Pre-Conference *Field Trip*

MAY 18 to 20, 2018

Monogenetic volcanism of the Catalan Volcanic Zone: Maar craters, scoria cones and rootless volcanoes of the Garrotxa volcanic field, and open fossil excavation in a Pliocene maar crater.

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Autor: Eduard Masdeu

Authors: Xavier Bolós and Joan Martí

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Monogenetic volcanism of the Catalan Volcanic Zone: Maar craters, scoria cones and rootless volcanoes of the Garrotxa volcanic field, and open fossil excavation in a Pliocene maar crater.

Xavier Bolós[1], Joan Martí[2], Oriol Oms[3], Gerard Campeny[4],[5], Bruno Gómez de Soler[4],[5]

[1] *Institute of Geophysics, UNAM, Campus Morelia, 58190 Morelia, Michoacán, Mexico.* *xavier.bolos@gmail.com*
[2] *Institute of Earth Sciences Jaume Almera, CSIC, 08028 Barcelona, Spain.*
[3] *Universitat Autònoma de Barcelona, Facultat de Ciències, Departament de Geologia. Campus Bellaterra, 08193, Spain.* *joseporiol.oms@uab.cat.*
[4] *Institut Català de Paleoecologia Humana i Evolució Social (IPHES). C/Marcel·lí Domingo s/n, Edifici W3 Campus Sescelades, URV, 43007 Tarragona.*
[5] *Universitat Rovira i Virgili (URV). Facultat de Lletres. Av. Catalunya 35, 43002 Tarragona.*

Introduction

The field trip will start on May 18th at the bus station of Olot at 8:00 am. During the first half of the day, participants will explore and discuss the evolution of La Crosa de Sant Dalmai maar volcano (Fig. 1, #1), the largest maar crater of the Iberian Peninsula, formed during the Pleistocene. Then, the group will debate on the stratigraphy of the basaltic tuff-ring of El Puig d'Adri (Fig. 1, #2) and its phreatomagmatic deposits, including basaltic ignimbrites. After these geological stops, we will visit Caldes de Malavella, a beautiful village declared historical monument of national interest, with a great tradition in spas and thermal water springs since Roman Empire in time of Emperor Augustus, who called this village Aquae Calidae. Moreover, we can find Medieval architecture such as the walls of the old castle Caldes with 3 towers of s. XII and also modernist and neoclassical buildings in the old town of the village

www.femturisme.cat/en/villages/caldes-de-malavella

After lunch in Caldes de Malavella, the group will visit the open fossil excavation in lacustrine sediments of the Camp dels Ninots Pliocene maar crater (Fig. 1, #3) located in the same village.

During the morning of the second day, the group will visit the Montsacopa complex cinder cone (Fig. 1, #4) that rises right in the heart of the city and is one of the five volcanoes that stand inside the city of Olot. This volcano exhibits a diversity of eruptive styles with strong evidence of vent migration controlled by tectonic features. After that, we will do a tour around the rootless volcanoes and tumuli lava field of Bosc de Tosca (Fig. 1, #5), with more than one hundred tossols (local name of rootless volcanoes) that have formed all along the lava flow emitted by the Puig Jordà volcano with an age of about 17,000-years old. After lunch in a popular restaurant in the region, the attendees will visit Sant Joan Les Fonts columnar-jointed lava flows (Fig. 1, #6). The last stop of the second day will be in the Quaternary Cairat maar volcano (Fig. 1, #7) and their phreatomagmatic deposits.

The first Stop of the last day we will visit the phreatomagmatic deposits of La Garrinada volcano (Fig. 1, #8), and then, the participants will enjoy the wonderful views and landscapes of the Garrotxa Volcanic Park and the Mediterranean coast from the Xenacs panoramic viewpoint (Fig. 1, #9).

An important aspect of this field trip is that it will also include discussions about the relation between science and society taking into account that in this region volcanoes are present in many aspects of local society, as its cultural heritage, local history, architecture, or even in its excellent cuisine. The local people are aware of living among volcanoes and that they represent the most characteristic feature of their region, in an extent comparable or even superior to areas with more active volcanism.

