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LAND OF GLACIERS

HOW THE MOUNTAINS WERE SHAPED BY GLACIERS

Edited by Marc Oliva, David Palacios, and José M. Fernández-Fernández

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CHAPTER 4.2

The glaciers of the Central-Eastern Pyrenees

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1. The geographical framework

On the border of the Eastern and Central Pyrenees lie the Valira and Noguera Pallaresa valleys (Fig. 4.2.1). To the east of the Valira-Segre, already in the center of the Eastern Pyrenees, are the Cerdanya and Baridà basins; to the south, the Urgellet Basin (see Chapter 4.1); and in the west, the Flamisell River, which converges with the Noguera Pallaresa River. These valleys end with the mountainous massifs at the head of the Noguera Ribagorçana River, in the core of the Central Pyrenees (see Chapter 4.3). Both rivers drain toward the Mediterranean through the Segre River, a tributary of the Ebro River. The headwaters of the Noguera Pallaresa Valley are located in the axial area of the Pyrenees, bordered to the north and northwest with the Atlantic Basin drained by the Garonne River (Val d'Aran) and its tributaries (Salat and Ariège rivers), along the main Pyrenean divide at heights between 1800 and 3000 m a.s.l. The study area of this chapter extends over 70 km (west—east) and 55 km (north—south) between the border peaks and the position reached by the glacial fronts during the Last Glacial Cycle (LGC). The valleys excavated by the main rivers follow a general north—south disposition, transversal to the east—west direction of the Pyreneees mountain range. The elevation difference between the peaks and the valley bottoms (located between 700 and 1500 m) reaches 1000—1500 m. The north-south and west-east valley directions organize the relief in a series of massifs with altitudes exceeding 2700 m and a morphology that mixes the typically alpine landscape of the Central Pyrenees with that of the extensive summit surfaces typical of the Eastern Pyrenees. The upper basin of the Noguera Pallaresa Valley is organized, from west to east, in four large valleys: (i) the Flamisell (Vall Fosca), (ii) the Noguera Pallaresa (Valls d'Àneu), (iii) the Noguera de Cardós (Vall de Cardós), and (iv)

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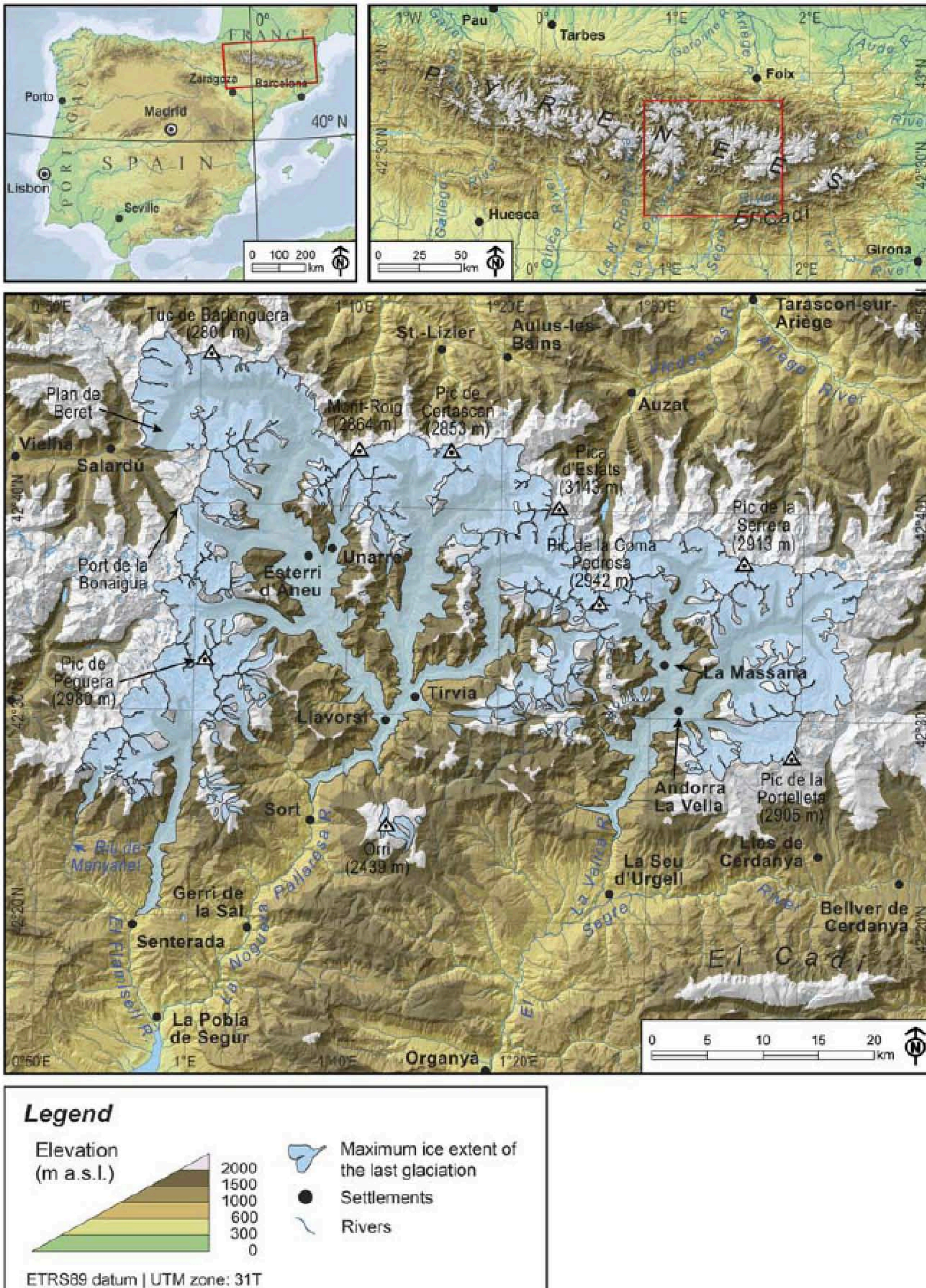

Figure 4.2.1

Location map of the Central-Eastern Pyrenees, with the delimitation of the maximum ice extent of the LGC.

the Noguera de Vallferrera (Vall Ferrera). The last three valleys converge in the village of Llavorsí (800 m), where a single glacier flowed during the maximum glacial advance of the LGC.

The following massifs are located from north to south: (i) Barlonguèra (2801 m) on the northernmost border ridge; (ii) Marimanha (2766 m), Mont-roig (2864 m), and Certascan (2853 m) at the headwaters of the Noguera Pallaresa and Cardós valleys; (iii) Pica d'Estats, (42° 40′ 09″ N and 1° 23′ 52″ E, 3143 m), the highest point in the Central-Eastern Pyrenees), and Monteixo-Medacorba (2915 m) at the head of the Vall Ferrera Valley; (iv) Salòria (2788 m) in the Tor Valley, to the south of the Vall Ferrera; (v) Bassiero-Peguera (2980 m) to the west of the Noguera Pallaresa Valley, organizing the headwaters of the valleys of the Bonaigua, Espot, Àssua, and Flamisell in a radial arrangement; and (vi) the Serra d'Altars (2494 m) and the Orri Massif (2439 m), the last massifs with glacial footprints, which are separated from the higher areas by the lateral valleys of Àssua and Santa Magdalena, and located to the west and east, respectively, of the Noguera Pallaresa River.

The Valira Basin is composed of four valleys that converge in the Andorran town of Les Escaldes (1025 m) whose ice masses also formed a single glacial tongue during the maximum glacial advance, as in the Noguera Pallarsea Valley: (i) The Valira d'Orient Valley, which follows the main valley of Andorra with numerous lateral valleys (Incles, Ransol, Cortals, etc.); (ii) the Valira del Nord Valley with its tributary, the Arinsal Valley; (iii) the Madriu Valley; and (iv) the Perafita-Claror Valley. The Valira d'Orient and the Valira rivers divide the basin into two large sectors, which include the following massifs: (i) one located to the north including, from west to east, the massifs of Coma Pedrosa (2942 m), Tristaina-Font Blanca (2903 m), Serrera-Estanyó (2915 m), and Juclar-Cabaneta (2818 m); and (ii) another located to the south and southeast, including the massifs of Port Negre and Pic de la Portelleta-Pessons (2905 m). Unlike the two large glacial valleys, only a single valley glacier along with some small glaciers at the head of secondary valleys existed for the Flamisell and Manyanet valleys.

The lithology and geological evolution of the Central-Eastern Pyrenees are similar to the descriptions in Chapter 4.1 and the Central Pyrenees as a whole in Chapter 4.3. The area affected by Quaternary glacial processes in the Pallaresa and Valira basins belongs to the morphostructural unit of the "Axial Pyrenees," formed exclusively of Paleozoic rocks, which were later involved in three thrust sheets (Nogueres, Orri, and Rialp) with a southern vergence and of Alpine age (ICGC, 2015). The mountain massifs can be grouped according to their lithology: (i) Those of Mont-Roig, Certascan, Pica d'Estats, Monteixo-Medacorba, Salòria, and Orri are made up of slate with intercalations of sandstone and quartzite from the Cambro-Ordovician, while those of Tristaina-Font Blanca, Serrera, and Cabaneta are composed of metamorphic mica-schists; (ii) the massifs of Bassiero-Peguera, Marimanha, the eastern sector of Certascan-Romedo, and Portelleta-Pessons are composed of granodiorites included in late Hercynian batholiths; (iii) the sectors to the east of Marimanha (Roca Blanca and Aulà), the periphery of the Bassiero-Peguera Massif (Tèsol and Encantats), and the summits of the Pic de Casamanya and Alt de la Capa in Andorra are made of limestone and marble; (iv) the other lithologies present in the region include the gneisses and black slates of Siluric age. Unlike the sectors located to the west and east, the morphological-structural unit of the Inner Pre-Pyrenean range between the Segre and the Noguera Ribagorçana presents lower altitudes (Boumort, 2070 m), including periglacial evidence and very scarce glacial footprints.

The Mediterranean high mountain climate prevails in the Central-Eastern Pyrenees and shows a marked Atlantic influence in the northwestern and northern sectors of the Noguera Pallaresa Basin. The mean annual temperature in the valley bottoms (800−1200 m) is 9°C, and precipitation ranges from 700 to 1250 mm yr^{-1}. The orographic disposition at the bottom of the central valleys of the Noguera Pallaresa Basin is responsible for a more continental climate, namely a higher thermal gradient and less precipitation. At higher elevations, the annual precipitation increases, reaching between 1000 and 1100 mm yr^{-1} at 2000 m, with >1250 mm yr^{-1} at the Bassiero-Peguera and Barloguèra massifs. At Port de la Bonaigua (2260 m), to the north of the Bassiero-Peguera Massif on the border with the Val d'Aran, the annual rainfall is 1232 mm yr^{-1} and the mean annual temperature is 2.7°C. At this altitude, there are 134 days of precipitation, 40% of which are in the form of snow (Carrillo and Ninot, 1998).

