The Pyrenees: glacial landforms prior to the Last Glacial Maximum

Magali Delmas, Yanni Gunnell, Marc Calvet, Théo Reixach, Marc Oliva

PART IV. European glacial landforms prior to the Last Glacial Maximum (before 29 ka)

SECTION 2 European regions that were not covered by the EISC

40. The Pyrenees: glacial landforms prior to the Last Glacial Maximum (Magali Delmas, Yanni Gunnell, Marc Calvet, Théo Reixach and Marc Oliva)

Abstract: Middle Pleistocene glaciation in the Pyrenees is still poorly documented, but the record of ice fluctuations that occurred before 29 ka within the time span of the Late Pleistocene has benefited from a growing catalogue of geochronological data. Here we provide an exhaustive review of results obtained from different generations of ice-marginal deposits for that period, including ^{14}C ages from glaciolacustrine deposits, ^{10}Be and ^{36}Cl exposure ages from boulders embedded in moraines and/or glacially-scoured bedrock steps, and optically-stimulated luminescence ages from glaciofluvial outwash terraces. Data currently available indicate that the most extensive Pyrenean glaciation of the Late Pleistocene occurred prior to the LGM, but that this outermost stadial position (LLGM, or local last glacial maximum) was reached on not just one, but several occasions between MIS 5b (or MIS 4) and MIS 3. Some preliminary results also document major glacier fluctuations during MIS 3.

Keywords: Middle Pleistocene, Late Pleistocene, ice-marginal deposit, radiometric dating, marine isotope stage 3, cave deposit.

40.1. The most extensive glaciation of the Late Pleistocene occurred before the LGM

Evidence has been growing that the Late Pleistocene's most extensive glaciation in the Pyrenees (sometimes previously referred to as the 'Würmian maximum ice extent'), hereafter termed local last glacial maximum (LLGM, Figure 40.1), occurred prior to the Last Glacial Maximum (LGM), albeit with lags and disparities requiring investigation. The first ^{14}C ages in support of this scenario were obtained from sediment cores in glaciolacustrine deposits. While aimed at reconstructing the vegetation history from pollen assemblages near the presumed glacier fronts (synthesis in Jalut et al., 1992), these radiocarbon-dated sequences also provided sedimentological evidence documenting the maximum advance of outlet glaciers and the timing and stages of their subsequent retreat (synthesis in Andrieu et al., 1988). While delivering a much more precise account of past glacier fluctuations than previous chronologies based on relative dating criteria ever had (see Chapter 16), inferences from palaeolake sediments nonetheless relied on indirect evidence from ice-marginal environments rather than on direct dating of the frontal or lateral moraines themselves.

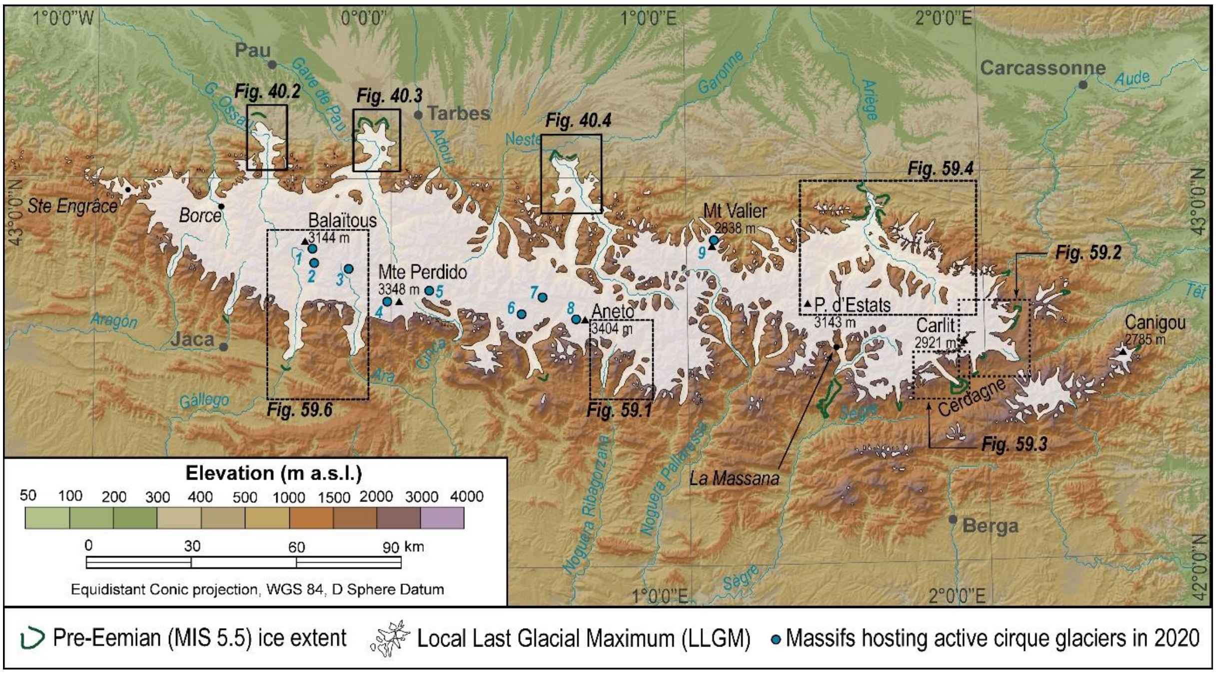

Figure 40.1. Pleistocene and present-day glaciation in the Pyrenees*. Numbers locate extant early 21st century cirque glaciers. 1- Balaïtous (1 glacier, 8 ha); 2- Picos de Infierno (1 glacier, 6 ha); 3- Vignemale (3 glaciers, 62.5 ha); 4- Gavarnie–Monte Perdido (7 glaciers, 70.5 ha); 5- Munia (2 glaciers, 9 ha); 6- Posets (3 glaciers, 17 ha); 7- Perdiguero (5 glaciers, 26 ha); 8- Aneto (4 glaciers, 120 ha); 9- Mont Valier (1 glacier, 2 ha). Statistics after René (2013).*

40.1.1 Evidence from northern massifs

Understanding the connection between the radiocarbon-dated ice-marginal sediments and the moraines is thus essential for correctly interpreting the chronostratigraphy and its palaeoclimatic implications. In most cases, the radiocarbon ages were obtained from samples of glaciolacustrine clays deposited immediately behind frontal or lateral moraines generated during the LLGM (sedimentary records of Estarrès, Biscaye, Lourdes, Le Monge, Barbazan, Llestui, Els Bassots, Figures 40.2, 40.3, 40.4 and 59.1). Samples from the base of these sequences at such locations are thus expected to capture the age of the LLGM moraines as well as the glaciolacustrine processes occurring soon after the LLGM. In the latter case, the presence of dropstones and other specific sedimentological features in the dated glaciolacustrine basal unit guarantees a reasonably close proximity between the receding glacier and the palaeolake impounded by the LLGM terminal moraine. The first appearance of carbonate- and organic-rich layers in these sedimentary sequences typically evidences the advent of warmer conditions suited to vegetation growth around the palaeolake. Such evidence is also used as an indirect indication of north-Pyrenean glaciers having retreated to their upper catchments, many kilometres from their LLGM frontal moraines.

