Glacial landscape of the Pyrenees

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PART II The distribution of glacial landscapes in Europe

SECTION 2 European regions that were not covered by the EISC

16. Glacial landscape of the Pyrenees *(Magali Delmas, Yanni Gunnell, Marc Calvet, Théo Reixach and Marc Oliva)*

Abstract: The Pyrenees form a continuous mountain barrier between France and Spain and a land bridge between the Atlantic and the Mediterranean. The highest elevations occur within a 140-km-long central segment where more than 100 summits exceed 3000 m, but present-day residual glaciers are extremely small. The modern climate hinges on two regional-scale rainfall and temperature gradients. The sharpest gradient opposes the cooler and moister, Atlantic-influenced, region of the north, to the warmer and drier, Mediterranean-influenced, climate in the south. The spatial distribution of reconstructed Late Pleistocene glaciers conforms quite narrowly to the modern climatic pattern. The inventory and stratigraphy of Pleistocene deposits and landforms started with maps and surveys in the late 19th century, but interest for glacial chronology arose later. The first 100 years of research were successful at documenting the positions of Late Pleistocene glaciers in a number of Pyrenean valleys. Since the 1980s, an ongoing drive towards obtaining multiple radiometric age constraints on ice-marginal deposits has shifted the focus to establishing the age of the Late Pleistocene's most extensive glaciation, to testing whether or not it was synchronous with the global LGM, and to documenting the post-LGM deglacial history in different parts of the mountain range.

Keywords: Pyrenees, modern climate, palaeoclimate, glacial extent, history of ideas, controversy

The Pyrenees form a 400-km-long and 80- to 130-km-wide continuous topographic barrier from the Atlantic to the Mediterranean. Having undergone substantial increments of uplift long after crustal shortening had ceased (Gunnell et al., 2009; Calvet et al., 2021), the mountain range attained elevations suitable for hosting Quaternary glaciers at this latitude from late Neogene time onwards. The Axial Zone is essentially a basement window (pre-Mesozoic metamorphic and igneous rocks) with its envelope of Mesozoic cover rocks still preserved in the west but eroded elsewhere. The highest elevations occur within a 140-km-long central segment between Mt. Balaïtous and Pique d'Estats, where > 100 summits exceed 3000 m. Pico de Aneto is the highest (3404 m). Lesser ranges flanking the Axial Zone to its north and south mainly consist of fold-and-thrust belts of Mesozoic and early Cenozoic sedimentary rocks, although in the north they also include several outposts of basement forming conspicuous massifs exceeding 2000 m. These more external belts attain lesser elevations of 1500–3000 m—with one exception: Monte Perdido, 3355 m—and are topographically more fragmented than the core of the orogen (Fig. 16.1).

