The Geology and Geomorphology of the Eastern Pyrenees

Field Trip Guidebook

Editors

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Preface

This field trip is organised as a post-conference event following the successful completion of the Mediterranean Geoscience Union (MedGU-24) meeting in Barcelona.

Established in 2020 by Dr. Nabil Khelifi and led by Dr. Attila Çiner, MedGU aims to create a unique federation for the Mediterranean geoscience community, emphasising Earth, planetary, and space sciences. We strive to create a significant organisation for the Mediterranean region that surpasses the impact of any local geoscience society. Through this organisation, we aim to advance fundamental geoscience and applied research that addresses pressing societal and environmental issues.

Field trips provide excellent opportunities to learn from each other and enjoy the pleasures of being outdoors in nature. During our three-day journey, we will explore Spain, France, and Andorra, admiring the stunning landscapes and geological features of the Pyrenees. We sincerely thank all the field trip guides for showcasing their work in their countries and sharing their enthusiasm.

Enjoy science and the outdoors.

Attila Çiner & Marc Oliva

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A Brief Introduction to the Geology of the Pyrenees and the Ebro Basin

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Geological Setting

This excursion will provide an overview of selected outcrops from the eastern Pyrenees and northwestern Ebro Basin (Fig. 1). During the three-day trip to three different countries, igneous, metamorphic, and sedimentary rocks will be inspected. The geodiversity will also cover different ages (from Paleozoic to Quaternary) and will be approached through various disciplines, including volcanology, stratigraphy, structural geology, geomorphology, and palaeoclimatology.

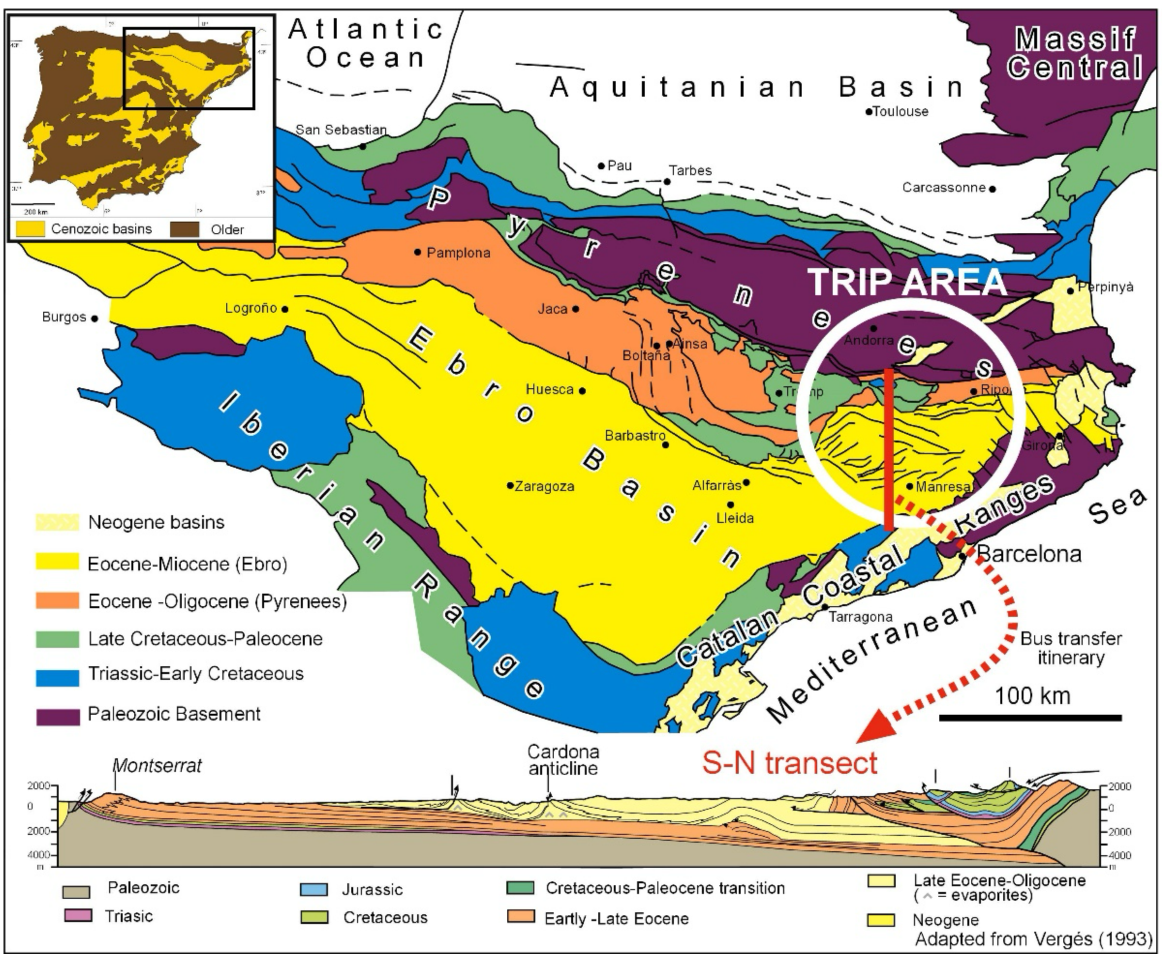

Fig. 1: Trip area in the context of Nortwestern Iberia. The map and transect are adapted from Vergés (1993).

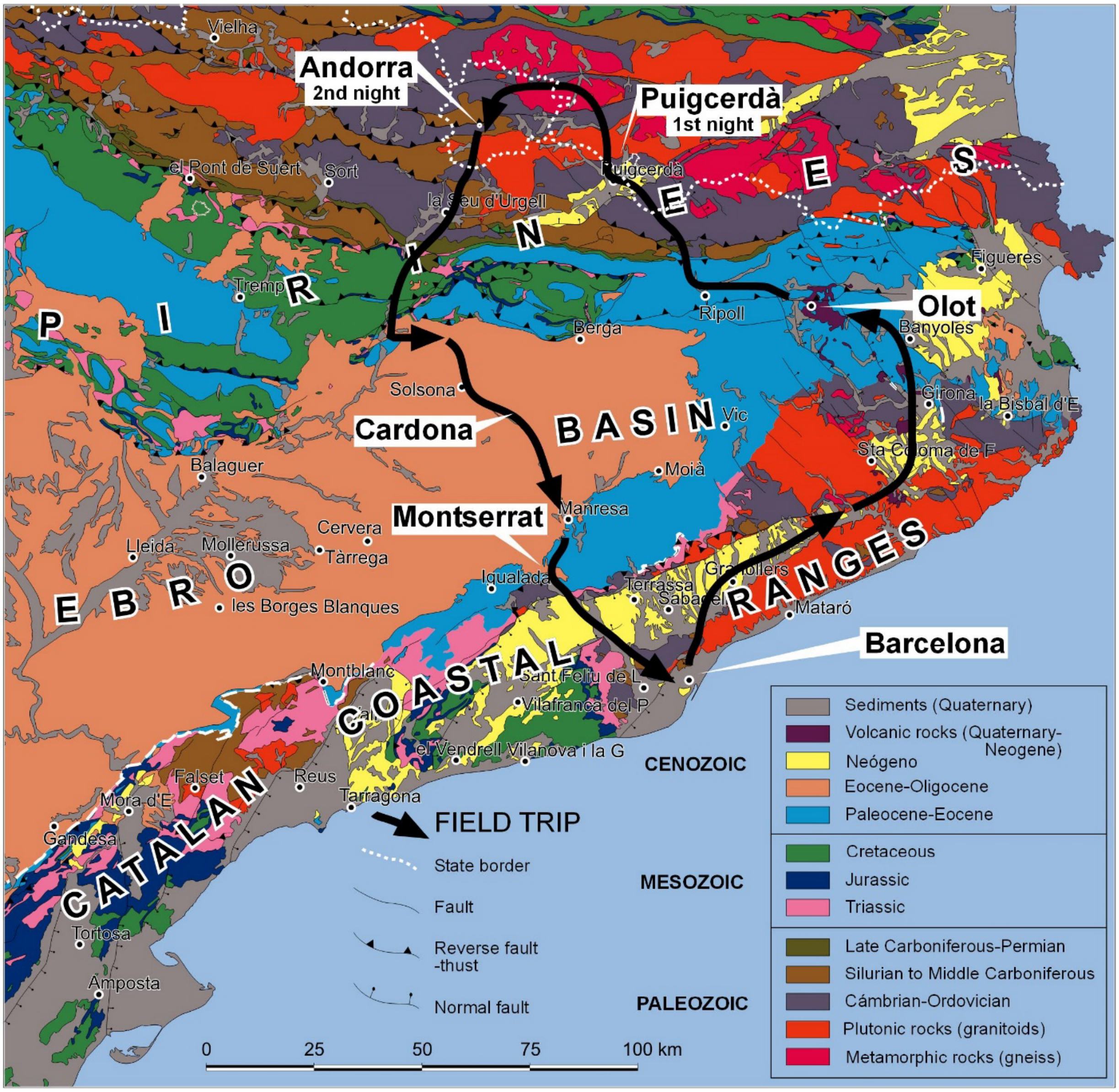

Fig. 2: Geological map of Catalonia, Andorra, and bordering areas with the location of the trip itinerary. Map modified from ICGC by Enric Vicens.

The Mediterranean is a complex plate boundary between the African and European plates. Several microplates, including the Iberian plate, exist in this region. Its complex evolution has led to the Pyrenean orogen, which formed after the collision between the Iberian and European plates (see Fig. 2) in the Late Cretaceous (Muñoz, 1992; Ford et al., 2022).

The Pyrenean structure is a double-verging orogenic wedge featuring an east-west elongated basement of crystalline Paleozoic rocks (Axial Zone). Two cover units extend on both sides: the South Pyrenean and North Pyrenean zones (Fig. 3). At the distal part of the orogen, these zones are bounded by the South Pyrenees Frontal Thrust and the North Pyrenees Frontal Thrust, respectively. This double-verging structure is also bounded by another major structural element of the Pyrenees: the North Pyrenees Fault Zone.

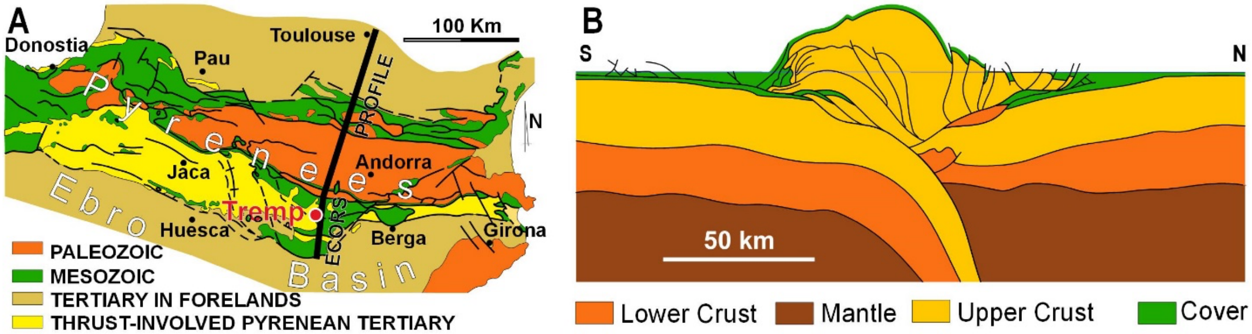

Fig. 3: Sketch of the geological map of the Pyrenees (A) and location of the Ecors deep profile (shown in B). After Muñoz (1992).