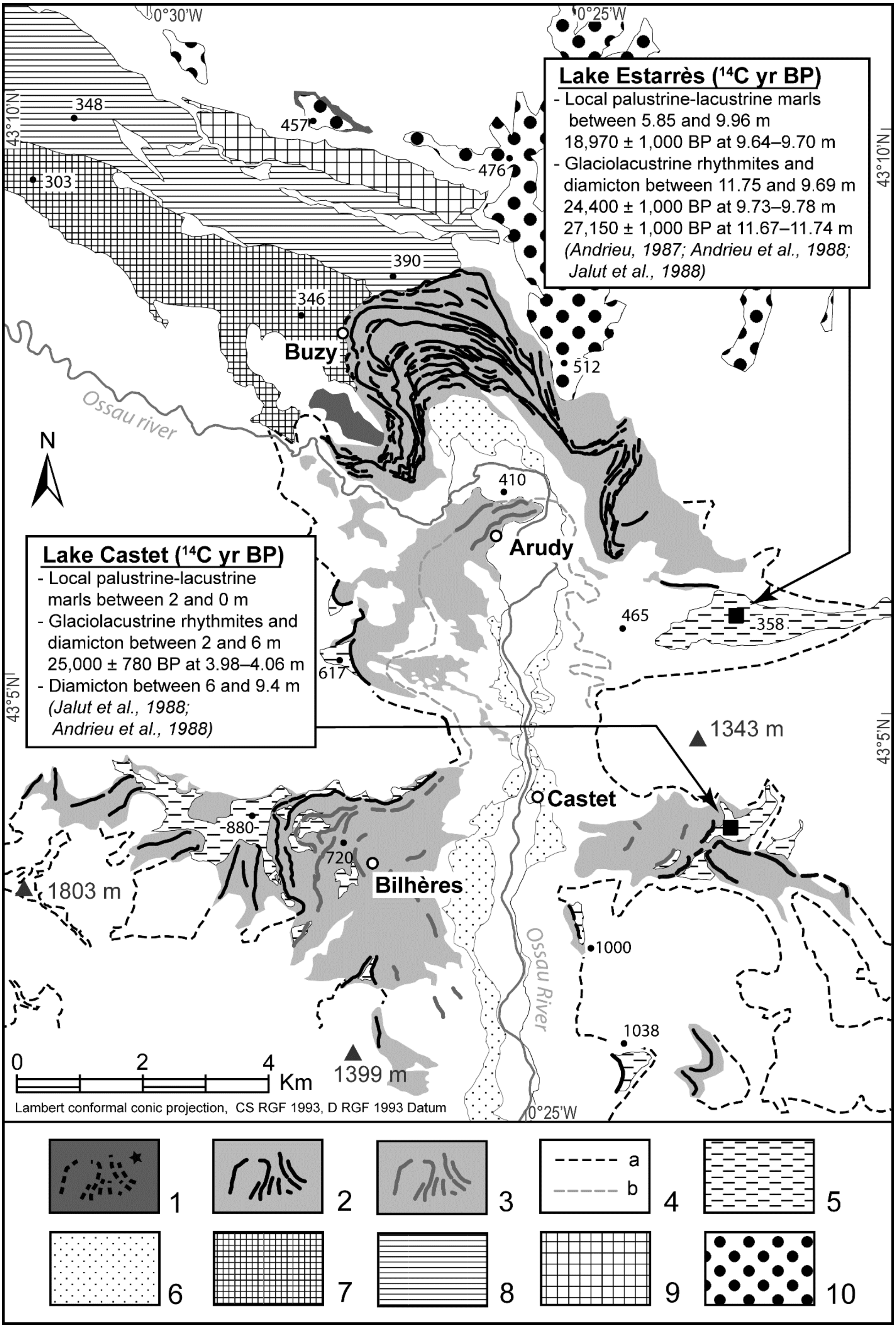
0°30'W
0°25'W
Lake Estarrès (14C yr BP)
- Local palustrine-lacustrine marls between 5.85 and 9.96 m
18,970 ± 1,000 BP at 9.64–9.70 m
- Glaciolacustrine rhythmites and diamicton between 11.75 and 9.69 m
24,400 ± 1,000 BP at 9.73–9.78 m
27,150 ± 1,000 BP at 11.67–11.74 m
(Andrieu, 1987; Andrieu et al., 1988; Jalut et al., 1988)
43°10'N
348
303
457
476
390
346
Buzy
512
Ossau river
N
410
Arudy
Lake Castet (14C yr BP)
- Local palustrine-lacustrine marls between 2 and 0 m
- Glaciolacustrine rhythmites and diamicton between 2 and 6 m
25,000 ± 780 BP at 3.98–4.06 m
- Diamicton between 6 and 9.4 m
(Jalut et al., 1988; Andrieu et al., 1988)
465
358
617
43°5'N
1343 m
Castet
880
720
Bilhères
1803 m
1000
Ossau River
1038
0 2 4 Km
1399 m
Lambert conformal conic projection, CS RGF 1993, D RGF 1993 Datum
0°25'W
1
2
3
a
b
4
5
6
7
8
9
10

***Figure 40.2. Gave d'Ossau terminal moraines and glaciofluvial outwash system**. Key to symbols and ornaments. 1- Pre-Eemian moraines; erratic boulders. 2- LLGM moraines. 3- Post-LLGM moraines. 4- Ice limits, a: during the LLGM; b: post-LLGM. 5- Late Pleistocene ice-marginal fluviolacustrine deposits. 6- Glaciofluvial terraces (T1) connected to the Late Pleistocene moraines. 7- Glaciofluvial terraces (T2) connected to pre-Eemian moraines. 8- Intermediate glaciofluvial terraces (T3). 9- Uppermost glaciofluvial terraces (T4). 10- Relict late Miocene to early Pleistocene alluvial fan deposits (Lannemezan Formation). Elevation spot heights in metres. In each box, chrono-lithostratigraphy given as a function of depth.*

Bearing these considerations in mind, the timing of the LLGM was first inferred from the ages of varved proglacial deposits of Biscaye (Figure 40.3), where dropstone-rich clays near the base of the sequence yielded an age of 38,400 ± 2,000 yr BP (Mardones and Jalut, 1983). Calibration of the analytical result converts to an age bracket of 39,736–48,252 cal yr BP (IntCal20, Reimer et al., 2020). Deriving a mean sedimentation rate from the two oldest ^{14}C ages of the sequence delivers an age of 45 ka for the very base of the sequence. Given that the dated sediment fill is situated immediately behind the LLGM terminal moraine on the Gave de Pau, Mardones and Jalut (1983) proposed that the moraine itself was older, perhaps emplaced between 50 and 70 ka. An LLGM chronology was likewise obtained for the Gave d'Ossau (Figure 40.2), where the base of the varved Estarrès glaciolacustrine fill sequence provided an age of 27,150 ± 1,000 yr BP (29,747–34,222 cal yr BP) (Andrieu, 1987; Jalut et al., 1988; Andrieu et al., 1988); and likewise for the Garonne (Figure 40.4) where, in identical stratigraphic conditions, the base of the Barbazan stratigraphic succession obtained an age of 31,160 ± 1,700 yr BP (32,291–40,689 cal yr BP) (Andrieu, 1991; Andrieu et al., 1988; Jalut et al., 1992). In the Ariège valley, an age from the base of the Freychinède core sequence (Figure 59.5) indicates that the LLGM occurred earlier than 21,300 ± 760 yr BP (23,991–27,276 cal yr BP; Jalut et al., 1982).