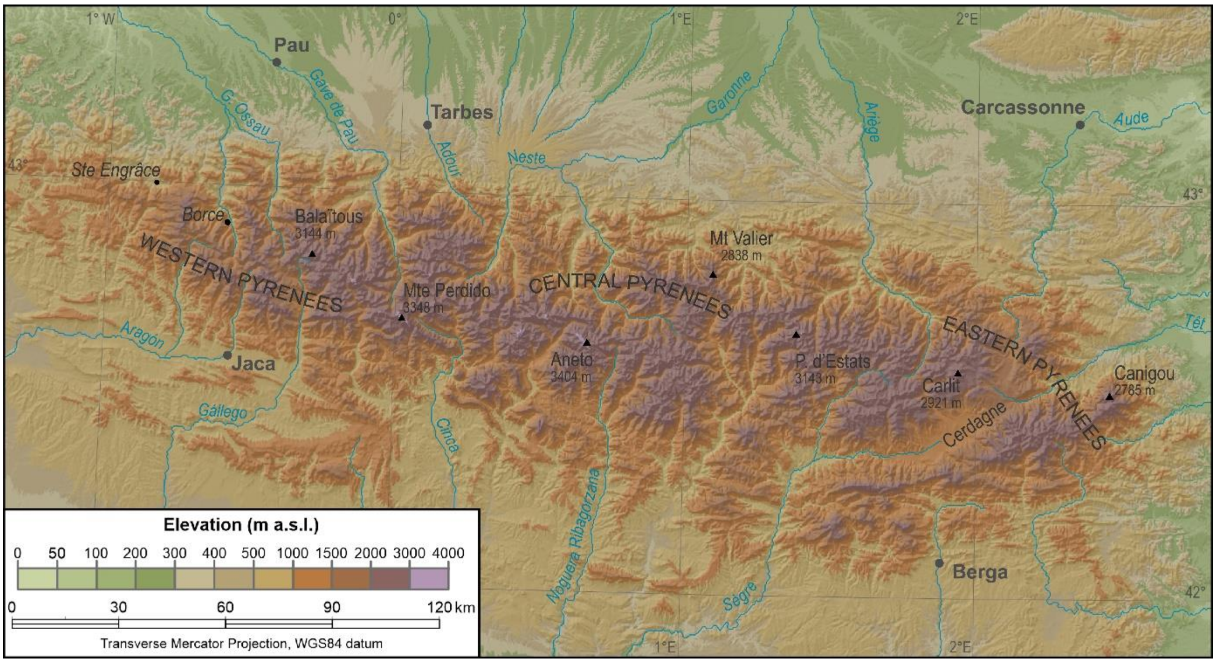

Figure 16.1. The glaciated ranges of the Pyrenees.

Glaciation today is residual. Glaciers covered an area of 320 ha in 2008 (2060 ha in 1850; René, 2013; Oliva et al., 2018) distributed among 27 dwindling cirque glaciers in 9 massifs of the central Pyrenees, all exceeding 3000 m except Mt. Valier (2838 m). Most of them (n = 17) are located in the French Pyrenees. The largest (69 ha) is hosted by Pico de Aneto, with another eight > 10 ha (largest among these: Ossoue, 46 ha; Maladeta, 33 ha; Monte Perdido, 32 ha). The equilibrium line altitude (ELA) ranges between 2500 and 3200 m, constrained by topography-related local climatic conditions such as shading (north-facing aspect) and avalanching snow.

The Pyrenees are narrow and dissected into a large number of strike-perpendicular, back-to-back drainage basins, themselves narrow and consequently not conducive to the build-up of powerful trunk glaciers supplied by large numbers of feeder tributaries. The only large catchments on the north side of the range were the Ariège, Garonne, and Gave de Pau because their trunk valleys include E–W segments that operated as collectors of N–S tributary glaciers. This resulted in generating the longest outlet glaciers (~65, 79, and 53 km long), with their farthest-reaching Late Pleistocene ice fronts descending respectively to 380, 450, and 370 m. On the Iberian side, the longest glaciers were located in the Gállego, Ara and Ésera valleys (40, 32 and 37 km), descending to elevations between 800 and 900 m (Oliva et al., 2019). The eastern Pyrenees are fragmented by a number of extensional tectonic basins, here also setting a low limit to ice accumulation and flow distance. This limit, however, is partly compensated by the occurrence of mountain-top and mountain-flank erosion surfaces (Calvet and Gunnell, 2008). The position of these plateau areas above the Quaternary ELA influenced glacier nourishment by forming reservoirs of snow upwind of east- to south-facing cirques.

Periglacial landforms (rock glaciers, protalus lobes), which are the most reliable indicators of past or present permafrost conditions in the Mediterranean region (Oliva et al., 2018, 2016), are abundant on both sides of the central and eastern Pyrenees, more scarce in the west, and present on almost all slope aspects. These landforms occur in glacial cirques between 2100 and 2700 m, more unusually on valley slopes (Fernandes et al., 2017), and with highest frequencies on granitic and metamorphic outcrops because these lithologies generate an abundance of coarse debris (Serrano et al., 2011). Most rock glaciers are currently inactive, except at the base of the highest peaks (Serrano et al., 2010). Their development was closely associated with Late Pleistocene deglaciation in a paraglacial environment (Andrés et al., 2018; Palacios et al., 2017, 2015).

The modern climate of the Pyrenees hinges on two regional rainfall and temperature gradients, both relevant to understanding the Quaternary glacial context. The sharpest contrast opposes the cooler and moister oceanic region of the north, more directly influenced by the Atlantic Ocean, to the warmer and drier climate in the south, more strongly conditioned by the Mediterranean Sea. The Cerdagne and Capcir intermontane basins, for example, receive 300 to 700 mm less precipitation than the Ariège valley (900–1200 mm), and the number of rainy days falls from 170 to 125. A steep gradient in total annual and daily sunshine hours likewise distinguished the southeastern (2,750 h/yr, with 50% of daily sunshine in December and 70% in July) from the northwestern massifs (<2,000 h/yr, 25–30% of daily sunshine in December and 50–55% in July; Kessler and Chambraud, 1986). The climatic boundary approximately coincides with the orogen's summit ridgeline, but with important local variations in the upper valleys where cols allowing Atlantic airstreams to spill southward into the Iberian domain ensure the persistence of fir (*Abies alba*) and beech (*Fagus sylvatica*) forests (upper Ribagorza, upper Gállego). Conversely, the upper valleys of some north-flowing rivers are drier and sunnier than average (upper Neste, Val d'Aran). Mediterranean summer droughts do not, however, truly take hold in the eastern and southern Pyrenees, where thunderstorms promote a summertime precipitation peak. West of the Segre River, the Mediterranean characteristics of the climate in Catalonia thus become distinctly more continental, also recording annual temperature amplitudes of up to 20 °C. The 0 °C isotherm in the central Pyrenees is now located at 2950 m (López-Moreno et al., 2019), but the montane climate itself is poorly documented because the weather stations are located in the valleys. The west-Pyrenean stations of Sainte-Engrâce (650 m) and Borce