The tectonic evolution during the formation of the Pyrenees led to the development of foreland basins, the final stage of which is the Ebro Basin. This basin is bounded by two other alpine fold and thrust belts: the Iberian Chain to the east and the Catalan Coastal Ranges to the west. A Neogene extensional phase occurred after compressive forces built up all three orogens. This extension was linked to the development of monogenetic volcanism and the structuring of the present-day coastline of the Iberian Levant. All this structuring and the associated sedimentation resulted in a paleogeographic evolution observed in Figs. 4 and 5.

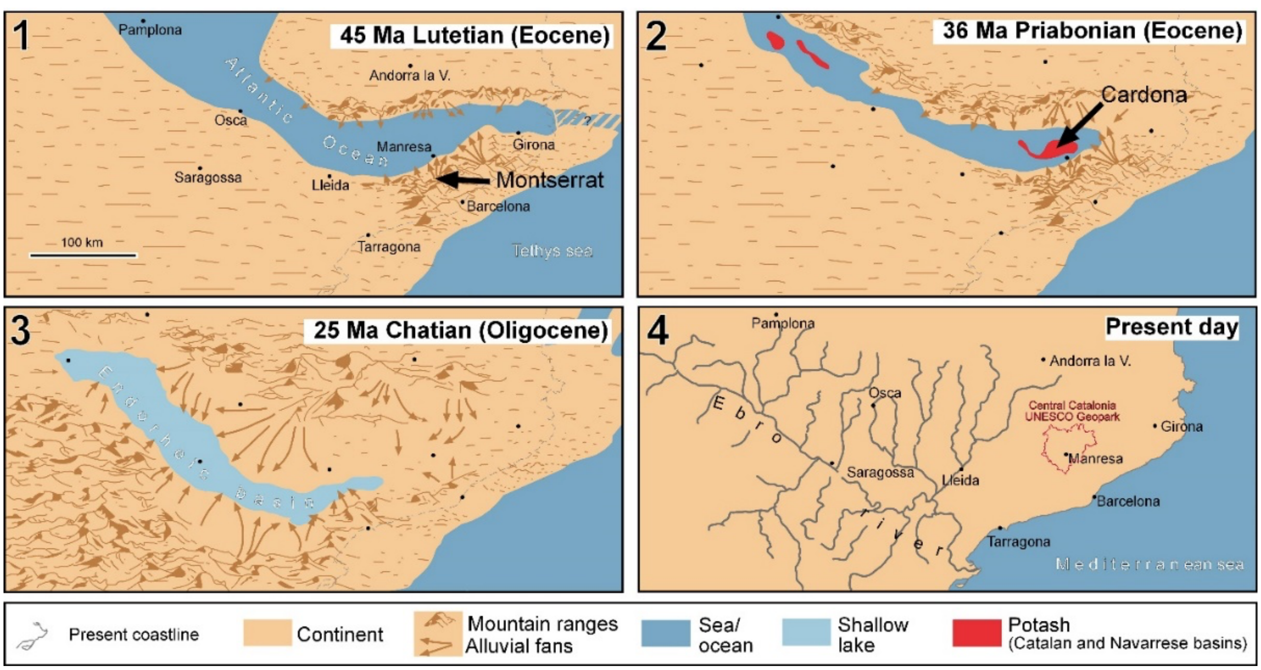

Fig. 4: Ebro Basin (Adapted from Oms et al., 2016) with an indication of Montserrat and Cardona.

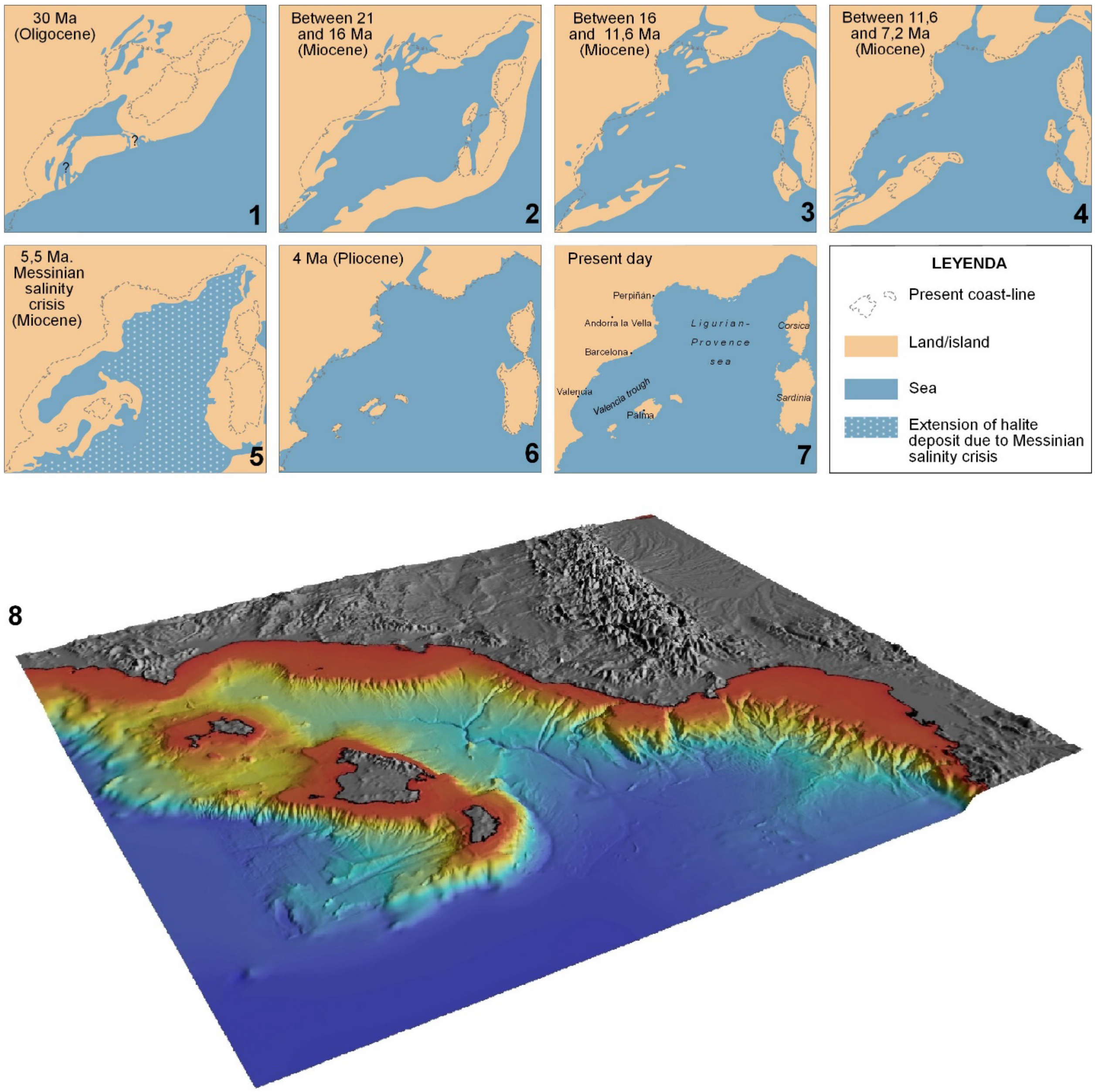

Fig. 5: Top: paleogeographic evolution of the Valencia trough (Oms et al., 2013, based on several sources). Bottom: the Valencia trough at the present day (courtesy of GRC Geociències Marines from Universitat de Barcelona). The littoral margin of this trough is passive and results from Neogene extension. The Balearic promontory margin of the trough was originally extensional (from Late Oligocene to Earliest Miocene) but underwent compression due to the Betic chain getting attached to Iberia.

The sedimentary infill of the Ebro Basin and related Pyrenean units is mainly characterised by terrestrial environments evolving into marine ones (connected to the Atlantic) from 56 to 36 Ma. From 35 Ma onwards (until the Miocene in other parts of the basin), sedimentation was entirely terrestrial (endorheic). About 3 Ma ago (Regard et al., 2021), the Ebro Basin underwent erosion, forming present-day geomorphology (Fig. 7).

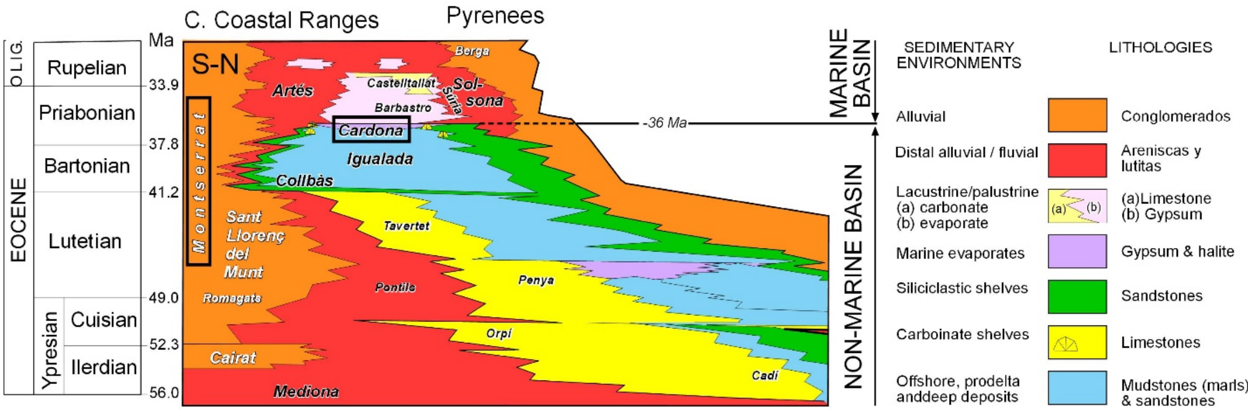

Fig. 6: Stratigraphic units of the infill of Northwestern Ebro Basin and related Pyrenean units (adapted from Cabrera et al., 2011, after several authors). See stratigraphic interval for Montserrat conglomerates (Lutetian to Priabonian) and Cardona evaporites (aged 36 Ma, within Priabonian).

