a till deposit which clearly forms a frontal moraine rising about 8 m over the Noguera Ribagorçana talweg. Vilaplana (1983a,b) and Bordonau (1992) considered that the altitudinal contrast between this frontal moraine and the lowest remnants of the Artigalonga-Llestui moraine system is too strong to allow correlation. This was the reason for Bordonau (1992) to attribute this morainic frontal arc to his "valley glacier phase", considered to correspond to a slight readvance during the deglaciation after the "post- maximum stabilisation phase" (Fig. 4).

North of Seminari de Vilaller moraine, no glacial deposits but few glacial erosion surfaces are observed for 15 km along the valley axis. The best preserved roches moutonnées on granodiorite are found at Refugi de l'Hospitalet, about 1,460 m a.s.l. (Fig. 2).

About 1,530 m a.s.l. and close to the UNRV talweg, there is a 0.5 km-wide group of morainic remnants which are termed in the present paper the Santet moraines (referred to as the Barranc de Bessiberri deposits by Vilaplana, 1983b) (Fig. 2). Roadcuts show that these moraines are made up of sandy till, with abundant granodioritic boulders that protrude conspicuously at the surface. The gently undulated terrain of the Outer Santet moraines allows the distinction of up to three discontinuous subdued ridges, which can be interpreted as deposited by a receding ice front. In contrast, the more prominent Inner Santet moraine (Fig. 5) rises 10-15 m over the valley floor and can be interpreted as the result of a longer stabilisation or a glacial readvance, when the ice tongue of Mulleres (and maybe Conangles) was c. 6.5 km-long. Upwards (c. 1,5 km) along the valley axis, at about 1,600 m a.s.l. there are two minor tightly-spaced left lateral moraines which are known as the Hospital moraines. The prolongation of these moraines towards the valley bottom indicates that they must be younger than the Santet moraines. Accordingly, they indicate two further small ice stabilisations or readvances. The

Santet and Hospital moraines are included in the "altitude valley glacier episode" (early "altitude glacier phase", Fig. 4) distinguished by Bordonau (1992).

At about 1,720 m a.s.l. in the Mulleres Valley axis, there is a protruding granodioritic roche moutonnée (Fig. 6a) which must have been deglaciated before the deposition of a bouldery moraine located a few meters upvalley (Fig. 2). This deposit, termed the Mulleres moraine, can be ascribed to a minor period of ice stabilisation or readvance when the Mulleres ice-tongue was c. 4 km-long.

At about 2,200 and 2,300 m a.s.l. on the Pleta Naua slope, there are three arcuated moraines referred to as Pleta Naua moraines (Fig. 2, Fig. 6b). Situated on an open slope oriented to the SE, they may have been deposited by small (< 2 km²) niche glaciers disconnected from the main Mulleres ice-tongue. Similar moraines are perched on the opposite southern flanks of the Mulleres Valley. The outer arcs were assigned to the "altitude valley glaciers episode" (early "altitude glacier phase"), whereas the inner moraines were attributed to the late "altitude glacier phase" (the "cirque glacier episode", Fig. 4) by Bordonau (1992).

In addition, the opposite (southern) flank of the Mulleres Valley also shows a single morainic arc oriented north at c. 2,460 m a.s.l., termed the Tallada moraine (Figs. 2, 6b). In contrast with the Outer and Inner Pleta Naua moraines, it shows a sharp moraine crest and its boulders display a low degree of alteration and lichen growth. The moraine surrounds a closed depression which, entrenched between two peaks, holds a permanent snow field. Despite the contrasting freshness of this morainic arc Bordonau (1992) also assigned it to his early "altitude glacier phase" (the "altitude valley glaciers episode", Fig. 4). Equivalent features associated with permanent snow fields are also present at the head of Salenques Valley, interpreted by Chueca *et al.* (2002) to be formed during the Little Ice Age.

At c. 2,000 m a.s.l. a glacially polished sill with abundant roches moutonnées separates the upper Bessiberri Valley from the UNRV. In addition, a large and prominent roche moutonnée is found in the valley floor at c. 2,100 m a.s.l. These are termed the Outer Bessiberri and Bessiberri roches moutonnées, respectively (Fig. 2).

Approximately midway between these two erosion surfaces and c. 2,000 m a.s.l., the upper Bessiberri Valley displays a right fronto-lateral moraine remnant which must have been deposited during a glacier stillstand or readvance when the Bessiberri glacier was about 2 km-long. At about 2,700 m a.s.l. there is a set of moraines referred to as Llastres de Bessiberri moraines (Figs. 2, 6c). Despite being topographically higher than the Pleta Naua moraines, they show a similar alteration pattern and morphology. South of Llastres de Bessiberri, there is an active rock glacier (Serrano *et al.*, 1991; Chueca *et al.*, 1994; Serrano and Agudo, 1998; Chueca and Julián, 2005), which is interpreted to derive from burial of a Little Ice Age glacier (Serrano *et al.*, 1991). This interpretation is consistent with lichenometric dating of limiting moraines (Chueca *et al.*, 1994).

5. Methods

Granodioritic glacial erosion surfaces and moraine boulders were selected for ^{10}Be surface exposure dating to cover the widest possible range of glacial phases (Table 2). To minimise the risks of shielding by till, soil cover, or snow, we chose the highest and most prominent roches moutonnées located far from areas covered by till. Similarly, in an attempt to avoid underexposure caused by block rotation or till cover, only boulders well anchored in till were selected. From these, boulders protruding more than 1 m over surrounding till were favoured. We selected up to three samples per moraine whenever suitable blocks were available. Only the two upper centimetres from selected rock surfaces were sampled.

Samples were crushed and sieved to extract the 250-1000 μm granulometric quartz fraction. Minerals other than quartz were dissolved by HCl and H_2SiF_6 , and remaining quartz grains were cleaned using sequential HF dissolutions to remove any potential atmospheric ^{10}Be (Brown *et al.*, 1991; Kohl and Nishiizumi, 1992; Cerling and Craig, 1994). Between 10 to 30 g per sample of clean quartz cores were then completely dissolved in HF and spiked with 300 μg of ^9Be carrier (Bourlès, 1988; Brown *et al.*, 1992). Beryllium was separated by successive solvent extractions and alkaline precipitations (Bourlès, 1988; Brown *et al.*, 1992). Measurements of ^{10}Be concentrations were taken at the Tandatron AMS facility of Gif-sur-Yvette, France

(Raisbeck *et al.*, 1994). AMS measurements were performed with reference to NIST Standard Reference Material 4325 using the certified ^{10}Be to ^9Be ratio of $(26.8 \pm 1.4) \times 10^{-12}$. Because ^{10}Be production rates are all referred to ICN standards, we normalized the measured concentrations based on the NIST standard to ICN standards by increasing them by a factor of 1.143, according to Middleton *et al.* (1993). Analytical uncertainties (reported as 1σ) were calculated based on counting statistics, a conservative estimate of 3% instrumental variability and a 50% uncertainty in the chemical blank correction. See Table 3 for additional details.

Among the slightly different ^{10}Be production rates available in the literature, the one deduced from the K fels calibration site (Kubik *et al.*, 1998; Kubik and Ivy-Ochs, 2004) is undeniably the most suitable when considering similarities in altitude, geographic location, and exposure age-range with respect to the study area. The re-evaluated sea level high latitude (SLHL) production rate of $5.44 \text{ }^{10}\text{Be}$ at $\text{g}^{-1} \text{ y}^{-1}$ quartz reported by Kubik and Ivy-Ochs (2004) was based on the nucleonic component scaling of Lal (1991), with no latitude scaling for the muonic component. Based on 1) the original ^{10}Be concentration data and the topographic and environmental correction factors reported in Kubik and Ivy-Ochs (2004, Tables 1 and 2, samples KOE4 to KOE101) for the calibration site of K fels, 2) the attenuation lengths and muonic contributions of Braucher *et al.* (2003), and 3) the widely used scaling method of Stone (2000), we recalculated a SLHL production of 5.41 ± 0.17 at $\text{g}^{-1} \text{ y}^{-1}$ quartz. Using this “corrected” K fels-derived SLHL ^{10}Be production value, we applied the scaling method of Stone (2000) to deduce the exposure ages reported in Figs 2, 7 and 8. The limitations of these and other recently developed scaling criteria (Dunai, 2000; Stone 2000) were reviewed by Desilets and Zreda (2003), who provide a more reliable scaling procedure based on mass shielding depth (instead of altitude) and effective vertical cutoff rigidity (instead of geomagnetic or geographic latitude). Building on the approach of Desilets and Zreda (2003), Pigati and Lifton (2004) provide an altitude-latitude scaling method that takes into account geomagnetic intensity variations and polar wander, and their time-integrated effects on production. Table 3 includes the exposure ages calculated for the Noguera Ribagor ana samples based on both Stone (2000) and Pigati

and Lifton (2004), showing that results from these two scaling methods only differ by a maximum of +7.5/-6.4 %, depending on altitude.

Even though uncertainty in the scaling models is difficult to assess, realistic errors for the nucleonic component attenuation length may be $> \pm 10\%$ of the widely used scaling polynomials of Lal (1991), which are also implicit in Stone (2000) polynomials, and in the range of +5/-2% in the case of Desilets and Zreda (2003) scaling, implicit in Pigati and Lifton (2004). As no corrections for erosion, sample thickness or irradiation geometry are applied, the calculated exposure ages for the UNRV must be seen as minimum estimates. However, the maximum deviation between calculated and true exposure ages in the most unfavourable cases is estimated as $< 9\%$ (c. 2.7% corresponding to a mean erosion of 1.5 mm ka^{-1} on granodiorite, c. 1.7% corresponding to 2 cm sample thickness, and c. 4.5% corresponding to the difference between irradiation on a flat geometry vs. the geometries of sampled surfaces based on Masarik and Wieler, 2003). Based on present day seasonal distribution of snow in the sampled sites, the effect of snow cover is assumed to be negligible, at least for the Holocene.