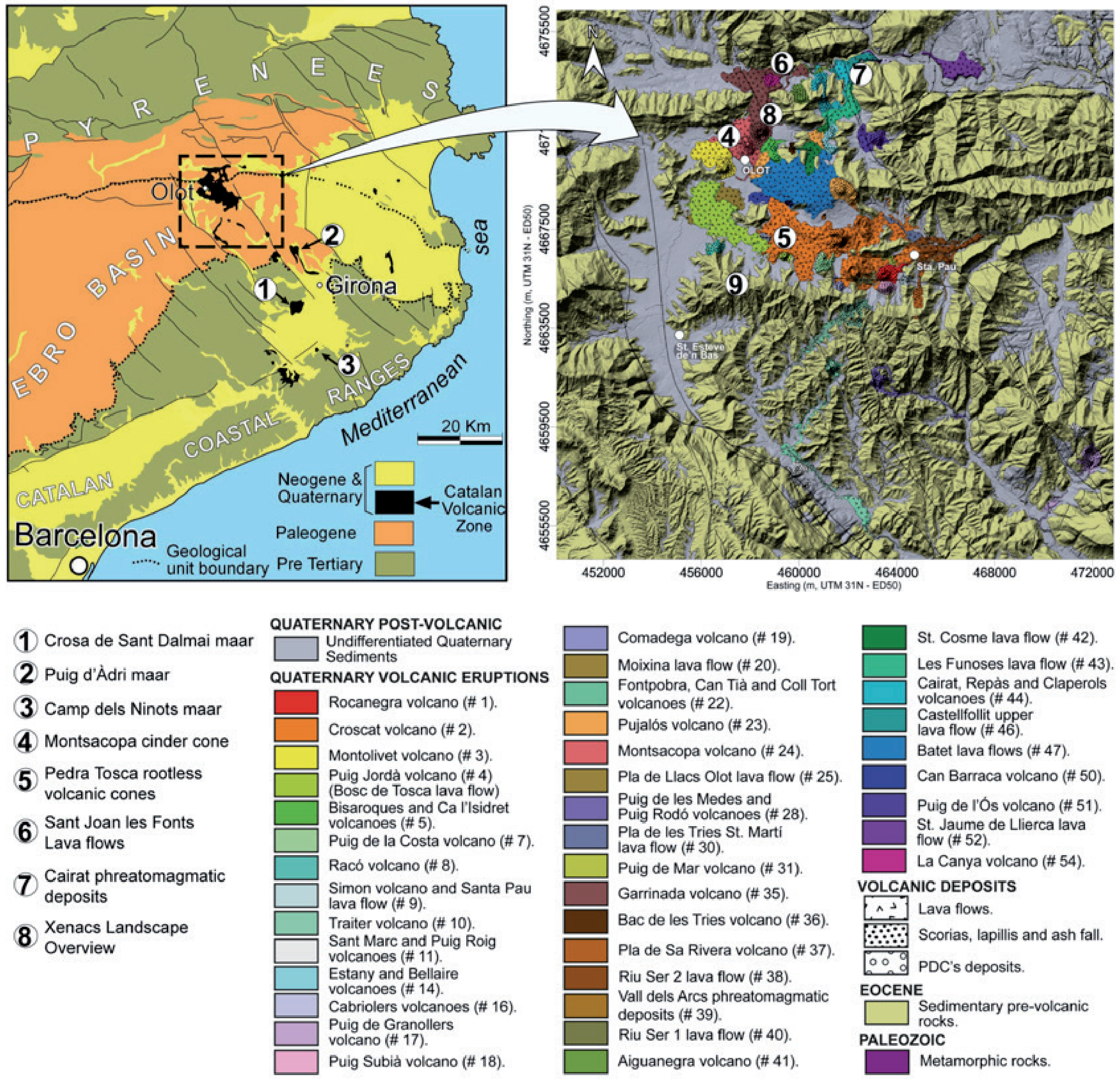

Figure 1. Left: Geological map of eastern Catalonia and location of the stops. Right: Detaied volcano-stratigraphyc map of the northern sector of the Garrotxa volcanic field with location of the stops. (modified from Bolós et al., 2014a).

Geological Settings

Catalan Volcanic Zone (CVZ), one of the volcanic provinces of the European Rift System (Martí et al. 1992), which extends into the Catalan Coastal Ranges (Fig. 1). The latter are an Alpine orogen that underwent extension during the Neogene (see regional setting in Roca 1996 and Tassone et al. 1994). This extension resulted in the formation of faults that are linked to the CVZ. This zone (see Araña et al. 1983; Martí et al. 1992) comprises an undetermined number of outcrops representing partially eroded volcanic edifices and more than 50 well-preserved monogenetic volcanoes. The tectonic evolution of this zone was controlled by a system of NW-SE Neogene-oriented fault system, which seems to have evolved over time beginning in the NE and shifting SW (see Bolós et al. 2015). Probably each eruption resulted from a single batch of magma that was rapidly brought up to the surface, representing an individual partial-melting event caused by tectonic reactivation (Martí et al. 1992; Bolós et al. 2015).

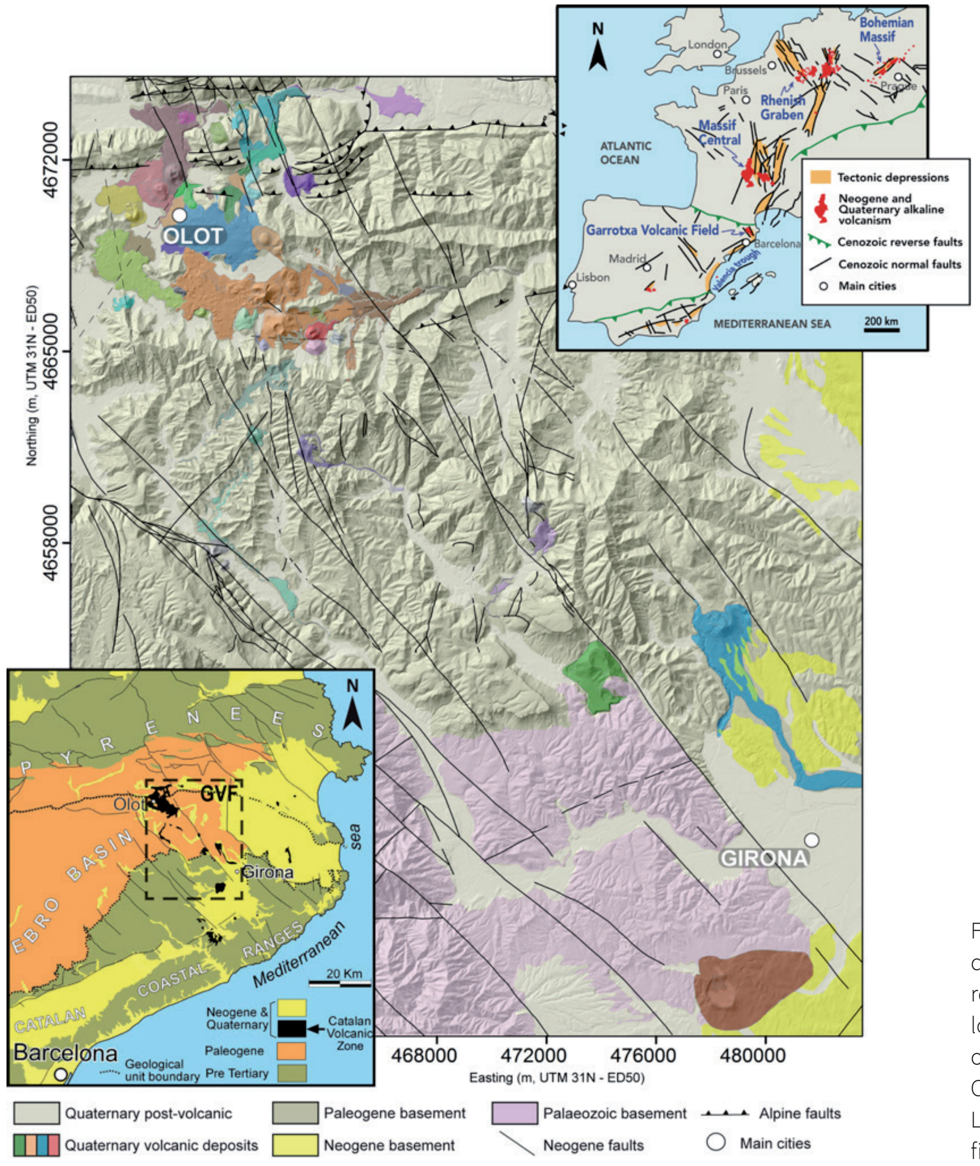

Figure 2. Inlet at the upper right corner structural map of the European Rift System. Inlet at the lower left corner geological map of the NE of Iberian Peninsula. Central image geological map of La Garrotxa Volcanic Field. (modified from Bolós et al., 2015).

Available data indicate that mafic volcanic products in the CVZ, like the parental magmas of the cumulate xenoliths, range from strongly silica-undersaturated to nearly silica-saturated compositions (Bianchini et al. 2007). This region comprises a suite of intracontinental leucite, basanites, nepheline basanites and alkali olivine basalts, which in most cases represent primary or near-primary magmas (see references in Bianchini et al. 2007, Martí et al., 2011 and Bolós et al. 2015). Some volcanoes host ultramafic to mafic xenoliths, with pyroxenite the most abundant ones (Bolós et al., 2015). At least for part of the CVZ, xenoliths are likely to have crystallized in magma chambers located at the crust-mantle boundary located at a depth of ~30 km according to geophysical data (Gallart et al. 1984); in contrast, the spinel lherzolites may derive from the source region in the asthenospheric mantle (Bianchini et al. 2007).