The current dominant vegetation on the subalpine level (1600 to 2250 m) comprises black pine (*Pinus uncinata*) forests, which are accompanied by spruce in the lower areas. The alpine floor with mountain bushes and grasses reaches the level of the peaks in the most favorable areas. The periglacial belt extends from 2300 m to the highest peaks (Carrillo and Ninot, 1998). Agricultural and forestry activities, extensive livestock farming, and (formerly) iron mining (Vall Ferrera) have transformed the vegetation at all altitudes, so that the current Pyrenean landscape is the result of a centuries-old interaction with the natural environment. The presence of glacial deposits explains the existence of relatively flat areas in the valley bottoms and on the mid-slopes as well as their use to locate settlements and the best pasture or farmland. However, some of the valleys (e.g., Andorra) have undergone an intense landscape transformation due to tourist activity.

2. The discovery of glacial landforms

The first notes about glacial processes in the upper Noguera Pallaresa Valley can be traced back to the 19th century. Durocher (1841) commented on the presence of rocks polished by ice between Esterri d'Àneu and Salardú villages. In addition, de Verneuil and Keyserling (1861) mentioned the presence of glacial deposits between Bonaigua and Esterri d'Àneu. Bladé (1875) was the first to locate lateral moraines and striated rocks in

Andorra. The first synthesis of glaciers in the Pyrenees was carried out by Penck (1883), who used the relationship between terminal moraines and terraces to determine the existence of three glaciations. This author situated the terminus of the 30-km-long Noguera Pallaresa Glacier at 920 m from the Guingueta d'Àneu and that of the 28-km-long Valira Glacier at 1080 m in Andorra la Vella. In the first half of the 20th century, several authors studied both basins and provided the locations of the main glacial deposits. In Andorra, Chevalier (1906, 1924) placed the front of the Valira Glacier further to the south, in Santa Coloma, at 1030 m and identified three glaciations, the penultimate (Riss) with the aforementioned front, and the most recent, less extensive (Würm), with its front at 1400 m. Panzer (1926) and Nussbaum (1934) located the glacial terminus 3 km further south, 960 m from the town of La Margineda. In his synthesis, Llobet (1947) maintained that three glaciations existed in Andorra and also sustained that the terminus corresponding to the Riss glacier was located in La Margineda, and he was the first author to comment on the glaciolacustrine deposits in La Massana. In the Noguera Pallaresa, García-Sainz (1933) studied the Flamisell Valley and located the front of the 18.5-km-long palaeoglacier in the village of Molinos during the LGC. Further south, in La Pobleta de Bellveí, some granite blocks on a terrace were used to relate this evidence to a previous, more extensive glaciation (Riss). Following the polyglacialist theory for the whole of Noguera Pallaresa Valley, the same author identified three glacial episodes (García Sainz, 1935): (i) an older and more extensive glaciation ("the penultimate glaciation," namely Riss), with its front at 920 m in the Guingueta d'Àneu; (ii) a more recent glaciation with a smaller spatial extension ("the last glaciation," or Würm), with fronts located between 1300 and 1600 m; and (iii) a more recent episode (referred to as the "epiglacial"), which occurred at glacial headwaters above 2000 m. Nussbaum's (1934) study was extended by Solé Sabarís (1936), who specified the glacial extension in the area with the following characteristics: (i) a much more extensive Noguera Pallaresa Glacier, with a length of 52 km (terminus located near Llavorsí, at 820 m) and a thickness of 450 m in Esterri d'Àneu; (ii) the 28-km-long Cardós Glacier; (iii) and the 22 km-long Vallferrera Glacier . Later, Nussbaum (1956) chronologically attributed most of the glacial deposits to the last glaciation (Würm). He also proposed the hypothesis of a more extensive previous glaciation (Riss) based on small fluvioglacial deposits at +30−40 m located downstream from Llavorsí and on the polished rock surfaces situated at a higher level than that reached during the LGC. In relation to the Flamisell Valley, the study provided locations of glacial deposits in the main valley between Capdella and Sallente villages and detailed the locations of the Espui deposits at 250−300 m above the valley floor. It also ascribed the deposits on the high valleys and cirques (between 1400 and 2200 m) to various phases of the deglaciation. Fontboté et al. (1957) described the glaciolacustrine deposit at Tírvia in the Noguera Pallaresa Valley, while they questioned the existence of the terminal moraine at La Margineda in Andorra. They described the moraines at Santa Coloma and Engolasters and interpreted the lacustrine and moraine sediments at La Massana as ice-dammed deposits. The Dutch geologists from Leiden also included geomorphological notes, among which Hartevelt (1970) and Zandvliet (1960) stand out for Andorra and the Noguera Pallaresa valleys, respectively, with specific contributions, namely: (i) the importance of glacial overfeeding from the Val d'Aran (Pla de Beret and Port de la Bonaigua); (ii) the Romedo ice field at the head of Cardós; and (iii) the presence of juxtaglacial deposits at 600–700 m above the valley floor.

Further research was undertaken in both basins during the 1980s. The new synthesis by Serrat and Vilaplana (1979) and the geomorphological studies of Prat (1980) in Andorra placed the Valira glacial front even further to the south (in Sant Julià de Lòria, at 900 m). Vilaplana and Serrat (1979) and Vilaplana (1985) focused on the Valira del Nord Valley and its La Massana glacial system (see Sections 3 and 4). Prat (1980) followed the model proposed by Chevalier (1924) and differentiated three phases in the glacial evolution of Andorra: (i) a phase of maximum glacial extent (located in the Riss), including the expansion, stabilization, and retreat periods; (ii) a postmaximum glacial phase (of Würm age, in Alpine terminology) located in the high valleys with valley glaciers; and (iii) a Late Glacial phase with cirque glaciers and protalus ramparts. In the Noguera Pallaresa Valley, Ventura (1982, 1983), Verdaguer (1986) and Bru (1985), and Furdada (1988) included detailed cartography (1:25,000) of the Escart and Espot valleys, the Cardós and Vallferrera valleys, and the Àssua Valley, respectively, and conducted field sedimentological studies. Later, the last synthesis on glaciers in the area was carried out focusing on a maximum glacial extension in the LGC (Bru et al., 1985; Bordonau et al., 1992; Serrat et al., 1994). Geophysical studies also began at this time, such as that of the Esterri d'Àneu Basin (Bordonau et al., 1989), together with the interest on rock glaciers (Gutiérrez Elorza and Peña Monné, 1981; Martí and Serrat, 1992).

In the case of Andorra, we highlight the synthesis of Gómez-Ortiz (1996) on glacial and periglacial processes, as well as the geomorphological map of Andorra (Copons, 2005), which built upon the one already started at the end of the last century in Cerdanya by the Instituto Geológico y Minero de España (IGME). Studies on glaciers have continued over the last three decades, focusing on geophysical prospecting, sequential stratigraphy, the production of absolute dating on the sedimentary deposits of the La Massana glacial complex, built in phases subsequent to the local Last Glacial Maximum (lLGM) (Turu, 1992, 1998, 2001, 2002a,b; Turu and Bordonau, 1997; Jalut and Turu, 2008; Turu et al., 2002, 2013, 2017), the locations of the glacial fronts of various glaciations, and the correlations and dating of fluvioglacial terraces with terminal moraines (Turu, 1994, 2011; Turu and Peña, 2006a,b).

The framework of the first AEQUA Symposium on Glaciers 2011 discussed the palaeogeography of the Noguera Pallaresa Glacier (Turu et al., 2011a), which was previously addressed by Ventura (2010a). The former located the terminal complex of the Noguera Pallaresa Glacier more to the south compared with the previous authors, namely close to Rialp, with connection or obturation phases on the Cardós-Vallferrera Glacier. These authors distinguished two terminal moraines with respect to the Flamisell Valley, namely Molinos and an as-yet-unpublished front located further to the south, near Senterada, belonging to different phases within the LGC. Correlation works have also been carried out based on fluvial and fluvioglacial terraces (Peña et al., 2011), sedimentological studies (Vizcaino et al., 2011) that have even facilitated correlations with global events (Pèlachs et al., 2011), geomorphological mapping, as well as the IGME mapping at a scale of 1:50,000 (sheet 149-Isil (Cabra, 2013) and sheet 181-Esterri d'Àneu (Suárez Rodríguez, 2016)) and others studies in the Filià Valley in the Flamisell Basin (Rallo et al., 2012).

3. The distribution of glacial landforms

The palaeoglacier system of the Central-Eastern Pyrenees is made up of six main tributaries with lengths exceeding 20 km: (i) Pallaresa, Cardós, Vallferrera, and Flamisell palaeoglaciers in the Noguera Pallaresa Basin, with three of them converging into a single glacial tongue exceeding 60 km in length; and (ii) Valira d'Orient and Valira del Nord palaeoglaciers in the Valira Basin. Glaciers from both valleys also came to converge, forming a single tongue longer than 40 km (Fig. 4.2.1; Table 4.2.1). In turn, several of the glacial tributaries that fed them reached lengths of between 4 and 15 km, the most extensive being those of Bonaigua, Espot, and Unarre in the Noguera Pallaresa Basin, Tavascan, and Lladorre in Cardós Basin, Arinsal in the Valira del Nord Basin and Incles, and Ransol and Madriu in the Valira d'Orient Basin. With regard to the Noguera Pallaresa Basin, we must also add the contributions from the Garonne Glacier (located on the northern slope of the Pyrenees) by means of two extensive glacial transfluences (Pla de Beret and Port de la Bonaigua) and several ice fields. Although of lesser importance, the glacial transfluence in the Port d'Incles, Valira Basin (with the French valley of Aston in the Ariège Basin), was also remarkable. Another evidence of the noteworthy glacial volume reached in the headwaters is the large number of transfluence or glacial diffluence cols located both at the crests at altitudes exceeding 2600 m and in the mountain passes between 2000 and 2500 m, which have been used since ancient times as communication routes between the valleys.

Glacial cirques of different sizes and morphologies constitute the headwaters of the two glacial systems. Shaped on ancient river headwaters, their cirque bottoms are located between 2000 and 2500 m. In the high massifs (2600 to 3000 m) and, particularly, in granite rock (Fig. 4.2.2A), we find the best well-developed landforms, with compound cirques of extensions exceeding 7 km^2 and organized internally (following fracture lines or lithological contacts) with a succession of overdeepened basins (currently occupied by numerous lakes) separated by rock thresholds (Fig. 4.2.2D). The cirques of Peguera,

Table 4.2.1: Parameters of the area covered by the glaciers during the ILGM in the Central-Eastern Pyrenees.

Parameters	Noguera Pallaresa Basinh	Valira Basin
Total area covered by the glaciers (km^2)	796.9	323.2
Total number of glaciers	65	47
Number of glaciers with area <1 km^2	42	42
Number of glaciers with area 1 < a <10 km^2	18	4
Number of glaciers with area >10 km^2	5	1
Area of the glacier with the largest surface (km^2)	609.5	308.5
Area of the glacier with the smallest surface (km^2)	0.04	0.002
Length of the longest glacier (km)	63	43
Length of the shortest glacier (km)	0.33	0.08
Maximum altitude of the glacier with the maximum elevation at its head (m)	3108	2915
Maximum altitude of the glacier with the minimum elevation at its head (m)	2250	2150
Minimum altitude of the glacier with the minimum elevation at its front (m)	695	775
Lowest ELA according to the Terminus Headwall Altitude Ratio (THAR) 0.4 method	1624	1631
Highest ELA according to the THAR 0.4 method	2244	2268

Cabanes, Romedo (Noguera Pallaresa), Pessons, and Gargantillar (Valira) are examples of large features. The crests delimited the cirques, but their lateral growth was not complete, leaving remnants of preglacial palaeosurfaces between them even at high altitudes (<2700 m). Staggered and highly uneven cirques with a lithology of slate and quartzite are located in massifs, including three or four overexcavated levels, such as those existing in Unarre (Noguera Pallaresa Valley) and Guerossos (Cardós Valley).