6. Results

Dating of the relevant moraine groups and erosion surfaces were performed to provide a chronology of the UNRV deglaciation. Twenty-five samples corresponding to 18 blocks from 9 different moraines, 2 erratic blocks, and 5 erosion surfaces were processed. Despite the fact that the sampling was designed to minimise the likelihood of selecting previously rotated or till covered blocks, some ^{10}Be dates are incoherent when compared with dates from the same moraine or dates from neighbouring sites (Table 3, Fig. 7). Such aberrant cases were avoided by withdrawing 1) one date (ART01) differing by more than two standard deviations with respect to the older dates from the same moraine, and 2) dates inconsistent with the geomorphologically-based relative chronology (see Fig. 7 and the following paragraphs for details). The minimum exposure age of each moraine was then deduced by calculating the error weighted mean of the remaining dates. The resulting ^{10}Be exposure ages obtained from the UNRV are summarized in Figs. 2 and 8.

According to their location, the Sant Antoni till and the Seminari de Vilaller moraine must be among the oldest glacial deposits in the UNRV. However, when compared with exposure ages from features located upvalley, the exposure ages of 12.3 ± 1.8 ka (STA01) and 6.1 ± 1.3 ka (SMV01) are too young and can be attributed to erosion of till cover or to block rotation. Hence, these two key localities did not yield dates that can be interpreted as ages of deposition or deglaciation.

^{10}Be data from boulders on the Artigalonga moraine provide exposure ages of 18.6 ± 2.2 ka (ART02), 16.6 ± 3.8 ka (ART03) and 4.4 ± 1.0 ka (ART01). The last one is an obvious outlier, whose underexposure may be due to block rotation. The two older dates indicate an exposure age of 18.1 ± 1.9 ka (weighted mean) for the Artigalonga-Llestui moraine system, corresponding to a minimum age for the culmination of the major phase of moraine building in the UNRV (Fig. 3, 7 and 8). In line with the geomorphological evidence, an older exposure age of 21.3 ± 4.4 ka is calculated for the Tinabre erratic (TIN01), which must have been deposited before the Artigalonga-Llestui moraine system, when the UNRV glacier near Tinabre was about 20 m thicker (Fig. 2). Given that significant erosion or rotation of blocks cannot be ruled out, the Artigalonga and Tinabre exposure ages must be interpreted as minimum ages of deposition.

The Refugi de l'Hospitalet erosion surfaces are found on a moderate slope which minimises the chance of till cover and, hence, the ^{10}Be exposure ages obtained for RLH01 (13.2 ± 3.3 ka) and RLH02 (11.7 ± 1.5 ka) are considered to provide relatively accurate deglaciation ages, and minimum ages for the disconnection between the Salenques and Mulleres glaciers, with a weighted mean of 11.9 ± 1.4 ka (Fig. 2). Statistically indistinguishable exposure ages for three block surfaces sampled from the Inner Santet Moraine (IST01, 14.4 ± 1.4 ka; IST02, 12.3 ± 1.5 ka, and IST03, 16.1 ± 2.8 ka) yield a weighted mean exposure age of 13.7 ± 0.9 ka. The exposure age of HOS03 (25.3 ± 2.4 ka, Fig. 7), when compared with the internally consistent exposure ages of Refugi de l'Hospitalet and the Santet Moraines, must be considered too old for the age of the Hospital Moraine, indicating inheritance. The angular boulder from where HOS03 was retrieved

must have been sitting on a higher ridge or rocky slope for several thousands of years before being deposited on the moraine.

The lowest erosion surfaces along the Bessiberri Valley (OBS01) provide an exposure age of 16.3 ± 2.2 ka, which must correspond to a minimum age for the disconnection of the Bessiberri ice tongue from the Noguera Ribagorçana glacier. Further upvalley, another *roche moutonnée* (BES01) yields a consistent deglaciation age of 11.7 ± 1.5 ka. Between these two erosion surfaces, there is a fronto-lateral morainic ridge at c. 2,000 m a.s.l. (Bessiberri moraine in Fig. 2) and a smaller morainic ridge found at a higher altitude. Despite the lack of suitable boulders for sampling, OBS01 and BES01 bracket the age of these moraines, providing strong support for correlation with the Santet Moraines.

The Mulleres *roche moutonnée* (MUL01, 10.3 ± 1.8 ka) is located a few metres downvalley from the Mulleres moraine (MUL04, 10.4 ± 1.2 ka), strongly constraining its minimum age. These dates mark the period when the Mulleres ice tongue was about 3.5 km long, and are statistically indistinguishable from the exposure ages determined for Outer Pleta Naua moraine (weighted mean of 10.2 ± 0.7 ka), and Llastres de Bessiberri moraine (weighted mean of 10.1 ± 0.6 ka), suggesting that they could be formed during the same phase of moraine building. However, given the age uncertainties these moraines could also correspond to different glacier fluctuations. The age of the Inner Pleta Naua moraine is less clear because different boulders yielded conflicting exposure ages. Block rotation of IPN01 (4.4 ± 0.7 ka) or inheritance for IPN02 (11.2 ± 1.6 ka) cannot be ruled out.

7. Discussion

7.1. Sources of ageing in radiocarbon dates from glaciolacustrine successions

Next, we discuss several theoretical points that will be applied later in our discussion on the reliability of the Pyrenean ^{14}C dataset. As generally acknowledged, ^{14}C dates from limnic material may be subject to a number of errors (e.g. Sutherland, 1980; Lowe *et al.*, 1988; Bowman, 1990; Lowe and Walker, 1997). First, a hard water error may be produced when old

carbon is leached from bedrock lithologies into lake waters. Uptake of such inert carbon by organisms in the lake results in ^{14}C -depleted organic matter, and yields ^{14}C ages that are too old. Second, mineral carbon contamination may affect sediment samples if old carbon from bedrock was introduced into the lake as fine-grained detritic sediments. The effect may be most important in areas of carbonate-rich bedrock, but it may also occur in recently deglaciated terrain where inert carbon may be released from other lithologies by glacial erosion (Sutherland, 1980). Third, organic carbon contamination may result from inclusion, in the lake sediments, of allochthonous organic matter reworked from older formations.

The fractionation laws of the different carbon isotopes provide an indirect way of evaluating to what extent dates are affected by the hard water effect or by mineral carbon contamination. $\delta^{13}\text{C}$ values higher than the normal values found in limnic organisms (i.e. $> -25 \pm 3 \text{ ‰}$, Bowman, 1990; Lowe and Walker, 1997) indicate a hard water error in the case of AMS samples, and/or a possible mineral carbon contamination in the case of bulk sediment samples. In contrast, detecting contamination by organic carbon is a more complex matter: its effect can only be estimated by biostratigraphical comparison, detailed taphonomical study of the microfossil assemblage, or by independent AMS dating of the different organic fractions (Nambudiri *et al.*, 1980; Lowe *et al.* 1988; Nelson *et al.*, 1988).

The magnitude of the hard water ageing may reach up to several hundred years (e.g. Andree *et al.*, 1986; Moore *et al.*, 1998). In contrast, the ageing produced by the mineral and/or organic carbon contamination may be much higher depending on the relative amount of allochthonous vs. autochthonous carbon component and the original concentration in ^{14}C of the former. When autochthonous organic production rates are small, they can be overwhelmed by even the smallest amounts of old mineral or organic allochthonous carbon, resulting in a large ageing effect (Olsson, 1979; Sutherland, 1980; Björck and Håkansson, 1982). Sparse vegetation cover and high rates of mechanical weathering may be responsible for increased erosion and enhanced allochthonous input of mineral and organic carbon into glaciolacustrine successions. These conditions are likely to be met at the start of glaciolacustrine sedimentation during the first stages of the deglaciation, when near-full glacial conditions still prevail (Sutherland, 1980).

While the ageing effect may be maximum in minerogenic sediments deposited during full glacial conditions, it can be significantly reduced or negligible during later deglaciation phases, when the relative detritic input is decreased by 1) the protective effect of the vegetation cover, 2) a greater distance from the glacier front, and by 3) the increased local lacustrine organic production. The correction needed for ^{14}C dates from contaminated postglacial lacustrine sediments is highly variable; with reported values ranging up to 25,000 yr (Nambudiri *et al.*, 1980).

7.2. Reliability of minimum limiting radiocarbon dates from Pyrenean glaciolacustrine successions

As shown in section 3, the deglaciation chronology in the Pyrenees has been based on a ^{14}C dataset obtained from glaciolacustrine, lacustrine and bog successions in a number of localities. Next, we discuss the validity of the most relevant Pyrenean ^{14}C dates, based on the compilation presented in Tables 1 and 2.

The oldest dates from the Pyrenean dataset (those $> 20,000$ ^{14}C yr BP) correspond to glaciolacustrine sediments deposited in juxtaglacial lakes during the Last Pleniglacial, or to proglacial sediments deposited during the early stages of glacial retreat. According to the arguments given in section 7.1., dates from these successions are relatively prone to ageing due to contamination. As shown in section 3.1., suspicion of ageing due to mineral carbon contamination was confirmed in the case of the juxtaglacial sediments of Llestui in the UNRV, where the initial dates of 34.0-31.5 ^{14}C ka BP were corrected to c. 21-18 ^{14}C ka BP (Bordonau *et al.*, 1993). Based on biostratigraphical correlation and on a new radiocarbon dataset Reille and Andrieu, (1995) (see Table 1 and section 3.1. for details) confirmed that the basal sediments of Biscaye were affected by an important ageing effect. Despite the 38,400 ^{14}C yr BP of Mardones and Jalut (1983), these sediments were assigned a maximum age of 25,000 ^{14}C yr BP by Reille and Andrieu (1995). Accordingly, the dates significantly older than 25 ^{14}C ka BP and 21 ^{14}C ka BP for the Llestui and Biscaye successions respectively can be considered to be unreliable (see the assessment column in Table 1).

In the northern Pyrenees other successions were emplaced during deglaciation, which yielded ages older than 20 ^{14}C ka BP (Tables 1 and 2). Despite the fact that contamination has not been proven for any of these sediments, biostratigraphic criteria suggest that the ^{14}C dates from the glaciolacustrine sites in the northern Pyrenees such as Barbazan (c. 31-26 ^{14}C ka BP), Estarrès (c. 27 ^{14}C ka BP) and Castet (c. 25 ^{14}C ka BP) were probably affected by significant ageing (Reille and Andrieu, 1995). In addition, the oldest dates from the Lake of Lourdes (33.7 ka BP) and Le Monge (34.5 ka BP) are unreliable given that they were obtained from tills, a kind of deposit in which the dated carbon is probably not coeval with deposition. All these dates might easily need corrections of several thousands of years and, in consequence, they can be considered as suspect (see Table 1). Similarly, in the southern Pyrenees there are several dates for which significant ageing is not proven but can be suspected. The oldest dates come from Els Bassots in the UNRV, a succession which yielded not only conflicting ages between c. 31.4 and c. 20.2 ^{14}C ka BP (Table 1), but also age inversion (Bordonau, 1992). As suggested by the youngest date, the oldest dates from this site are probably affected by allochthonous mineral carbon input from the same bedrock units as Llestuï, which is located only a few km upvalley.