La Garrotxa Volcanic Field (GVF) contains the most recent volcanism in the CVZ and is also the most tectonically active area, with historically high-magnitude seismicity. This volcanic field covers about 600 km2 and lies between the cities of Olot and Girona (Fig. 1). This basaltic volcanic field contains over 50 volcanoes including scoria cones, tephra cones, and maar-diatremes dating from the Middle Pleistocene to the early Holocene (Bolós et al. 2014a), which rest either on upper Palaeozoic granites and schists or on sedimentary Eocene and Quaternary substrata (Fig. 1). Available petrological and geochemical data indicate that this region is represented by primary or near-primary magmas, their geochemical characteristics being very similar to analogous petrologic types found in other European Cenozoic volcanic zones (Martí et al., 2011).

GVF embraces two geographically distinct zones, the larger area located in the north of the county of La Garrotxa, mostly corresponding to La Garrotxa Volcanic Zone Natural Park (Fig. 2), and a southerly area that contains fewer but larger and more complex volcanic edifices (See Day 1). Although both correspond to tectonically controlled depressions, the northern zone has substrata consisting of thick layers of Tertiary and Quaternary sediments, whereas the southern zone is underlain by unconsolidated Quaternary sediments in combination with the Palaeozoic basement (Bolós et al., 2014a).
Volcanic activity in La Garrotxa Volcanic Field is characterized by numerous small cinder cones built during short-lived monogenetic eruptions occurring along tectonic-related volcanic fissures (Martí et la., 2011; Bolós et al., 2015). The total volume of extruded magma in each eruption was between 0.01 and 0.2 km3 (DRE) (Bolós et al., 2014a). Strombolian and phreatomagmatic episodes alternated in most of these eruptions and gave rise to complex stratigraphic sequences with a broad range of pyroclastic deposits. The eruption sequences differ from one cone to another and demonstrate that the eruptions did not follow a common pattern, particularly in cases of magma/water interaction. This complex eruptive behavior is likely to be due to the differing stratigraphic, structural and hydrogeological characteristics of the substrata below each volcano rather than to any differences in the physicochemistry of the erupting magmas, which are generally fairly homogeneous throughout La Garrotxa Volcanic Field. It becomes an important aspect in monogenetic volcanism that will be discussed during the field trip.

The existence of this volcanism is linked to the complex geodynamic evolution of the area following the Alpine orogeny that involved great stretching and breakage of the continental lithosphere, thereby allowing the generation of mafic magmas in the mantle and their subsequent ascent and eruption. The evolution of La Garrotxa Volcanic Field is chiefly controlled by two major Neogene faults, the Amer and Llorà faults, oriented NW-SE like most of the major post-Alpine extensional faults that have defined horst and graben structural patterns in NE Iberia (Bolós et al., 2015). However, most of the eruptive fissures and secondary structural lineaments that control the volcanic activity in La Garrotxa Volcanic Field exhibit a NNW-SSE trend that runs slightly obliquely to the main faults (Bolós et al., 2015).

The volcanic activity in La Garrotxa Volcanic Field occasioned the accumulation of thick layers of volcanic rocks that, in combination with the particular microclimate of the area, has guaranteed the formation of fertile soils covered by dense vegetation, a process that has helped preserve some of the original volcanic morphologies (Martí et al. 2017a).

DAY 1

Crosa de Sant Dalmai, Puig d'Àdri and Camp dels Ninots maar volcanoes.

STOP 1: Crosa de Sant Dalmai maar crater.

The Crosa de Sant Dalmai volcanic edifice corresponds to a typical maar-diatreme volcano, almost completely constructed from phreatomagmatic deposits, that forms a circular tuff-ring surrounded by a shallow crater of about 1.3 km in diameter (Fig. 2).

Figure 1. Left: Geological map of eastern Catalonia and location of the stops. Right: Detaied volcano-stratigraphyc map of the northern sector of the Garrotxa volcanic field with location of the stops. (modified from Bolós et al., 2014a).

It lies between the villages of Aiguaviva, Estanyol and Sant Dalmai, and straddles the borders of the counties of La Selva and El Gironès. From Girona, take the Santa Coloma road (GI-533) through Aiguaviva. About 1 km after the junction with the road to Estanyol, there is an esplanade on the right of the road from where volcanic material used to be quarried. The group will visit this outcrop as the Stop 1-1 (Fig. 4). In the part farthest from the road, you can climb a low mound, about 5-m high, formed of pyroclasts, which offers a good view across the Crosa de Sant Dalmai crater (Stop 1-2). The phreatomagmatic deposits, mostly lithic-rich breccias and fine surge and fallout deposits, can be observed in the quarry located below this observation point.

Figure 4. Outcrop 1 showing the main characteristics of the La Crosa de Sant Dalmai sequence.

This volcano is located at the boundary between La Selva tectonic depression, infilled with Pliocene and Quaternary sediments, and the mountains of the Sistema Transversal formed from Palaeozoic granites and metamorphic rocks (Bolós et al., 2012; Pedrazzi et al., 2014) (Fig. 5).

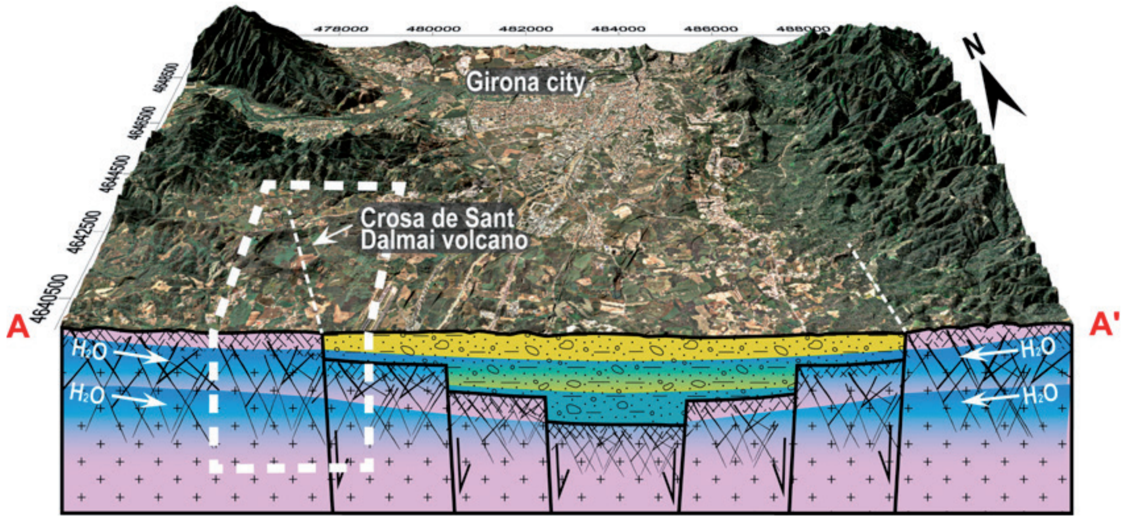

Figure 5. Geographical and geological setting of La Selva Basin, with the watershed boundaries with the two main subbasins (Onyar and Santa Coloma Rivers) marked. Arrows indicate the recharging area of the basin. The A–A' profile consists of a block diagram showing the general hydrogeological characteristics of the substrate below La Crosa de Sant Dalmai and La Selva depression and the infilling of the tectonic graben of La Selva Basin and the crystalline materials (igneous and metamorphic rocks). The orthophoto was provided by ICC (UTM 31N-ED50 Institut Cartogràfic de Catalunya, 2013, www.icc.cat). (Pedrazzi et al., 2014).