The main valleys present few evidence of glacial origin, mainly due to the influence of the prevailing rock (shales), which was not very favorable for its conservation. The valleys mostly exhibit V-shaped cross sections, including narrow river gorges, and only some isolated U-shaped sections appear, as in the slopes over the basins of Esterri d'Àneu

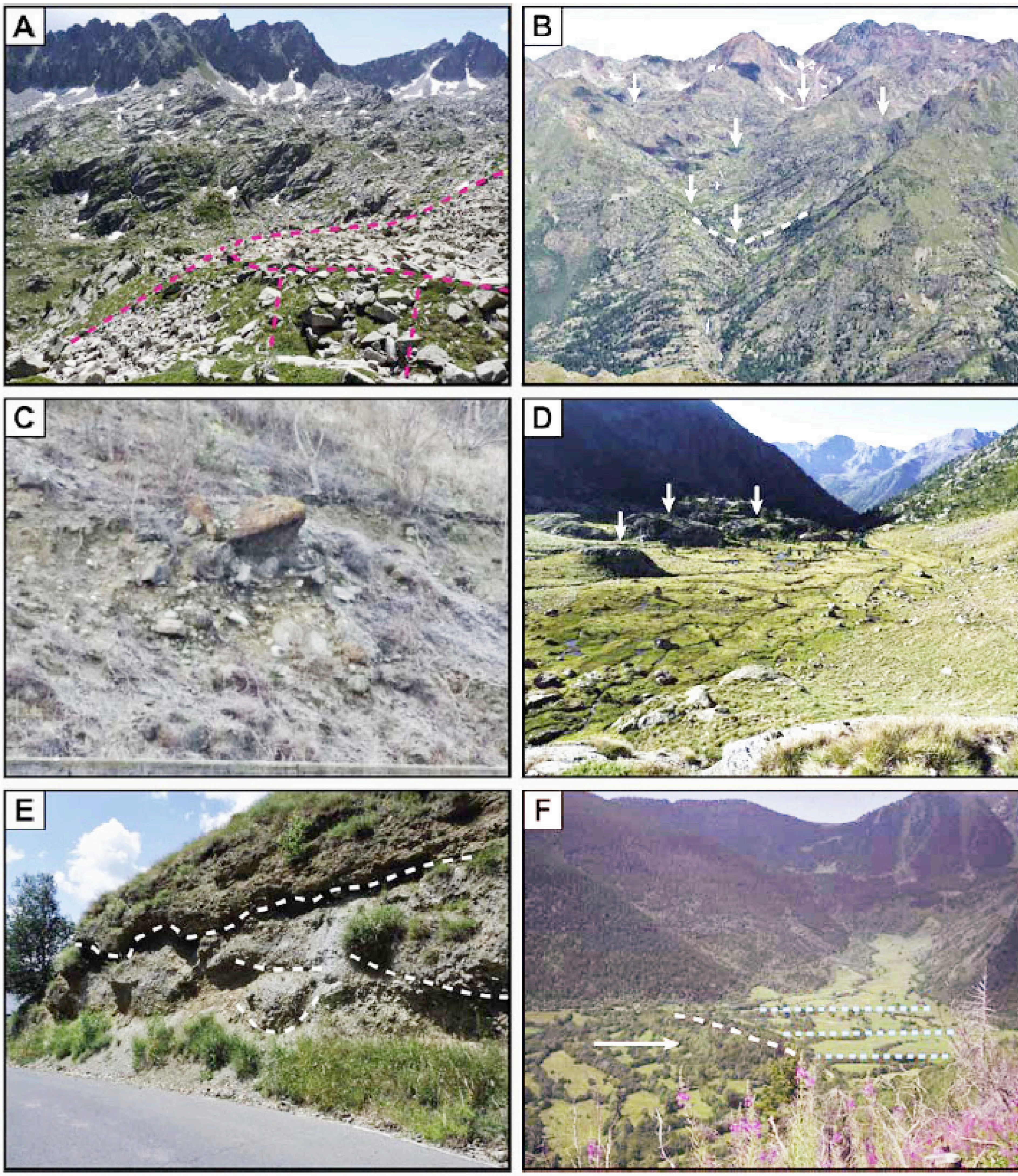

Figure 4.2.2

Glacial morphology and glacial deposits in the upper Noguera Pallaresa Valley. (A) View of the Gerber cirque (Bonaigua Valley) shaped in granite rocks including ridges and headwalls (height > 200 m) and extensive sectors with *roches moutonnées* and glacial abrasion. (B) Glacial valley of the Barranc de Sotllo (Vallferrera Valley) hanging over the main valley (400 m). The arrows indicate the location of the overdeepened basins at its head. The summit of Pica d'Estats (3143 m) appears in the background (on the right). (C) Details of the fluvioglacial terrace of La Bastida de Sort (697 m) that includes glacial boulders (F1). (D) The overdeepened basin of Plans de Sotllo (Ferrera Valley) at an altitude of 2185 m is currently filled with sediments and peat bogs. On the left there are large glacially polished surfaces. (E) Details of the fluvioglacial deposits outcrop of the Unarre glacial system where channel structures are observed. F) Upper section of the Son glacial complex. The moraine (1550 m) closes the palaeolake of Les Planes de Son (40 m thick sediment infill). The arrow indicates the direction of the Noguera Pallaresa Glacier reaching the Son Valley.

(Noguera Pallaresa), Espui (Flamisell), and Andorra la Vella (Valira), or between the villages of Lladorre and Cassibrós (in Cardós), with a succession of lateral widenings or “false basins” (Bru, 1985) separated by rocky outcrops. U-shaped cross sections are more frequent in the high valleys (altitudes > 1600 m), especially those with granite rocks and gneiss, as well as longitudinal profiles with slope breaks or rock thresholds and hanging valleys.

The following main glacial collectors follow one another from west to east. We first discuss the **Flamisell Valley**, whose head was formed by the extensive cirque of Capdella (6 km wide, 5 km long, and 22 km^2 in area). It was shaped on granite rock, organized into three levels between 2600 and 2150 m, and is occupied by glacial overdeepened basins with lakes today. Inside, the Estany de Mar occupies the largest basin, which is 1.9 km long. The valley begins by crossing the last threshold of the cirque, after a difference in level of 450 m and a little further south, in the village of Capdella (1425 m), where the glacial valleys of Riquerna and Filià converge with the main collector. Along the first 11 km, up to the town of Molinos (982 m), the valley has a marked transversal U-shaped profile, and longitudinally, it includes two rock thresholds and the 3-km-long Espui overdeepened basin. Glacial deposits exist in several locations, the main and most extensive being the tills located between the Sallente and Capdella reservoirs at 1400−1630 m, those at the bottom of the Filià Valley, and those on both sides of the Riquerna Valley between 1300 and 1850 m. The glacial deposits in Espui lie halfway up the valley (up to 1500 m), indicating ice thicknesses of 250−340 m. Several deposits and outcrops are located in the terminal zone of the palaeoglacier, pointing to the position of the terminus in different phases. To the north of Molinos (982 m) there is a terminal moraine (Oller, 1992), considered by several authors to be the glacial front of the lLGM, after 18.5 km (García Sainz, 1933; Nussbaum, 1956). Still to confirm with further field work, the outermost glacial deposits in Borda de Casanou (750 m), north of the village of Senterada (740 m), were associated by Turu et al. (2011) with the lLGM. Up to this point, the Flamisell Glacier had reached a distance of 26.7 km.

The Noguera **Pallaresa Valley** is located at the top of the western cirques in the Marimanha Massif. The palaeoglacier covered the surface of the Beret-Montgarri valley (1700 to 1900 m), which in turn was fed by a glacial transfluence from the Garonne Glacier. Between Montgarri (1648 m) and Alós d’Isil (14 km), the valley runs in a west-east direction, parallel to the structural setting, surrounding the Marimanha Massif to the north. The accumulated glacial volume, exceeding 700 m thick, was significant, as shown by the existence of wide diffluence and glacial transfluence cols in the main divide. The scarce development of its slopes facilitated the formation of an extensive 6-km-wide ice field at Bonabé at 1900−2200 m. In contrast, the valley in this sector presents a clearly fluvial morphology, with sections of fluvial gorges and remains of erosion terraces. Near the village of Alós d’Isil, at 1270 m, the valley takes a north-south orientation, where it received new glacial contributions from Mont-roig and from east-southeast of Marimanha.

The main accumulations at the head of the valley are the juxtaposed glacial deposits, which are located on three successive levels between 400 and 650 m above the valley floor. Some deposits preserve the flat terrace topography and are a good indicator of the level reached by the ice. The best examples are the Sumis (1870 m; +635 m), Vinyals (1950 m; +540 m), and Clavera (1830 m; +340 m) terraces.

In the village of Esterri d'Àneu (955 m), the Noguera Pallaresa palaeoglacier received ice from the tributaries descending from Unarre, Bonaigua, and Espot valleys. At the head of the Bonaigua Valley was the second great glacial transfluence (Port de la Bonaigua, 2072 m) from the Garonne Glacier. The confluence of the three valleys explains the formation of the overdeepened basin of Esterri d'Àneu, located between 940 and 980 m, the largest and deepest of the southern Pyrenees (area: 6.5 × 1.5 km; depth: 400 m). Geophysical studies identified three sedimentary units interpreted as glacio-lacustrine rhythmites at the base, fluvio-delta deposits in the center and on the surface, alluvial and dejection cone deposits, and three levels of aquifers (Bordonau, 1992; Turu et al., 2007).

The main glacial accumulations in the area are located around the Esterri d'Àneu Basin, with juxtaposed deposits and glacial complexes (Son, Espot, and Unarre) and three altitudinal levels of deposits (1550, 1400 and 1300 m) including the presence of erratic boulders at higher altitudes. The Son glacial complex (Ventura, 2010a), formed by the damming of this lateral valley by the Noguera Pallaresa Glacier, includes (i) erratic boulders in the divides (1765 m; +817 m); (ii) tills from the Cabanes Valley (Bonaigua) brought to the Son Valley by a glacial transfluence; (iii) the lateral moraine of Les Planes de Son (1550 m; +600 m) filling up a palaeolake with glaciolacustrine and fluvioglacial deposits (sediment thickness: 40 m) (Fig. 4.2.2F); and (iv) the moraines of Beiero (1395 m; +447 m) and Casterasso (1320 m; +372 m) near the Son village. The Espot glacial complex (Ventura, 1983) is located very close to the confluence with the main valley and includes (i) erratic boulders on the slopes (1550 to 1650 m; +400 m above the Espot Valley); (ii) the Berrader lateral moraine (1500 m; +255 m above the Espot Valley), the lateral moraine and the proglacial cone of Els Estanyets from a local glacial valley blocked by the Berrader Moraine; and (iii) the Estais Moraine (1000−1400 m; +465 m above the main valley), the glaciolacustrine deposits of the Estais palaeolake, and the stratified debris (including glacial boulders) that partially fossilize it. The different deposits and accumulation landforms in the Unarre glacial complex indicate the relationships (of obturation or confluence) between the main glacier entering the Unarre Valley and the local glacier (Ventura, 2010b). Their detailed descriptions can be found in Section 5.