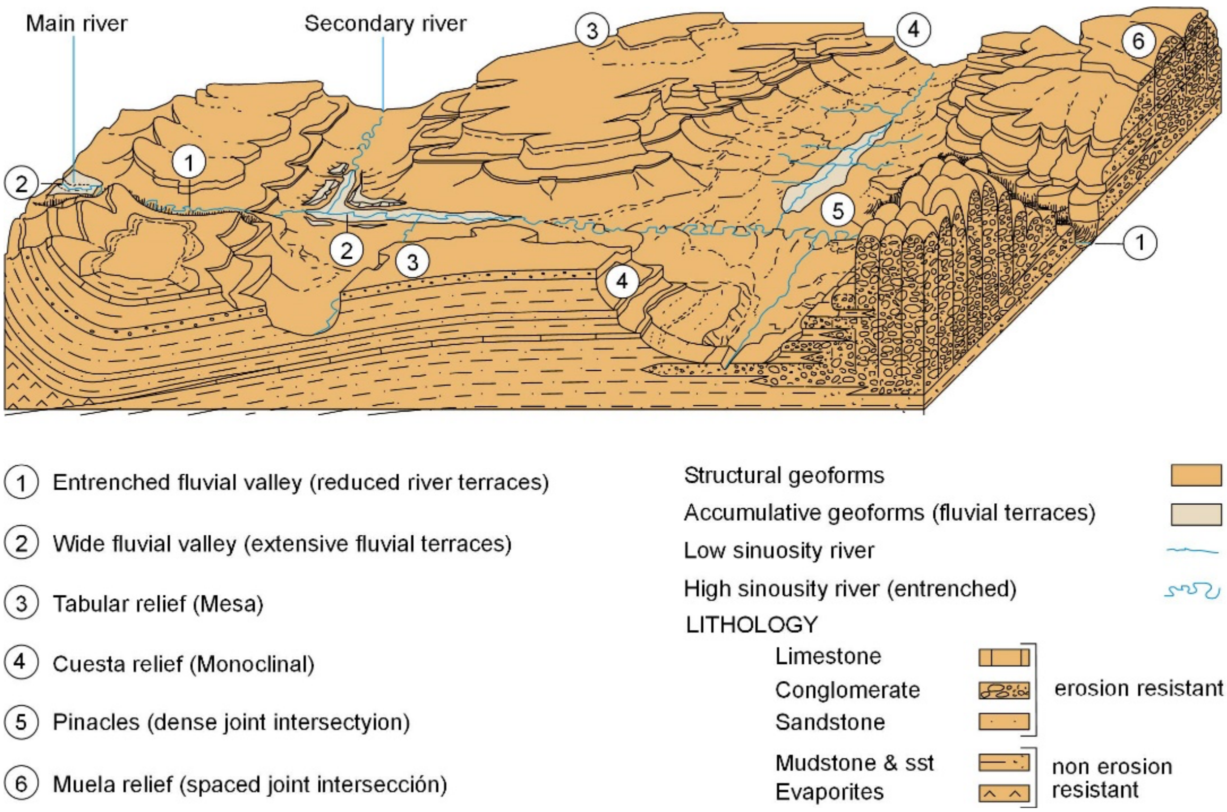

Fig. 7: Simplified forms of Central Catalonia (Oms et al., 2016).

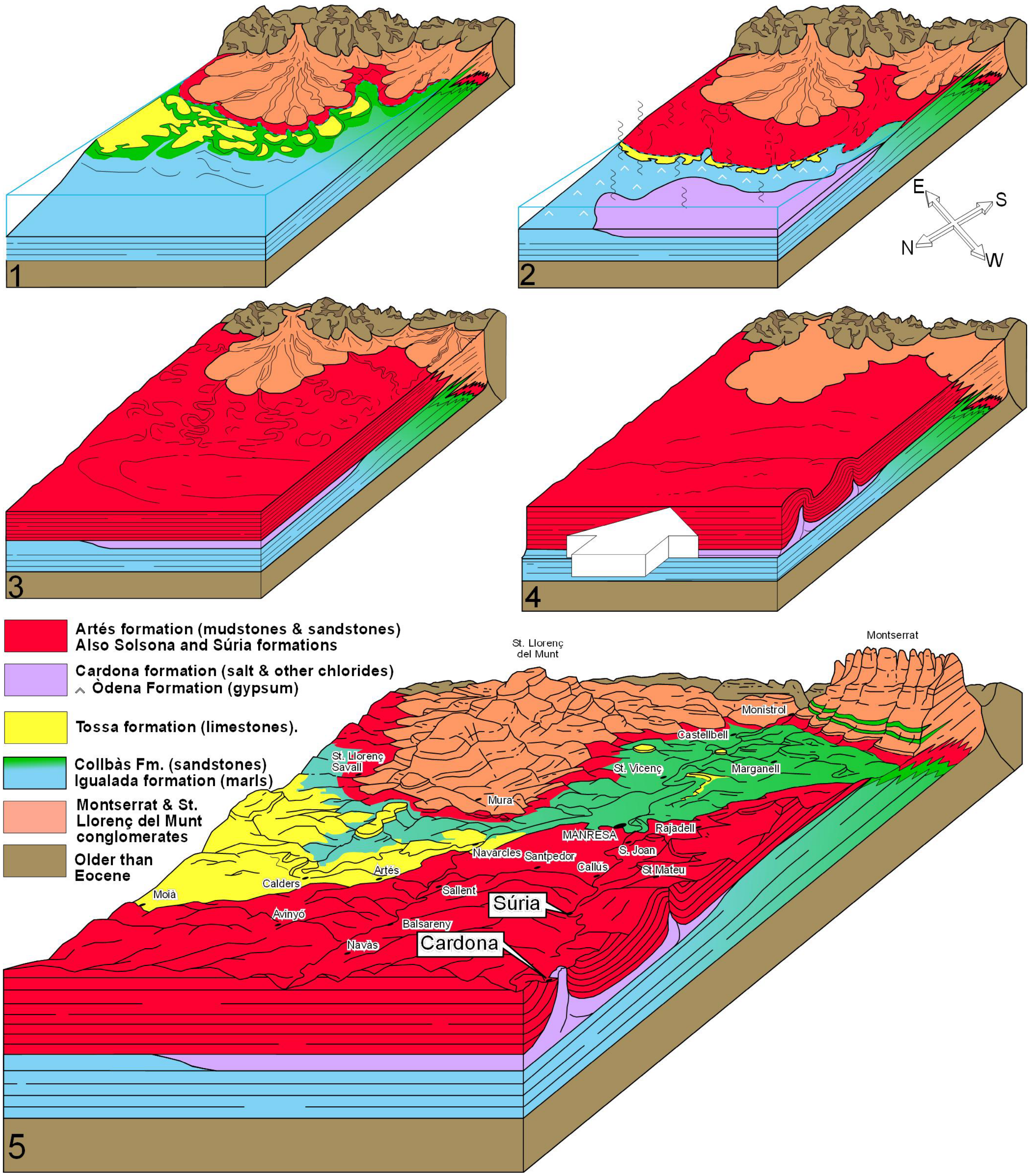

Fig. 8: Schematic geological history of Central Catalonia. 1: Fan delta development during Middle-Late Eocene. 2: At 36 Ma, restriction of the marine basin and precipitation of evaporites (including Cardona salt). 3: Continentalization of the Ebro Basin and development of alluvial fans. 4: Deformation due to salt tectonics. 5: Erosion and formation of present-day landscape during the last 3 Ma (Adapted from Oms et al., 2016).

Stop 1 at Cardona: Muntanya de sal and Bòfia gran

We will visit the salt extrusion at Cardona and Muntanya de Sal (Salt Mountain) (Fig. 9). At Muntanya de Sal, we will enter a tourist mine to observe banded chlorides deformed due to ductile behaviour. At Bòfia gran ('the large sinkhole'), we will observe the general geomorphology of the extrusion.

Fig. 9: Images from the Muntanya de sal (A, D) and Bòfia gran (B, C). Cardona salt is mainly banded halite (although silvinite and carnalite are also present) with a distinctive ductile deformation (C). Surface outcrops are always affected by dissolution marks—images from Oms et al. (2016).

Stop 2: Montserrat Massif

Montserrat Massif will be observed from a distance and within (the monastery area). This massif is distinctive for its conglomerate pinnacles, resulting from a very penetrative high-density joint system developed throughout a very homogeneous conglomerate (Figs. 10, 11). Montserrat contains the world's most significant conglomerate pinnacles within a massif.

Fig. 10: Images from the Montserrat Massif (arterial Picture in A, courtesy of X. Bolós).

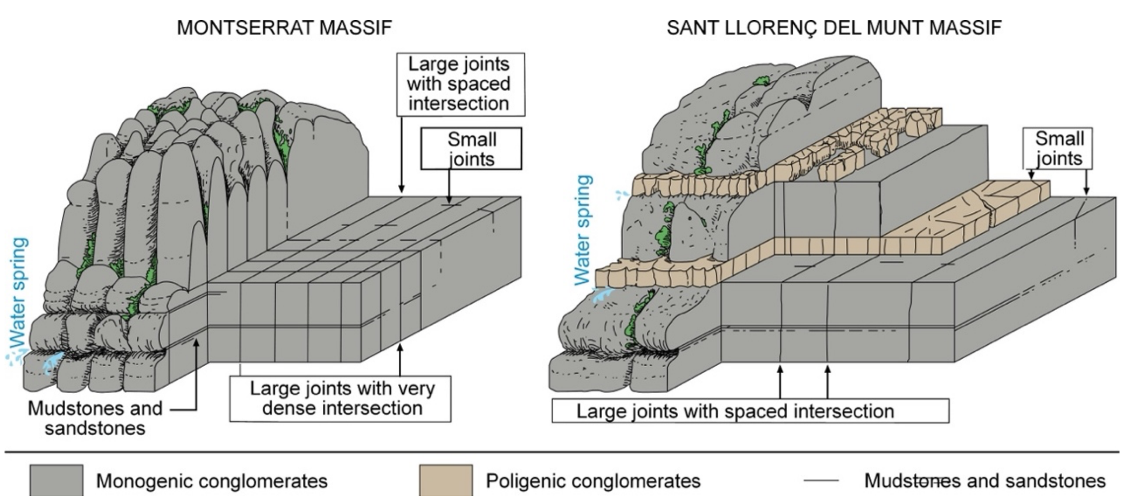

Fig. 11: Joints pattern and relief formation of Montserrat and Sant Llorenç de Munt conglomerate massifs. (Oms et al., 2016).

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The Garrotxa Volcanoes: Quaternary Monogenetic Volcanism and its Landforms

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Introduction

The volcanic landscape of La Garrotxa represents a distinctive scenic locale within Catalonia, characterised by an elevated topography sculpted by the Fluvià and Ter rivers. This region exhibits a suite of remarkable geomorphological features shaped by distributed volcanic activity of the Quaternary age. This volcanic field exemplifies the demographic expansion over a monogenetic volcanic field, with the last known eruption occurring approximately 10 ka ago (Bolós et al., 2014a).

The first stop will be a visit to the Montsacopa Volcano. This scoria cone, located in the old town of Olot, is one of five volcanoes within the city. It exhibits a variety of eruptive styles, with compelling evidence of vent migration influenced by tectonic features. We will visit the volcanic museum in the town of Olot (Espai Crater), a geoscience museum housed within a fully urbanised scoria cone near the first stop. Then, we will travel by bus to the final stop of the field trip: a stunning view of the Castellfollit de la Roca basalt cliff. This magnificent outcrop consists of two superimposed lava flows with well-developed columnar jointing. Additionally, the aesthetic and visual impact of the Medieval village of Castellfollit de la Roca, perched atop the volcanic outcrop, is noteworthy (Fig. 1).