The tuff-ring is asymmetrical as it is higher (maximum height: 50 m) in the west where the internal and external slopes are also steeper than in the east (maximum height: 30 m). The deposits surrounding the rim are also asymmetrical in the same sense and extend further eastwards. The sequence of deposits that form this tuff-ring shows consistent stratigraphy, thereby suggesting that most deposits were radially distributed from the vent up to almost 4 km eastwards and only a few hundred metres westwards (Pedrazzi et al., 2014). This asymmetry in the distribution of the deposits seems to be related to the differences in the strength of the rocks that form each side of the basement below the volcano (Fig. 6).

To the east, the basement consists of unconsolidated Pliocene and Quaternary gravels, whereas westwards the country rock is composed of Palaeozoic granites and schists. This difference in rock competence seems to have played a major role during the eruption and to have facilitated the eastward excavating effect of each explosion (Bolós et al., 2012).

The sequence of deposits consists of 30 alternating units of lithic-rich explosion breccias and phreatomagmatic fallout deposits, as well as crudely stratified coarse-grained pyroclastic surge deposits. The eruption ended with a Strombolian episode originating from a new vent that opened in the interior of the maar and gave rise to a small cinder cone and a lava flow emplaced within the maar (Fig 6). (More information in Bolós et al., 2012 and Pedrazzi et al., 2014).

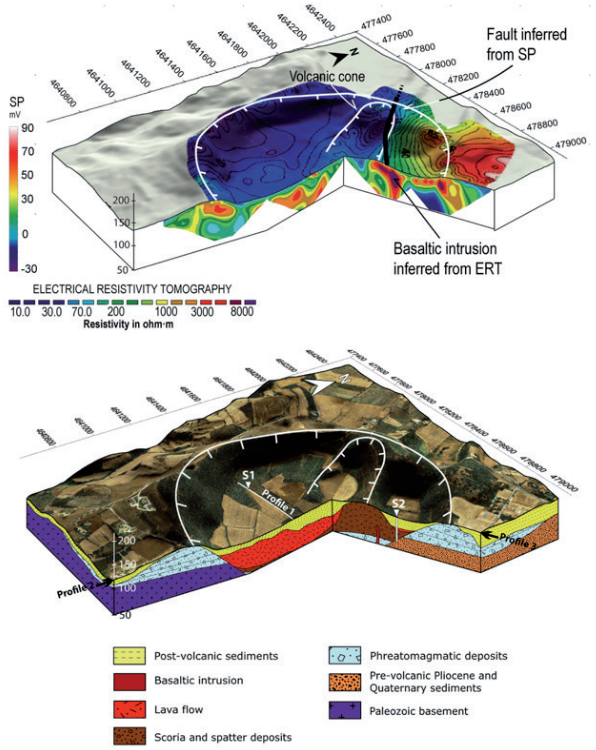

Figure 6. Inlet at the upper 3D block diagram of the self-potential and the ERT profiles. Inlet at the lower Synthetic 3D model. Orthophotomap overlapped on the DEM with geologic interpretation through cross sections corresponding to ERT profile (N–S direction) and 3 (SW–NE direction). The locations of S1 and S2 drillings are indicated. (Modified from Bolós et al., 2012).

STOP 2: Puig d'Àdri. Pyroclastic Flow Deposits from Puig d'Adri volcano.

The stop 2 owes its importance to a particular type of volcanic deposits that are not common in other similar volcanic areas: basaltic ignimbrite from massive pyroclastic flows that share features with typical siliceous volcanic activity. The best observation point is at Font de la Torre, a natural spring in the village of Canet d'Adri (El Gironès), where two streams, Riera de Rocacorba and Riera de Rissec, converge. From Girona, take the GI-531 road towards the Llémena Valley. About 3 km past the village of Sant Gregori, turn right along the GIV-5313 to Canet d'Adri. Roughly 300 m after Canet d'Adri village centre, turn left towards Mas de la Torre and park next to this house. From here, a track takes you down to the spring on the streambed of Riera de Rocacorba.

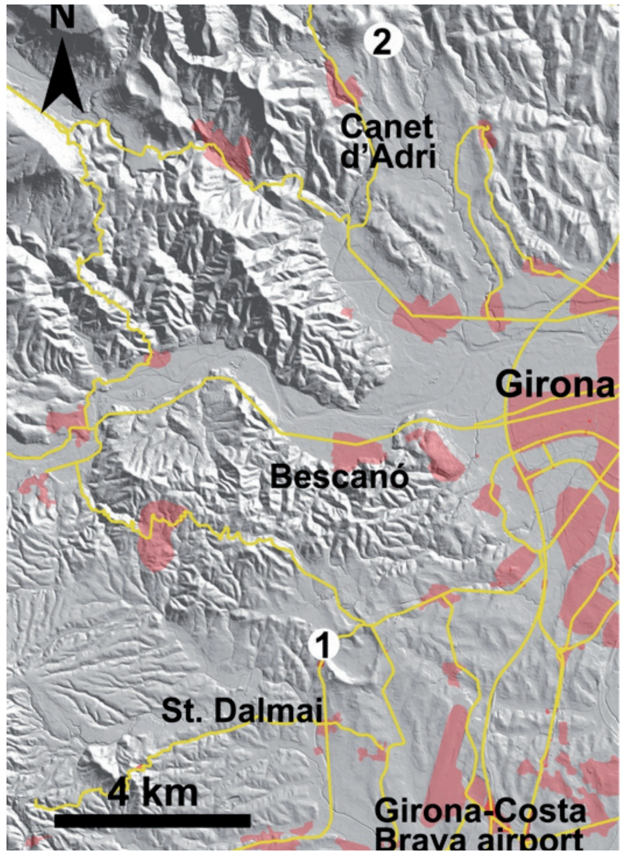

Figure 7. Location of the stops 1 and 2. 1 Crosa de Sant Dalmai maar crater, 2 Puig d'Adri volcano.

The volcano of Puig d'Adri lies at the foot of the Rocacorba mountain chain, between the village of Canet d'Adri and the hamlet of Adri. This is the easternmost volcano in the Llémena valley, and stands just seven kilometres from the city of Girona. Three identifiable superposed volcanic edifices were built during different phases of the same eruption (Fig. 8). A cinder cone (408 m a.s.l) is the most remarkable edifice and can be easily viewed from behind the church in Canet d'Adri.