Between the threshold that borders the Esterri d'Àneu basin and the town of Llavorsí at the confluence with the Cardós-Vallferrera Valley, the Noguera Pallaresa Glacier in Escaló created a second 3.8-km-long overdeepened basin and penetrated several kilometers into the lateral valleys, depositing sediments in at least two different glacial phases: (i) 2.8 km in the Berrós Valley, with a kame terrace deformed and fossilized by periglacial deposits (1325 m; +385 m); and (ii) erratic boulders in the Escart Valley, located at 1200 m (+340 m) and 2.2 km inland, and deformed kame deposits at 1020 m (+165 m) and 1.2 km inland (Ventura, 1982). Close to Llavorsí are the juxtaposed terraces of Aidí (at 1000−1020 m; +185/165 m) and the Boès Ravine (1170 m; +365 m), built by periglacial deposits, including the granite glacial boulders in the Boès deposit (Turu et al., 2011a).

Downvalleys Llavorsí, the Noguera Pallaresa Glacier ran through a stretch of river gorge until it reached its terminal complex between the towns of Rialp and Sort (686 m). With no frontal or lateral moraines, the terminal area includes only several fluvioglacial deposits belonging to two different glacial cycles, namely: those on the route to Escàs over Rialp (880 m; +170 m), marked by the presence of altered granite blocks, and those on the Bressui terrace (+30−40 m), the most external and the oldest. In a more internal position, the fluvioglacial terrace of the Bastida de Sort (712 m; +20 m) includes interspersed supraglacial till and slope deposits (Fig. 4.2.2C). The Bastida de Sort deposit was related to the outermost frontal position of the Noguera Pallaresa Glacier during the ILGM (63.8 km).

The **Cardós Glacier** system had two symmetrical glacial valleys (each of length 12 km) at its head, which merged in the locality of Tavascan (1105 m). To the west, the Tavascan River drains the group of glacial cirques situated between the massifs of Mont-Roig and Certascan. The Cuanca Basin (1360 m) was excavated at the beginning of the valley in the zone of ice accumulation. To the west, the Lladorre River, in a similar arrangement than the previous one, collected the ice coming from the cirques between the Certascan and Pica d'Estats massifs and excavated the Boavi Basin (1460 m). At this head was the Romedo ice field, located on the main divide; the Certascan Lake overdeepened basin at 2235 m, one of the largest in the Pyrenees (1270 × 775 m); and the preserved and extensive fragments of an erosion terrace located 200−300 m from the valley floor. Between Tavascan and Llavorsí villages, the Cardós Glacier did not receive any other direct glacial contribution, reaching a total distance of 29.6 km. As in the case of the other collectors of the Noguera Pallaresa palaeoglacier, no terminal complexes are preserved, as the most frequent glacial deposits are located in the middle of the main valley or in the interior of the lateral valleys. Glacial accumulations and juxtaglacial terraces are found at different heights above the valley, always dominated by erratic boulders. The main deposits are as follows: (i) The deposits of Lleret and Boldís (1650 m; +627 m), with subglacial tills and accretion at the base in several outcrops (Bru, 1985); (ii) Esterri de Cardós-Ginestarre (1450 m; +510 m), with tills fossilized by fluvioglacial deposits and periglacial sediments; and (iii) the tills and a juxtaglacial terrace in Estaón village (1270 m; +340 m), deposited by the entry and blocking of the tributary valley of Estaón by the Cardós Glacier at the bottom of the valley in the Surri village (1190 m, +300 m). After the confluence of the Vallferrera and Cardós glaciers at 3.8 km from Llavorsí, we find the Tírvia glacier complex (850–950 m, +100 m). The Tírvia deposits have been studied by different authors (Nussbaum, 1956; Fontboté et al., 1957; Butzer and Franzle, 1959; Bru et al., 1983; Bru, 1985; Turu et al., 2011a) and represent one of the key locations for the interpretation of the glacial occupation of the Noguera Pallaresa Basin. The deposit was formed by two separate units that include basal tills (from the Cardós Glacier) and glaciofluvial and glaciolacustrine sediments generated by the proglacial drainage of this glacier, which was blocked by the Noguera Pallaresa Glacier in later phases of the lLGM. Some glaciolacustrine levels are deformed due to sedimentary, glacial, and seismic processes (Rodríguez-Pascua and Perucha, 2008).

The head of the **Vallferrera Valley** was located in the cirque of Baiau and the other cirques located to the north of the massif of Monteixo-Medacorba, converging in the Pla de Boet (1860 m). From Baiau to Pont de la Farga (1453 m), the glacier followed an east-west direction for 11 km and was fed on both sides by ice coming from 11 cirques facing south (Areste, Sotllo, Baborte, Aixeus, etc.) from the Pica d'Estats Massif (Fig. 4.2.2B). The ravines hanging 400 m above the valley floor served as the link between the cirques and the main drainage system. From the Pont de la Farga, the valley is oriented north-south and passes the town of Alins in the west-southwest direction until it reaches the confluence with the Cardós Valley after 26.7 km and overcoming a stretch with a fluvial gorge in the last 2 km. Glacial deposits are scarce in the Vallferrera, with tills and juxtaglacial terraces located at medium altitude inside side ravines such as Costuix (1710 m; +485 m) and Ose (1545 m; +405 m). In Vallferrera Valley, the glacial deposits located at a higher altitude, c. 100 m lower than in Cardós or Noguera Pallaresa valleys. Before the town of Alins (1050 m), the glacier penetrated c. 2 km into the lateral valley of Tor, where accretion till deposits covered by lake and fluvioglacial sediments can still be observed at 1200 m (+120 m). In the terminal zone of the palaeoglacier, 3.5 km from the confluence with the Cardós Glacier, are the last glacial deposits with accumulations of erratic boulders (1100–1200 m; +272 m) on the slopes and tills at the bottom of the valley (at 928 m).

The head of the **Valira Glacier** was located in the Pessons compound cirque. Along the first 25 km, the palaeoglacier received various tributaries (Incles, Ransol, Riu, etc.). The valley constantly changes direction (south-north, east-west, and finally north-south after the confluence with the **Valira del Nord Valley**) and exhibits a morphology of open high sectors and medium embedded sections (i.e., it is a V-shaped valley) while crossing more resistant rocks. At the confluence with the Cortals Valley lies the Encamp Basin (1250 m), and the Andorra la Vella overdeepened basin is located after a new section of the valley (1000 m; area: 3.6 $\times$ 0.6 km; depth: $>$ 90 m) (Turu, 1999; Miquel et al., 2011), just at the confluence with the Valira del Nord and Madriu valleys. The valley takes on a marked transversal U-shaped profile in this sector. The glacial morphologies of the valleys are also shown in the middle sections of the Madriu, Ordino, and Arinsal valleys. To the south of

Andorra la Vella, the lower section of the Valira Glacier (i.e., its last 20 km) ran through a river gorge embedded in the remains of a hanging glacial valley (+240 m) built during the penultimate glaciation (Riss) or in even during older glaciations.

The main glacial deposits in Andorra are located in the middle and lower sections of the valleys. There are four key locations: (i) the four lateral moraines at Engolasters, above the town of Encamp (between 1500 and 1750 m), together with glaciolacustrine and fluvioglacial deposits, indicating a maximum glacial thickness of 500 m; (ii) the lateral moraines of La Comella, (1200−1268 m; +240 m) in the Andorra la Vella Basin, developed by the main glacier in more recent phases (gLGM); (iii) the La Massana glacial complex (Vilaplana and Serrat, 1979; Vilaplana, 1985; Turu and Bordonau, 1997; Turu et al., 2017; Turu, 2018), created after the lLGM by the filling of the Valira del Nord Valley by the main Valira Glacier, with tills and glaciolacustrine and fluvioglacial deposits in its sedimentary record (Fig. 4.2.3); and (iv) the remnants of moraines located at the bottom of the valley and in lower areas of the slopes in the final section of the glacier. They include various moraines (i.e., Andorra la Vella, Santa Coloma, and Pont de la Margineda) that were historically considered to be the terminus of the Valira Glacier (Panzer, 1926; Llobet, 1947), the terminal complexes of the penultimate glacial cycle at Sant Julià de Lòria (Prat, 1980; Turu, 1994) and of the lLGM in Pont Trencat (780 m), a 43-km-long glacier, and the Calbinyà moraine (Turu and Peña, 2006a,b), the outermost, well-preserved, and oldest in the valley (Early or Middle Pleistocene).

Several cirque and valley glaciers that did not converge with the main glaciers were located inside the six large glacier basins in the massifs or in a more external position in the southern massifs, at heights of less than 2500 m. As a whole, they were between <1 and 9 km long and, depending on their orientation and the extents of their headlands, their fronts were located between 1300 and 2000 m. However, most of them were located at 1500−1700 m. The following were some of the most extensive glaciers in the Noguera Pallaresa Basin: (i) The Manyanet Glacier (9.5 km) was the most extensive, given the large volume of moraines at its head, and its front was located at 1050 m; (ii) the Berasti Glacier (7.4 km) was located in the Àssua Valley; (iii) the Estaon Glacier (5.6 km) lied in a tributary of the Cardós Valley; (iv) the Bords and Finestres glaciers (7.1 and 4.0 km, respectively) were located in the Tor Valley (Vall Ferrera) and share a sedimentary record with moraines at 1500 m and a succession of deposits, including cirque moraines and rock glaciers; (v) and the Coma de Burg Glacier (3.8 km), located over the town of Tírvia, whose valley conserves the most interesting sequence of glacial deposits in the group. Up to nine moraine groups exist between 1400 and 2180 m. One of the moraines in an intermediate position dams the Coma de Burg Lake, whose sedimentary base has been