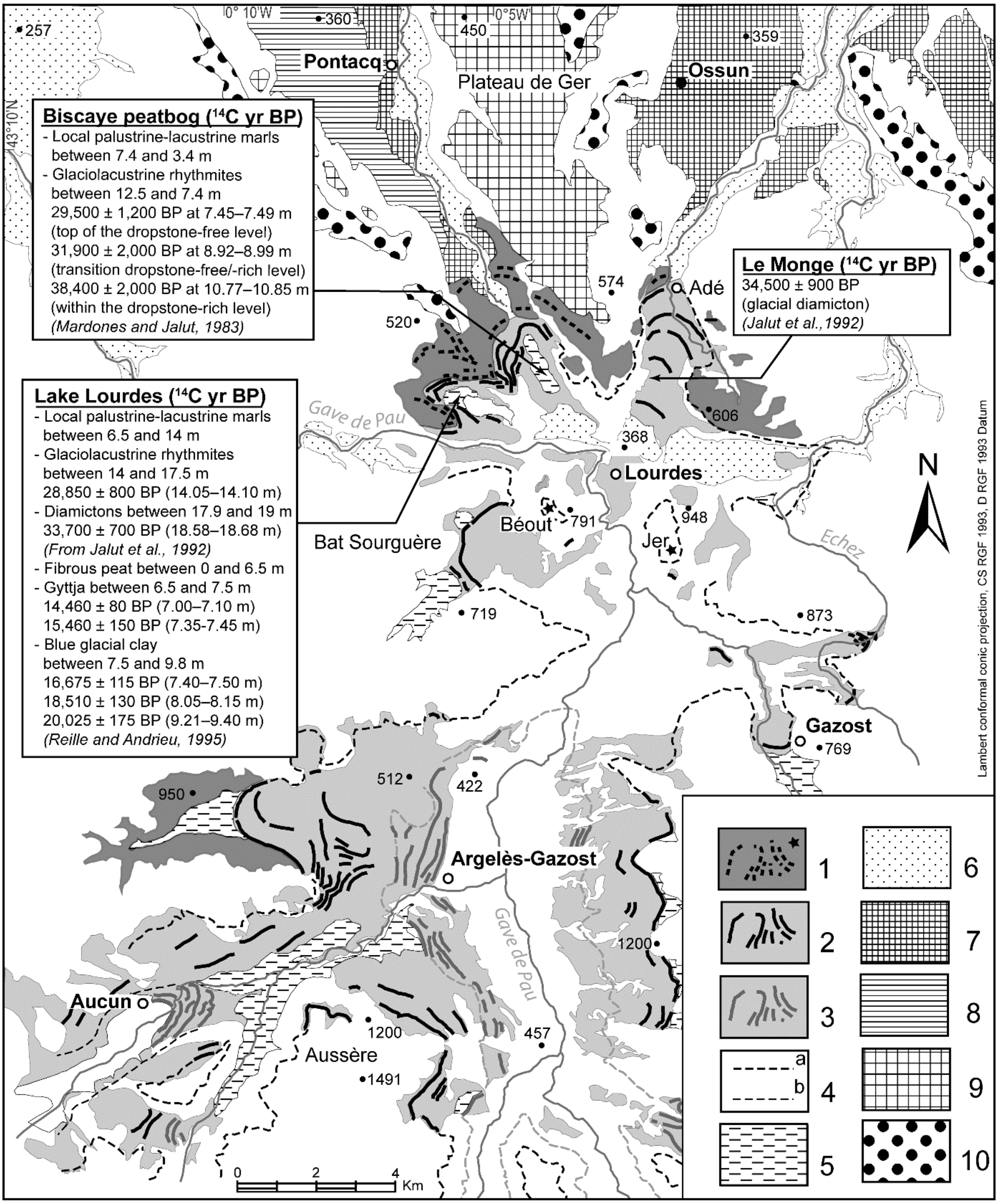

Figure 40.3. Gave de Pau terminal moraines and glaciofluvial outwash system*. Symbols and ornaments as in Fig. 40.2.*

Outlet glaciers remained stationary for some time on the piedmont before receding to the upper valleys. Along the Gave de Pau, dropstone-rich proglacial sedimentation ceased around 31,900 ± 2,000 yr BP (Biscaye, 33,056–42,210 cal yr BP), but the glacier conceivably only retreated from the piedmont very soon after 29,500 ± 1,200 yr (31,297–36,809 cal yr BP), a period when the lithostratigraphy of the Biscaye deposits clearly records a definitive cessation of proglacial sedimentation (Mardones and Jalut, 1983; Figure 40.3). Along the Gave d'Ossau, a similar pattern occurred at lakes Estarrès and Castet based on sedimentary sequences that place glacier recession between 24,400 ± 1,000 yr BP (27,111–31,063 cal yr BP) and 18,970 ± 1,000 yr BP (20,871–25,706 cal yr BP) (Andrieu, 1987; Jalut et al., 1988; Andrieu et al., 1988; Figure 40.2). Along the Garonne, results from Barbazan indicate that glacier recession started around 26,600 ± 460 yr BP (30,077–31,608 cal yr BP) or soon after 23,980 ± 680 yr BP (27,216–29,936 cal yr BP; Andrieu, 1991; Andrieu et al., 1988; Jalut et al., 1992; Figure 40.4). Given the location of these radiocarbon-dated sites on the piedmont (Biscaye, Estarrès, Barbazan) or very close to it (Castet), such outposts obviously document the very earliest post-LLGM stages of glacier recession.