Puig d'Adri exhibits one of the most complex eruption sequences, involving five different eruption phases, of any of the volcanoes in this volcanic field. It is located on the Adri normal fault, which brings into contact Palaeocene and Eocene materials and is fossilised to the south by Neogene sediments. The Puig d'Adri eruption began with the building of a 850-m-wide tuff-ring, followed by the development on its western side of a small scoria cone and then by the construction of a new cinder cone that today forms the main volcanic edifice covering most of the previous volcanic structures (Pedrazzi et al., 2016) (Fig. 8).

The eruption started with a phreatomagmatic event that generated an irregularly distributed deposit of explosion breccia and diluted pyroclastic density currents, which emplaced south-eastwards along the main existing gullies and ravines to distances of over 5 km from the vent (Martí et al., 2017a) (Fig. 8).

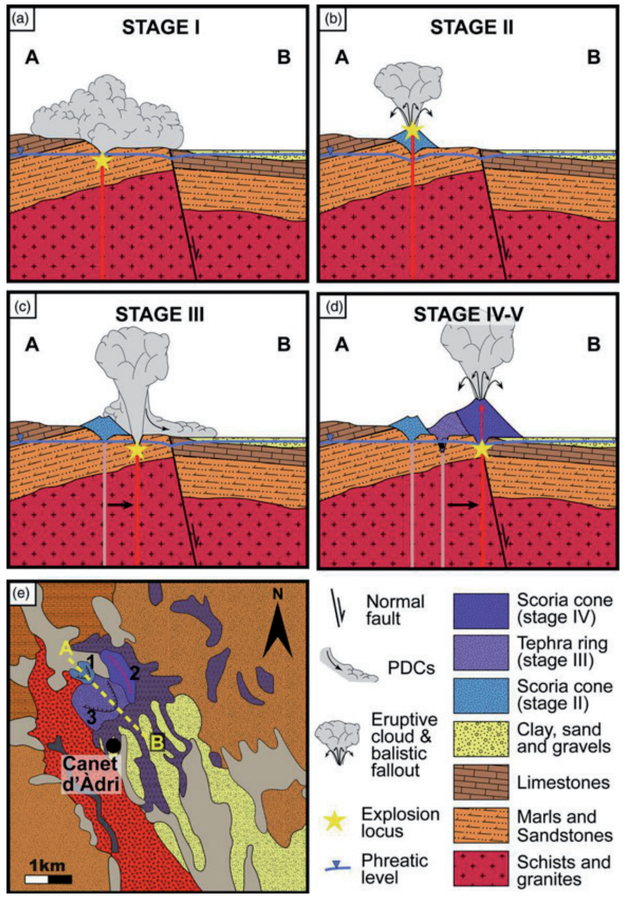

Figure 8. Five stages in the evolution of Puig d'Àdri: (a) initial vent-opening explosive phreatomagmatic event; (b) Strombolian activity and formation of the first cone; (c) renewed phreatomagmatic activity generating pyroclastic density currents and explosion breccias; (d) second Strombolian phase and construction of the main scoria cone; (e) geological map of the Puig d'Àdri volcano showing the AB profile illustrated in (a)–(d).

The resulting deposits consist of thinly laminated, classical dry pyroclastic surges with high-energy sedimentary structures (Martí et al., 2017a) (Fig. 9). This initial explosive phase was then immediately followed by a short Strombolian phase that generated a small scoria and lapilli deposit. The eruption then returned to more intense phreatomagmatic activity and generated a series of pyroclastic surges similar to the previous ones, explosion breccias and a pyroclastic flow that emplaced for over 5 km southwards following the course of Riera de Canet. Most of the tuff-ring was constructed during this second phreatomagmatic episode. The eruption continued with a sustained Strombolian phase, which generated a widespread scoria and lapilli deposit around the main vent that covered most of the proximal phreatomagmatic products and gave rise to the main cinder cone. The eruption ended with an effusive phase that generated two lava flows that breached the north-western flank of the cinder cone, one of which emplaced southwards for more than 12 km (Fig 8). Most of the lithic clasts contained in the phreatomagmatic deposits of Puig d'Adri correspond to red sandstones and marls from the Eocene Bellmunt Formation, which once again indicates the significance of this unit as a regional aquifer. This unit is located several hundred metres below Puig d'Adri (Pedrazzi et a., 2016) (Fig. 9).