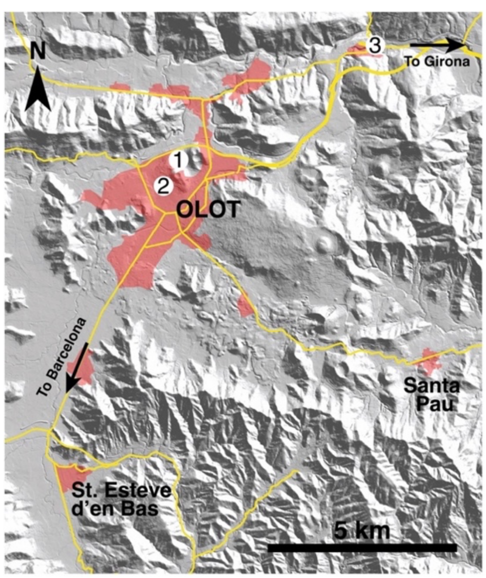

Fig. 1: Stop locations: 1. Espai Cràter Museum, 2. Montsacopa Volcano, 3. Castellfollit de la Roca Cliff.

Geological Setting

The Catalan Volcanic Zone (CVZ), encompassing the La Garrotxa Volcanic Field, is situated in the northeastern corner of the Iberian Peninsula. It is bordered by the eastern Pyrenees to the north, the Ebro Basin to the west, and the Catalan Coastal Ranges to the south. The CVZ is an intraplate alkaline volcanic zone associated with the opening of the Western Mediterranean and the development of the European Rift System. Volcanic activity in the CVZ began in the L'Empordà area (ca. >12–8 Ma), extended to La Selva (7.9–1.7 Ma), and finally migrated to the Garrotxa Volcanic Field (<0.7–0.01 Ma) (Miranda-Muruzábal et al., 2024). The geological evolution of the CVZ is complex, involving the formation of a Paleozoic basement heavily deformed by the Hercynian orogeny, the deposition of a thick sequence of Mesozoic and Tertiary sediments, folding and faulting during the Alpine orogeny, and finally, the Neogene-Quaternary extensional phase that has influenced recent sedimentation and volcanism (Martí et al., 1992). Consequently, the lithostratigraphic units exposed in the La Garrotxa Volcanic Field, which constitute the substrate of the volcanic edifices, include materials from the upper Paleozoic, Eocene, and Quaternary periods (Fig. 2). Due to Alpine folding, Neogene normal faulting, and subsequent erosion, the basement composition beneath each volcano varies (Martí et al., 2011; Bolós et al., 2015).

La Garrotxa Volcanic Field contains the youngest and most well-preserved volcanic edifices in the Catalan Volcanic Zone (CVZ). Over 50 volcanic structures are identifiable, primarily concentrated in the northern sector, which includes the Natural Park of La Garrotxa Volcanic Zone, to be visited during the field trip (Fig. 2) (Bolós et al., 2014a). The southern sector holds fewer but larger cones. The substrate underlying these monogenetic volcanoes differs between the two sectors: in the north, the volcanic rocks overlie Tertiary sediments, whereas in the south, they sometimes rest directly on the Paleozoic granites and schists. Volcanism in the GVF is characterised by small cinder cones formed during brief monogenetic eruptions along widely dispersed fractures of limited lateral extent (Martí et al., 2011; Bolós et al., 2015). Each eruption extruded a relatively small volume of magma (0.01–0.2 km^3 DRE), indicating a limited magma supply (Bolós et al., 2014a). These eruptions typically involved alternating Strombolian and phreatomagmatic episodes, resulting in complex stratigraphic sequences composed of diverse pyroclastic deposits (Martí et al., 2011; Planagumà et al., 2023).

The distributed volcanoes of this field were formed during a single eruptive episode, categorising them as 'monogenetic,' characterised by multiple distinct phases without significant temporal separations (Martí et al., 2011). These volcanoes can be classified into two groups based on their eruptive history: those constructed solely through Strombolian activity and those that also underwent phreatomagmatic phases. In the first group, the volcanic structures typically exhibit symmetrical or horseshoe-shaped cinder cones formed by the accumulation of scoria and lapilli, occasionally interspersed with lava flows. Conversely, volcanic cones affected by phreatomagmatic activity display more complex morphologies while retaining Strombolian characteristics. These cones experienced eruptions characterised by alternating phases, such as phreatic explosions emitting lithic clasts from the substrate and phreatomagmatic phases generating diverse pyroclastic density currents and fall deposits. They also exhibited Strombolian phases marked by explosive eruptions and effusive lava flows. The variability in deposit sequences observed among these volcanoes reflects distinct eruptive behaviours, likely influenced by differences in local substrate and hydrogeological conditions, identifiable through their componentry (Fig. 2).

In summary, the volcanoes of the La Garrotxa Volcanic Field provide an excellent opportunity to illustrate the complexity of distributed volcanic fields, even within a relatively small area, when erupting magmas interact with groundwater. This complexity is particularly relevant when aquifers with varying hydraulic characteristics are present, and the substrate structure is influenced by local tectonics and stratigraphic differences. The diverse eruption sequences observed in La Garrotxa's volcanoes indicate that the controlling variables depend on local geology and the magma discharge rate (Planagumà et al., 2023).

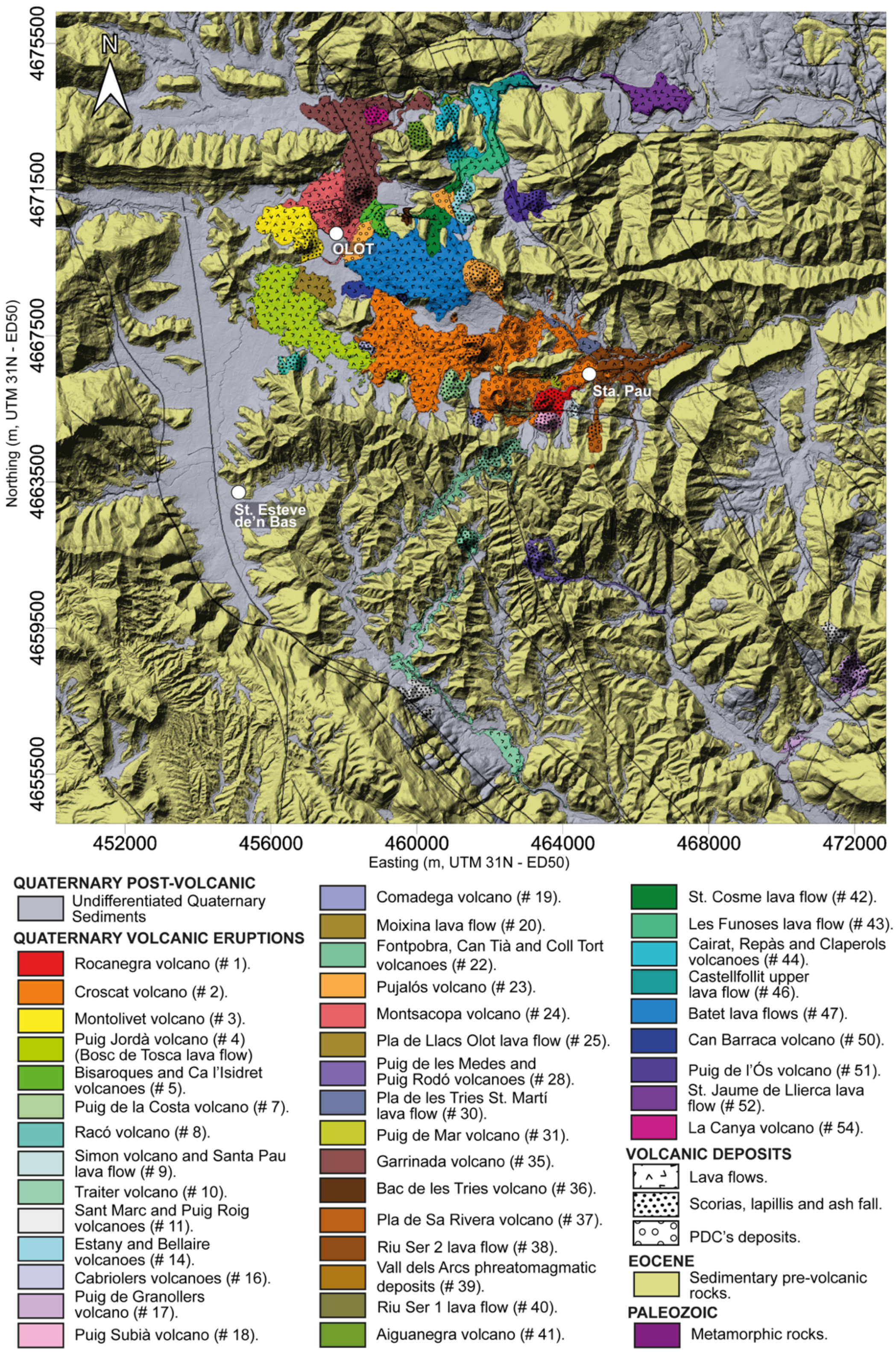

Fig. 2: Volcano-stratigraphic map of the northern sector of the Garrotxa volcanic field (Bolós et al., 2014a).

Stop 1: Montsacopa summit crater and outcrops

Montsacopa is one of five volcanoes in Olot. It is located in the city's heart, between the volcanoes of La Garrinada to the northeast and Montolivet to the southwest. At its summit, the chapel of Sant Francesc, constructed in the 19th century, and two historical watchtowers stand.

During this field trip stop, we will ascend to the phreatomagmatic crater at the summit of the volcano (Fig. 3) (Barde-Cabusson et al., 2014; Bolós et al., 2014b). Once there, we will be introduced to the regional geology of the area from the awesome overview of the summit. Following this, we will visit the base of the cone, where a significant outcrop from an old quarry is located adjacent to the cemetery of Olot.

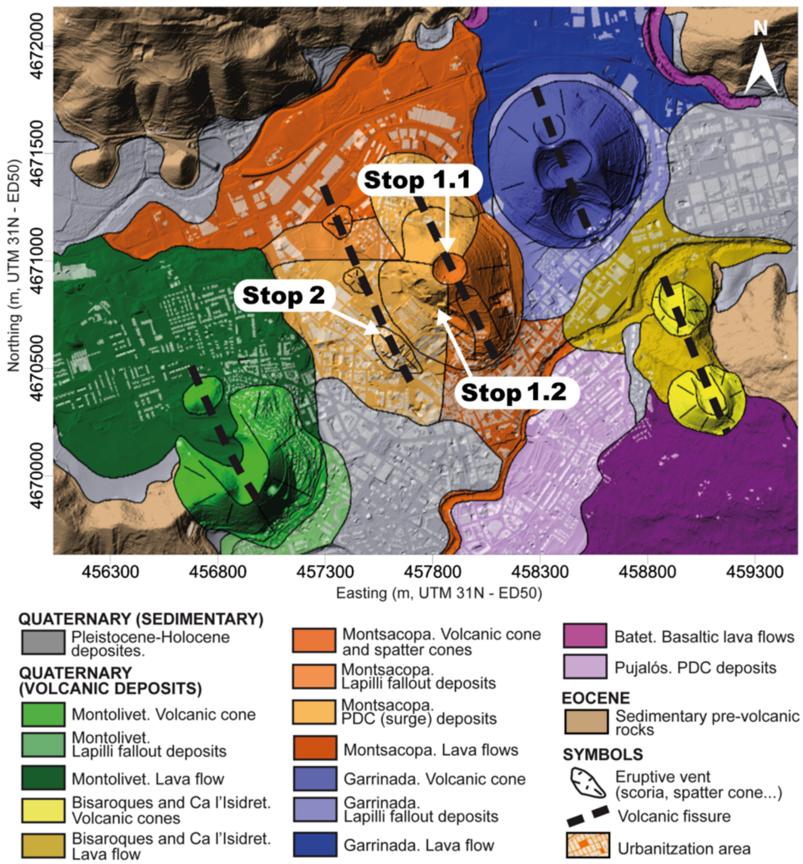

Fig. 3. Geological map of the city of Olot and the location of the sub-stops.