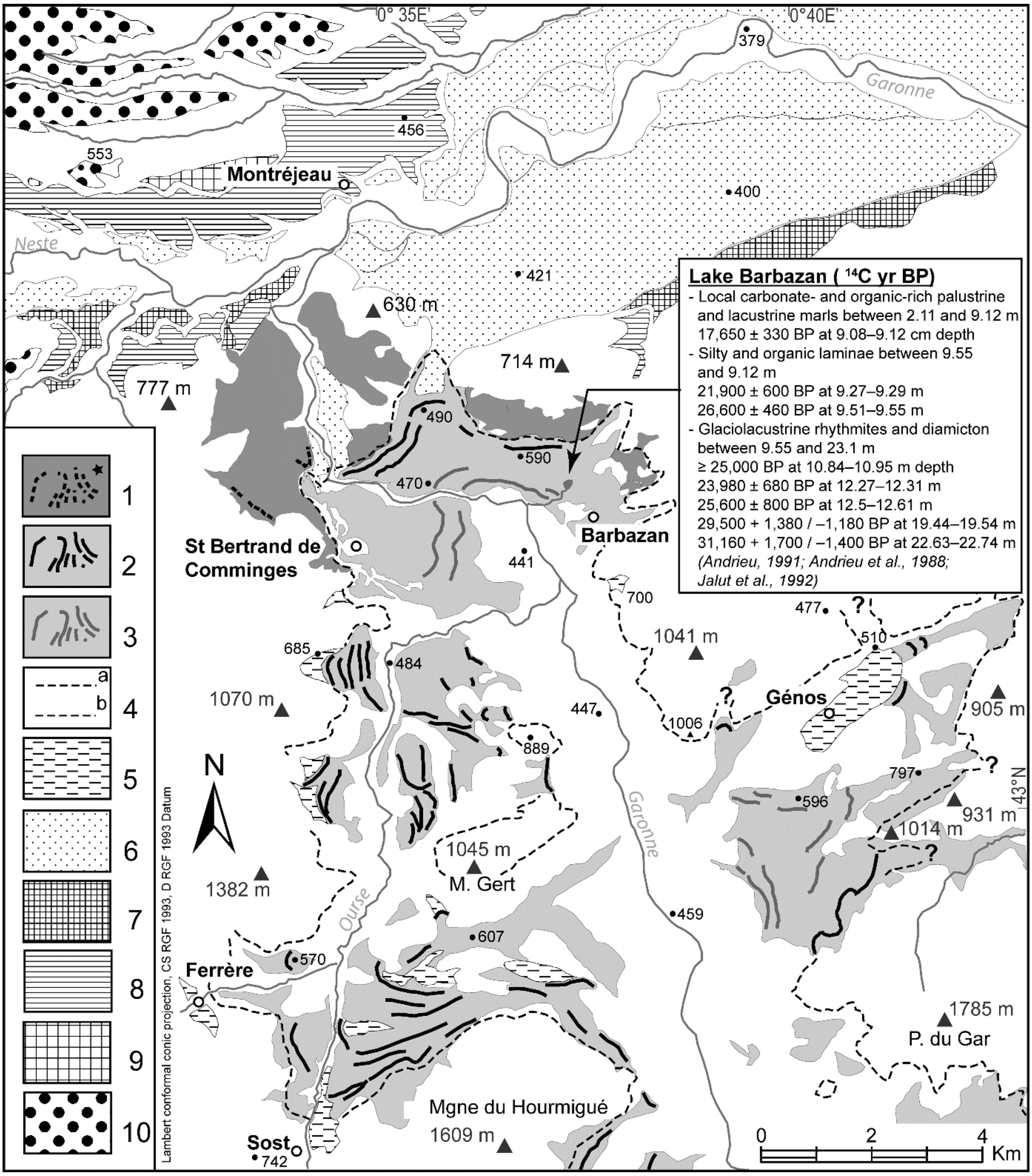

Figure 40.4. Garonne terminal moraines and glaciofluvial outwash system. *Symbols and ornaments as in Fig. 40.2.*

Radiocarbon ages from glaciolacustrine sedimentary sequences on the south side of the range, particularly from the Noguera Ribagorçana valley, initially confirmed the same scenario as on the north side of the Pyrenees (Vilaplana 1983; Vilaplana and Bordonau, 1989). New data acquired subsequently, however, generated conflicting results, thereby reopening a debate initiated by Turner and Hannon (1988) about whether the Pyrenean LLGM was in or out of step with the global record of Quaternary climatic change based on δ^{18}O variations in marine sediment stratigraphies (synthesis in Pallàs et al., 2006). Vilaplana (1983), for example, obtained an age of > 33 ka BP for the base of the ice-marginal fill sequence at Llestui (refer to Figure 59.1). Bordonau (1992) likewise obtained an age of 31,410 ± 1,200 yr BP (33,891–39,572 cal yr BP) for the base of Els Bassots sequence (see Figure 59.1), but also highlighted inconsistencies in the various ^{14}C ages obtained at the site. Inconsistencies noted among the ^{14}C ages previously obtained at Els Bassots further prompted Bordonau et al. (1993) to redate palaeolake deposits at Llestui using a protocol designed to separate the mineral carbon from the organic, and thereby correct for the so-called 'old carbon' effect. This resulted in ascribing much younger ages to the LLGM (21,650 ± 900 yr BP / 24,008–27,862 cal yr BP to 18,240 ± 600 yr BP / 20,742–23,474 cal yr BP; Figure 59.1), thus narrowing the distance between the LLGM and LGM stadial positions for these southern valleys. Following this revised chronology, the Biscaye, Lourdes, and Monge sites were cored once again (Reille and Andrieu, 1995), but only the palaeolake at Lourdes produced ^{14}C ages relevant to an understanding of the glacial chronology (Figure 40.3). The oldest age obtained (glaciolacustrine blue clays from the base of the profile) was 20,025 ± 175 yr BP (23,819–24,602 cal yr BP), suggesting that the LLGM and LGM stadial positions, as on the south side of the range and contrary to earlier conclusions, had stood within a short distance of one another. The age obtained from the base of the overlying gyttja layers further revealed that glaciolacustrine sedimentation had ceased between 16,675 ± 115 yr BP (19,919–20,511 cal yr BP) and 15,460 ± 150 yr BP (18,637–19,112 cal yr BP); by that time, the valley glaciers had thus retreated into the mountain range.

40.1.2 Evidence from southern massifs

Farther east and south, stratigraphic analysis and radiocarbon ages for the palaeolacustrine sequence of La Massana (Turu, 2002) have provided an early deglacial chronology for the two main valleys of Andorra (location in Figure 40.1). During the LLGM, Andorra hosted a large trunk glacier fed by the upper Valira d'Orient (Gran Valira) and Valira del Nord valley glaciers. The Valira del Nord was itself supplied by two local glaciers (Arinsal and Ordino) joining it at La Massana. Palaeolake Massana formed at a time when these local glaciers had retreated to their upper valleys but the Valira d'Orient trunk glacier was still impounding the deglaciated lower valley of its Valira del Nord tributary. In that context, a sequence stratigraphy approach provided constraints (i) on variations in lake water depths, and thereby in Gran Valira glacier thicknesses; and (ii) on fluctuations in the Arinsal and Ordino tributaries, which at regular intervals produced prograding sediment sequences over the lakebed. The large number of ^{14}C AMS ages obtained from the various depositional sequences dated the disconnection between the two Valira glaciers and the first appearance of the lake between 30,770 ± 230 yr BP (basal till at Canillo–El Forn: 34,646–35,667 cal yr BP) and 25,640 ± 190 yr BP (basal glaciofluvial unit at La Massana: 29,350–30,298 cal yr BP). The lake persisted until

17,600 ± 140 yr BP (20,955–21,839 cal yr BP), but the lake deposits were nonetheless overridden between 23,560 ± 130 yr BP (27,953–27,525 cal yr BP) and 21,510 ± 70 BP (26,024–25,706 cal yr BP), thus indicating that the Ordino glacier reconnected with the Gran Valira during the LGM, albeit with a lesser amplitude than at the time of the LLGM (Turu et al., 2017).

Radiocarbon ages obtained from glaciolacustrine sequences at different locations along the Gállego valley (Paúl de Búbal, Ibón de Tramacastilla, Nord Tramacastilla; see Figure 59.6) concur with early interpretations obtained for the north side of the range (synthesis in García-Ruiz et al., 2003), i.e., that the LLGM glacier extended further than its LGM successor. Palaeolakes Ibón de Tramacastilla and Nord Tramacastilla are located in a topographic saddle (1680 m) which, at the time of the LLGM, lay beneath ~175 m of ice supplied by the Escarra and Lana Mayor tributaries to the Gállego glacier (refer to Fig. 59.6). Two radiocarbon ages from bulk organic matter were obtained from the basal glaciolacustrine unit at Ibón de Tramacastilla (Montserrat Marti, 1992). The deeper (11.5 m) and shallower (10.4 m) samples provided ages of 29,400 ± 600 yr BP (32,231–35,195 cal yr BP) and 21,970 ± 200 yr BP (25,919–26,572 cal yr BP), respectively. García-Ruiz et al. (2003) and Guerrero et al. (2018) have argued on that basis that the low divide between the Escarra and Lana Mayor catchments was ice-free as early as the end of the MIS 3 (i.e., shortly before 32,231–35,195 cal yr BP), and remained so during the LGM.

Analytical pitfalls commonly suspected with radiocarbon ages obtained from bulk organic matter were avoided in the context of another core from the palaeolake at Nord Tramacastilla by dating, instead, a concentrate of terrestrial pollen taxa. An AMS age of 20,600 ± 170 yr BP (24,331–25,269 cal yr BP) was obtained from a depth of 2.75 m. In this case, any risk of bias from a 'hard water' effect was ruled out given the absence of pollen from aquatic plants and the absence of carbonate rocks in the catchment. Moreover, the scarcity of pollen from warmth-loving plants indicates that the pollen assemblages were unpolluted by allochtonous inputs, and thus that all the dated pollen grains were in situ and synchronous with the glaciolacustrine deposits. The new ^{14}C AMS age thus provides further confidence in confirming that the local divide between the Escarra and Lana Mayor streams was free of ice during the LGM (García-Ruiz et al., 2003).