(650 m) record 2000 mm of annual precipitation, suggesting this may rise to 3000 mm or more above elevations of 2000 m. In the central Pyrenees, evidence points to totals exceeding 3000 mm above 3000 m. Southern massifs, e.g. the upper Pallars, record 1300–1500 mm around 2000 m a.s.l. (Panareda and Nuet, 1976). Farther east, annual data obtained from scattered rain and snow gauges between 1700 and 2200 m report 1500 mm over the Carlit and >1500 mm over Mt. Canigou (Vigneau, 1986). Model-based interpolations suggest that precipitation exceeds 2000 mm above 1000 m in the western Pyrenees (Gottardi, 2009; Batalla et al., 2018). This critical isohyet rises steadily eastward, nonetheless more gradually in the north (reaching 1500 m in the Ariège) than in the south (>2000 m in Cerdagne).

The distribution of reconstructed Late Pleistocene glaciers conforms quite narrowly to the modern climate pattern. With a low ELA (1200 to 1600 m from west to east), the north-facing catchments concentrated 75% of Pyrenean glacial ice and its longest outlet glaciers, two of them forming piedmont lobes (Gave de Pau, Gave d'Ossau). Despite wider catchments and a larger population of feeder tributaries, trunk valleys on the Iberian side hosted smaller and shorter glaciers controlled by an ELA rarely descending below 1800 m. Because of the additional effects of topographic fragmentation into horsts and grabens, the eastern, most Mediterranean area was the least glaciated, with an ELA >2000 m generating few valley glaciers.

The inventory and stratigraphy of Pleistocene deposits and landforms in the Pyrenees started with maps and surveys by Penck (1883, 1894), but interest for glacial chronology arose later. Research thereafter continued on the north (Mengaud, 1910; Depéret, 1927; Faucher, 1937; Goron, 1941) and south sides of the range (Panzer, 1926; Llopis-Lladó, 1947; Fontboté, 1948), converging in the 1960s on the characterisation of three groups of sedimentary units ascribed to three very distinct generations of glacier margins (Viers, 1961; Taillefer, 1963; Barrère, 1963): the 'outermost moraines' outlined the terminal ice positions, so-called 'innermost moraines' documented a time when trunk glaciers had become disconnected from their feeder tributaries, and a population of 'cirque moraines' recorded the ultimate stages of glacier recession. A similar model was advocated until the early 1990s for Iberian glaciers.

Until the late 1960s, analogues available for understanding the glaciation chronology of the Pyrenees were calibrated on the European Alps model. Partly because of this, scientific debate at the time became locked in a controversy between 'polyglacialists' and 'monoglacialists'. Polyglacialists, such as Alimen (1964), postulated that the outwash terrace sequences of the north-Pyrenean foreland (Gave d'Ossau, Gave de Pau, Adour, Neste d'Aure) were coeval with those of the Alps. The two uppermost terraces were ascribed to the Donau (after Eberl, 1930) and Günz (after Penck and Brückner, 1909–1910) glaciations because their abundance in quartzite pebbles was reminiscent of the Alpine ‘Deckenschotter’ (cover gravels). The third terrace, featuring much less intensely weathered deposits but capped by red soils, allegedly belonged to the Mindel because, once again in the Alps, the Mindelian outwash terrace was the lowest unit bearing red soils. Ticking the final box of Alpine analogues, the lowest Pyrenean terrace was considered to be a legacy of the Rissian glaciation. Given further that this generation of lower terraces connects topographically to the terminal moraines of the outlet glaciers, Alimen (1964) concluded that these ‘outermost moraines’ must likewise be Rissian. By logic of elimination, the ‘innermost moraines’ of the upper valleys were legacies of the Würm.

Monoglacialists, in contrast, considered that the ‘innermost’ and ‘outermost’ moraines had been produced by one and the same glaciation because the intensities of till weathering were similar (Taillefer, 1951, 1960, 1961; Barrère, 1963; Viers, 1960, 1962, 1963). After a protracted period of valley incision in the mountain belt during ‘Villafranchian’ time (i.e., 3.5–1 Ma), and of pediment and alluvial fan development in the foreland zone (generating Alimen’s two uppermost outwash terraces), the Pyrenees would have thus recorded just one glaciation during the Pleistocene—a theory nonetheless at the time already at odds with global Quaternary palaeoclimate models (Emiliani, 1954).