Despite using minute samples, and provided that a careful selection of the organic matter is made, AMS dating is the best choice to avoid contamination from mineral carbon (Cwynar and Watts, 1989). Accordingly, the pollen concentrate AMS ^{14}C dates in the southern Pyrenees (Portalet, Linás de Broto, Corral de las Mulas and Tramacastilla paleolake, see Table 1 and references therein) can probably be regarded as the most reliable dates available for the early stages of the Pyrenean deglaciation. However, given the absence of detailed biostratigraphical and taphonomical studies devoted to assessing the accuracy of these dates, organic contamination cannot be ruled out. Reille and Lowe (1993) have suggested that a portion of *Pinus*, *Artemisia* and *Ephedra* pollen grains found in the lateglacial successions of the Pyrenees might come from far field areas such as North Africa. Even minute amounts of this allochthonous pollen could be recycled from older formations, inducing a significant ageing in the AMS ^{14}C dates, especially for the virtually sterile successions corresponding to the early deglaciation period. It is also worth noting that the Linás de Broto date (30,380 ^{14}C ka BP, Table 1)

corresponds to deposits coeval with extensive (Last Pleniglacial) glaciation, whereas the Portalet date (28,300 ^{14}C ka BP, Table 1) is interpreted as a minimum age for deglaciation of cirque areas in the Gállego Valley. Considering that a difference of 2,000 years is insufficient to pass from full glacial conditions to nearly full deglaciation, there are two alternative possibilities; either 1) the Portalet date puts a minimum age for the end of glacial transfluence across the Portalet col, instead of a minimum age for the whole Gállego Valley deglaciation, or 2) some of these AMS ^{14}C dates are in error.

The aim of the above discussion is to show that most of the ^{14}C ages that have generally been taken as proof of an early deglaciation centred about 70-40 ka BP do not stand up to a rigorous analysis. Our review of ^{14}C dates shows that the widely cited chronology of Bordonau (1992) was mainly based on data that may now be considered unreliable or, at least, suspect (Table 1). In addition, the correction of the Llestui succession from 34 ka BP (Vilaplana, 1983a,b) to around 18-20 ka BP (Bordonau *et al.*, 1993) has often been overlooked in the literature. If the corrected age of the Llestui succession is accepted, the ages of the "post-maximum stabilisation" and the "valley glacier" phases of Bordonau (1992) need to be shifted towards significantly younger ages.

7.3. Suggestions for constructing a chronology of the Pyrenean deglaciation

Studies in different valleys have subdivided the glacial record according to their associated distribution of ice masses, giving rise to terms such as "disjunction stage" (Taillefer, 1969, Serrano, 1991), "valley glacier phase", "altitude glacier phase", "cirque glacier episode" (Bordonau, 1992; García Ruiz *et al.*, 2003). However, it is recognised that morainic arcs corresponding to the same glacial pulse may have formed at different heights and distances from divides, depending on local topographic configuration, exposure and snow feeding. Some areas might have been largely or totally deglaciated when others were still occupied by long valley glaciers or by cirque glaciers. This may be especially relevant when comparing the central Pyrenean glaciers with the possibly relatively starved glaciers of the drier southeastern Pyrenees (Taillefer 1969; Calvet 2004). For these reasons we consider that locally-derived descriptive

terms are inappropriate when making intervalley correlations across and along the mountain range, and when attempting the construction of a general chronological framework. Given the present knowledge, we suggest that a simple and broad division between Last Pleniglacial, Deglaciation, and Neoglacial is all that is required to easily accommodate all the local observations. Such a simple approach minimises errors of attribution between the local geological record and the glacial phases framework. As soon as new dates from different local records and different dating methods are made available, the distinction of subphases and intervalley correlations should emerge naturally.

The “pleniglacial” concept applied to the last Pyrenean glaciation corresponds to the period when the maximum or near-maximum glacial extent, and the major phase of moraine building took place. As summarized in section 2, at least three lateral moraines and a group of frontal moraines record this phase in several valleys in the northern and south-western Pyrenees. This moraine group spreads over several km along the valleys axes, and is interpreted as resulting from several periods of glacial readvance or stability. In this context, the distinction between “pre-maximum”, “maximum” and “post-maximum” phases made by Bordonau (1992) may not provide a complete picture of the Late Pleniglacial period since it was deduced from observations in valleys where terminal moraines are mostly lacking, and where the glacial record is fragmentary. Taken together, the three phases defined by Bordonau (1992) can be accommodated as part of the Last Pleniglacial concept. Similarly, as summarized in section 2.2, the “valley glacier phase” of Bordonau (1992) included the record of only two localities; the Seminari de Vilaller frontal moraine (Noguera Ribagorçana Valley), which had previously been attributed to the “post-maximum phase” (Vilaplana, 1983a,b), and the Massana glaciolacustrine complex (Valira Valley), which had been ascribed to a glacial stabilisation after the glacial maximum (Vilaplana, 1985). According to our definitions, both localities can also be included in the Last Pleniglacial fluctuations rather than to subsequent deglaciation phases.

7.4. Chronology of the Last Pleniglacial in the Upper Noguera Ribagorçana Valley. Implications for the early Pyrenean deglaciation hypothesis

The 18.1 ± 1.9 ka cosmic ray exposure age of the Artigalonga-Llestui moraine system must be interpreted as a minimum age for deposition given that a rejuvenation by erosion of the morainic surface is likely. However, an additional constraint on the age of the Artigalonga-Llestui moraine system is provided by the corrected date of 21-18 ^{14}C ka BP (equivalent to c. 25.5-21.0 cal ka BP, Reimer *et al.*, 2004) derived from the glaciolacustrine deposits of Llestui (Bordonau *et al.*, 1993, see Table 1 and section 2.1. for a detailed explanation). Considering that the glaciolacustrine sediments sampled by Bordonau *et al.* (1993) correspond to lower, and thus older, stratigraphic levels than the moraine top, the difference between the ^{10}Be exposure age and the actual age of the last phases of moraine building must not exceed a few thousand years. In addition, despite its relatively large error bar, the exposure age of the Tinabre erratic (21.3 ± 4.4 ka) suggests that the phases of maximum glacier extent and thickness (Last Pleniglacial conditions) recorded in the UNRV are probably younger than 25 ka.

As summarised in section 3.1., the Last Pleniglacial and most of the deglaciation in the Pyrenees are generally believed to have taken place tenths of thousands of years before the Last Glacial Maximum (LGM). As discussed in section 7.2. such a view is based on ^{14}C data from glaciolacustrine deposits whose accuracy is highly suspect. The corrected ^{14}C data of Bordonau *et al.* (1993) and the new ^{10}Be chronology presented here do not support the generally accepted hypothesis of an early deglaciation. Our chronology suggests that the Noguera Ribagorçana glacier could have been in a pleniglacial condition until the LGM, or until a few thousand years earlier.

However, the Noguera Ribagorçana chronology could be consistent with a relatively early start of the Last Pleniglacial. We recognise that the record of the Last Pleniglacial may be more fragmentary in the UNRV than in other Pyrenean valleys where several terminal moraines possibly corresponding to slightly more extensive glacial phases are preserved. Hence, the Artigalonga-Llestui moraine could correspond to the *late* stages of the Last Pleniglacial, whereas some of the relatively old ^{14}C dates from juxtaglacial deposits (Table 1) or the relatively old OSL dates (Sancho *et al.*, 2002, Peña Monné *et al.*, 2004), if confirmed, could correspond to its *early* stages. Such an explanation would allow us to reconcile all the

observations, and would imply a relatively long Last Pleniglacial (e.g. between $\gg 30$ and c. 20 ka).

7.5. Chronology of the Deglaciation in the Upper Noguera Ribagorçana Valley. Implications for Lateglacial and early Holocene glacial fluctuations in the Pyrenees

The lack of significant glacial deposits between the till outcrops corresponding to the Last Pleniglacial and the deposits from subsequent glacial phases in most Pyrenean valleys suggests fast deglaciation subsequent to the Last Pleniglacial. Although this may be the case in the Noguera Ribagorçana, the distribution of erosion surfaces suitable for ^{10}Be sampling does not provide a proper constraint on the deglaciation rate. However, according to dated erosion surfaces, disconnection between the Bessiberri and the Noguera Ribagorçana glaciers took place before c. 16.3 ± 2.2 ka, and disconnection between the Salenques and Mulleres glaciers took place before c. 11.9 ± 1.4 ka (Fig. 2). These dates are slightly younger than the former estimations of c. 16,000-13,000 ^{14}C yr (equivalent to c. 19.3-15.2 ka cal BP, Reimer *et al.*, 2004) for retraction of glaciers to high mountain areas in other valleys in the Pyrenees suggested by Bordonau (1992) and Reille and Lowe (1993).

The record of the Deglaciation in the UNRV reveals a series of glacial stillstands or readvances which, according to ^{10}Be exposure ages, occurred between c. 13.7 ± 0.9 ka and c. 10.1 ± 0.6 ka (Fig. 2). Within this relatively short period the Noguera Ribagorçana glacial fluctuations formed the composite Santet moraines (three subdued ridges plus a prominent one), the Hospital moraines (two minor ridges) and the Mulleres moraine (one minor ridge, 10.4 ± 1.0 ka, weighted mean). The Outer Pleta Naua moraines (weighted mean of 10.2 ± 0.7 ka) were formed by a small glacier that had disconnected from the Mulleres ice tongue. Also in this relatively short period, the Bessiberri glacier formed the Bessiberri moraine (possibly a correlative to the Inner Santet moraine), and some smaller morainic remnants found upvalley including the Llastres de Bessiberri moraine (weighted mean of 10.1 ± 0.6 ka). Exposure ages clearly indicate that these glacial oscillations can be partly correlated with the Greenland Stadial

1 (spanning 12.65 - 11.5 k GRIP yr BP, Björck *et al.*, 1998), widely known as the Younger Dryas. Hence, according to the evidence from the Noguera Ribagorçana, the Lateglacial and perhaps the early Holocene periods can be envisaged as a dynamic period involving numerous glacial oscillations, which suggest a highly unstable climatic pattern. Exposure ages support the inclusion of the Mulleres, the Outer Pleta Naua and the Llastres de Bessiberri moraines in the Deglaciation rather than in the Neoglacial despite the fact that they may have been formed, especially the latter, during the early Holocene.