A radiocarbon age of 20,800 ± 400 yr BP (24,168–25,953 cal yr BP) was likewise obtained from the lowermost glaciolacustrine unit at Paúl de Búbal, a palaeolake located ~15–20 km upvalley from the LLGM frontal moraines, in an area where the Gállego River has cut a gorge (Montserrat Marti, 1992). Given that the deposit (at 1115 m a.s.l.) fills a sinkhole situated on a topographic bench ca. 100 m above the gorge, the lake could only be fed by meltwater at times when the Gállego glacier was in a position to raise the local base level in the valley, and thus when it was stationed upstream of the gorge between Panticosa and Paúl de Búbal (see Figure 59.6). The Gállego trunk glacier is thus currently inferred to have been substantially shorter during the LGM (~15–20 km) than during the LLGM (38–40 km).

OSL ages obtained from weakly weathered moraines and glaciofluvial deposits in the distal regions of the Ara, Cinca, Gállego and Aragón rivers also support a Pyrenean LLGM occurring at the time of MIS 3 and/or MIS 4 (Lewis et al., 2009; García-Ruiz et al., 2013). Along the Ara River, for example, the glaciodeltaic basal unit at Linás de Broto the related Viu lateral moraine yielded ages of 55 ± 9 ka and 49 ± 8 ka, respectively (Sancho et al., 2018). Along the Cinca River, the Salinas till deposits and their associated glaciofluvial terrace Qt7 respectively produced weighted mean ages of 64 ± 11 ka and 61 ±

4 ka (based on 3 and 6 OSL results, respectively). Data obtained for the Aragón valley broadly match those for the Cinca (LLGM at 67 ± 8 ka, 1 data point; García-Ruiz et al., 2013). Along the Gállego River, the Aurín terminal moraine was ascribed an age of 85 ± 5 ka (38 ± 4 ka outlier considered invalid by the authors), whereas the proglacial Sabiñánigo middle terrace (Qt7), which extends downstream from the Aurín till beds, provided a weighted OSL age of 68 ± 7 ka (69 ± 8 ka at Sabiñanigo, 66 ± 4 ka at Hostal de Ipiés, and 74 ± 10 ka at Llano de Yeste). A frontal moraine at Senegüé, 2 km upstream of Aurín, formed around 36 ± 3 ka (based on 2 OSL ages; Lewis et al., 2009). Guerrero et al. (2018), however, consider that the Senegüé OSL results should be treated as minimum ages given that the two samples were collected from fine-grained deposits inset in the moraine itself (perhaps a kettle-hole fill unit). The authors argued further that a LLGM position at Senegüé occurring as late as 36 ± 3 ka would be incompatible (i) with an absence of ice in the upper Gállego valley, inferred from an extract of terrestrial pollen taxa collected from the Portalet glaciolacustrine basal unit with a ^{14}C AMS age of 28,300 ± 370 yr BP (31,630–33,707 cal yr BP; González-Sampériz et al., 2006); and (ii) with an OSL age of 41.5 ka ± 3.9 ka from the base of a landslide-dammed lake sequence at Sextas, slightly further downvalley from Portalet (Guerrero et al., 2018).

In the eastern Axial Zone (Malniu valley, Campcardos massif; see Figure 59.3), ^{10}Be exposure ages of 84.0 ± 2.2 ka and 54.2 ± 1.4 ka obtained from two closely-spaced boulders emerging from a terminal moraine both suggest a LLGM occurring long before the LGM (Pallàs et al., 2010). A calibrated Schmidt hammer exposure age of 40.9 ± 1.1 ka was obtained from a frontal moraine in the Têt valley, confirming the regional trend (Tomkins et al., 2018; Figure 59.2). In the Ariège valley, the LLGM was documented by a ^{10}Be exposure age of 89.1 ± 15.7 ka from an erratic boulder at Tarascon, near the valley junction with the Vicdessos tributary (see Figures 59.4 and 59.5). This MIS 5b age is consistent with U–Th age constraints obtained from nearby cave deposits and examined in Section 40.3.

Table 40.1: Pyrenean glaciers between MIS 5d and MIS 3 (cold and dry climate)

Valley name	ELA during LLGM (m)	Maximum distance from summit to glacier front (km)	Altitude of LLGM frontal moraine (m)	Late Pleistocene Most Extensive Glaciation (LLGM) age constraints	Key references
Ariège	1600–1800 m	65	400	^{10}Be exposure age: 87.4 ± 4 ka (boulder related to LLGM moraine at Tarascon-sur-Ariège)	Delmas et al., 2011
Garonne	1500–1600	79	450	^{14}C age: 31,160 ± 1,700 yr BP (32,291–40,689 cal yr BP; Barbazan glaciolacustrine basal unit) LLGM moraine was generated prior to palaeolake sedimentation	Mardones and Jalut, 1983
Gave de Pau	1400–1500	53	370	^{14}C age: 38,400 ± 2,000 yr BP (39,736–48,252 cal yr BP; Biscaye glaciolacustrine basal unit) LLGM moraine was generated prior to palaeolake sedimentation	Andrieu et al., 1988

Gave d'Ossau	1400	43	380	^{14}C age: 27,150 ± 1,000 yr BP (29,747–34,222 cal yr BP; Estarrès glaciolacustrine basal unit) LLGM moraine was generated prior to palaeolake sedimentation	Andrieu, 1987 Jalut et al., 1988 Andrieu et al., 1988
Aragón	1900	23	960	OSL ages: 68 ± 7 ka (+20 m terrace) and 51 ± 4.5 ka (m2 moraine located 1.25 km upstream of LLGM terminal position)	García Ruiz et al., 2013
Gállego	1900–2000	40	790	OSL ages: 85 ± 5 ka and 38 ± 4 ka (Aurín LLGM moraine) and at 68 ± 7 ka (mean weighted age) on Sabiñanigo (Qt7) middle terrace. OSL age at 36 ± 3 ka (Senegüé terminal moraine)	García Ruiz et al., 2003
Cinca	2100–2200	26	750	OSL mean weighted ages: 64 ± 11 ka (Salinas LLGM till) and 61 ± 4 ka (terrace Qt7)	Lewis et al., 2009
Ara	2100–2200	32	760	OSL age: 49 ± 8 ka (Viu lateral moraine) and 55 ± 9 ka (glaciodeltaic basal unit of Linás de Broto palaeolake)	Sancho et al., 2018
Ésera	2100–2200	34	860	No data	
Noguera Ribagorçana	2100–2200	25	940	No consistent data prior to LGM	Bordonau et al., 1993 Pallàs et al., 2006
Valira	2300	31	840	^{14}C AMS age: 30,770 ± 230 yr BP (34,646–35,667 cal yr BP; basal till at Canillo–El Forn)	Turu et al., 2017
Arànser	2200–2300	7	1650	No data prior to LGM	Palacios et al., 2015 Andrés et al., 2018
Llosa	2200–2300	14	1250	No data prior to LGM	Palacios et al., 2015 Andrés et al., 2018
Duran	2200–2300	6	1530	No data prior to LGM	Palacios et al., 2015 Andrés et al., 2018
Malniu	2200–2300	6	1800	^{10}Be exposure ages: 81.2 ± 2 ka and 52.2 ± 2.3 ka (two boulders related to LLGM outermost moraine)	Pallàs et al., 2010
Querol	2100–2200	20	1200	No data prior to LGM	Pallàs et al., 2010
Têt	2000–2100	18	1600	Calibrated Schmidt hammer exposure age: 40.9 ± 1.1 ka	Tomkins et al., 2018

40.2. Preliminary indications of major glacier fluctuations during MIS 3

A number of sites have highlighted the sensitivity of the Pyrenean icefield to western Europe's Late Pleistocene climatic fluctuations, with the latitudinal position of the Polar Front most likely one of the controlling factors on precipitation in the higher massifs of the range. Evidence of valley glaciers receding by 10 to 30 km during MIS 3 has been mounting, for example, on the basis of ^{10}Be nuclide inheritance occurring on ice-polished bedrock steps situated far upstream of the position of the LLGM frontal moraines in the Ariège valley (Delmas et al., 2011; see Fig. 59.5). Radiocarbon ages obtained from north-Pyrenean glaciolacustrine basal units (Estarrès: Gave d'Ossau, Barbazan: Garonne) also indicate glacier recession during MIS 3; in those two valleys, glacier retreat distances from their LLGM frontal positions initially remained small (1–2 km at most before 31–30 ka cal BP), but increased after 31–27 ka cal BP (see above).