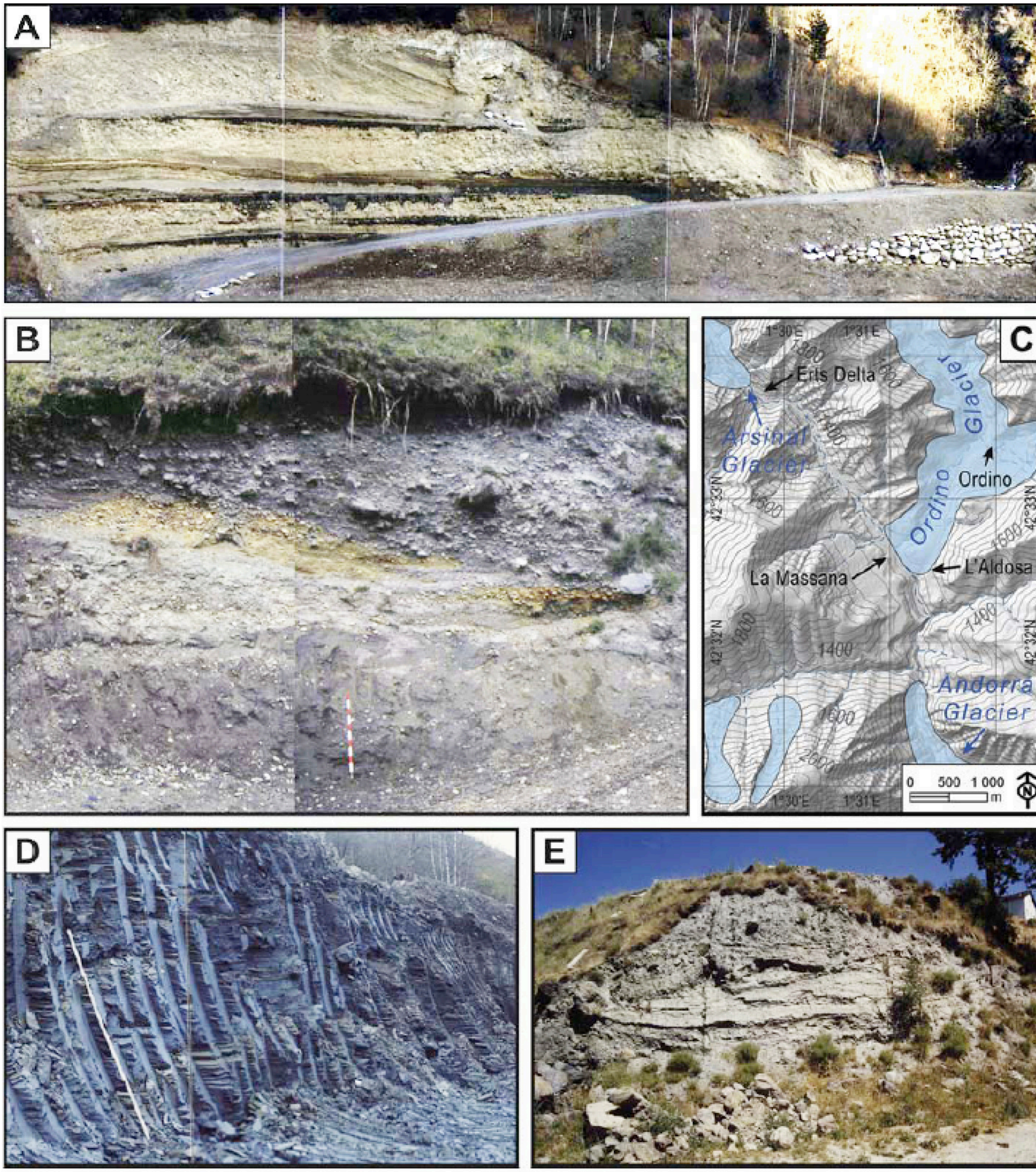

Figure 4.2.3

Deposits of the La Massana glacial complex (Valira del Nord Valley). (A) Overview of the Erts Delta deposits. (B) Laminites and deformed glaciofluvial deposit of the Ordino Delta with an accretion till on top left by the Ordino Glacier. (C) Position of the fronts during the deglaciation: The La Massana glacier complex started forming at 32 ka cal BP as a result of the obturation of the Valira Glacier in the Valira del Nord basin (Ordino and Arinsal glaciers). The fronts of the local Ordino and Arinsal glaciers were unstable and fluctuating (with advances and retreats), leaving alternating levels of tills, glaciolacustrine rhythmites, and deltaic sediments of the La Massana palaeolake, which disappeared at 16.5–17 cal ka BP. (D) Details of the laminites of the Ordino Delta. (E) Laminites deformed by an accretion till related to a push-moraine in the village of l'Aldosa (Bony de les Planes moraine) included in the La Massana glacier complex.

dated at 17 cal ka BP (Vizcaino et al., 2011). The glaciers were smaller in the southern massifs, and except for a few small glacier tongues, they were limited to cirque glaciers. Eight cirques are located in the Serra d'Altars, and five, in the Orri Massif, where the confluence of two of them generated a 4.3-km-long glacier tongue, with its front at 1800 m. Fewer small glaciers existed in the Valira Basin: (i) The area of Setúria, which lies to the east and south of the Salòria Massif (Riu d'Os Valley) and contains 16 glacial cirques, which produced several ice tongues, the longest of which was 4 km long, with its front at 1500 m. Furthermore, (ii) one cirque exists in the Civís Valley, and (iii) eight cirques were excavated from the eroded surface of Calm de Claror-Pic Negre.

A heterogeneous range of glacial and periglacial deposits, including ablation tills, lateral and frontal moraines, debris-covered glacial moraines and rock glaciers are found in numerous high valleys and cirques of the highest massifs. The rock glaciers occupy an altitudinal range between 1550 and 2750 m, indicating their formation in various phases within the deglaciation. Some are polymorphic, and the most extensive reach 1.2 km in length.

4. The chronology of glacial landforms

Research conducted prior to the most recent glacial chronology studies for the central Catalan Pyrenees (including the Pallaresa and Valira basins) dates back to the mid-1980s (i.e., the last century) (Bru et al., 1985) and was based on various regional studies that were carried out following the scheme developed by Bordonau et al. (1992). This relative chronology focuses on the LGC, including: (i) the former glacial cycles; (ii) the LGC with pre-maximum glacial, maximum glacial, and deglaciation with stabilization phases as well as valley glacier and altitude phases (valleys and cirques); (iii) the rock glaciers phase; and (iv) the historic postglacial phase or Little Ice Age (LIA). Later, a few absolute ages were obtained using radiocarbon dating in the other Pyrenean valleys (Bordonau, 1992), placing the LGC between 80 and 10 ka, with a maximum between 50 and 45 ka, diachronic with the gLGM (20−18 ka).

Currently, many differences can be observed in the existing documentation on the chronologies of the glacial processes for both basins. The Noguera Pallaresa Valley has a previous relative chronology and only two absolute dates. A few subsequent studies have continued to use this chronology as a reference (Ventura, 2010a,b; Turu et al., 2011a; Vizcaino et al., 2011). In contrast, the Valira Valley has a more robust glacial chronology (Turu et al., 2017, 2018) associated with marine isotopic stages (MIS) (Table 4.2.2).

Table 4.2.2: Chronology of glacial evolution in the Central-Eastern Pyrenees.

Phase	Chronology	Landforms and environments	References
Pre-LGC glaciations and the early Würm	Early/Middle Pleistocene (Valira) Penultimate glaciation in Valira and Noguera Pallaresa valleys (>162 ka)	Presence of eroded moraines and fluvioglacial sediments at elevations and outer positions (46.5-km-long glacier) lower than the moraines of the penultimate glaciation (Sant Julià de Lòria – Valira Valley). The early Würm had higher positions (La Margineda – Valira Valley) than the penultimate. Moraines and fluvioglacial terraces of the penultimate glacial cycle hang over the valley bottom (Valira) and in an outer position (Noguera Pallaresa)	Furdada (1988), Turu (1994), Turu and Peña (2006a), Peña et al. (2011), Turu et al. (2011c), Turu et al. (n.d. in prep.), this work
Local Last Glacial Maximum (lLGM)	Maximum glacial advance of the Last Glacial Cycle in Valira at c. 59 ka (MIS 4). Outer glacier fronts prior to 36 ka (Noguera Pallaresa) and 32.7 ka (Valira)	Glacial confluences in a single extensive glacier both in Valira and Noguera Pallaresa valleys (lengths exceeding 40 and 60 km, respectively; and ice thicknesses of 600 m). Overfeeding in both catchments associated to glacial transfluences. Glacier complexes and lateral terraces.	Bru et al. (1983), Ventura (1983), Bru (1985), Furdada (1988), Turu et al. (2007), Ventura (2010a), Turu et al. (2011a,c), Planas et al. (2011), Turu et al. (2017), this work
Global Last Glacial Maximum (gLGM)	Glacial fluctuations during MIS 3, MIS 2 and gLGM	Valira: front recession of 25 km. The disconnection of the Valira del Nord glacier from the main one triggered the formation of the La Massana palaeoglacier. During the gLGM both glaciers converged again, with the terminus located in the Andorra La Vella basin (at 12.2 km from the lLGM position). Noguera Pallaresa: intense retreat during MIS 3 has been identified in the sediments of the Tírvia glacial complexes and the fluctuations in the Unarre glacial complex. During the gLGM, glacier termini are in inner locations within the great valleys.	Turu et al. (2007), Jalut and Turu (2008), Turu et al. (2017), Turu (2018) Turu et al. (2011a,b), this work

Continued

Table 4.2.2: Chronology of glacial evolution in the Central-Eastern Pyrenees.—cont'd

Phase	Chronology	Landforms and environments	References
Deglaciation	Onset of the deglaciation at 19–18 ka OD at c. 17 ka YD at c. 13–12 ka	Rapid deglaciation. Subsequent glacial growth (Oldest Dryas; OD) produces valley glaciers 7–16.5 km long (fronts and proglacial deposits at 1400-1500 m). At the end of the OD, new moraines were deposited at 2000 m, in coexistence with the formation of the first rock glaciers. New glacier recession (Bølling-Allerød; BA) and glacier growth (Younger Dryas; YD) restricted to the highest massifs, with ice tongues 1.5–2.5 km long and fronts located at 2100-2500 m, in coexistence with debris-covered glaciers and abundant rock glaciers.	Miras et al. (2007), Turu et al. (2011b), Vizcaino et al. (2011), Ventura (2017), Turu et al. (2017), Ventura (2020)
Holocene	From the Early Holocene (10–9 ka) until present-day	Moraines at >2500 m (separated from other moraine groups, located in the N aspect of the highest massifs exceeding >2800 m). The highest rock glaciers, possibly of Holocene age.	Turu et al. (2011b), Ventura (2016, 2017, 2020)
Little Ice Age (LIA)	18th–19th centuries	Moraines of the Broate cirque (2650 m), in the Pica d'Estats massif; and fresh rock glaciers with fronts located at 2650–2750 in the northern slope of the Pica d'Estats, Bassiero and Monteixo-Medacorba massifs.	Ventura (2016, 2017, 2020)
Present-day	Disappearance of the small LIA glaciers	Current activity of small snow patches, rock glaciers and protalus lobes.	Ventura (2016, 2017, 2020)

The sequence of glacial events in the Valira Basin is as follows:

(a) Ancient glaciations and the early Würm. The glacial deposits, fluvial and fluvioglacial terraces in the final sector of the valley are ascribed to glaciations prior to the last one due to their topographical positions, moraine–terrace relationships, and degree of weathering. The oldest and outermost are the moraines of Calbinyà (833 m; +80 m), near La Seu d'Urgell. They are related to terraces SV-T1 and SV-T3 of the Valira-Segre and are of approximately Lower or Middle Pleistocene age (Turu and Peña, 2006a), indicating a glacier length of 46.5 km. The moraine deposits and fluvioglacial terrace of Sant Julià de Lòria, which hangs over the valley floor (+80 m), and La Margineda (+65 m) are related to an early Würm glaciation in MIS 5c-5d (Turu et al., 2021).