¹⁰Be exposure ages are the basis for correlation between moraines from different tributary valleys in the UNRV. These correlations reveal a clear asymmetry in glacial development associated with orientation of the valley heads. During the Lateglacial, glaciers oriented eastward in the UNRV were the largest (Mulleres-Noguera Ribagorçana, and probably Salenques). In contrast, the Bessiberri glacier may have fluctuated synchronously but, oriented westward, shows much smaller dimensions. When the Mulleres-Ribagorçana ice tongue was c. 6.5 km long with its terminus at c. 1,560 m a.s.l., the Bessiberri glacier was c. 3.5 km long, its front descending to only c. 2,000 m a.s.l. Such asymmetric pattern, can be attributed to 1) predominant northwesterly winds, which produce large leeward snow accumulation on southeast-oriented slopes (Taillefer, 1982), and to 2) atmospheric temperatures higher in the late-afternoon than in the early-morning, which could lead to increased ablation of snow on westward-oriented valley heads. The UNRV data demonstrate that during the Lateglacial and perhaps the early Holocene some of the factors affecting glacial equilibrium displayed a pattern that resembled the one today. In addition, these data illustrate that geomorphological correlations based on moraine altitude between different valleys can be misleading and may result in significant errors.

The conflicting exposure ages for the Inner Pleta Naua (4.4±0.7 ka for IPN01 and 11.2±1.6 ka for IPN02) can be interpreted in the following opposite ways: IPN02 provides roughly true ages of deposition, while IPN01 is underexposed due to block rotation, or IPN01 provides roughly true ages of deposition, while IPN02 is affected by inheritance. The first option would yield an age of deposition akin to that of the Outer Pleta Naua moraine, which seems to be

consistent with the apparently similar weathering aspect of both moraines. However, the occurrence of several glacial pulses at c. 10 ka is not reflected in the probably correlative Llastres de Bessiberri, lending some support to the second interpretation. If the exposure age of IPN01 is interpreted as the age of deposition, the Inner Pleta Naua moraine could be correlative with some of the moraines estimated to be Holocene (between 5,190 and 4,654 ^{14}C yr BP) by Gellatly *et al.* (1992) in Lac des Aires (Cirque de Troumouse, northern Pyrenees, Fig. 1). However, given the marked contrast in orientation and altitude between both areas, this correlation is difficult to accept, and the paucity of exposure age data for the Inner Pleta Naua moraine prevents us from drawing a definitive conclusion on the age of this moraine. As for the Neoglacial, the most recent evidence of glacial activity in the UNRV is provided by the Tallada, and the Salenques moraines. These are extremely fresh morphologically, are located close to the present-day permanent snow fields, and can be attributed to the Little Ice Age.

8. Conclusions

There are some ^{14}C , OSL and U-Th data suggesting that the last Pyrenean glacial maximum took place earlier than the Last Glacial Maximum (LGM). However, the ^{14}C data supporting this hypothesis are fewer and less conclusive than generally acknowledged. Most of the ^{14}C dates used to support a last Pyrenean glacial maximum taking place between 70-40 ka BP can indeed be rejected, and others are suspect. In addition, some corrected ^{14}C dates suggest extensive glaciation at c. 20-18 ka BP (c. 25.5-21.0 cal ka BP), contradicting the generally accepted hypothesis of largely deglaciated valleys during the LGM. We thus consider that the chronological framework of the Pyrenean deglaciation should be built with a critical and restrictive approach, involving several dating methodologies, such as ^{14}C , U-Th, luminescence, and cosmic ray exposure dating. It is of paramount importance however that any new dating should be provided with all the necessary information to enable an evaluation of its validity and significance in terms of deglaciation pattern.

In some cases, the deglaciation phases previously defined in the Pyrenees have been used for correlation purposes as if they were chronological units. This practice should be avoided,

especially when comparing the glacial records of distant areas. We suggest the use of a simplified and flexible relative chronological framework based on the concepts of Last Pleniglacial, Deglaciation and Neoglacial phases. The "pre-maximum stabilisation", the "maximum", the "post-maximum stabilisation", and the "valley glacier" phases of Bordonau (1992) can all be included into the Last Pleniglacial concept (Fig. 4). As indicated by the glacial record of several valleys in the northern and southern Pyrenees, the Last Pleniglacial includes a minimum of three glacier fluctuations that took place when the Pyrenean glaciers were close to their maximum extent. This period was responsible for the largest phase of moraine building recorded in the Pyrenees.

The UNRV glacial record shows three distinctive periods of glacial deposition: First, the Last Pleniglacial is represented by perched erratics (e.g. the Tinabre erratic) and the largest phase of moraine building and juxtaglacial deposition in the UNRV (the Artigalonga-Llestui moraine system). The combination of new ^{10}Be exposure ages and corrected ^{14}C dates available in the literature indicates that these features were probably formed after c. 25 ka. Second, the Deglaciation period in the UNRV is represented by a series of moraines appearing in different tributary valleys (the Outer and Inner Santet, Hospital, Mulleres, Outer Pleta Naua, Bessiberri, and Llastres de Bessiberri moraines). According to ^{10}Be exposure data, most of these Deglaciation moraines are restricted to the short period ranging between c. 13.7 ± 0.9 and c. 10.1 ± 0.6 ka. Third, the Neoglacial is represented by a few fresher undated moraines (Salenques and Tallada moraines), which were probably built during the Little Ice Age.

According to published corrected ^{14}C dates and new ^{10}Be exposure ages, the major phase of moraine building in the UNRV (responsible for deposition of the Artigalonga-Llestui moraine system during the Last Pleniglacial) could have been synchronous with the global LGM, or could have slightly predated it. Thus, the data available does not lend support to the generally accepted hypothesis of a very early (70-30 ka BP) deglaciation of the Pyrenees with respect to the global LGM. However, we do not exclude the possibility that the maximum glacier extent during the last glacial cycle had taken place much earlier than the LGM. A simple way of

reconciling the relatively young ages of the UNRV glacial features with the older ^{14}C data (e.g. the 30 ^{14}C ka BP date from Linás de Broto glaciolacustrine succession, Table 1) and the recently published OSL ages (c. 85 to 35 OSL ka from glacial and glacio-fluvial sediments in the Cinca and Gállego valleys), if confirmed, would be to consider that pleniglacial conditions could have taken place during a longer period than generally assumed. Hence, the data available suggest a long Last Pleniglacial (e.g. >>30-20 ka), which would include several glacier fluctuations recorded irregularly in different valleys, with a last major glacier readvance taking place around the LGM. There is little information at present on the amplitude and duration of retreating phases separating different pleniglacial advances. Some evidence has been provided by U-Th dating of cave sediments, which indicates that between 90 and 19 ka the length of the Ariege glacier would have been maintained at more than 75% of its assumed maximum length for the last glacial cycle. Further geochronological work in other Pyrenean valleys is needed to test the validity of such interpretations.

The earlier stillstands or readvances that built the morainic ridges during the Deglaciation between c. 13.7 ± 0.9 ka and c. 10.1 ± 0.6 ka correlate well with the Greenland Stadial 1, generally referred to as the Younger Dryas. Exposure ages suggest that the last fluctuations of the Deglaciation in the UNRV might have extended into the early Holocene. The numerous glacial fluctuations during the Deglaciation suggest a highly unstable climatic pattern for the Last Termination and, perhaps, the early Holocene in the Pyrenees.

^{10}Be surface exposure dating allows correlation of moraines between tributary valleys in the UNRV. This reveals an asymmetric distribution of ice masses during the Lateglacial and perhaps the early Holocene, demonstrating that altitudinal correlation of moraines between different valleys is unreliable.

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Figure captions

Figure 1. Location map of the study area and place names referred to in text. A, B and C correspond to enlarged boxes for the upper Gállego, Noguera Ribagorçana, Aude-Têt valleys, respectively. Black dots are lacustrine and bog sites with associated ^{14}C dates, reported in Tables 1 and 2.

Figure 2. Geomorphological sketch map of the Noguera Ribagorçana Valley showing the main glacial features, ^{10}Be sampling sites, and selected surface exposure ages. Numbers correspond to ^{10}Be exposure ages in ka. Bold numbers are weighted means. LDB, Llastres de Bessiberri; BES, Bessiberri roche moutonnée; OBS, Outest Bessiberri roche moutonnée; OPN, Outer Pleta Naua moraine; MUL, Mulleres moraine and roche moutonnée; IST, Inner Santet Moraine; RLH, Refugi de l'Hospitalet roches moutonnées; ART, Artigalonga-Llestui moraine system; TIN, Tinabre erratic (TIN01).

Figure 3. Deposits and geomorphological features of the Artigalonga-Llestui moraine system, corresponding to the major phase of moraine building in the Upper Noguera Ribagorçana Valley, included in the Last Pleniglacial. A) The left lateral Artigalonga moraine with location of ^{10}Be sampling sites. In the background, the Upper Noguera Ribagorçana Valley looking north. B) The left lateral moraine and associated juxtaglacial deposits of Llestui with location of the ^{10}Be sampling site.

Figure 4. Attribution of moraines to glacial phases in the Upper Noguera Ribagorçana Valley and relative chronology. Not scaled vertical axis corresponds to time.