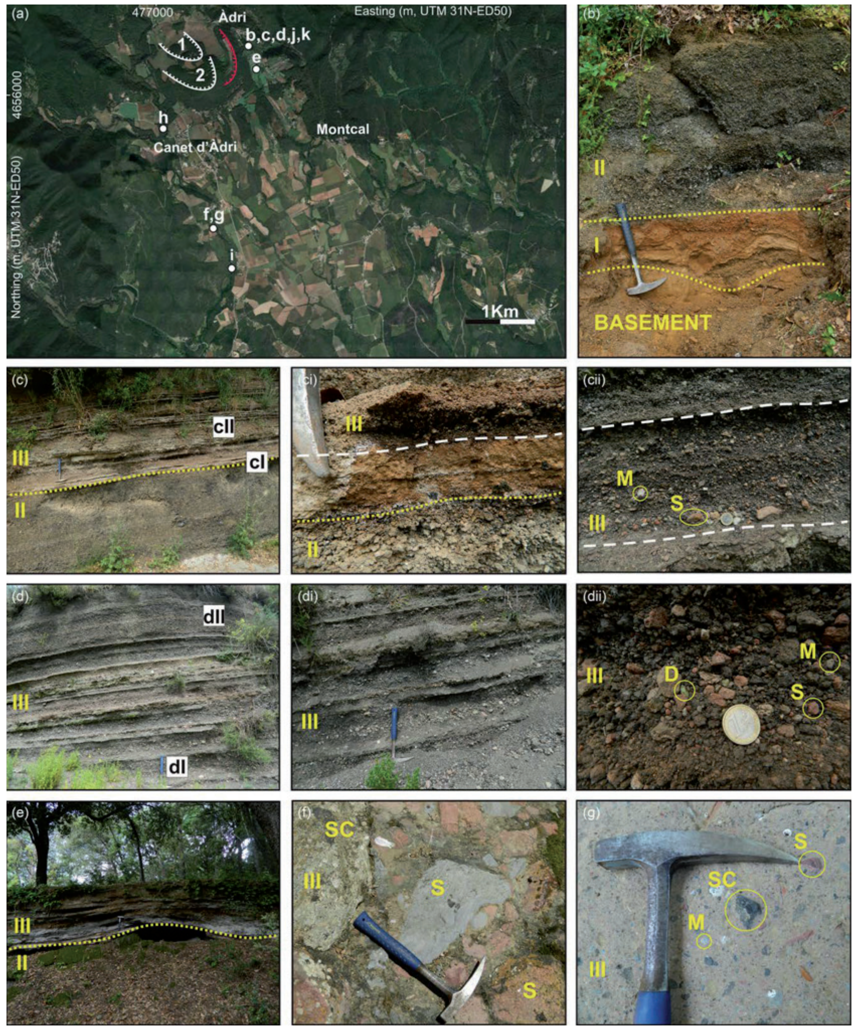

Figure 9. Field photographs of the units with views of details. (a) Google Earth image (2016-Instituto Geografico Nacional) with the locations of the field pictures. 1 and 2, scoria cones; dotted line indicates the ring. (b) Contact between Unit I (mainly characterized by massive deposits) and the basement and between Units I and II. (c) Unit II with juvenile basaltic vesicular black scoriae and the lower part of Unit III characterized by couplets of fine-grained lapilli layers with intercalated, well-sorted layers of coarse lithic-rich lapilli; (cI) detail of the stratified deposits; (cII) detail of coarse lapilli deposits. (d) Unit III: (dI) detailed pictures of Unit III; (dII) detailed picture of lithic content inside Unit III. (e) Distal laminated deposits with undulate structures belonging to Unit III in direct contact with Unit II. (f) Unit III, detail of the flow deposit with lithic content. (g) Detail of the lithic content of the pyroclastic flow. (h) Planar contacts between flow units of the pyroclastic flow. (i) Small laminated layer that forms the lower part of the flow with an erosive base resting directly on the sandstone–conglomerate basement. (j) Upper part of Unit III; (jI) contact with Unit IV characterized by (jII) lithic-rich vesiculated deposits. (k) Transition between lithic-rich deposits and pure scoriae deposits belonging to Unit IV. Roman numerals and dotted lines refer to the stage of the eruption; dashed lines outline the various pulses; L, limestone; M, marls; S, sandstone; SC, scoria. (modified from Pedrazzi et al., 2016).

In the Puig d'Adri Strombolian cone we started to implement the use of geophysical surveys, especially the ERT method published in Barde Cabusson et al. (2013). This geoectrical technic is a powerful tool for the study of the internal structure of monogenetic volcanoes, allowing us to understand the hide facies of this volcano from their physical properties (Barde-Cabusson et al., 2013). Combining these indirect methods with complementary surface geological observations, we could highlight various elements of the structure of these volcanoes and evidence several types of volcanic products such as spatter deposits in the central part of the cones, contrasts between hydromagmatic and Strombolian deposits, buried lava flows, the eruptive vents and conduits. (Fig. 10) (Barde-Cabusson et al., 2013).

The detailed structural and geological interpretation of such data is a valuable contribution to enhance knowledge about volcanic structures in monogenetic volcanic fields and allow us to understand the role of the basement in eruptive dynamics. (More information in Barde-Cabusson et al., 2013).

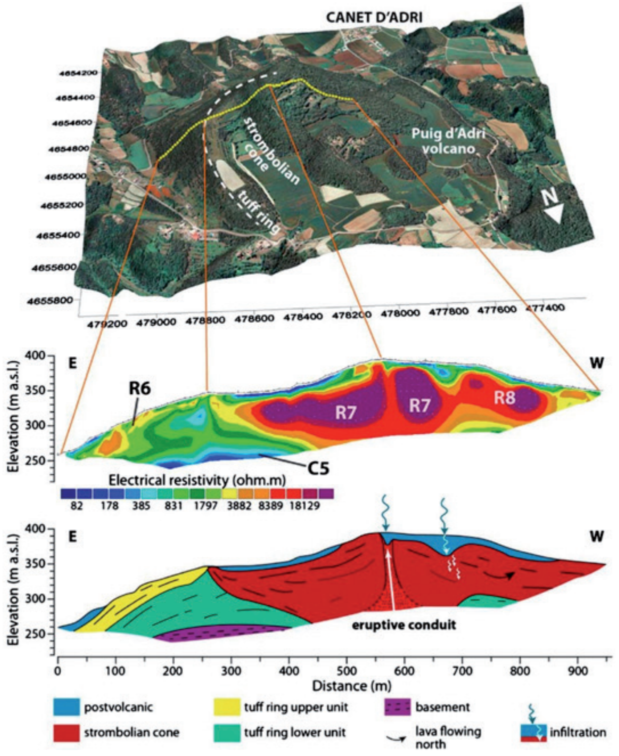

Figure 10. The Puig d'Adri volcano, a complex monogenetic volcano built by hydromagmatic and Strombolian activity. Orthophotography overlaid on a digital elevation model with localization of the ERT profile (yellow dotted line). Central image ERT profile. R and C stands for resistive and conductive units respectively. Lower image geological cross section of the Puig d'Àdri interpreted. (Modified from Barde-Cabusson et al., 2013).

The main stop of this volcano will be the basaltic ignimbrites (massive pyroclastic flow deposit) at Font de la Torre (Fig. 11). Here, it forms a 25-m-thick succession of massive flows units, each 1–5-m thick, with planar contacts, crude columnar jointing and strong induration due to post-emplacement cementation processes. These deposits contain large lithic clasts of Eocene rocks, up to 1 m in diameter, and decimetric juvenile highly vesiculated scoria fragments, immersed in an abundant fine-grained matrix composed of small lithics and juvenile clasts that has been mostly transformed into clay aggregates, zeolites and iron oxides. Lithic clasts tend to show normal grading, while the largest juvenile fragments show reverse grading. Columnar jointing has permitted the vertical erosion of the deposit by pervasive infiltration of meteoric water along the joints (Fig. 11). (More information in Martí et al., 2017a).

Figure 11. Basaltic ignimbrite deposits of Font de la Torre outcrop.

We infer, in Martí et al. (2017a), that these basaltic ignimbrites were derived from transient phreatomagmatic episodes occurring during Strombolian eruptions whose dynamics suddenly changed and gave rise to a substantial increase in their explosivity and mass flow rate. This generated overloaded eruption columns that immediately collapsed, forming the flows that emplaced chiefly along the main valleys and gullies (Fig. 12). These pyroclastic flows achieved velocities of several metres per second, with run-out distances of up to 6 km from the vent, and were deposited at relatively high temperatures (up to 550 °C). The fact that the resulting deposits present very similar features to medium-to-low-volume silicic ignimbrites implies that despite the differences between their eruptions dynamics and nature of juvenile components, the transport and depositional mechanisms in both types of volcanic processes were similar. Eruptions with these dynamics and capable of producing such deposits thus represent an inherent and significant hazard in monogenetic basaltic volcanism, which is traditionally assumed to represent only a low threat (Martí et al., 2017a).