At Stop 1-1, we will walk around the crater rim, enjoying excellent views of La Garrinada, Montolivet, and Bisaroques—three other Olot volcanoes. To the northeast, the three craters of La Garrinada are visible: at the base of this volcano, the first crater, part of a tuff ring formed during a phreatomagmatic phase, can be seen. This crater is almost entirely covered by the cinder cone created during subsequent Strombolian phases, which also produced two additional craters at the summit—one on the southern side and another on the northern side. Montolivet, located to the southwest of Olot, is a cinder cone embedded in the slopes of La Pinya Mountain (pre-volcanic relieves), with its crater opening to the northeast. Bisaroques, situated to the southeast on the northern slopes of the Batet Plateau, features a horseshoe-shaped crater similar to the Montolivet Volcano.

Montsacopa Volcano consists of a single, regularly shaped cinder cone (Fig. 4). The cone was formed through an initial fissure eruption with effusive and Strombolian phases, followed by a final phreatomagmatic activity. The deposits from these phases are well exposed in the quarry behind the cemetery (Stop 1-2) (Figs. 4 and 5) (Martí et al., 2011; Bolós et al., 2014b).

Fig. 4. Picture of Montsacopa Volcano. Credit: Pep Callís.

The stratigraphic succession of deposits in this outcrop consists of a lower, 20-m-thick dark unit formed by well-stratified scoria with alternating layers of varying grain sizes, including some centimetre-sized bombs, identified as Strombolian fall deposits. This unit is topped by a 15-m-thick upper unit characterised by gray-to-brown cemented ashes forming stratified pyroclastic layers identified as diluted pyroclastic density currents (PDCs) and some syn-eruptive reworked deposits (Fig. 5)

Fig. 5. Montsacopa outcrop showing the volcanic deposits and their stratigraphic relationships. Top: conformable contact between Strombolian (lapilli scoria) and phreatomagmatic (PDC) deposits from the main cone-building phase of the Montsacopa eruption. (Modified from Bolós et al., 2014b).

Bolós et al. (2014a, 2014b) identified through direct and indirect methods that the construction of this scoria cone resulted from a multi-vent fissure eruption. In total, up to five different vents at Montsacopa were identified: a central cone and crater, which was the only previously known feature; two additional vents whose products are covered mainly by those from the main crater; and scoria and spatter deposits from two further vents (Fig. 6). This multi-vent eruption included effusive, Strombolian, and phreatomagmatic phases that generated a diverse range of deposits, including fallout, ballistic bombs, PDCs, and lava flows.

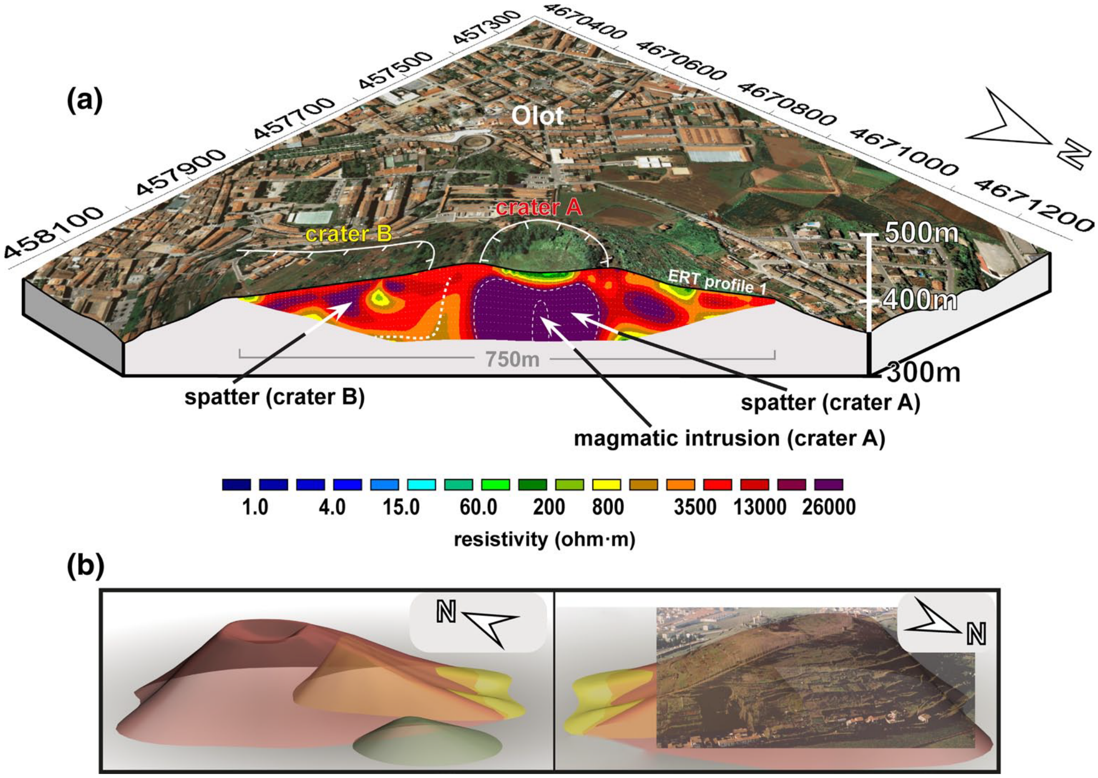

Fig. 6. Orthophotograph overlaid on a 3D block diagram of ERT profile 1 corresponding to Montsacopa Volcano (RMS error 5.7%). (b) 3D interpretation model showing the overlapping cones inside the edifice. Coordinates in UTM—31 N—ED50. (Bolós et al., 2014b).

<u>Stop 2: The new Espai Crater volcanic museum of the city of Olot inside a scoria cone</u>

This innovative centre offers a fully interactive experience with audiovisual displays, immersive environments, virtual reality, gaming, and video mapping (Fig. 7). Espai Crater allows visitors to learn about worldwide volcanoes, geoheritage, and the geological history of the Garrotxa volcanic field from inside a real scoria cone, providing a unique experience designed for all ages. https://espaicrater.com/en/

Espai Cràter's strategy focuses on raising awareness of the values associated with earth sciences, promoting knowledge about both local and global volcanism, and fostering a balance between preserving natural heritage and economic development. Espai Cràter has become a benchmark in Spain in education, tourism, and scientific collaboration. The centre has a collaboration agreement with GEO3BCN-CSIC, the Autonomous University of Barcelona, the University of Girona, and the Natural Park of the Volcanic Zone of La Garrotxa, illustrating its commitment to partnerships that promote knowledge and scientific dissemination.

Fig. 7: Espai Crater exhibition hall.

The museum showcases a volcanic outcrop from the Puig del Roser volcano, explicitly excavated for this exhibit. Using video mapping, the museum illustrates the evolution process of the outcrop formation. Visitors can see how different layers were deposited by the fall of pyroclasts of various sizes and processes, gradually filling the outcrop. The video mapping also identifies and explains a paleo fumarole, highlighted by the hydrothermal alteration processes in the pyroclastic deposits. This is particularly noteworthy, as few preserved examples of such processes exist in other outcrops within the Garrotxa volcanic field.

The group will be able to explore the entire centre and its exhibits. They will also engage with the museum's director, staff, and educators to discuss the importance of disseminating science and educating citizens of all ages about the region's natural volcanic heritage, one of its most important values.

Stop 3: Castellfollit de La Roca Basalt Cliff

From an overlook along the old road connecting Olot to Girona, visitors can enjoy a panoramic view of the basalt cliff of Castellfollit de la Roca. This cliff formed through the deposition of two lava flows along riverbeds, subsequently shaped by erosion from the Fluvià and Turonell rivers and showing well-defined columnar jointing. The town of Castellfollit de la Roca itself is perched atop this volcanic outcrop, approximately seven kilometres southwest of Olot. Access to Castellfollit from Girona involves taking the N-260 road through Banyoles and continuing past Besalú. At the 45-km mark, where the road intersects with the route to Oix, visitors can park and follow Natural Park itinerary 13 to the Fluvià River. After crossing the river on a wooden footbridge and walking 500 m, one can approach the base of the cliff to observe the intricate basalt columns up close (Fig. 8).

About nine meters from the top of the volcanic materials, a layer (0.2–1.5 m thick) of clay and pyroclasts, easily recognisable by the abundant herbaceous plants that grow there, divides the escarpment into two discrete parts. a. The lower part has three differentiated layers: (1) the first (starting from the bottom) is 5.5-m thick and has columnar jointing with prisms around 50 cm in diameter; however, it is often hidden by the riparian vegetation; (2) the second has lenticular jointing and is 3.5-m thick; (3) the final layer is less than a meter thick and again has columnar jointing but with columns that are only 30 cm in diameter (Martí et al., 2018 and references therein).

The cliff, standing 50 m high and stretching over 1 km, offers a clear view into the internal structure of a lava flow (Fig. 8). Over thousands of years, erosion by the Fluvià River has been the dominant agent, aided by frost weathering caused by the columnar jointing structure of the rock. The cliff's fractures concentrate weathering, causing blocks to crumble and fall, which are carried away during the river's periodic floods, preventing accumulation at its base.

At the base of the cliff lies layers of Eocene sandstone and marl, overlain by a gravel mixture containing limestone, sandstone, and occasional basalt pebbles. Above these substrates rests a 40-m-thick layer of black and grey basalt. Nine meters below the top volcanic layer, a distinctive 0.2–1.5-m-thick stratum of clay and pyroclastic material supports abundant herbaceous plant growth, marking a notable division within the cliff (Martí et al., 2018 and references therein).

The lower part has three differentiated layers:

1. The first layer, starting from the bottom, is 5.5 m thick and exhibits columnar jointing. Its prisms are approximately 50 cm in diameter. However, riparian vegetation often obscures this layer.

2. The second layer, 3.5 m thick, features lenticular jointing.

3. The final layer is less than 1 m thick and also displays columnar jointing but with columns only 30 cm in diameter.

The upper part has four layers:

1. The first three layers range from 5 to 9 m thick and exhibit prominent columnar jointing.

2. The final layer near the top is about 9 m thick and shows well-developed spheroidal weathering.

Approximately 217.000 years ago, a lava flow from the Batet plateau volcanoes descended into the ancient Fluvià valley, extending beyond the present-day town of Sant Jaume de Llierca. Around 192.000 years ago, another lava flow from the volcanoes near Begudà moved down the Turonell Valley to Castellfollit de la Roca. The differential cooling of these lava flows resulted in the formation of distinct internal layers. The interval between these two events allowed for soil development and the deposition of sedimentary materials, now visible as a clear layer between the two lava flows (Martí et al., 2018 and references therein).