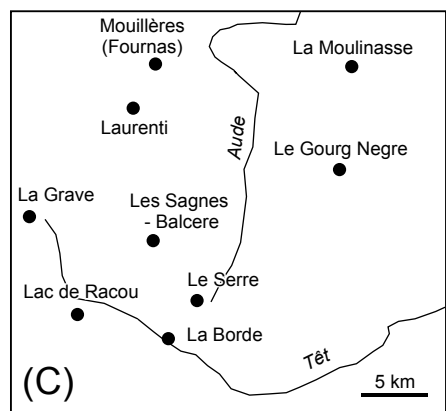
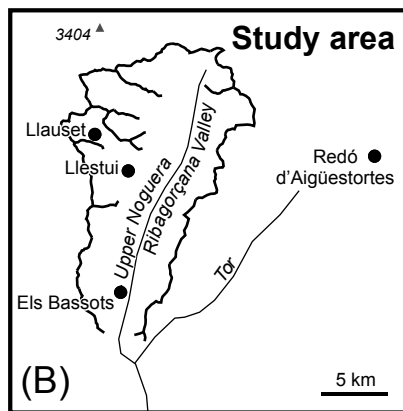
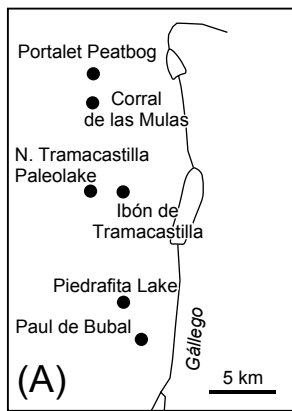
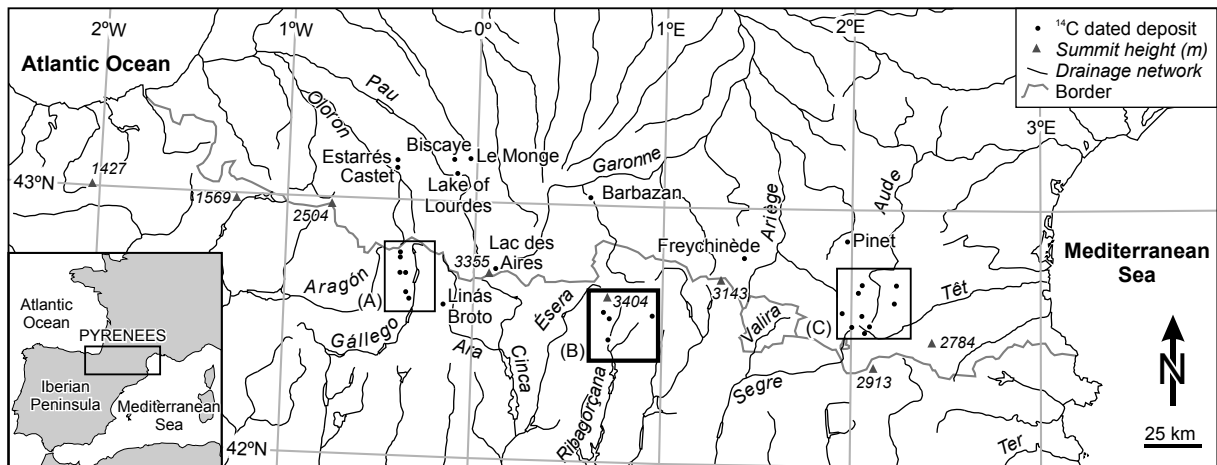
Figure 5. Inner Santet moraine in the Upper Noguera Ribagorçana Valley showing the ^{10}Be sampling site IST01.

Figure 6. A) Mulleres roche moutonnée, rucksack for scale is 0.6 m long, B) Pleta Naua cirque moraine ridges. The Tallada moraine in the background is the freshest moraine in the Upper Noguera Ribagorçana Valley, probably deposited during the Little Ice Age (LIA). C) Llastres de Bessiberri cirque moraine.

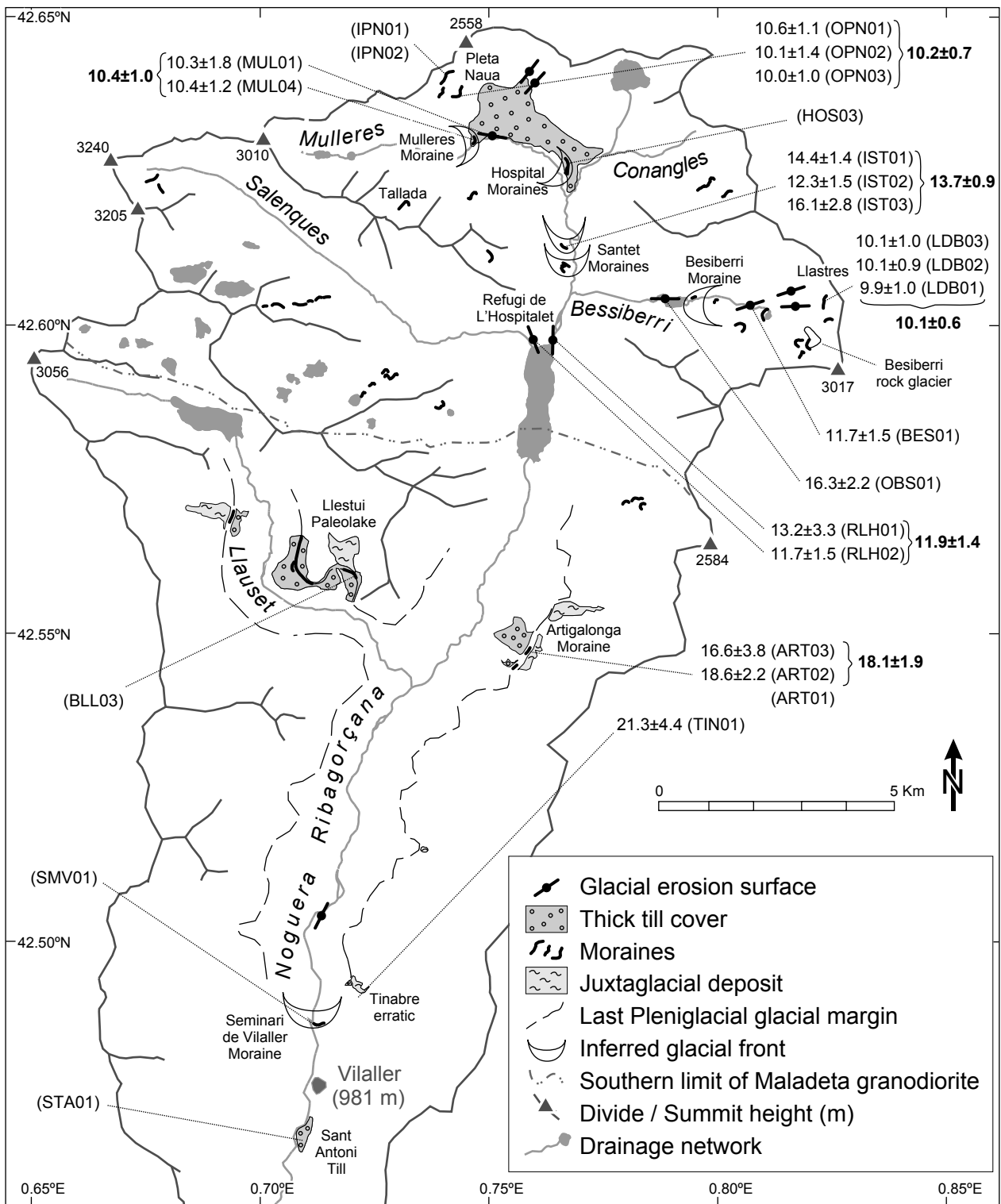
Figure 7. Complete ^{10}Be exposure age dataset from the Upper Noguera Ribagorçana Valley, corresponding to the numerical data presented in Table 3. Error bars are 1 standard deviation. Dotted dates are consistent with the geomorphological relative chronology and are considered to yield actual exposure ages. Crossed dates provide too old exposure ages, are

inconsistent with the relative chronology, and are interpreted as affected by inheritance. Squared dates yield too young ages, are inconsistent with the geomorphological relative chronology and are interpreted as affected by block rotation or removal of till cover. IPN01 and IPN02 are consistent with the relative chronology but yield conflicting exposure ages relative to each other. See detailed data analysis in text.

Figure 8. The Noguera Ribagorçana Valley weighted mean ^{10}Be exposure ages versus distance of the glacial front to the divides. The location of the glacial front for ART and TIN is a minimum estimate. LDB, Llastres de Bessiberri (weighted mean of LDB01, LDB02, LDB03); BES, Bessiberri roche moutonnée; OBS, Outest Bessiberri roche moutonnée; OPN, Outer Pleta Naua moraine (weighted mean of OPN01, OPN02, OPN03); MUL, Mulleres moraine and roche moutonnée (weighted mean of MUL01, MUL04); IST, Inner Santet Moraine (weighted mean of IST01, IST02, IST03); RLH, Refugi de l'Hospitalet roches moutonnées (weighted mean of RLH01, RLH02); ART, Artigalonga-Llestui moraine system (weighted mean of ART02, ART03); TIN, Tinabre erratic (TIN01).



Pallàs et al. Fig. 1



Pallàs et al. Fig. 2



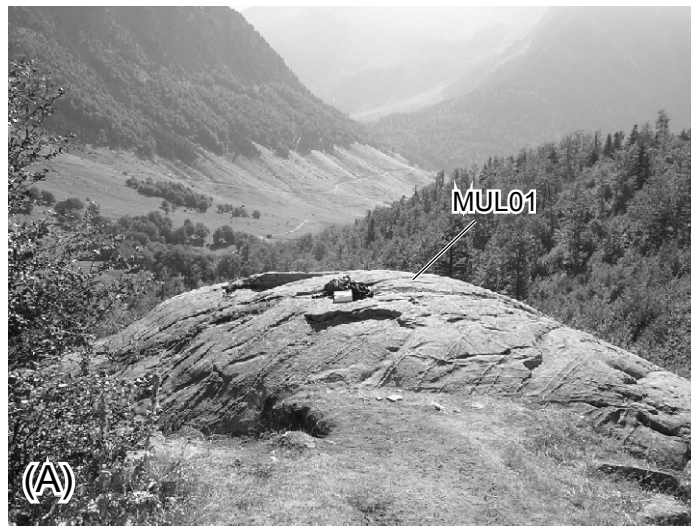
Pallàs et al. Fig. 3

BORDONAU (1992)				THIS WORK			
UPPER NOGUERA RIBAGORÇANA GLACIAL RECORD	Terminology of glacial phases			Terminology of glacial phases	UPPER NOGUERA RIBAGORÇANA GLACIAL RECORD		
					Bessiberri Valley	Pleta Naua	Nog. Ribagorçana & Mulleres Valley
	Holocene phases			Neoglacial			Tallada m.
	Rock glacier phase			?	Llastres Bessiberri m.	? Inner Pleta Naua m.	
		Altitude valley glacier episode	Altitude Glacier phase	Deglaciation		Outer Pleta Naua m.	Mulleres m.
Inner Pleta Naua m.	Cirque glacier episode						
		Altitude valley glacier episode	Altitude Glacier phase	Deglaciation			Santet m.
Tallada m., Outer Pleta Naua Hospital m., Santet m.							
	Valley glacier phase			Last Pleniglacial	Seminari de Vilaller moraine		
Seminari de Vilaller m.							
	Post-max. stabilisation ph.				Artigalonga-Llestui system		
Artigalonga-Llestui m.					Sant Antoni till		
	Glacial Maximum phase						
Sant Antoni till							
	Pre-maximum stabilisation ph.						