The age data reported in Section 40.1 for the upper Gállego River valley after Guerrero et al. (2018) would suggest glacier recession to the very top of the catchment at the time of MIS 3, i.e., a recession of much greater magnitude than so far documented anywhere else in the Pyrenees (see Fig. 59.6). An important caveat, however, to the implications of such a conclusion is that the ice-free valley descending from Col du Portalet (1794 m), which was the focus are of Guerrero et al., was a relatively minor tributary to the Gállego trunk glacier. Portalet is a particularly low saddle in the mountain range, with hypsometry ranging extensively between 1700 and 1900 m and forming a low-relief upland rather than a sharp ridgetop. This contrasts very strongly with the NE tributaries of the Gállego valley (Aguas Limpias, Caldares), which descend from a much more elevated and extensive part of the catchment situated between 2500 and 3000 m (e.g., Mt. Balaïtous: 3144 m). Those other valleys were the main feeders of the Gállego trunk glacier (see Fig. 59.6 for hypsometric frame). Whether or not the dated moraine at Senegüé truly is the legacy of MIS 3 would thus require further age data, but its position just ~2 km inboard of the LLGM moraine at Aurín would be entirely consistent with the configuration observed along the north side of the range among valleys extending from the Garonne to the Gave d'Ossau (see Section 40.1). It is thus not inconceivable that the Sallent–Portalet tributary segment was almost fully glacier-free and undergoing intense paraglacial relaxation while the Gállego trunk valley was still hosting a 38-km-long glacier.

Such a scenario, moreover, is compatible with the existence of a small glacier in the uppermost Gállego valley at the time of trunk glacier advance to Senegüé (33–39 ka). The small glacier was fed by the Estrèmere and Peyrelu cirques, amid ridgetops in the Portalet area not exceeding 2100–2300 m. Glacial till recorded at the base of the Portalet fill sequence, below the late MIS 3 glaciolacustrine deposits (28,300 ± 370 ^{14}C yr BP, i.e., 31,630–33,707 cal yr BP), is probably a legacy of this local glacial advance (González-Sampériz et al., 2006). OSL ages at Sextas (an upper Gállego valley segment ca. 500 m a.s.l.), which document continuous lacustrine deposition from 41.5 ± 3.9 ka to 16.9 ± 1.1 ka (Guerrero et al., 2018), further suggest that this small cirque glacier did not merge with the trunk glacier descended from the Aguas Limpias catchment (see Figure 59.6). At that time, the col at Tramacastilla was also ice-free (base of glaciolacustrine sequence at Ibón de Tramacastilla: 29,400 ± 600 yr BP, i.e., 32,231–35,195 cal yr BP; Montserrat Marti, 1992; Garcia-Ruiz et al., 2003), although local cirque glaciers were probably present in the Lana Major and Escarra catchments given their hypsometry. By contrast, after 33–31 ka cal BP (^{14}C AMS age from the base of Portalet palaeolake floor), the small upper Gállego glacier retreated from the Portalet peatbog area and gave way to a lake. Lake sedimentation was ongoing until 27,850–28,903 cal yr BP (^{14}C AMS age from the top of the Portalet lacustrine fill sequence: 24,170 ± 240 ^{14}C yr BP). During that sedimentation interval, the palaeolake was receiving quartz-rich fine sand in millimetre-thick beds interlayered among massive, siliciclastic, blueish-grey rock flour deposits and sporadic dropstones, thereby suggesting a glacier front still very close to the lake shores. These indications suggest that the upper Gállego glacier at the beginning of the LGM was essentially confined to the Estrèmere and Peyrelu cirques, with an ELA ca. 2000–2100 m a.s.l. (see Chapter 59).

A similar timing also occurred in Andorra during MIS 3, when the Valira trunk glacier advanced substantially ca. 30,770 ± 230 yr BP (basal till at Canillo–El Forn: 34,646–35,667 cal yr BP) before receding after 25,640 ± 190 yr BP (basal glaciofluvial unit at La Massana: 29,350–30,298 cal yr BP), becoming disconnected from its own receding tributaries and exposing ice-free areas hosting a lake and large landslides (see Turu et al., 2017). Valley glacier recession ca. 31–30 ka cal BP was also recorded in the upper Cinca catchment (Pineta valley), where an ice-marginal lake (palaeolake Larri, 1580 m) formed on the left side of the glacier descending from Monte Perdido–Marboré. The age of the sedimentary fill sequence has been documented by three AMS radiocarbon results from depths of 8.30, 15.50, and 17.40 m, respectively (Salazar Ricón et al., 2013): 25,333 ± 147 yr BP (29,281–30,006 cal yr BP); 31,172 ± 202 yr BP (35,215–36,168 cal yr BP); 27,417 ± 132 yr BP (31,207–31,713 cal yr BP).

Overall, evidence of fairly major glacier fluctuations during MIS 3 is becoming increasingly well documented among the southern valleys of the central Pyrenees, but the magnitudes of these recessions and readvances are not precisely established, and some radiocarbon ages (e.g., in the upper Cinca, see above) and not always consistent. Magnitudes probably varied as a function of catchment hypsometry, i.e., for any given increment of regional cooling or warming, different valley glaciers would respond differently depending on size and altitude of the accumulation zone. Palaeoenvironmental tie-points suitable for estimating ELA fluctuations during MIS 3 are currently too scarce for such reconstructions to be achieved in any detail.

40.3. Middle Pleistocene glaciation: still poorly documented

Most evidence concerning ice-margin fluctuations prior to the Late Pleistocene glacial cycle has been provided by indirect clues from sediment sequestered in the cave systems of limestone massifs. The groundwater karst contains several generations of allogenic sediment as a result of being successively watered and dewatered in response to ice-thickness fluctuations in the adjacent valleys. U–Th dating of successive generations of cave speleothems has provided upper and lower age brackets to the glaciofluvial deposits sandwiched between them, revealing by this method at least four glacial cycles during the last 400 ka. In the Ariège and its feeder valleys, the base of the Late Pleistocene cave deposit ('Formation alluviale de Niaux') yielded an age of 91.4 ± 2.4 ka, while its top is sealed by a 19.7 ± 0.4 ka speleothem (Sorriaux, 1981, 1982; Bakalowicz et al., 1984; see Figure 59.5). Three other glaciofluvial sequences at Niaux have likewise been correlated with MIS 6, MIS 8 and MIS 10 based on speleothem sample ages dating respectively to MIS 5e, MIS 9, MIS 11, but also—more unexpectedly—with sub-stages MIS 5c and MIS 6b (synthesis in Sorriaux et al., 2016). At La Pierre Saint-Martin in the western Pyrenees, U–Th ages from the Aranzadi cave document interglacial limestone concretions from MIS 7 and MIS 9. By inference, the alluvium interlayers correlate with MIS 8 and MIS 10 (Quinif and Maire, 1998).