The Fluvià and Turonell rivers overcame the barriers to their flow by initiating the erosion of the interface between basaltic lava rocks and sedimentary formations. Castellfollit de la Roca, a medieval settlement, was constructed atop these lava flows, predominantly utilising the rocks and stones derived from these flows as primary construction materials.

Fig. 8. Picture of the village of Castellfollit de la Roca. Credits: © Turisme de la Garrotxa.

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The Querol Valley Pleistocene Glacial Chronology and Paleoclimate

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We start our journey at Puigcerdà, one of the most important towns in the Cerdanya region in Catalonia. The Cerdanya is a depression between the central Pyrenean axis (the so-called Axial Zone, which is mainly composed of Palaeozoic metamorphic and plutonic rocks) and the outer mountain ranges (the Pre-Pyrenees, such as the Cadí-Moixeró, which is composed of Mesozoic and Cenozoic limestones, sandstones, and conglomerates), crossed by the Segre River (de Andrés et al., 2023) (Fig. 1).

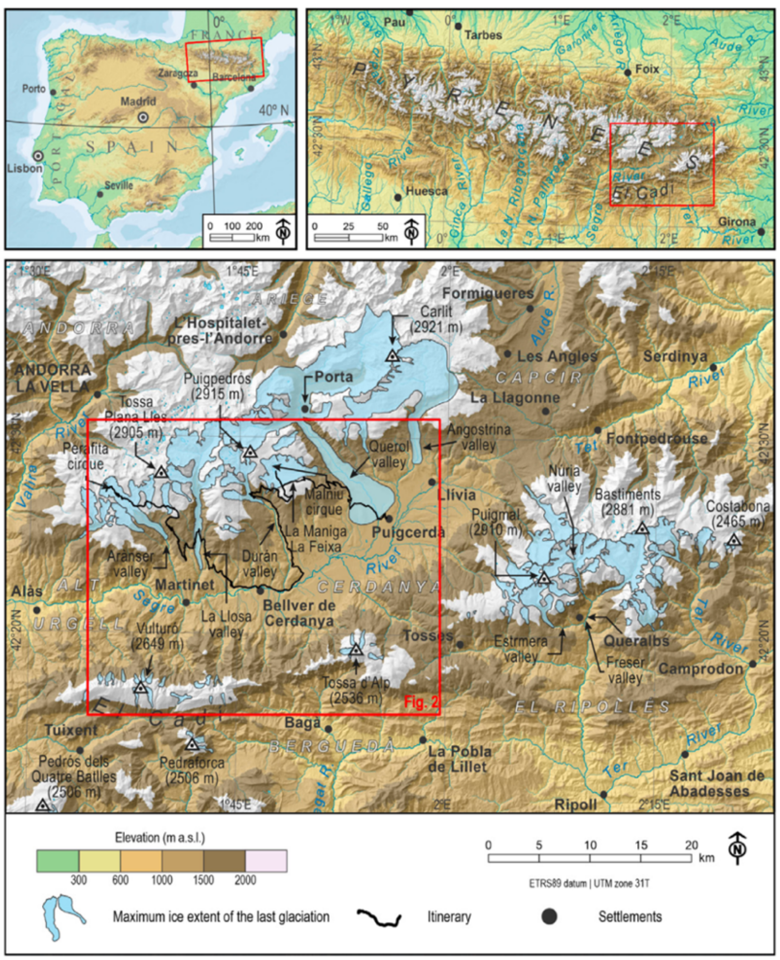

Fig. 1: The maximum ice extent of the last glaciation in the Cerdanya area. The figure was taken from de Andrés et al. (2023), who adapted it from Salvador-Franch et al. (2021).

Stop 1: Querol Valley's lateral and frontal moraine system

This stop at Guils aims to observe the stunning view of the Querol Valley's lateral and frontal moraine system (Figs. 2 and 3). This is the most significant moraine system on the southern slope of the eastern Pyrenees, where a former glacier descended from Carlit Peak (2921 m) and terminated in the plains near the town of Puigcerdà, at least during the last three or four glaciations. The description below is taken from Delmas et al. (2022).

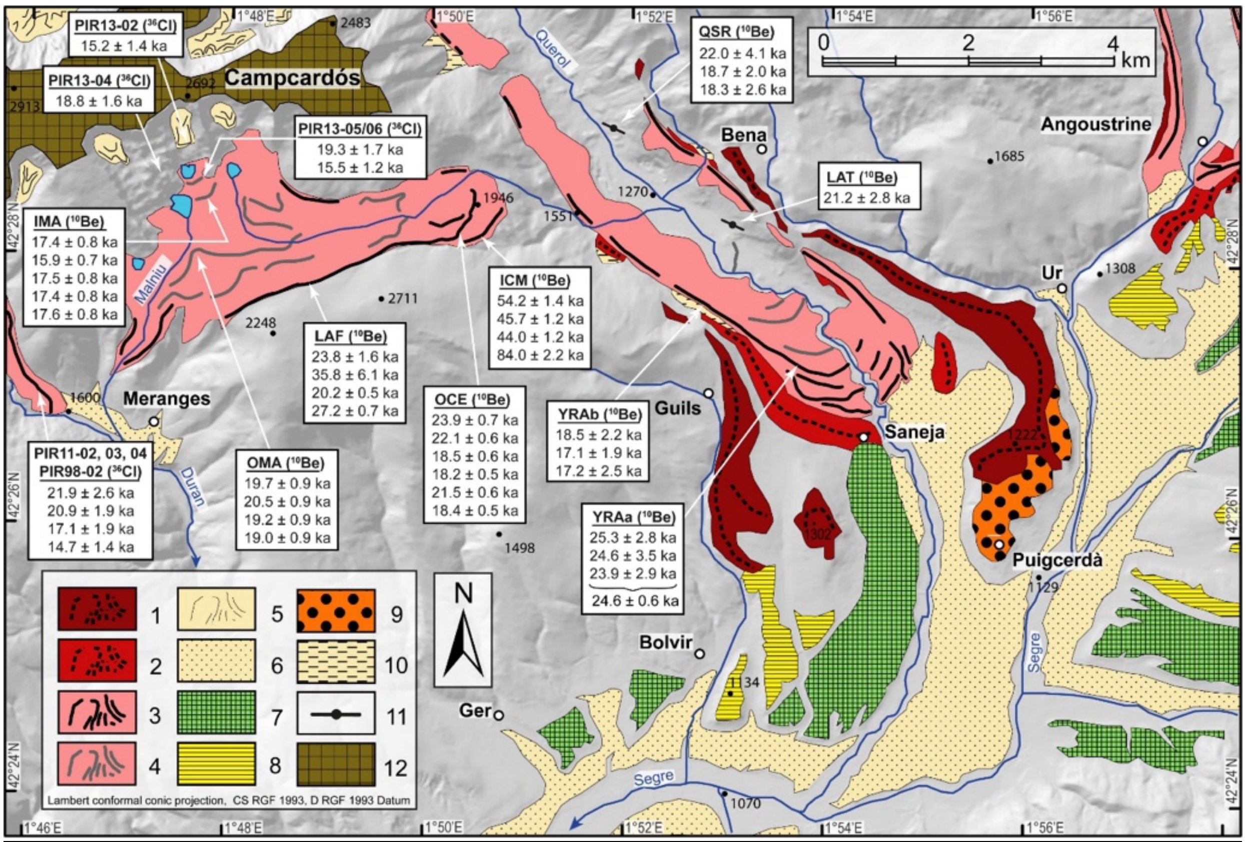

Fig. 2: Glacial deposits in the Querol River Basin with the existing dates (After Delmas et al. 2022). 1- Pre-Eemian moraines (MIS 8-10). 2- Pre-Eemian moraines (MIS 6). 3- LLGM moraines. 4- Post-LLGM moraines. 5- Rock glaciers. 6- Glaciofluvial terraces (generation T1) connected to the Late Pleistocene moraines. 7- Glaciofluvial terraces (generation T2) connected to pre-Eemian moraines. 8- Intermediate glaciofluvial terraces (generation T3). 9- Uppermost (and oldest) glaciofluvial terraces (Puicerdà outwash plain). 10- Late Pleistocene ice-marginal glaciolacustrine deposits. 11. Ice-polished bedrock step. 12. Low-gradient pre-Quaternary erosion surfaces). The red stars locate the point of the route stops, and the associated number indicates their sequence. Spot elevations in metres above the sea level. Adapted from Delmas et al. (2022) and Calvet et al. (2022). ^{10}Be exposure ages after Pallàs et al. (2010). ^{36}Cl exposure ages after Palacios et al. (2015) and Andrés et al. (2018). Geomorphological map (landforms and deposits) after Calvet (1996).

Fig. 3: The Querol Valley, located upstream of Puigcerdà to the north, features lateral and frontal moraines from at least three glacial cycles and their corresponding fluvioglacial terraces. On the left is the Puigpedrós Massif (2914 m) and its glacial cirques (from de Andres et al., 2023).

The innermost moraine system, divided into several ridges that show evidence of frequent pulsations, is dated to the LGM (terrestrial cosmogenic nuclide average age around 24 ka). The outermost ridges are older (no dates, which possibly formed during MIS 2, 3, or 4). A second moraine system, possibly originating during MIS 6, is located ahead of the younger moraines mentioned above. It forms an important crest just below Guils de Cerdanya and is visible from the hill (Puig San Martín, 1302 m) just south of Saneja. This moraine connects with the intermediate fluvioglacial terraces (T2), clearly visible to the south of Saneja and east of Puig de San Martín. A golf club currently occupies the terrace at 1120 m elevation. At a slightly lower altitude, around 1110 m, are the terraces (T1) that link up with the LGM moraines, located to the north of the town of Puigcerdà.

Just east of the village of Guils de Cerdanya, the outer lateral moraine connects with the fluvial terraces (T3) near Bolvir. The only features dated in the entire complex are the innermost moraines and their corresponding terraces (T1), originating during the LGM. The correlation between the terraces T2, T3, and T4, and the Stadial MIS 6, MIS 8, and MIS 10-12, respectively, is based on ages obtained from similar relative chronostratigraphic positions in the central and eastern Pyrenees (synthesis in Delmas et al., 2022 and Calvet et al., 2022).

Stop 2: Col de Puymorens (Coll Pimorent)

This mountain pass is a broad paleovalley that experienced drainage beheading from a northern stream and now feeds into the Ariège catchment. During the Late Pleistocene, Puymorens served as a transfluence col through which the Ariège Glacier, better supplied by precipitation from the Atlantic and therefore having a much lower Equilibrium Line Altitude (ELA: 1500 m vs. 2200 m), flowed southward into the Querol Valley. This continued until the end of the Last Glacial Maximum (LGM), extending to 18-17 ka, as indicated by numerous ^{10}Be exposure ages acquired from lateral moraines in the Ariège and Orri glacial troughs.

Twenty-two ^{10}Be exposure ages were obtained from a population of moraines in the upper Ariège Valley and around Col du Puymorens (Fig. 4, Reixach et al., 2021). Puymorens connects the drainage divide between the north-flowing Ariège and the south-flowing Querol rivers, tributaries of the Garonne (Atlantic influence) and the Ebro (more Mediterranean influence) rivers.