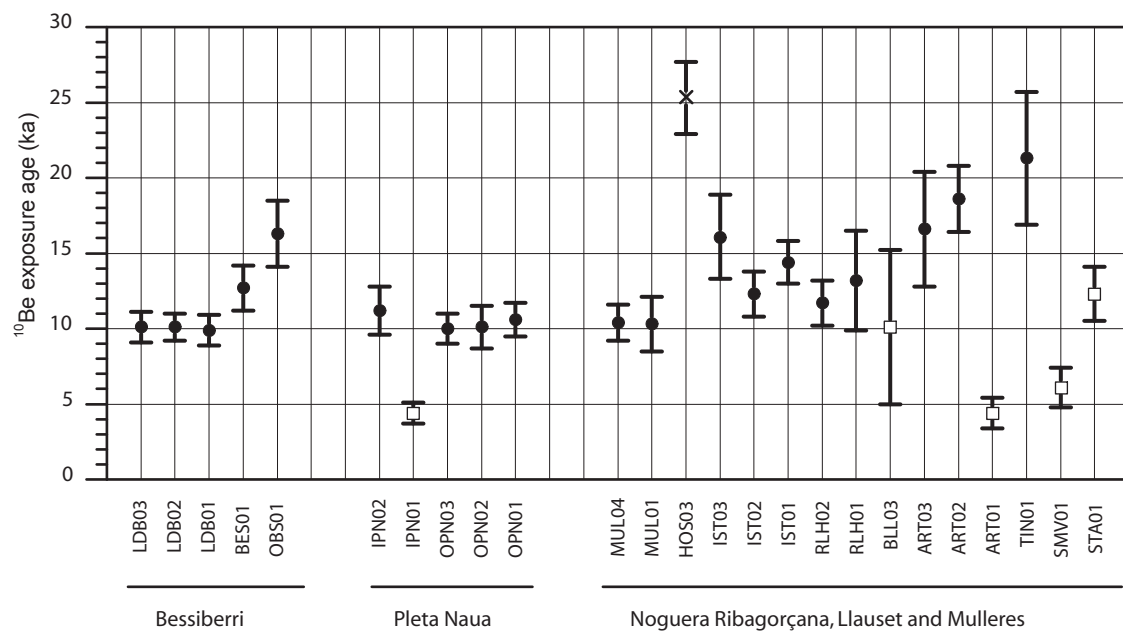
Pallàs et al. Fig. 4



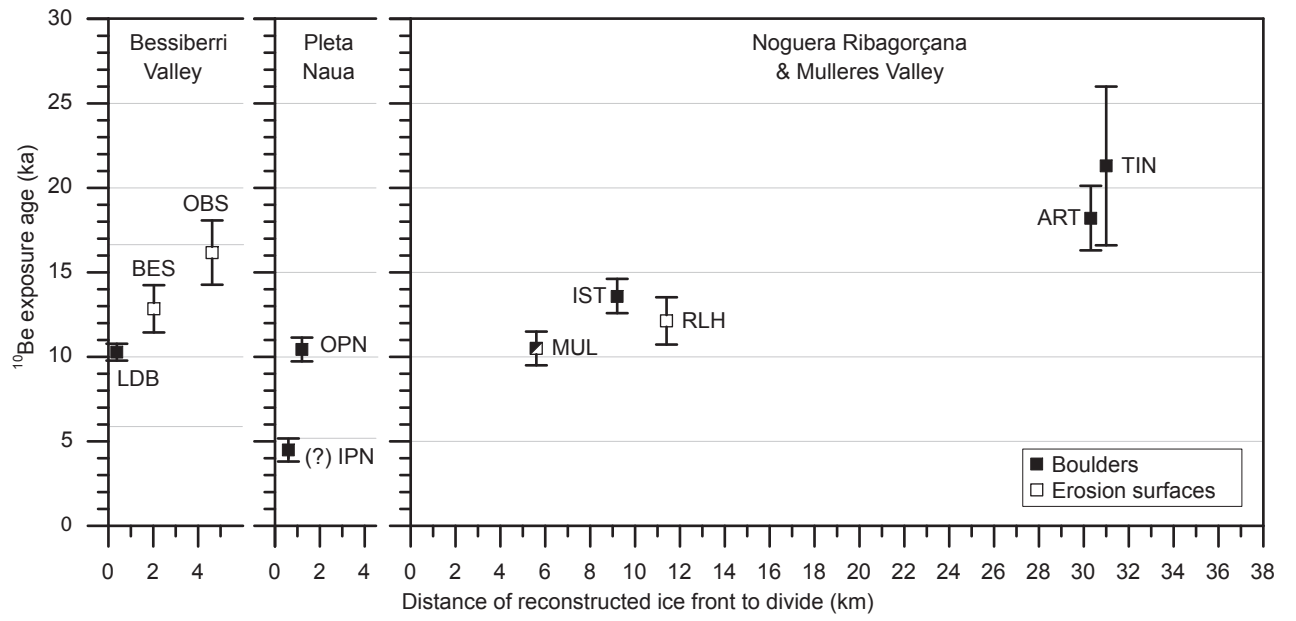
Pallàs et al. Fig. 5



Pallàs et al. Fig. 6



Pallàs et al. Fig. 7



Pallàs et al. Fig. 8

Table 1: Potential minimum limiting ^{14}C dates for the Last Pleniglacial in the Pyrenees, with an assessment of their reliability.
Only the basal and near-basal dates of each succession are selected.

Northern Pyrenees							
Site	lat / long	altitude [m]	Valley	Geomorphic location	core depth [cm]	Dated material	Lab. Ref.
Castet	43°03'N/00°22'W	850	Gave d'Ossau	juxtaglacial lake	398-406	glaciolacustr. rhythmmites	Gif 7536
					192-198	peat	Gif 7075
Estarès	43°05'N/00°22'W	356	Gave d'Ossau	juxtaglacial karst depr.	1,167-1,174	glaciolacustr. rhythmmites	Gif 6868
					973-978	glaciolacustr. rhythmmites	Gif 6867
					964-970	lacustrine marls	Gif 7252
Lake of Lourdes	43°02'N/00°05'W	430	Gave de Pau	proglacial lake	1,858-1,868	till	Gif 8184
					1,405-1,410	glaciolacustr. rhythmmites	Gif 8687
					920-960	blue glacial clay	AA 7072
					835-850	blue glacial clay	AA 7074
					770-780	blue glacial clay	AA 7071
					740-750	gyttja	A 6294
					700-710	gyttja	A 6293
					625-635	lacustrine organic silt	GrN 8675
Biscaye	43°06'N/00°04'W	410	Gave de Pau	proglacial lake	11,077-1,085	carbonate rich bulk sed.	Gif 5685
					892-899	silty clay	Gif 5684
					745-749	lacustrine organic silt	Gif 5683
					960-975	gyttja	A 6221
Le Monge	43°03'N/00°02'W	394	Gave de Pau	proglacial lake	1,740-1,750	till	Gif 8185
					880-890	gyttja	A 6287
Barbazan	43°02'N/00°37'E	450	Garonne	proglacial lake	2,263-2,274	glaciolacustr. rhythmmites	Gif 7647
					1,944-1,954	glaciolacustr. rhythmmites	Gif 7646
					1,250-1,261	glaciolacustr. rhythmmites	Gif 7579
					1,227-1,231	glaciolacustr. rhythmmites	Gif 7459
					1,084-1,095	glaciolacustr. rhythmmites	Gif 7973
					951-955	carbonated silty laminae	TAN 82282
Southern Pyrenees							
Site	lat / long	altitude [m]	Valley	Geomorphic location	core depth [cm]	Dated material	Lab. Ref.
Portalet	42°48'N /00°23'W	1,802	Gállego	peatbog in cirque	608	pollen concentrate	NSRL 11969
Linás de Broto	42°36'N/00°09'W	1,250	Ara-Cinca	juxtaglacial lake	outcrop	pollen concentrate	AZ-35868
Llestui	42°34'N/00°43'E	1,650	Noguera Rib.	juxtaglacial lake	outcrop	glaciolacustrine rhythmmites	Ly-2942
					outcrop	glaciolacustrine rhythmmites	Ly-3046
					outcrop	glaciolacustrine rhythmmites	Ly-3045
					outcrop	glaciolacustrine rhythmmites	Gif-8780
					outcrop	glaciolacustrine rhythmmites	Gif 8778
Els Bassots	42°29'N/00°43'E	986	Noguera Rib.	proglacial lake	2,610-2,620	glaciolacustrine rhythmmites	Gif 8638
					2,610-2,590	glaciolacustrine rhythmmites	Gif 8639
					2,204-2,187	glaciolacustrine rhythmmites	Gif 8640

Table 1: (Continued)