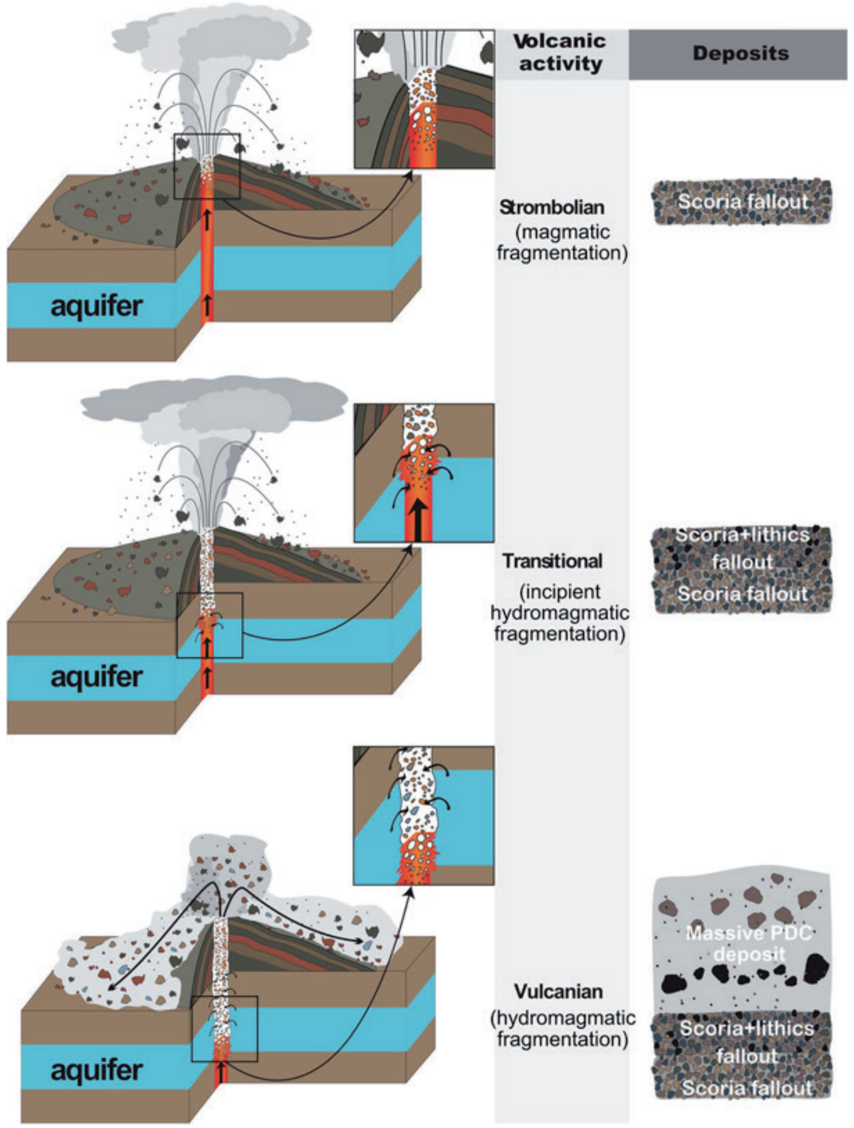

Figure 12. Interpretative sketch of the eruption mechanisms that generated the basaltic ignimbrites in La Garrotxa Volcanic Zone. In all cases of ignimbrite deposits observed in the GVF, the succession of deposits is very similar, which suggest a common eruption mechanism for all of them. These eruption phases were preceded by pure Strombolian magmatic episodes, characterised by magmatic fragmentation and formation of scoria fallout deposits. Progressively magma/water (from the Eocene aquifer) interaction started giving rise to the initiation of hydromagmatic fragmentation and the incorporation of lithic clasts from the Eocene aquifer in the scoria deposit. The phreatomagmatic character of the eruption suddenly increased due to a more effective magma/water interaction, generating vulcanian explosions that gave rise to the formation of overloaded eruption columns, rich in scoria fragments and lithic clasts from the Eocene aquifer and the substrate rocks above it. These eruption columns collapsed very rapidly, forming dense PDCs mostly emplaced down the main valleys and gullies. The transport and deposition of these dense basaltic PDCs occurred in a similar way as some small-volume silicic ignimbrites, giving rise to the same facie association as that first described by Sparks et al. (1973) (see Martí et al., 2017a for further explanation).

STOP 3: The open fossil excavation of the Camp dels Ninots Pliocene maar crater.

Back to Canet d'Adri we will make a 30 Km trip to Camp dels Ninots maar diatreme volcano in Caldes de Malavella, which is half an hour driving. From Canet we successively follow roads GIV-5313 and GI-531 towards Girona. After 9 km driving, when road GI-531 gets to the surroundings of Girona we'll came across the access to AP-7 highway (Domeny roundabout). We take the fourth exit of the roundabout where the AP-7 toll is found (Barcelona direction). We follow AP-7 for some 7 km until exit at km 65.5, where we follow the way to Barcelona through N-II A2 road. After some 20 km we take exit 700 to road GI-673 (Caldes de Malavella). We follow this road to Caldes de Malavella for some 3 km and when we are arriving close to the surroundings of the village we take a roundabout with a monument and letters indicating 'Camp dels Ninots'. From there we follow Carrer de Ramon Muntaner 500 m until it's end, where a junction with Carrer de la granota its found. We turn left and after 340 m we are at Camp dels Ninots (coordinate points lat. 41°49'55.90"N, long. 2°47'57.16"E).