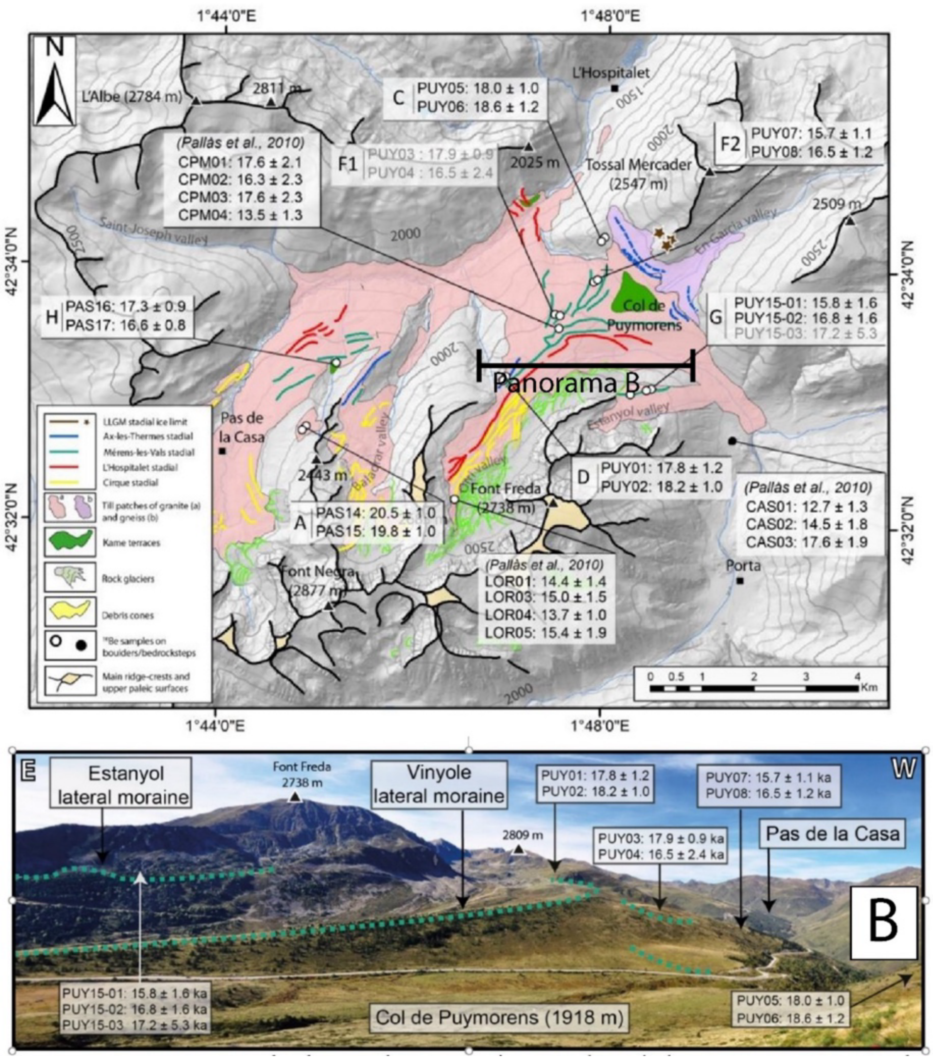

Fig. 4: Geomorphological map and ^{10}Be exposure ages at and around Col de Puymorens. Modified after Reixach et al. (2021).

A detailed analysis of chronological and palaeogeographical evidence from this valley segment has documented the extent of the Ariège Glacier at four successive stades during the last glacial to interglacial transition (Fig. 5):

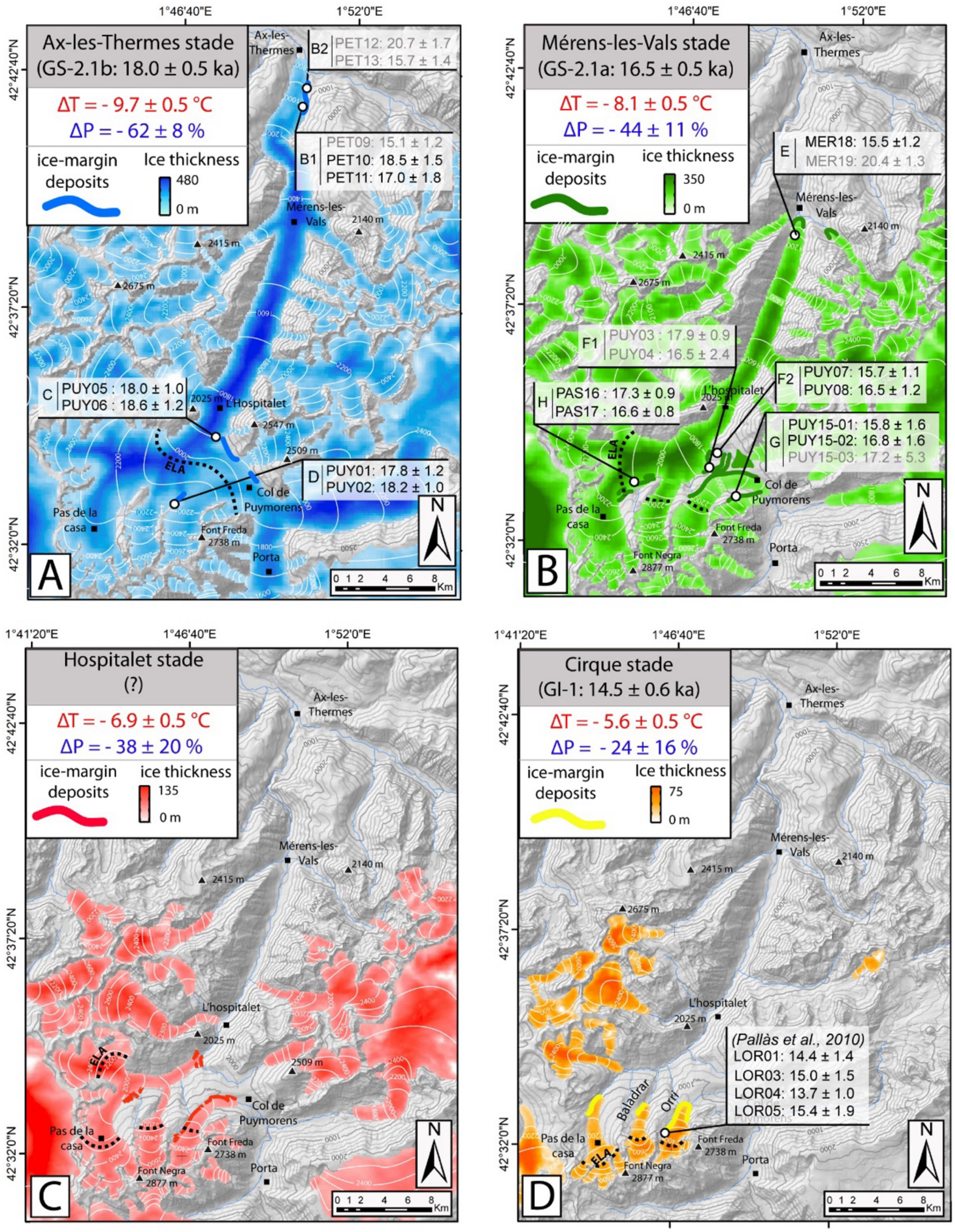

Fig. 5: Extent of successive glacial stages in the upper Ariège Valley (after Reixach et al., 2021).

- During the Ax-les-Thermes stadial (Fig. 5A), the valley contained a composite glacier approximately 20 km long, its presence now indicated by remnants of the lateral moraines at Petches (upstream from Ax-les-Thermes) and by the outermost band of lateral moraines further up the valley. At that time, the glacier was linked to the south-facing Querol Valley glacier by transfluent ice at Puymorens. Exposure ages on the lateral moraine at Petches and from a ribbon of glacier-margin boulders in the upper valley (Fig. 5A) place the Ax stadial within the Oldest Dryas (GS-2.1b: 18.0 ± 0.5 ka).

- During the Mérens stadial (Fig. 5B), the glacier was approximately 15 km long, had lost several tributaries, and the Ariège icefield was cut off from the Querol at Puymorens. Frontal moraines at Mérens-les-Vals and in disconnected tributary valleys within the catchment indicate that the Mérens stadial coincided with the Oldest Dryas (GS-2.1a: 16.5 ± 0.5 ka).

- During the Hospitalet stadial (Fig. 5C), the glacier was about 10 km long and produced several closely spaced frontal moraines upstream of the village of l'Hospitalet. The precise age of this stadial position remains unknown due to unsuitable dating material. Considering the ages of local stades 2 (see above) and 4 (see below), the glacier recession was occurring quickly.

- The cirques stade is the final episode of the deglacial history, a time when the landscape hosted a population of small cirque and short valley glaciers such as Orri and Baladrar (Fig. 5D). Updated age models of exposure data previously obtained by Pallàs et al. (2010) from lateral moraines above Puymorens (Orri Valley) yield a Bølling-Allerød age (GI-1: 14.5 ± 0.6 ka).

Amplitudes of paleotemperatures and paleoprecipitation have been retrieved from glaciological and paleoclimatic models calibrated on the positions of each successive generation of glacial landforms (Fig. 6). Results indicate that the climate in the upper Ariège Valley was overall colder and drier than today, with an acceleration towards milder conditions between GS-2.1b and GI-1. The ELA rose by 410 m over that period, and the increase in mass-balance gradient (MBG) of 0.04 m/yr/100 m indicates a rise in temperature and precipitation of 4.2 °C and 38%, respectively.

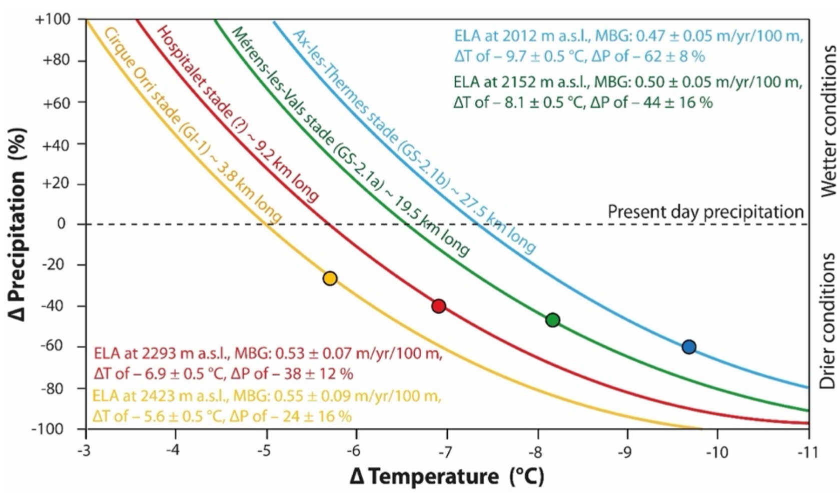

Fig. 6: Reconstructed P and T pairs relative to present conditions, here applied to the four glacial stillstands (local stades) identified in the upper Ariège catchment. From Reixach et al. (2021).