In valleys of the north side of the range, post-depositional weathering intensity criteria help to differentiate between the Late Pleistocene moraines (MIS 2 to MIS 5d) and moraines older than MIS 5e (see Chapter 16). A ^{10}Be exposure age of 133.9 ± 5.3 ka obtained from an erratic boulder abandoned by the Ariège glacier at Caraybat has confirmed the validity of this rationale (Delmas et al., 2011; see Fig. 59.4). In the eastern Pyrenees, three generations of moraines were likewise mapped on that basis, particularly in the Querol valley (see Fig. 59.3), where weakly weathered generation M1 grades topographically to outwash terrace T1, and increasingly weathered generations M2 and M3 grade to T2 and T4, respectively (Gourinard, 1971; Calvet, 1996). Terrace levels T2, T3 and T4 have not yet been dated but are likely to correlate with MIS 6, MIS 8 and MIS 10–12 on the basis of OSL and ESR ages obtained in similar relative chronostratigraphic positions in the central and eastern Pyrenees (synthesis in Delmas et al., 2018).

In the western Pyrenees, similar observations have been emerging. At the mouth of the Gave d'Aspe valley, a till level has been discovered beneath alluvial deposits corresponding to terrace T2 (Gangloff et al., 1991). At the mouth of the Gave d'Ossau, a deeply weathered till layer covering glacially-polished bedrock occurs beneath the uppermost terrace level (perhaps generation T5, i.e., the Lannemezan Fm., noted 'Fu' on geological maps) (Hétu and Gangloff, 1989; Hétu et al., 1992).

On the south side of the Pyrenees, till deposits from the Penultimate Glacial Cycle have been reported from several valleys. One of these connects topographically with older terrace deposits in the upper Valira (Turu and Peña, 2006; Turu et al., 2007). Remnants of a frontal moraine and scattered erratic boulders occur downvalley from the Late Pleistocene Ésera terminal moraine. Boulders bearing glacial scour marks have also been dislodged from the upper glaciofluvial terrace of the Gállego at Sabiñánigo, providing two OSL ages at ~155 ka compatible with this scenario (Lewis et al., 2009). Along the Aragón River at Castiello de Jaca, the outermost moraine was OSL-dated at 171 ka, and would thus have been constructed during MIS 6 (García Ruiz et al., 2013).

Table 40.2: Middle Pleistocene glaciers in the Pyrenees

REGION (main glacial catchments)	Maximum glacier length (km)	Glacier length differential with LLGM (km)	Middle Pleistocene Most Extensive Glaciation age constraints	Key references
Ariège	71 76	+6 +11	^{10}Be exposure age: 131.4 ± 5.5 ka (boulder related to MIS 6 glacial advance at Caraybat) Middle to Lower Pleistocene advance at Pech-de-Varilhes based on Pleistocene fluvial terrace sequence	Delmas et al., 2011
Garonne	82	+3	Pre-Eemian (Riss). Chronology based on relative weathering intensity of glacial deposits	Hubschman, 1984
Gave de Pau	55.5	+2.5	Pre-Eemian (Riss). Chronology based on relative weathering intensity of glacial deposits	Hubschman, 1984

Gave d'Ossau	46	+3	Pre-Eemian (Riss) and Middle to Lower Pleistocene (Belair till). Chronology based on relative weathering intensity of glacial deposits and Pleistocene fluvial terrace sequence	Hétu and Gangloff, 1989 Hétu et al., 1992
Aragón	24	+1	OSL ages: 171 ± 22 ka (M1 frontal moraine), and 65 ± 4.8 ka (+50–60 m terrace)	García Ruiz et al., 2003
Gállego	42	+2	OSL mean weighted age: 151 ± 11 ka (Sabiñanigo upper terrace Qt5)	Lewis et al., 2009
Valira	40	+9	Middle to Lower Pleistocene advance (Calbinyà moraine) based on Pleistocene fluvial terrace sequence	Turu and Peña, 2006 Turu et al., 2007
Llosa	15.5	+1.5	Middle to Lower Pleistocene advance (Serrat d'en Bret lateral moraine). Relative chronology based on relative weathering intensity of glacial deposits	Calvet, 1996
Querol	20.8 22	+0.8 +2	Middle Pleistocene advance (Saneja moraine, MIS 6) Lower Pleistocene advance (Ur moraine). Relative chronology based contrasting weathering intensities of fluvial terrace sequence	Gourinard, 1971 Calvet, 1996

Note: Middle Pleistocene palaeoclimate and ELA are undocumented

References

Andrieu, V., 1987. Le paléoenvironnement du piémont nord-pyrénéen occidental de 27 000 BP au Postglaciaire : la séquence d'Estarrès (Pyrénées Atlantiques, France) dans le bassin glaciaire d'Arudy. Comptes-Rendus de l'Académie des Sciences Série II 304, 103–108.

Andrieu, V., 1991. Dynamique du paléoenvironnement de la vallée montagnarde de la Garonne (Pyrénées centrales, France) de la fin des temps glaciaires à l'actuel. PhD thesis (unpubl.), Université de Toulouse–le–Mirail, 311 pp.

Andrieu, V., Hubschman, J., Jalut, G., Hérail, G., 1988. Chronologie de la déglaciation des Pyrénées françaises. Dynamique de sédimentation et contenu pollinique des paléolacs : application à l'interprétation du retrait glaciaire. Bulletin de l'Association Française pour l'Étude du Quaternaire 34/35, 55–67.

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

Bordonau i Ibern, J., 1992. Els complexos glacio-lacustres relacionats amb el darrer cicle glacial als pirineus. Geoforma édiciones, Logroño, 251 pp.

Bordonau, J., Vilaplana, J.M., Fontugne, M., 1993. The Glaciolacustrine complex of Llestui (Central Southern Pyrenees): A key-locality for the chronology of the last glacial cycle in the Pyrenees. Comptes-Rendus de l'Académie des Sciences Série II 316, 807–813.

Calvet,M. 1996. Morphogenèse d'une montagne méditerranéenne: Les Pyrénées orientales. Document du BRGM n° 255, BRGM Éditions, Orléans, 1177 pp.

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

Delmas M., Calvet M., Gunnell Y., Voinchet P., Manel C., Braucher R., Tissoux H., Bahain J.J., Perrenoud C., Saos T., 2018. Terrestrial 10Be and Electron Spin Resonance dating of fluvial terraces quantifies Quaternary surface uplift in the eastern Pyrenees. Quaternary Science Reviews 193, 188–211.

Gangloff, P., Hétu, B., Courchesne, F., 1991. Présence d'un dépôt glaciaire sous la terrasse moyenne d'Agnos, vallée d'Aspe (Pyrénées-Atlantiques). Quaternaire 2, 131–133.

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

García-Ruiz, J.M., Martí-Bono, C., Peña-Monné, J.L., Sancho, C., Rhodes, E.J., Valero-Garcés, B., González-Sampériz, P., Moreno, A., 2013. Glacial and fluvial deposits in the Aragón Valley, central-western Pyrenees: Chronology of the Pyrenean Late Pleistocene glaciers. Geografiska Annaler, Series A, Physical Geography 95, 15–32.

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

Gourinard, Y., 1971. Les moraines de la basse vallée du Carol entre Latour et Puicerda (Pyrénées orientales franco-espagnoles). Compte Rendu Académie des sciences, série D 272, 3112-3115.

Hétu, B., Gangloff, P. 1989. Dépôts glaciaires du Pléistocène inférieur sur le piémont des Pyrénées Atlantiques. Zeitschrift für Geomorphologie 33, 384–403.

Guerrero, J., Gutiérrez, F., García-Ruiz, J.M., Carbonel, D., Lucha, P., Arnold, L.J., 2018. Landslide-dam paleolakes in the Central Pyrenees, Upper Gállego River Valley, NE Spain: timing and relationship with deglaciation. Landslides 15, 1975–1989.