Northern Pyrenees					
Lab. Ref.	¹⁴ C yr BP	δ ¹³ C [‰] ^a	Dating method ^b	Reference	Assessment ^c
Gif 7536	25,000±780	unreported	rad	Andrieu et al., 1988	suspect (1,2)
Gif 7075	9,400±140	unreported	rad	Jalut et al., 1988	
Gif 6868	27,150±1,000	-21.69	rad	Andrieu, 1987; Andrieu et al., 1988; Jalut et al., 1988, 1992	suspect (1,2,3)
Gif 6867	24,400±1,000	-24.82	rad	Andrieu, 1987; Andrieu et al., 1988; Jalut et al., 1988, 1992	
Gif 7252	18,970±390	-24.36	rad	Andrieu, 1987; Andrieu et al., 1988; Jalut et al., 1988, 1992	
Gif 8184	33,700±700	-24.60	rad	Jalut et al., 1992	suspect (1,3,4)
Gif 8687	28,850±800	-24.15	rad	Jalut et al., 1992	suspect (1)
AA 7072	20,025±175	unreported	AMS	Reille and Andrieu, 1995	
AA 7074	18,510±130	unreported	AMS	Reille and Andrieu, 1995	
AA 7071	16,675±115	unreported	AMS	Reille and Andrieu, 1995	
A 6294	15,460±150	-25.20	rad	Reille and Andrieu, 1995	
A 6293	14,460±80	-20.80	rad	Reille and Andrieu, 1995	
GrN 8675	13,480±140	unreported	rad	Jalut et al., 1992	
Gif 5685	38,400+200/-1,800	unreported	rad	Mardones, 1982; Mardones and Jalut, 1983; Andrieu et al., 1988	rejected (1,2,3,5)
Gif 5684	31,900±2000	unreported	rad	Mardones, 1982; Mardones and Jalut, 1983; Andrieu et al., 1988	rejected (1,2,3,5,6)
Gif 5683	29,500±1200	unreported	rad	Mardones, 1982; Mardones and Jalut, 1983; Andrieu et al., 1988	rejected (1,2,5,6)
A 6221	12,480±150	-27.10	rad	Reille and Andrieu, 1995	
Gif 8185	34,500±900	-26.37	rad	Jalut et al., 1992	suspect (1,4)
A 6287	10,360±100	-28.00	rad	Reille and Andrieu, 1995	
Gif 7647	31,160+1,700/-1,400	unreported	rad	Hubschman and Jalut, 1989; Andrieu, 1991; Jalut et al., 1992	suspect (1,3)
Gif 7646	29,500+1,380/-1,180	-23.25	rad	Hubschman and Jalut, 1989; Andrieu, 1991; Jalut et al., 1992	suspect (1,3)
Gif 7579	25,600±800	unreported	rad	Hubschman and Jalut, 1989; Andrieu, 1991; Jalut et al., 1992	suspect (1,3)
Gif 7459	23,980±680	-23.43	rad	Hubschman and Jalut, 1989; Andrieu, 1991; Jalut et al., 1992	suspect (1,3)
Gif 7973	≥ 25,000	-24.97	rad	Hubschman and Jalut, 1989; Andrieu, 1991; Jalut et al., 1992	suspect (1,3)
TAN 82282	26,600±460	-22.70	rad	Hubschman and Jalut, 1989; Andrieu, 1991; Jalut et al., 1992	suspect (1,3)
Southern Pyrenees					
Lab. Ref.	¹⁴ C yr BP	δ ¹³ C [‰] ^a	Dating method ^b	Reference	Assessment ^c
NSRL 11969	28,300±370	-22.70	AMS	García Ruiz et al., 2003; González Sampérez et al., in press 2006	(7)
AZ-35868	30,380±400		AMS	González Sampérez, 2004	
Ly-2942	≥ 33,000	unreported	rad	Vilaplana, 1983a,b	rejected (1,8)
Ly-3046	≥ 31,500	unreported	rad	Vilaplana, 1983a,b	rejected (1,8)
Ly-3045	≥ 34,000	unreported	rad	Vilaplana, 1983a,b	rejected (1,8)
Gif-8780	18,240±600	-21.68	rad	Bordonau et al., 1993	(9)
Gif 8778	21,650±900	-20.42	rad	Bordonau et al., 1993	(9)
Gif 8638	30,800+1,500/-1300	-23.55	rad	Bordonau, 1992	suspect (1,10)
Gif 8639	20,180±350	-24.02	rad	Bordonau, 1992	suspect (1,10)
Gif 8640	31,410±1,200	-23.45	rad	Bordonau, 1992	suspect (1,10)

^a δ¹³C values higher than c. -25‰ suggest ageing by old carbon contamination. Dates for which the δ¹³C are not reported may have a significant contamination by the hard water effect

^b When non specified in the literature, counting method is assumed to be radiometric (rad)

^c Dates are *rejected* when strong lines of evidence indicate that they are affected by ageing in the order of several thousands of years.

Dates are considered *suspect* when there is strong suggestion that they might differ from true ages by several thousands of years

1 Low organic carbon contents and general conditions in the early stages of the deglaciation suggest that this sample is likely to be aged by contamination (see text for discussion).

2 Date considered too old and rejected by Reille and Andrieu (1995, p.18), based on inconsistencies with their regional biostratigraphy. Their palynological correlations suggest ages < 25,000 yr BP.

3 Appearance of the "15 ka BP palynological event" suggests an age > 15,000 yr BP (Reille and Lowe, 1993)

4 The origin of organic material in till is unknown, and possibly not synchronous with deposition

5 Date considered too old and rejected by Turner and Hannon (1988, p. 56), based on inconsistencies with their regional biostratigraphy, and on sedimentologic criteria

6 A layer from another core located at depths between those of Gif 5684 and Gif 5683 was later dated as 12480±150, ref A 6221 (Reille and Andrieu, 1995)

7 Considering the geomorphological setting, it might be difficult to reconcile with other AMS dates from nearby sites if interpreted as indicating near full deglaciation. Gonzalez-Sampérez (2004) and González-Sampérez et al. (in press 2006) suggest interruption of sedimentation by a later glacial readvance c. 20 ka BP.

8 Proven contamination by mineral carbon effect (Bordonau et al., 1993)

9 This date can only be a rough estimate because separation of organic and mineral components is not accurate. Inaccuracies are probably responsible for age inversion.

10 Inconsistency between dates from the same succession, and age inversion (Bordonau, 1992). Dates from the same basin (Llestui and Llauset) are proven to be strongly contaminated by old carbon (Bordonau et al. 1993)

Table 2: Potential minimum limiting ^{14}C dates for the Deglaciation and the Neoglacial in the Pyrenees, with an assessment of their reliability. Only the basal and near-basal dates of each succession are selected.

Northern Pyrenees							
Site	lat / long	altitude [m]	Valley	Geomorphic location	core depth [cm]	Dated material	Lab. Ref.
Lac des Aires bog	42°44'N/00°07'E	2,099	Gave de Pau	proglacial bog in cirque	310	organic-rich silts	Q-2722
Freychinède	42°48'N/01°26'E	1,350	Suc-Ariège	juxtaglacial lake	520-525	glaciolacustr. rhythmites	Gif 5068
					459-453	glaciolacustr. rhythmites	Gif 4957
					452-453	glaciolacustr. rhythmites	Gif 5015bis
La Grave-amont	42°35'N/1°57'E	2,150	Têt	peat bog fossiliz. by progl. fan	345-350	peat	Ly 12122
					295-300	peat	Ly 8727
					240-245	peat	Ly 12123
Lac de Racou	42°33'N/02°00'E	2,000	Têt	proglacial pond in upper v.	396.5-384	Ranuncul. batrach. seeds	LYON-1446(OXA)
La Borde	42°32'N/02°05'E	1,660	Têt	progl. lake/bog in lower valley ^a	900-916	glaciolacustr. rhythmites	Gif TAN
					170-180	gytja	LGC 212
Le Serre	42°33'N/02°06'E	1,750	Têt	progl. bog on glacial divide ^a	90-100	peat	LGC 194
Le Gourg Negre	42°38'N/02°13'E	2,080	Têt	proglacial bog in cirque ^a	485-490	gytja	LGQ 365
Laurenti	42°40'N/02°02'E	1,860	Aude	proglacial bog in cirque ^a	325-335	gytja	LGQ 370
Balcère	42°35'N/02°03'E	1,764	Aude	progl. lake/bog in lower valley ^a	c. 300-340	gytja-glacial clay	Ly 4800
					260-270	lacustrine organic silt	Gif 792
Mouillères (Fourmas)	42°42'N/02°03'E	1,510	Aude	juxtaglacial in lower valley ^a	230-240	peat	LGQ 223
Les Sagnes	42°35'N/02°03'E	1,670	Aude	progl. bog in lower valley ^a	160-170	peat	Ly 4804
La Moulinasse	42°42'N/02°14'E	1,330	Aude	juxtagl. bog in lower valley ^a	320-330	peat	Ly 4712
Southern Pyrenees							
Site	lat / long		Valley	Geomorphic location	core depth [cm]	Dated material	Lab. Ref.
Corral de las Mulas	42°47'N /00°23'W	1,585	Gállego	landslide obturat. in upper valley	< 100	pollen concentrate	AZ-35867
N.Tramacastilla paleolake	42°43'N /00°23'W	1,640	Gállego	landslide obturat. in upper valley	275	pollen concentrate	AZ-35870
Ibon de Tramacastilla	42°43'N /00°21'W	1,732	Gállego	juxtaglacial lake in upper valley	1,152-1,138	massive glaciolacustr. sed.	Gif 8239
					1,035-1,050	massive glaciolacustr. sed.	Gif 8238
Piedrafita lake	42°39'N/00°21'W	1,602	Gállego	proglacial lake in cirque	c. 40	wood	WHOI 17539
Paul de Bubal	42°37'N/00°20'W	1,115	Gállego	proglacial doline in upper valley	565-575	glaciolacustr. rhythmites	Gif 8237
Llauset	42°35'N/00°41'E	2,132	Noguera Rib.	proglacial lake in cirque	outcrop	glaciolacustr. rhythmites	UZ-490
Redó d'Aigüestortes	42°34'N/00°57'E	2,110	Noguera Tor	proglacial lake in cirque	780	glaciolacustr. rhythmites	BETA-88385

^a M. Calvet, personal communication

Table 2: (Continued)