(b) Last Glacial Maximum. The lLGM was identified by ^{21}Ne dating of the glacial polished surface in the Roc del Quer at 1750 m over the village of Canillo. Given its estimated age of 59 ka, it was located in MIS 4 and, therefore, previous to the gLGM. The Valira d'Orient and Valira del Nord glaciers converged. At the time, the Valira d'Orient glacier was 600 m thick and overflowed through the Col d'Ordino, at 1980 m, into the Valira del Nord Valley (Planas et al., 2011). This valley was home to smaller glacial headwaters, and thus, the thickness of the ice was estimated to be c. 300 m (Redort glacial lacustrine deposits, 1540 m; +290 m) and 200 m in a later phase (Segudet glacial lacustrine deposits, 1440 m; +190 m). The Valira glacial front must have been located at Pont Trencat (780 m), 4 km south of the Spanish–Andorran border, where a fluvioglacial terrace can be observed in a proximal position along a 43-km-long route, and it is estimated to be older than 32.7 ka (Turu et al., 2017).

(c) Glacial fluctuations during MIS 3, MIS 2, and the gLGM. Important glacial advances and retreats in cycles of 3–5 ka marked the period between the lLGM and the gLGM. Retreat phases were detected by the presence of slope deposits that reached the bottom of the Valira d'Orient Valley, covering tills. In the village of Canillo, which is located at 1520 m, the base of a large landslide was radiocarbon-dated at 39.6 to 35.2 ka, indicating retreat of the main glacier exceeding 25 km with respect to the lLGM fronts (Turu et al., 2017). At the end of MIS 3, the two Valira glaciers separated, forming a palaeolake in the village of La Massana (Turu, 2018). The sedimentation in the palaeolake began with the juxtaglacial obturation during the advance of the Valira d'Orient Glacier (the main collector) prior to 32.7 cal ka BP (Jalut and Turu, 2008). The sediments of the La Massana palaeolake show that the local glacial fronts (i.e., the Ordino and Arinsal glaciers) were unstable and fluctuating, with diamictons interspersed with glaciolacustrine rhythmites up to the gLGM (20.3–19.8 cal ka BP, Turu et al., 2017). The La Massana obturation ceased to exist at 17.0–16.5 cal ka BP (Turu, 2018). The glacial front at the end of MIS 3 was located near the town of Sant Julià de Lòria (8.7 km north of the lLGM front), where proglacial deposits were dated at 32.7 ka via Optically Stimulated Luminescence (OSL) (Jalut and Turu, 2008). The glacial fluctuations during MIS 2 were of lesser magnitude than those of MIS 4 and MIS 3. The Arinsal and Ordino glaciers converged with the main glacier during the gLGM, which was marked with more local glacial advances and retreats. Its thickness in the Andorra la Vella Basin was estimated to be 300 m. Moreover, two lateral gLGM moraines of the main glacier at Engolasters were radiocarbon-dated at 18.9–18.6 ka, while cosmic-ray exposure dating (^{10}Be) revealed an exposure age of 18.0 ka (Turu et al., 2017). The front of the gLGM glacier was located at the exit of the Andorra la Vella Basin, on those moraines that were considered to be the most external glacial fronts in the first half of the 20th century. The best preserved is that of Santa Coloma. The gLGM glacial front was situated 10.2 km to the north of the lLGM terminal complex.

(d) Deglaciation. This stage is less well documented in Andorra than the previous ones. At the beginning of the final retreat, the Ordino Glacier left the La Massana Basin, and its front stabilized after 13.7 km during the OD to the south of Sornàs (1300 m) around 17–16 ka (Turu et al., 2011b). During the interstadials, the glacier retreated to Arans (11.1 km), where it stabilized during the Older Dryas (Turu et al., 2011b). In the main valley (Valira d'Orient), a frontal moraine in the town of Canillo (1500 m) was dated at 13.3–12.9 ka. It belonged to a valley glacier of 16.5 km long (Turu and Planas, 2005). In the YD and the beginning of the Holocene (Miras et al., 2007), the glaciers were confined to the interior of the highest north-facing cirques, which became definitively ice-free at 9.8 ka (Turu et al., 2011b).

The lack of a glacial chronological update in the last 30 years for the Noguera Pallaresa Basin has led us to fill in this gap by trying to correlate its glacial deposits with the MIS. The new proposed glacial chronology is based on the following aspects: (i) the interconnection between the Garonne and Noguera Pallaresa glacial basins; (ii) information and data from the sedimentary record of the Barbazan alaeolake, which is located in the former terminal area of the Garonne Glacier; (iii) a review of information from the Tírvia glacial complex; (iv) a comparison with the bordering basin of the Valira (Andorra); (v) inclusion in the new chronology of the few absolute data existing for the basin; and (vi) incorporation of the deglaciation phase.

The key to interpreting the evolution of the Noguera Pallaresa Glacier lies in its connection with the Atlantic Garonne Basin. The two great glacial transfluences between the two valleys can decisively explain the length reached by the Noguera Pallaresa Glacier (>60 km) and the advances and retreats led by the Garonne Glacier. When the front of the Garonne Glacier left its lLGM position, a proglacial lake formed, i.e. the Garonne palaeolake (Hubschman and Jalut, 1989), which extended along c. 12 km. In this sense, the sedimentary record of Barbazan (Andrieu et al., 1988; Andrieu, 1991) becomes a fundamental chronological correlation tool. Thus, we will base our estimates on the calibrated ages provided by Stange et al. (2014). Another key piece of information concerns the detection of the important glacial retreat during MIS 3 in Andorra (Turu et al., 2017), which we interpret as having been identified in the Tírvia complex. This generalized glacial retreat during MIS 3 has also been detected in the Central Pyrenees (García Ruiz et al., 2001, 2003; González-Sampériz et al., 2006). Both valleys (Garonnne and Valira) allow the temporary reassignment of the time before and after the aforementioned retreat from the glacial sedimentary records of the Noguera Pallaresa Valley, ordered to date only by topographical, geomorphological, and sedimentological criteria.

The sequence of glacial events in the Noguera Pallaresa Basin is as follows:

(a) Ancient glaciations. Glacial deposits prior to the LGC are very rare. The fluvioglacial deposit of Bressui (south of Sort), whose ceiling is located at +30−40 m (Peña Monné et al., 2011), has been dated with OSL, providing an age of 162 ka (Turu et al., 2021 in prep.). This result correlates with MIS 6 or earlier, placing the front of the 66-km-long glacier in the locality of Sort. Other ancient deposits related to the Bressui terrace include the weathered fluvioglacial sediments along the Escàs area (880 m; +170 m above Rialp). A group of deposits formed by erratic boulders, glacial sediments within periglacial deposits, and some till material at +150−200 m indicate the existence of a glacial phase prior to the lLGM. The Son Valley is a key location, with erratic boulders located up to 1765 m (+817 m in the Esterri d'Àneu Basin). Moreover, a till, the Cabanyeres-Estaró (1760 to 2010 m) is located on an old glacial transfluence col between the Cabanes and Son valleys (Ventura, 2010a).

(b) Last Glacial Maximum. The Noguera Pallaresa Glacier formed an extensive basin, with a thickness exceeding 600 m over the Esterri d'Àneu Basin in the lLGM. In Llavorsí, the Cardós-Vallferrera Glacier merged with the main glacier (Turu et al., 2011a), maintaining a considerable thickness (+365 m). The front of the 63-km-long glacier would have been close to the Bastida de Sort. The glacial diffluence between the Garonne and the Noguera Pallaresa palaeoglaciers would have contributed to the maximum advance of the Noguera Pallaresa Glacier. This phase may have taken place prior to 36 cal ka BP, marking the oldest age for Barbazan (Stange et al., 2014), and we place it in MIS 4 or earlier by correlation with Andorra (Turu et al., 2017). Some key locations that identify the lLGM are: (i) the upper moraines (at an altitude of 1500 m) of the glacial complexes of Les Planes de Son (Ventura, 2010a, Fig. 4.2.2F) and Espot (Ventura, 1983); (ii) the highest juxtaposed terraces in the collector valleys, such as those of Sumís (1870 m, +635 m) in the Noguera Pallaresa, Lleret, and Boldís (1650 m, +625 m) in the Cardós Valley; (iii) the subglacial tills at the base of the Tírvia glaciolacustrine complex (Bru et al., 1983) and those of Aurós (1200−1420 m) in Unarre (Ventura, 2010b); (iv) the juxtaglacial terrace of Boès (1170 m; +365 m) over Llavorsí (Turu et al., 2011a); and (v) the fluvioglacial deposit of La Bastida de Sort (Furdada, 1988), located at +20 m and linked to the terminal area of the palaeoglacier.

(c) Glacial fluctuations during MIS 3 and the onset of MIS 2. The Garonne Glacier retreated, and the first proglacial lake was formed by moraine damming in the terminal zone of this valley (Andrieu et al., 1988). In Barbazan, lake sedimentation progressed between diamicton layers. This episode is dated to 35.8 cal ka BP (Stange et al., 2014). In the Noguera Pallaresa Glacier, this retreat was detected in the Unarre Valley, where the glacier became disconnected from the main glacier and retreated above 1500 m, depositing a fluvioglacial deposit that fossilized the subglacial till of the previous phase. With the first subsequent glacial retreat (F2), the Cardós and Vallferrera valleys were blocked by the Noguera Pallaresa glacial front once again to the south of Llavorsí, near the confluence of the Santa Magdalena River at 57 km from the source. The main glacier overflowed into the Noguera de Cardós, blocking the valley and causing the sedimentation of glaciolacustrine rhythmites in the Tírvia complex (Fontboté et al., 1957). Later, the Cardós Glacier advanced and deformed the glaciolacustrine sediments by glaciotectonics (Bru et al., 1983) in the same episode. To the north, the terminus of the Garona palaeoglacier advanced over Lake Barbazan and the diamicton sediments (Andrieu et al., 1988) among the glaciolacustrine laminites at the bottom of the lake. This episode occurred between 35.7 and 33.9 cal ka BP (Stange et al., 2014). Other key locations of this advance phase are: (i) the latero-frontal moraines of Cerbi (1365 to 1515 m) and the subsequent proglacial plain (1405 m) in Unarre; and (ii) the moraines at 1400 m from the Son and Espot glacial complexes. The Valira Glacier experienced, as indicated above, a major retreat prior to 35.2 to 34.2 cal ka BP (Turu et al., 2017) with the triggering of the Canillo mass movement (Planas et al., 2011) shortly afterward. Certain traces lead us to deduce that the Garonne Glacier must have experienced something similar during this phase (Bordonau, 1985). However, unlike the glaciers of the Western Pyrenees, the Garonne Glacier advanced again to positions close to the lLGM (Stange et al., 2014), possibly already at the end of MIS 3, as was the case in Andorra (Jalut and Turu, 2008). This new advance of the Garonne Glacier blocked the Sost Valley before it reached positions similar to the lLGM (Hérail and Jalut, 1986; Hubschman and Jalut, 1989). Evidence of this important glacial retreat in MIS 3 in the Noguera Pallaresa must be sought in the Tírvia glacial complex, after the deformation of the glaciolacustrine sediments. The top of the sequence presents an alteration level (Butzer and Franzle, 1959), indicating that the glacier retreated with enough time to allow the formation of an altered soil. Pieces of fluvioglacial deposits from this second retreat remain in the main valley (at +30−40 m) on the left side of the gorge to the south of Llavorsí. The glacial retreat of the Noguera Pallaresa opened its front to the very north of Llavorsí, since the alteration of the deformed glaciolacustrine deposits of Tírvia was produced in the absence of any more blockage. Later, a last phase of glacial advance (F3) of the Noguera Pallaresa Glacier obstructed the drainage of the Cardós Valley once again (south of Llavorsí, along a 52-km-long route) and culminated with the sedimentation of a second glaciolacustrine body by the Cardós Glacier in Tírvia, which was more reduced, not deformed, and located above the palaeosoil.