The Ariège results have been integrated into a broader database of palaeoenvironmental proxy evidence and age results from other valleys across the eastern Pyrenees. The data suggest that deglaciation in the eastern Pyrenees occurred rapidly, with only small cirque glaciers remaining around 12.3 ka (GS-1) wherever local climatic conditions (typically controlled by slope aspect) allowed it. Glaciological modelling contrasts the colder and wetter north-facing mountain front and massifs with the milder south-facing mountain front under the Mediterranean influence. ELAs were thus systematically lower in the north, and mass-balance gradients were steeper than in the south. Such a north-south contrast is still observed today but is much less pronounced. It appears to have prevailed in this manner since at least the LGM (~19 ka).

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MedGU 25–28 NOV. 2024 BARCELONA, SPAIN MEDITERRANEAN GEOSCIENCES UNION 4th ANNUAL MEETING

Glacial and Periglacial Landforms at Menera Cirque (Andorra)

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Geomorphology

The Valira Valley, characterised by its well-defined U-shaped profile, is often regarded as the boundary between the Central Pyrenees to the west and the Eastern Pyrenees to the east. Originating at its headwaters, the valley initially trends northwest to west before gradually curving southwest to south as it traverses Andorra. The headwaters are shaped by a composite glacial cirque, which consists of four north-to-northeast-facing units (Fig. 1). The base of this composite cirque lies at an elevation of 2100–2200 m, while the upper cirques have bases ranging between 2400 and 2500 m.

Fig. 1: Google Earth image of the composite cirques at the head of the Valira Valley. Menera Cirque to the east.

Our study focuses on the easternmost unit, the Menera Cirque. This north-facing cirque spans 1.1 km in length and 1.3 km in width. It is framed by two prominent summits: Menera Peak (2775 m, 42°30'48"N, 1°42'46"E) and Envalira Peak (2815 m, 42°31'06"N, 1°43'21"E). These peaks form a hydrological divide that governs the drainage patterns of nearby valleys, directing flow toward the Ariege Valley to the northeast, the Segre Valley to the south and east, and the Valira Valley to the north.

In this cirque, we have performed a wide range of studies to understand the timing and processes that have shaped the current landscape in the highest mountains of the Pyrenees:

The Menera Cirque features diverse glacial and periglacial landforms shaped by the Pleistocene glaciation and subsequent deglaciation phases (Ventura and Turu, 2021). Its high elevation (2400–2500 m) and northern exposure promoted glacier growth during Pleistocene cold periods. Although the timing of maximum ice coverage in the valley remains uncertain, geomorphological evidence—including frontal and lateral moraines, polished bedrock, and erratic boulders—indicates that extensive glaciation once covered much of the Valira Valley (Ventura and Turu, 2021). Within the cirque, numerous depositional and erosional features, such as moraines and glacially abraded outcrops, confirm a series of glacial advances preceding the area's final deglaciation (Fig. 2).

Fig. 2: Glacially polished rock surface. Unpublished ages indicate the Younger Dryas stadial.

Like many cirques in the central-eastern Pyrenees, the slopes of the Menera Cirque underwent paraglacial adjustments following glacial retreat, forming rock glaciers and large-scale landslides (Fernandes et al., 2020, 2023). While most rock glaciers in the region are believed to be inactive under the current climate, this has not been thoroughly studied (Fig. 3). Additionally, the Grau-Roig ski resort has significantly altered the lower slopes of the Menera Cirque, reshaping the landscape to support winter sports.

Fig. 3: Field view of the Menera Cirque (left) and close-up view of the rock glaciers (right).

Absolute dating

Our unpublished cosmic ray exposure (CRE) dating of glacially polished rock surfaces indicates that the Menera Cirque was fully deglaciated after the Younger Dryas, approximately 10–12 ka. During this period, rock glaciers began forming on the newly exposed slopes of the cirque. CRE dating of surface boulders on these rock glaciers suggests they stabilised shortly after their formation, around 10 ka. Tritium dating of spring water emerging from the rock glaciers indicates an age of 9–12 ka, aligning with the CRE-dated stabilisation period.

Geophysical surveys

Magnetic resonance data reveal the presence of a frozen core within the rock glaciers, likely consisting of buried ice and permafrost. This frozen mass, protected by a thick debris layer, appears to have endured since past cold climatic periods. These observations suggest a glacial origin for the subsurface frozen body, emphasising its significance as a permafrost-related landform developed under glacial conditions.

INSAR measurements

Contemporary monitoring using InSAR data reveals that these rock glaciers are still actively creeping downhill at rates of approximately 2–5 cm/year.

Ground thermal regime

Temperature logger data indicate consistent winter temperatures of approximately -4°C, suggesting the presence of a frozen body within the interior of the rock glacier.

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A short review of the El Forn giant landslide: A deep-seated gravitational slope deformation in Andorra

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This document provides a detailed chronology of studies and findings regarding the El Forn and Encampadana landslides in Andorra (Figs. 1, 2).

Fig. 1: Location of the study area in a general map of Andorra

Initial Studies (1984-1990)

- Corominas and Alonso (1984) first identified the large-scale features of the landslide, although they initially misinterpreted its origins (e.g., as a glacial feature).

- Slope gliding was recognized earlier, as indicated by historical structures such as the Sant Miquel Romanesque church, haystacks, roads, and deformations of hydroelectric pipeline tunnels at slow displacement rates (up to 5 mm/year).

Comprehensive Research

- Corominas (1990) expanded the study to include the Encampadana Massif, revealing varying reactions of the softer (Silurian black silts) and harder (Devonian calcschists) massifs to paraglacial-induced stress during successive deglaciation phases.

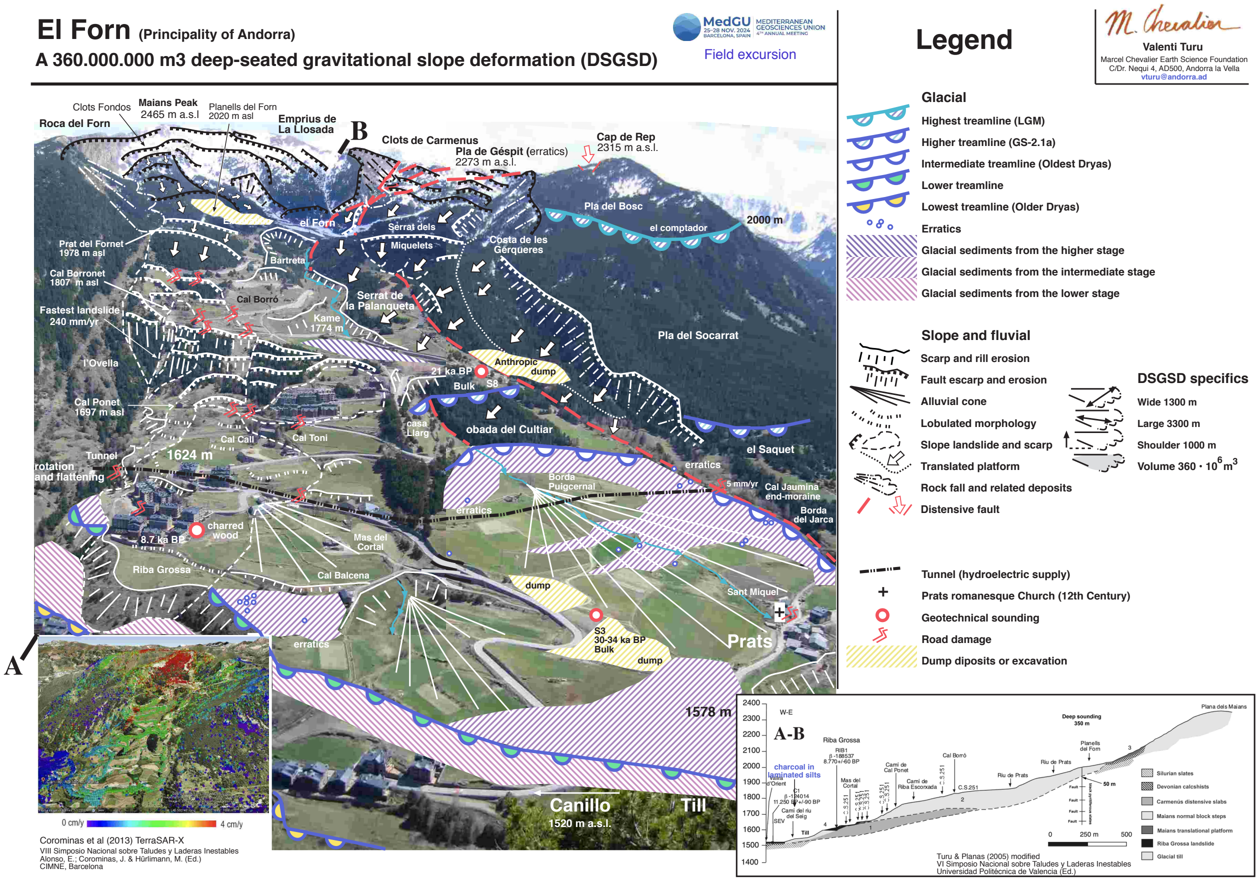

Fig. 2: Geomorphological photo-map of the El Forn giant landslide. The southern foothill of the Cap del Rep massif settled due to river over-excavation, causing a southward distensive motion to the palaeo-El Forn massif over the Clots de Carmenús. The Roca del Forn scarp was formed during the distensive phase, and several translational platforms slid downhill by imbricated steps. The main glacier advanced over the El Forn slope but has been observed at least four times since the Last Glacial Maximum (LGM). During the early Holocene, a new landslide affected the outer area of the landslide at Riba Grossa. The current motion is at mid-altitude (Cal Borronet) and on top at Clots Fondos.

Landslide Evolution (2011-2016)

- New dates from Planas et al. (2011) suggest a glacial origin for some morphological features from its foothills. The oldest glacial phases correspond to the Last Glacial Maximum and Termination I periods.

- Instrumental monitoring revealed active displacements of 2–3 cm per month during heavy rainfall at Cal Borronet.

Modern Investigations (2006-2021)

Advanced models by Hürlimann et al. (2006) and McCalpin and Corominas (2019) explained deformation via deep-seated gravitational processes since the last deglaciation occurred at least 15.000 years ago. Installing Cal Borronet boreholes and measuring devices (2005–2008) faced several issues. However, subsequent campaigns (Seguí et al., 2021) identified a sliding surface and determined its characteristics. The high velocity of the Cal Borronet landslide (24 cm/year) is linked to groundwater pressure effects.

Remote Sensing Advances

- Ground-based SAR (GBSAR) and satellite techniques (DInSAR, TerraSAR-X, Sentinel-1) monitored the general motion over the area, confirming displacements on El Forn's mid- and upper slopes.

- Campaigns revealed instability impacting the ski resort infrastructure and significant rock formations that had not been previously noticed.

Challenges with Measurements

- Remote sensing and GPS data provide insights, but orientation and environmental factors limit their effectiveness. Long-term displacement rates and their damaging implications for infrastructure remain uncertain.

Forty years of studying El Forn highlight the evolution of techniques and challenges in understanding complex slope dynamics, emphasising the role of multidisciplinary approaches (engineering, geology, geomorphology, geochronology, geoarchaeology). However, the original slope's comprehensive evolution and reconstruction are still pending. This exercise will shed light on the origin of the area's tectonic motion.

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