The monoglacialist view prevailed until two pivotal studies by Sorriaux (1981) and Bakalowicz et al. (1984) revealed two generations of fluvioglacial deposits (MIS 8 and MIS 2–4) sandwiched between U–Th-dated speleothems in a cave system of the Ariège catchment (see Chapter 40 for details). Post-depositional weathering intensity of glacier-related deposits, soil maturity, and altitude-related landform criteria continued thereafter to underpin relative dating methods, but the polyglacialist view prevailed (Taillefer, 1985) and new refinements to it were adduced. Hubschman (1984), for example, showed that the Riss–Würm boundary lay not between the ‘outermost’ and ‘innermost’ moraines, as initially imagined by Alimen (1964), but between two generations of ‘outermost’ frontal moraines exhibiting contrasting intensities of weathering. Based on its feldspar- and mica-rich sand and gravel matrix, low vermiculite content, and fresh cobbles, the younger generation was ascribed to the Würmian glaciation (MIS 5.d to MIS 2). These light-coloured deposits make up the largest volume of frontal and lateral moraines, and grade topographically to the lowest Pyrenean terraces also studied by Hubschman (1975a, b). Because of their much finer-textured, ochre to brown matrix, depleted in feldspar, enriched in vermiculite, and featuring weathered mica crystals in advanced states of internal decohesion, the older deposits were affiliated to one or more episodes of pre-Eemian (pre-MIS 5.e) glaciation. They survive as relict till patches rather than as pristine landforms.

In summary, the first 100 years of research were successful at documenting the positions of Late Pleistocene glaciers in a number of Pyrenean valleys (Figure 40.1). Since the 1980s, opportunities for multiplying radiometric constraints on ice-marginal deposits using radiocarbon, optically-stimulated luminescence and terrestrial cosmogenic nuclide dating methods have shifted the focus to (i) establishing the age of the Late Pleistocene's most extensive glaciation and testing whether or not its fluctuations were synchronous with the global LGM (see Chapters 40 and 59); and to (ii) tracking the post-LGM deglacial history in different parts of the mountain range.

REGION	**LATITUDE**	**Maximum altitude**	**Main glaciated massifs and maximum altitudes** (From E to W)	**Synthesis publications**
Pyrenees	42–43° N	3404 m (Aneto)		Penck, 1883 Taillefer, 1967 Hérail et al., 1986 Calvet, 2004 Calvet et al., 2011 Delmas, 2015
Eastern Pyrenees	42–43° N	2945 m (Coma Pedrosa, Andorra)	Canigou (2784 m), Madrès (2469), Puigmal-Carança (2911 m), Carlit (2921 m), Campcardos-Tossa Plana (2914 m), Andorra (2945 m)	Viers, 1961, 1963 Gómez Ortiz et al., 1994 Calvet, 1996 Delmas, 2005
Central Pyrenees	42–43° N	3404 m (Aneto)	***North:*** Aston-Hospitalet (2911 m), Montcalm-Pica d'Estats (3143 m), Bassiès (2699 m), Mt Vallier-Maubermé (2880 m), Tabe (2368 m), Trois Seigneurs (2199 m), Arize (1716 m), Perdiguero-Gourgs Blancs (3222 m), Néouvielle-P. Long (3192 m), P. du Midi de Bigorre (2876 m), Vignemale (3298 m) ***South:*** Comaloforno (3028 m), Aneto	Depéret, 1923 Panzer, 1926 Faucher, 1937 Goron, 1941 Fontboté, 1948 Vilaplana, 1983 Taillefer, 1985 Martínez de Pisón,

			(3404 m), Posets (3368 m), Cotiella (2912 m), Mt Perdu-Gavarnie (3348 m)	1989 Bordonau, 1992, Delmas et al., 2012
Western Pyrenees	42–43° N	3145 m (Balaïtous)	***North:*** Balaïtous (3145 m), Ger-Gabizos (2692 m), P. Midi d'Ossau (2884 m), Jaout (2050 m), P. d'Anie (2504 m), P. d'Orhy (2017 m). ***South:*** P. de Infierno (3081 m), Tendeñera (2845 m), Collarada (2883 m), Bisaurín (2676 m)	Llopis-Lladó, 1947 Viers, 1960 Barrère, P., 1963 Alimen, 1964 Martínez de Pisón, 1989 Marti Bono, 1996 Garcia Ruiz et al., 2003

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