The palaeogeography of the Noguera Pallaresa Glacier in this last phase (F3), which included stabilizations and retreats, was characterized by a lower thickness than during the previous episodes, both in Esterri d'Àneu (with moraines at 1300 m and a glacial thickness of 350 m) and in the lower section (periglacial deposits in Aidí at 1000 m and a thickness of 185 m). The functionality of the transfluence cols implies that the Garonne Glacier was still an extensive valley glacier, with a front that fed the Garonne palaeolake (Hubschman and Jalut, 1989). In this situation, Barbazan shows evidence of two new diamictons between laminites, which is interpreted as a new glacial advance prior to the 30.2 cal ka BP (Stange et al., 2014). Another key location linked to this last great glacial advance is the Unarre glacial complex (see Section 5), where two pulsations correlated with the Barbazan diamictons prior to 30.2 cal ka BP were identified. One built the Aurós proglacial cone (1310 m; +360 m) from the local glacier disconnected from the main glacier and the periglacial breccias (1315 m) located on the sides of the valley that fossilized the previous subglacial tills from F1. In a lower position lie the fluvioglacial terraces of Unarre (1275 m, +325 m), deposited on the same subglacial tills and correlated with the Barbazan carbonate rhythmites of 27.8 cal ka BP (Stange et al., 2014), which were also deposited on diamicton.

(d) The deglaciation: gLGM and Termination 1. To find the deposits that identify later glacial phases in the Noguera Pallaresa (within the context of deglaciation), using the villages of Aidí and Tírvia in F3 as a base, we retrace our steps by 15−20 km toward the headwaters. The water level of the Garonne palaeolake fell and the Barbazan deposit was fed by local runoff only (Andrieu et al., 1988). This stage correlated with the sedimentation of carbonate sludge after 19 cal ka BP (Stange et al., 2014). It is possible that the Garonne Glacier was already in the interior of the Aran Valley and far from Barbazan. It was precisely in Vielha (38 km from the terminal complex) that the glacial terminus stabilized, possibly during the OD. It deposited moraines 1.6 km inland from the Pla de Beret in the Noguera Pallaresa Basin (Fernandes et al., 2017). The glacial retreat caused glacial fragmentation, leading to individualized tongues in the high valleys, where their evolution (length, thickness, and number of pulses) was influenced by local factors (aspect, height, and extension of the accumulation area). The following three groups of deposits can be individualized within the deglaciation in the Noguera Pallaresa Basin: (i) The fluvioglacial terraces at 1400 m in the headwaters of Vallferrera and Tavascan (Bru, 1985), with tongues of 11 and 7 km long respectively, indicate the proximity of the glacial front. This phase might have occurred in the OD and would correlate with that identified in the other Pyrenean valleys, namely Caldarés-Panticosa (12-km-long glacier; Palacios et al., 2015) and Ribagorçana (7.6 km; Pallàs et al., 2006). The moraine that plugs the Coma de Burg Lake (1821 m) and is dated at 17 cal ka BP, belongs to this group. (ii) The moraines in the high valleys, at 1500–2000 m from valley glaciers of lengths spanning 5–6 km, were placed at the end of the OD. In parallel, some rock glaciers must have formed during this period (Ventura, 2020). (iii) The frontal moraine complexes built by cirque glaciers and small tongues (1.5–2.5 km in length), located between 2100 and 2500 m in northern aspects and coexisting with debris-covered glaciers and rock glaciers (Ventura, 2017, 2020) are temporarily placed between the YD and the beginning of the Holocene.

(e) Holocene and LIA. A group of single moraines are located at 2540 to 2650 m, very close to the cirque walls (Ventura, 2017, 2020), north of the summits of the highest massifs (>2800 m). These landforms could have formed during the Mid- or Late Holocene, as described by Gellatly et al. (1992) and García Ruiz et al. (2014), in the Central Pyrenees. The last group of deposits, which includes the subrecent moraines of the Pica d'Estats Massif (at 2680 m) and small rock glaciers with fronts at 2550 to 2750 m, are placed in the LIA (Ventura, 2016, 2017).

5. The Unarre glacier complex

The Unarre glacier complex was located in the valley of the same name that drained the southern sector of the Mont-roig Massif, converging with the Noguera Pallaresa palaeoglacier at the Esterri d'Àneu overdeepened basin. Although it is cited by authors who have worked in the area since the 1930s, we have only a brief description of the units that form it (Ventura, 2010a,b). Nussbaum (1934) located "final moraines of the last glacial period" in the vicinity of Cerbi (Unarre). García Sainz (1935) repeated the citation of the laterofrontal moraine of Cerbi (1440 m) and associated it with a front of a local glacier from the Mont-roig Massif. Later, Zandvliet (1960) framed the glacial palaeogeography, which is accepted, detailing the relationship between the main glacier (Noguera Pallaresa) and the tributary glacier (Unarre). The Unarre deposits are located in the center of the valley, occupying its bottom, between 1100 and 1600 m (surface area: 2.8 km^2). The course of the Unarre River and the tributary torrents overlap the deposit over a length of 25−60 m, forming slopes that facilitate the presence of numerous outcrops. The valley hangs 100 m above the Esterri d'Àneu Basin, linking it with a subglacial gorge and the large Escalarre dejection cone (length: 1.2 km) built by eroding the glacial sediments of Unarre. The Unarre glacial complex presents some characteristics that make it unique, such as its great variety of shapes and deposits and their correlations with different glacial phases of advance and retreat within the LGC. The relationship with the main glacier of the Noguera Pallaresa, which entered the valley on the opposite side (4.1 km), either blocking it or connecting it with the local glacier of Unarre, can be appreciated (Fig. 4.2.4). The following eight units have been identified from older to more recent times: (i) **The glacial deposits of Gavàs-Aurós (Mo-1):** These are the oldest glacial deposits. Located at the base of outcrops between 1200 and 1400 m, these deposits are subglacial tills formed by diamicton with a great abundance of bluish clays (>50%), including glacial clasts, among which we find granites (a lithology that is absent in Unarre), indicating sedimentation coming from the Noguera Pallaresa Glacier. Groups of granite boulders in this area reach up to 1420 m in the interior of the valley. (ii) **Upper Cerbi moraine (Mo-2):** These glacial deposits contain an accumulation of blocks and cobbles of an old degraded moraine located above the town of Cerbi, between 1465 and 1590 m. The clasts are of local lithology (shales and quartzite) from the Unarre Glacier. (iii) **Lateral laterofrontal moraines of Cerbi (Mo-3):** Two well-preserved lateral moraines are located at the exit of the upper Unarre Valley, topographically below the Mo-2 moraine. The moraines are located between 1365 and 1515 m, with lengths of 400−500 m and heights of 15−30 m. On the surface is a supraglacial till deposit of the Unarre Glacier. The deposits include clasts of local lithology only, some with samples of glacial striae and facets. (iv) **Blocking deposits (Do-1):** The Cerbi moraines (Mo-2 and Mo-3) blocked the lateral ravine of Corriols in several phases and generated extensive juxtaglacial deposits. The surface of the valley floor is flat for 1.25 km. (v) **Proglacial plain of Cerbi (FlGl-2):** The drainage of the Unarre Glacier retreating toward its headwaters led to the development of a proglacial plain formed by fluvioglacial and till deposits between the moraines (Mo-3). Its roof lies at an altitude of 1405 m in relation to the base owing to the proximity of the main glacier blocking the lower part of the valley. (vi) **Aurós proglacial cones (FlGl-1 and FlGl-3):** In the center of the valley lies a deposit of sediments (25 m of observable thickness) formed by pebbles, gravels, and sands of fluvioglacial origin due to erosive contact with subglacial till Mo-1, differentiating two units. The lower unit (FlGl-1) presents "channel" structures with levels of sands, fines, and ferruginous crusts marking their basal limit. The upper unit (FlGl-3) also exhibits channel

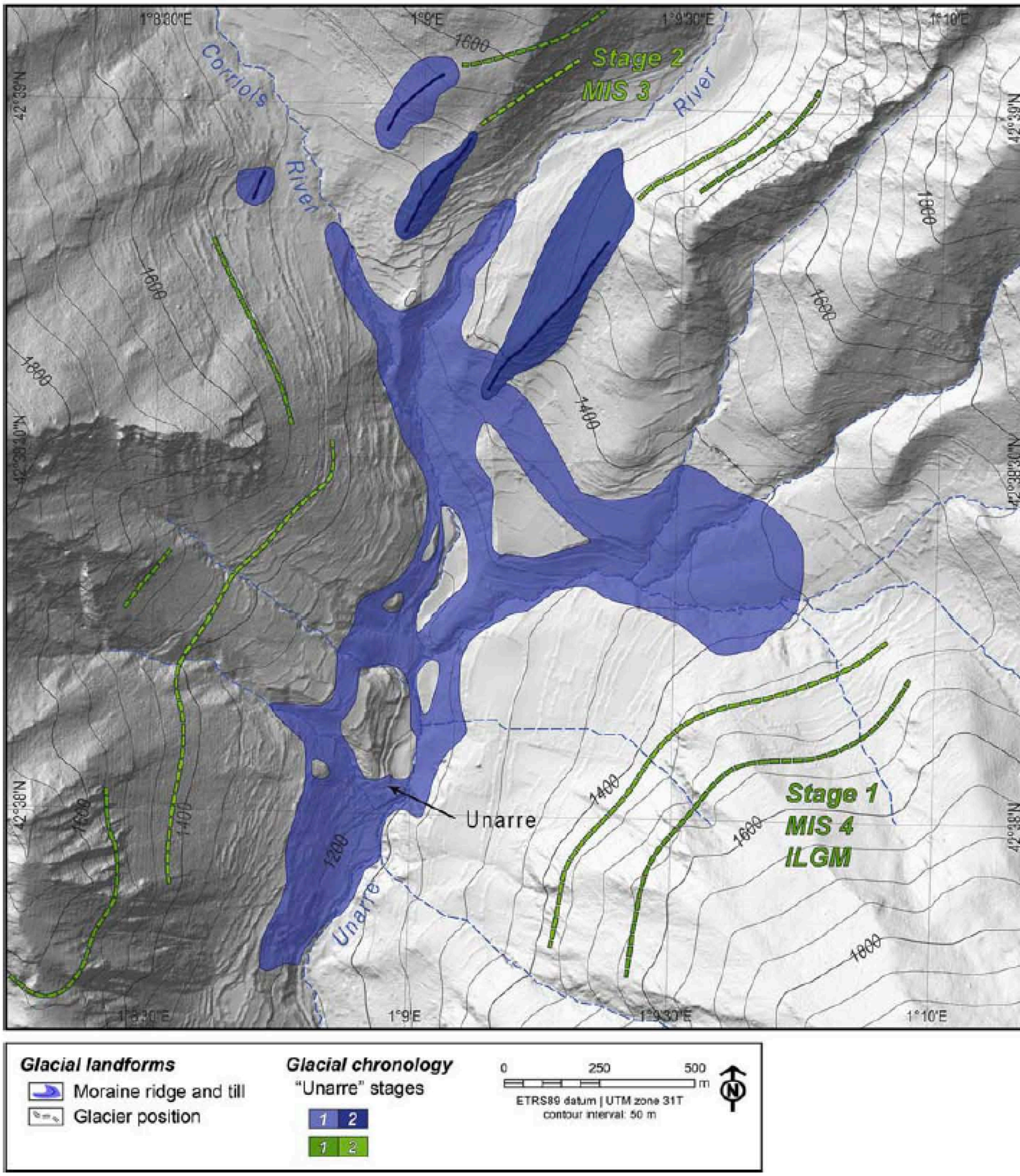

Figure 4.2.4

Geomorphological sketch of the Unarre glacier complex (Noguera Pallaresa Glacier): deposits and glacial stages.