Northern Pyrenees					
Lab. Ref.	¹⁴ C yr BP	δ ¹³ C [‰] ^b	Dating method ^c	Reference	Assessment ^d
Q-2722	5,190±90	unreported	rad	Gellatly et al., 1992	
Gif 5068	19,900±1,400		rad	Jalut et al., 1992	
Gif 4957	21,300±760	unreported	rad	Jalut et al., 1982; Jalut et al., 1992	suspect (1,2,3,4)
Gif 5015bis	> 22,000	unreported	rad	Jalut et al., 1982; Jalut et al., 1992	suspect (1,2,3,4,5)
Ly 12122	16,585±197	-15.86	rad	Delmas, 2005, pers. com.	(6)
Ly 8727	16,000±100	unreported	rad	Delmas, 2005, pers. com.	(6)
Ly 12123	16,795±85	-16.00	rad	Delmas, 2005, pers. com.	(6)
LYON-1446(OXA)	10,360±55	-24.17	AMS	Guiter et al., 2005, pers. com.	
Gif TAN	14,960±200	-30.50	AMS	Jalut et al., 1992	(7,8)
LGC 212	11,530±250	unreported	rad	Reille and Lowe, 1993	(4)
LGC 194	7,050±160	unreported	rad	Reille and Lowe, 1993	(4)
LGQ 365	9,890±380	unreported	rad	Reille and Lowe, 1993	(?)
LGQ 370	10,610±300	unreported	rad	Reille and Lowe, 1993	(4)
Ly 4800	13,773±135	unreported	rad	Reille and Lowe, 1993	(4)
Gif 792	11,240±280	unreported	rad	Jalut et al., 1992; Reille and Lowe, 1993	(4)
LGQ 223	4,180±140	unreported	rad	Reille and Lowe, 1993	(4)
Ly 4804	11,930±125	unreported	rad	Reille and Lowe, 1993	(4)
Ly 4712	12,810±160	unreported	rad	Reille and Lowe, 1993	(4)
Southern Pyrenees					
Lab. Ref.	¹⁴ C yr BP	δ ¹³ C [‰] ^b	Dating method ^c	Reference	Assessment ^d
AZ-35867	20,120±150	-24.60	AMS	García Ruiz et al., 2003; González Sampéris, 2004	
AZ-35870	20,600±170	-26.10	AMS	García Ruiz et al., 2003; González Sampéris, 2004	
Gif 8239	29,400±600	unreported	rad	Montserrat, 1992; Jalut et al., 1992	suspect (9)
Gif 8238	21,970±200	unreported	rad	Montserrat, 1992; Jalut et al., 1992	suspect (9)
WHOI 17539	3,710±60	unreported	AMS	Valero Garcés et al., 1998; García Ruiz et al., 2003	
Gif 8237	20,800±400	unreported	rad	Montserrat, 1992; Jalut et al., 1992	
UZ-490	20,930±310	unreported	rad	Vilaplana, 1983b; Vilaplana et al., 1989	rejected (9,10)
BETA-88385	13,470±60	-24.90	AMS	Copons and Bordonau, 1996; unpublished data	

^b δ¹³C values higher than c. -25‰ suggest ageing by old carbon contamination. Dates for which the δ¹³C are not reported may have a significant contamination by the hard water effect

^c When non specified in the literature, counting method is assumed to be radiometric (rad)

- ^d Dates are *rejected* when strong lines of evidence indicate that they are affected by ageing in the order of several thousands of years. Dates are considered *suspect* when there is strong suggestion that they might differ from true ages by several thousands of years
- 1 Low organic carbon contents and general conditions in the early stages of the deglaciation suggest that this sample is likely to be aged by contamination (see text for discussion).
 - 2 Date considered too old and rejected by Turner and Hannon (1988, p. 56), based on inconsistencies with their regional biostratigraphy
 - 3 Date considered too old by Reille (1990), based on inconsistencies with his regional biostratigraphy
 - 4 Absence of the "15 ka BP palynological event" in the succession suggests an age < 15,000 yr BP (Reille and Lowe, 1993)
 - 5 Despite unreported δ¹³C, Jalut *et al.* (1982) provide arguments based on comparison of carbonate rich and carbonate poor portions of the sequence that suggest that mineral contamination is unlikely. Organic contamination is not assessed
 - 6 Presence of Cambrian schists in the headwaters does not allow to rule out a possible ageing effect by graphite contamination (M. Delmas, pers. com.)
 - 7 Appearance of the "15 ka BP palynological event" suggests an age > 15,000 yr BP (Reille and Lowe, 1993)
 - 8 Considered too young by Jalut *et al.* (1992) due to inconsistencies with regional biostratigraphy. Considered reliable and coherent with a re-evaluated biostratigraphy by Reille and Lowe (1993)
 - 9 Low organic carbon contents and general conditions in the early stages of the deglaciation suggest that this sample is likely to be aged by contamination (see text for discussion).
 - 10 Likely mineral carbon contamination, inconsistent with regional biostratigraphy (Vilaplana *et al.* 1989). Inconsistent with the correction of dates from Llestui made by Bordonau *et al.* (1993)

Table 3

Noguera Ribagorçana sample location information and ^{10}Be cosmogenic exposure ages

Sample	Long.	Lat.	Altitude (m a.s.l.)	Production rate ^a	Production rate ^b	Horizon correction	^{10}Be conc. (10^5 atoms g^{-1})	^{10}Be exp. age ^a	^{10}Be exp. age ^b	Increment in ^{10}Be exp. age Pigati and Lifton (2004) respect to Stone (2000) (%)
				Stone (2000) scaling (atoms g^{-1} yr^{-1})	Pigati & Lifton (2004) scaling (atoms g^{-1} yr^{-1})			Stone (2000) scaling (ka)	Pigati & Lifton (2004) scaling (ka)	
<i>Noguera Ribagorçana, Llauset and Mulleres</i>										
STA01	0.71	42.47	1,004	12.16 ± 0.38	11.94 ± 0.07	99.4%	1.49 ± 0.21	12.3 ± 1.8	12.8 ± 1.8	3.8
SMV01	0.72	42.49	993	12.06 ± 0.38	11.56 ± 0.10	98.6%	0.73 ± 0.15	6.1 ± 1.3	6.6 ± 1.4	7.5
TIN01	0.72	42.49	1,301	15.30 ± 0.48	15.66 ± 0.08	96.8%	3.13 ± 0.65	21.3 ± 4.4	21.1 ± 4.4	-0.8
ART01	0.76	42.55	1,714	20.81 ± 0.65	20.95 ± 0.30	97.6%	0.88 ± 0.20	4.4 ± 1.0	4.4 ± 1.0	1.0
ART02	0.76	42.55	1,717	20.86 ± 0.66	21.71 ± 0.14	97.6%	3.77 ± 0.44	18.6 ± 2.2	18.1 ± 2.1	-2.8
ART03	0.76	42.55	1,717	20.86 ± 0.66	21.56 ± 0.15	97.6%	3.36 ± 0.76	16.6 ± 3.8	16.2 ± 3.7	-2.2
BLL03	0.72	42.56	1,650	19.87 ± 0.62	19.96 ± 0.19	97.8%	1.96 ± 0.99	10.1 ± 5.1	10.2 ± 5.1	1.0
RLH01	0.76	42.60	1,455	17.22 ± 0.54	17.33 ± 0.13	94.3%	2.13 ± 0.54	13.2 ± 3.3	13.3 ± 3.4	0.8
RLH02	0.76	42.58	1,471	17.42 ± 0.55	17.48 ± 0.14	95.0%	1.93 ± 0.25	11.7 ± 1.5	11.9 ± 1.5	1.7
IST01	0.77	42.61	1,565	18.68 ± 0.59	19.00 ± 0.14	90.7%	2.43 ± 0.23	14.4 ± 1.4	14.4 ± 1.4	0.1
IST02	0.77	42.61	1,565	18.68 ± 0.59	18.87 ± 0.15	91.9%	2.10 ± 0.25	12.3 ± 1.5	12.3 ± 1.5	0.2
IST03	0.77	42.61	1,565	18.68 ± 0.59	19.13 ± 0.13	91.9%	2.76 ± 0.47	16.1 ± 2.8	16.0 ± 2.7	-0.9
HOS03	0.77	42.63	1,636	19.69 ± 0.62	20.73 ± 0.11	94.9%	4.70 ± 0.45	25.3 ± 2.4	24.3 ± 2.3	-4.1
MUL01	0.75	42.63	1,722	20.96 ± 0.66	21.16 ± 0.20	94.6%	2.05 ± 0.35	10.3 ± 1.8	10.4 ± 1.8	0.5
MUL04	0.75	42.63	1,721	20.95 ± 0.66	21.16 ± 0.20	93.9%	2.04 ± 0.23	10.4 ± 1.2	10.5 ± 1.2	0.8
<i>Pleta Naua</i>										
OPN01	0.74	42.64	2,217	29.64 ± 0.93	30.89 ± 0.34	95.4%	2.98 ± 0.30	10.6 ± 1.1	10.3 ± 1.0	-2.5
OPN02	0.74	42.64	2,197	29.25 ± 0.92	30.37 ± 0.34	95.8%	2.81 ± 0.39	10.1 ± 1.4	9.8 ± 1.4	-2.6
OPN03	0.74	42.64	2,195	29.21 ± 0.92	30.33 ± 0.34	95.8%	2.80 ± 0.28	10.0 ± 1.0	9.8 ± 1.0	-2.4
IPN01	0.74	42.64	2,384	33.15 ± 1.04	34.87 ± 0.62	88.8%	1.30 ± 0.20	4.4 ± 0.7	4.3 ± 0.7	-2.8
IPN02	0.74	42.64	2,378	33.02 ± 1.04	34.88 ± 0.39	88.8%	3.28 ± 0.46	11.2 ± 1.6	10.7 ± 1.5	-4.5
<i>Besiberri</i>										
OBS01	0.79	42.60	1,998	25.49 ± 0.80	26.78 ± 0.22	95.4%	3.96 ± 0.53	16.3 ± 2.2	15.7 ± 2.1	-3.9
BES01	0.81	42.60	2,137	28.06 ± 0.88	29.36 ± 0.29	92.6%	3.28 ± 0.40	12.7 ± 1.5	12.2 ± 1.5	-3.6
LDB01	0.82	42.61	2,712	40.94 ± 1.29	44.19 ± 0.59	93.7%	3.80 ± 0.38	9.9 ± 1.0	9.3 ± 0.9	-6.4
LDB02	0.82	42.61	2,720	41.15 ± 1.29	44.41 ± 0.59	93.7%	3.90 ± 0.35	10.1 ± 0.9	9.5 ± 0.8	-6.3
LDB03	0.82	42.61	2,723	41.23 ± 1.30	44.51 ± 0.59	90.5%	3.76 ± 0.36	10.1 ± 1.0	9.5 ± 0.9	-6.0

^a Exposure ages based on Stone (2000) are the ones reported throughout the text and figures. See text for details on calculation of SLHL production

^b Exposure ages based on Pigati and Lifton (2004) scaling are based on a Köffels recalculated SLHL production of 5.49 ± 0.7 at $\text{g}^{-1} \text{y}^{-1}$. Blank values vary from $1.14 \cdot 10^{-14}$ to $1.16 \cdot 10^{-14}$ atoms of $^{10}\text{Be}/\text{Be}$.

Analytical uncertainties result from counting statistics (1s), a 50% uncertainty in the chemical blank correction,