Hétu, B., Gangloff, P., Courchesne, F., 1992. Un till de déformation du Pléistocène inférieur à la basé de la Formation du Lannemezan (Piémont des Pyrénées Atlantiques, France). Quaternaire 3, 53–61.

Jalut, G., Delibrias, G., Dagnac, J., Mardones, M., Bouhours, M., 1982. A palaeoecological approach to the last 21 000 years in the pyrenees: The peat bog of Freychinède (Alt. 1350 m, Ariège, South France). Palaeogeography, Palaeoclimatology, Palaeoecology 40, 321–359.

Jalut, G., Andrieu, V., Delibrias, G., Fontugne, M., Pagès, P., 1988. Palaeoenvironment of the valley of Ossau (Western French Pyrenees) during the last 27,000 years. Pollens et Spores 30, 357–394.

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

Lewis, C.J., McDonald, E.V., Sancho, C., Peña, J.L., Rhodes, E.J., 2009. Climatic implications of correlated Upper Pleistocene and fluvial deposits on the Cinca and Gállego Rivers (NE Spain) based on OSL dating an soil stratigraphy. Global and Planetary Change 67, 141–152.

Mardonnes, M., Jalut, G., 1983. La tourbière de Biscaye (alt. 409 m, hautes Pyrénées): approche paléoécologique des 45 000 dernières années. Pollen et Spores 25, 163–211.

Montserrat Marti, J.M., 1992. Evolucion glaciar y postglaciar del clima y la vegetacion en la verdient sur del Pirineo : estudio palinológico. Monografías del instituto pirenaico de ecología n°6, Consejo superior de investigaciones científicas, Saragosse, 147 p.

Pallàs, R., Rodés, A., Braucher, R., Carcaillet, J., Ortuño, M., Bordonau, J., Bourlès, D., Vilaplana, J.M., Masana, E., Santanach, P., 2006. Late Pleistocene and Holocene glaciation in the Pyrenees: a critical review and new evidence from ^{10}Be exposure ages, south-central Pyrenees. Quaternary Science Reviews, 25, 2937–1963.

Pallàs, R., Rodes, A., Braucher, R., Bourles, D., Delmas, M., Calvet, M., Gunnell, Y., 2010. Small, isolated glacial catchments as priority target for cosmogenic surface dating of Pleistocene climate fluctuations, SE Pyrenees. Geology 38, 891–894.

Quinif, Y., Maire, R., 1998. Pleistocene deposits in Pierre Saint-Martin cave, French Pyrenees. Quaternary Research 49, 37–50.

Reille, M., Andrieu, V., 1995. The late Pleistocene and Holocene in the Lourdes Basin, Western Pyrenees, France: new pollen analytical and chronology data. Vegetation History and Archaeobotany 4, 1–21.

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hajdas, I., Heaton, T., Hogg, A., Hughen, K., Kromer, B., Manning, S., Muscheler, R., Palmer, J., Pearson, C., van der Plicht, J., Reimer, R., Richards, D., Scott, E., Southon, J., Turney, C., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62, 725-757.

Salazar Rincón, A., Mata Campo, M.P., Rico Herrero, M.T., Valero Garcés, B.L., Urcia, B.O., Ibarra, P., Rubio, F.M., Grupo HORDA, 2013. El paleolago de La Larri (Valle de Pineta, Pirineos): significado en el contexto del último máximo glaciar en el Pirineo. Cuadernos de Investigación Geográfica 39, 97–116.

Sancho, C., Arenas, C., Pardo, G., Peña-Monné, J.L., Rhodes, E.J., Bartolomé, M., García-Ruiz, J.M., Martí-Bono, C., 2018. Glaciolacustrine deposits formed in an ice-dammed tributary valley in the south-central Pyrenees: New evidence for late Pleistocene climate. Sedimentary Geology 366, 47–66.

Sorriaux, P., 1981. Étude et datation de remplissages karstiques : nouvelles données sur la paléogéographie quaternaire de la région de Tarascon (Pyrénées ariégeoises). Comptes Rendus de l'Académie des Sciences série II 293, 703–706.

Sorriaux, P., 1982. Contribution à l'étude de la sédimentation en milieu karstique. Le système de Niaux-Lombrives-Sabart (Pyrénées Ariégeoises). PhD thesis (unpubl.), Université Toulouse 3, Toulouse, 255 pp.

Sorriaux, P., Delmas, M., Calvet, M., Gunnell, Y., Durand, N., Pons-Branchu, E., 2016. Relations entre karst et glaciers depuis 450 ka dans les grottes de Niaux-Lombrives-Sabart (Pyrénées ariégeoises). Nouvelles datations U/Th dans la grotte de Niaux. Volume spécial en Hommage à R. Maire, Karstologia 67, 3–16.

Tomkins, M.D., Dortch, J.M., Hughes, P.D., Huck, J.J., Stimson, A., Delmas, M., Calvet, M., Pallàs, R., 2018. Rapid age assessment of glacial landforms in the Pyrenees using Schmidt hammer exposure dating (SHED). Quaternary Research 90, 26–37.

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

Turu i Michels, V., 2002. Analisis secuencial del delta de Erts. estratigrafia de un valle glaciar obturado intermitentemente. Relacion con en ultimo ciclo glaciar. Valle de Arinsal, Pirineos Orientales. In: Estudios recientes (2000–2002) en geomorfologia, patrimonio, montana y dinamica territorial, SEG– Departamento de geografia UVA, Valladolid, pp. 555–574.

Turu i Michels, V., Peña Monné, J.L., 2006. Las terrazas fluviales del sistema Segre–Valira (Andorra–La Seu d'Urgell–Organyà, Pirineos Orientales): relación con el glaciarismo y la tectónica activa. In: Pérez-Alberti, A., López-Bedoya, J. (Eds.), Geomorfología y Territorio, IX Reunión Nacional de Geomorfología. Universidad de Santiago de Compostela, Santiago de Compostela, pp. 113–128.

Turu i Michels, V., Boulton, G.S., Ros i Visus, X., Peña Monné, J.L., Martí i Bono, C., Bordonau i Ibern, J., Serrano-Cañadas, E., Sancho-Marcén, C., Constante-Orrios, A., Pous i Fábregas, J., González-Trueba, J.J., Palomar i Molins, J., Herrero i Simón, R., García-Ruiz, J.M., 2007. Structure des grands bassins glaciaires dans le nord de la péninsule ibérique : comparaison entre les vallées d'Andorre (Pyrénées orientales), du Gallego (Pyrénées centrales) et du Trueba (Chaîne cantabrique). Quaternaire 18, 309-325.

Turu, V., Calvet, M., Bordonau, J., Gunnell, Y., Delmas, M., Vilaplana, J., Jalut, G., 2017. Did Pyrenean glaciers dance to the beat of global climatic events? Evidence from the Würmian sequence stratigraphy of an ice-dammed palaeolake depocentre in Andorra. In: Hughes, P.D., Woodward, J.C., Eds. Quaternary Glaciation in the Mediterranean Mountains. Geological Society, London, Special Publications 433, 111–136.

Vilaplana, J.M., 1983. Quaternary Glacial Geology of Alta Ribagorça Basin (Central southern Pyrenees). Acta Geologica Hispanica 18, 217–233.

Vilaplana, J.M., Bordonau, J., 1989. Dynamique sédimentaire lacustre de marge glaciaire : le paléolac de Llestui (Noguera Ribagorçana, Versant sud des Pyrénées). Bulletin de l'Association Française pour l'Étude du Quaternaire 40, 219–224.