structures, but of smaller dimensions, along with deformation structures (convoluted lamination and kettle-type collapses). The lithologies of the two units are local without the presence of granites (which appear in the underlying till), and therefore, they are related to the proglacial environment of the local glacier of Unarre. In the most distant sector of the deposit (roof at 1310 m), the current topography coincides with the topography of the old proglacial dejection cone that builds the upper unit. (vii) **Fluvioglacial terraces (FlGl-4 and FlGl-5):** On the right-hand side of the valley, between Unarre and Aurós, are several fluvioglacial terrace remains (individualized by scarps) deposited on the subglacial tills (Mo-1). The deposit is formed by fluvioglacial sediments with channel structures (Fig. 4.2.2E). The terrace level is 1275 m (+60 m), 35 m below the level of the Aurós proglacial cone. The last fluvioglacial deposit (FlGl-5) with interspersed slope deposits can be found 1.4 km to the south of the town of Unarre, between 1100 and 1125 m (+45 m). (viii) **Periglacial slope deposits (Peri-3):** On the right-hand side of the valley, debris has been fossilized into glacial deposits. The roof is located at 1300 m (the same level as the Aurós proglacial cone). These are massive and compact periglacial breccias (10 m deep) that include glacial clasts of slate, quartzite, and granite. The upper level presents a strong compaction with ferruginous crusts on the surface, modeling the erosion *dames coiffées* in its upper part.

Chronologically, in the absence of absolute data, the Unarre deposits are linked to the following glacial phases (see Sections 4 and 6): (i) the subglacial till (Mo-1), the upper Cerbi moraine (Mo-2), and the sealing deposits (Do-1) with the lLGM or F1; (ii) the lower fluvioglacial deposit of Aurós (FlGl-1) with the strong glacial retreat after F1; (iii) the laterofrontal moraines of Cerbi (Mo-3) and the proglacial plain of Cerbi (FlGl-2) with the new advance of F2; and (iv) the upper fluvioglacial deposit (FlGl-3) or proglacial cone of Aurós, the fluvioglacial terraces (FlGl-4 and 5), and the periglacial debris (Peri-3) with several episodes of advance and retreat within F3. Numerous deposits and moraines are located at an altitude of 1300 m on the slopes above the basin of Esterri d'Àneu (F3).

6. The significance of the glacial landforms of the Central-Eastern Pyrenees in the context of the climatic evolution of the Iberian Peninsula

The upper Noguera Pallaresa glacial basin is located in the Central-Eastern Pyrenees on the border with the Eastern Pyrenees, making it an excellent area to study the differential behavior of the lLGM and the gLGM. To this end, we refer to the glaciers of the westernmost Central Pyrenees (characterized by a larger lLGM and prior to the gLGM with a smaller spatial footprint) and those of the Eastern Pyrenees (marked by the spatial proximity between the frontal glacial complexes of the lLGM and the gLGM). The one in the lLGM (F1) formed earlier and was more extensive; it was 63 km long and 600 m thick in Esterri d'Àneu and 365 m thick in Llavorsí. It served as the confluence of the Noguera Pallaresa and Cardós-Vallferrera glaciers. During MIS 4, the Valira (Andorra) Glacier reached its maximum glacial extent (Turu et al., 2011c), as did the Garonne Glacier (Stange et al., 2014) and, therefore, the Noguera Pallaresa one. An incipient deglaciation after the lLGM ended in a significant glacial retreat in MIS 3, perhaps less than during the gLGM. During MIS 3, it possibly kept drawing the same pattern at the eastern end of the Central Pyrenees in the Noguera Pallaresa and the Garonne glaciers, as well as at the northwestern end of Andorra, where the La Massana palaeolake is located (Fig. 4.2.5). The last great glacial phase (F3) occurred in the beginning of MIS 2, with the glacial front only c. 10 km from its previous position. It was 52 km long and 350 m thick in Esterri d'Àneu and 185 m thick in Llavorsí. The Noguera Pallaresa Glacier blocked the proglacial drainage of the Cardós-Vallferrera glaciers with its fronts, which were located further inland. The gLGM is characterized here by a fragmentation of the Noguera Pallaresa Glacier into multiple glacial tongues, following the pattern of the glacial system located further west. This aspect underscores its differences from the Valira Glacier and in general those from the Eastern Pyrenees.

The characteristics of the glaciers of the Noguera Pallaresa and the westernmost Central Pyrenees (González-Sampériz et al., 2006; Peña et al., 2011; García Ruiz et al., 2013; Guerrero et al., 2018) in the neighboring Valira Valley to the east showed some similarities and differences. This valley functions as a connection between the Eastern and Central Pyrenees. During deglaciation, the west-east gradient observed in Andorra (Turu et al., 2018) progressed dramatically toward the Noguera Pallaresa Valley, increasing the fragmentation of the glacial tongues. The palaeoclimatic hypothesis is that the Noguera Pallaresa area was under the influence of three climatic domains: (i) the continental influence of the Ebro Valley, which reduced the extent of the glaciers of the Western Pyrenees during this period; (ii) the Atlantic influence, via the connection with the Garonne Glacier and the climatic influence in part of the headwaters of the Noguera Pallaresa; and (iii) the Mediterranean influence (providing humidity), which, as in Andorra (Turu et al., 2017), allowed glacial recovery in MIS 2 after the general retreat in MIS 3. Below is a summary of the glacial phases that were distinguished using the Tírvia glaciolacustrine complex as the "Rosetta stone" and the Garonne and the Valira as the chronological correlations:

(1) Maximum glacial extension phase (F1) during MIS 4.
(2) Glacial retreat and readvance phase (F2) during the first half of MIS 3.
(3) Widespread glacial retreat phase in the second half of MIS 3.
(4) Last major glacial expansion phase (F3) during MIS 2.
(5) Glacial fluctuations during deglaciation: the LGM and Termination 1.
(6) The Holocene, including LIA.

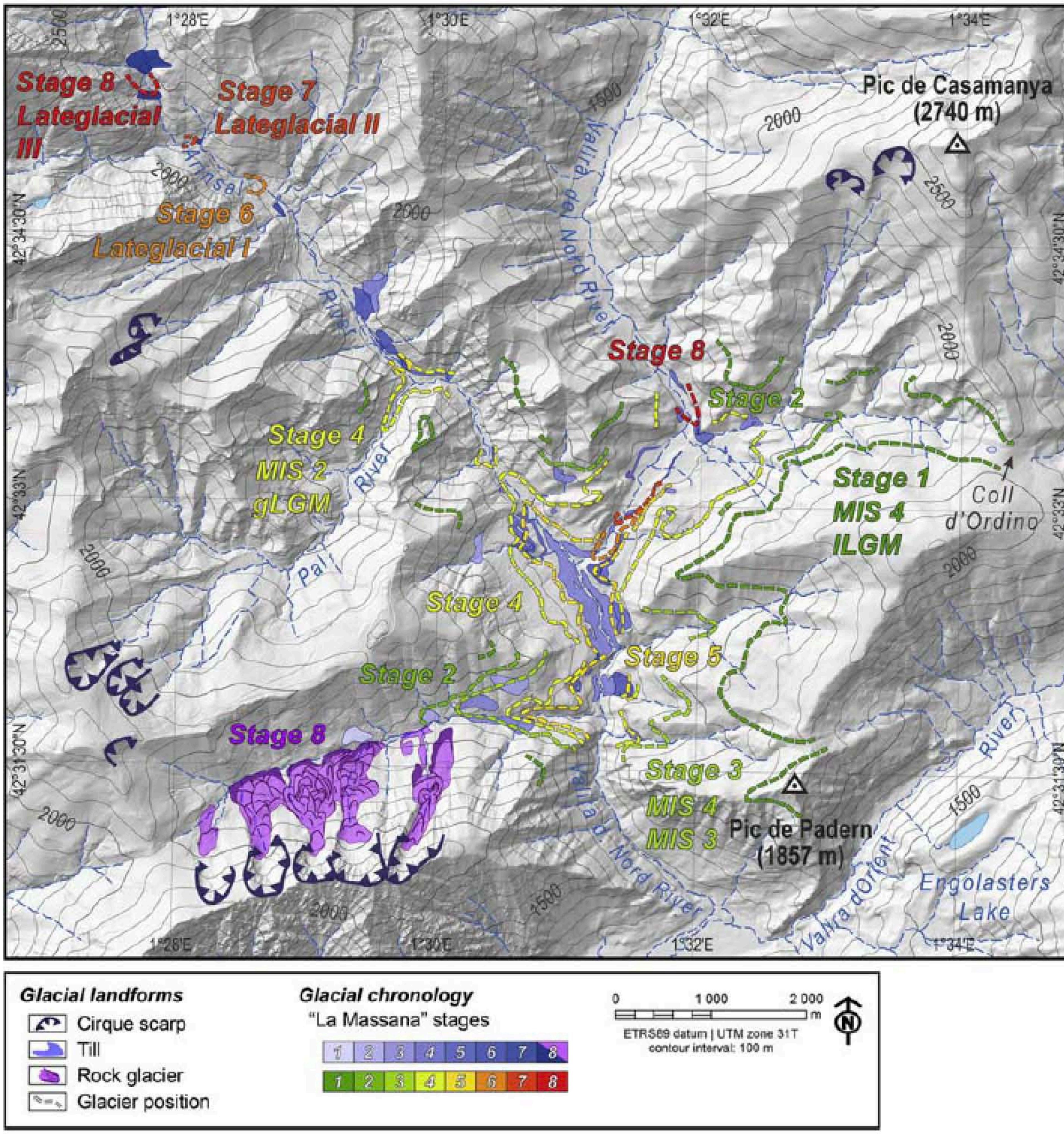

Figure 4.2.5
Geomorphological sketch of the La Massana glacier complex (Valira del Nord Glacier): deposits and glacial stages.

In the different glacial phases described in the Noguera Pallaresa Valley, glacial advances were accompanied by a progressive decrease in the scope of the glacial fronts from F1 to F3. This aspect was also observed in Andorra (Turu and Boulton, 2021) for the same period.

Currently, apart from the need to strengthen the glacial chronology of the upper Noguera Pallaresa by means of absolute datings, the following territories and themes deserve further study: (i) the terminal complex of Sort-Rialp; (ii) the palaeoglaciers in the Flamisell Valley and the western valleys (Manyanet); (iii) the palaeoglaciers in the southern massifs; (iv) the glacial phases during deglaciation and the relationships between glaciers, debris-covered glaciers, and rock glaciers; and (v) the identification of the Holocene glacial phases.

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