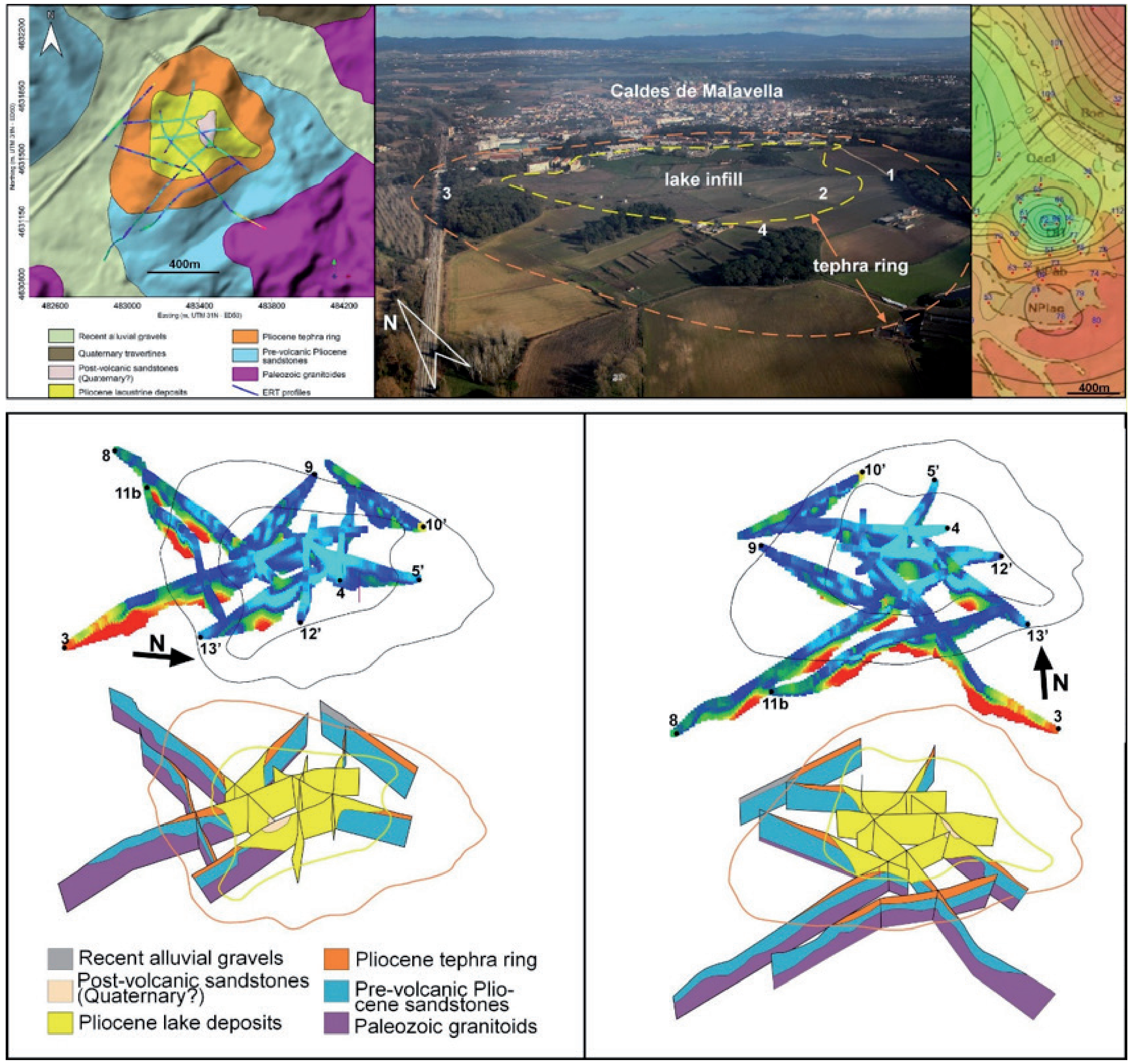

Figure 13. Geology of CNMD (Oms et al. 2015, modified). Top right: geological map and location of transects in bottom plots. Top centre: aerial view (see Fig. 14 for 3 and 4 outcrops and 2 or Can Argilera section). Top right: gravity survey, with the concentric anomaly depicting the maar-diatreme. Bottom: 3D grid of electric resistivity tomographies.

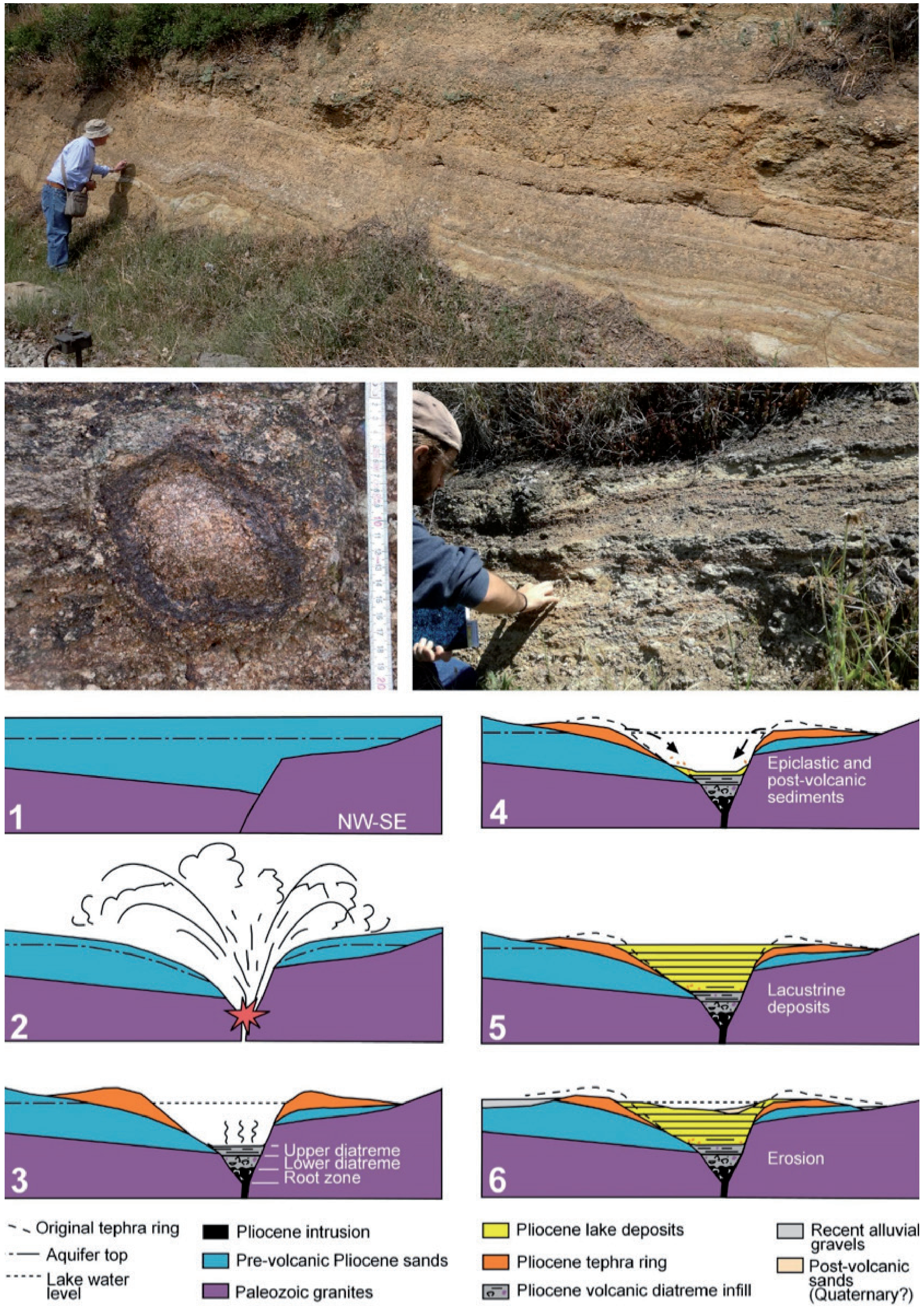

Figure 14. Top: tephra ring by the railroad (top) and Can Tranquil (middle, with granite lithic to the left and lapilli to the right). Bottom: CNMD formation stages from pre volcanic context to present day morphology (modified from Oms et al., 2015).

Once arrived at Camp dels Ninots (number '1' in top center picture in Fig. 13) we have a nice view of the la Selva Basin (lowlands), the Montseny Massif (to the west) and the Camp dels Ninots Maar Diatreme (CNMD) volcano. At this point we are located at the border between the tuff ring and the diatreme lacustrine infill. This last one is basically built up by soft mudstones where the adjacent cereal crops are found. Forests basically grow on the tuff ring substrate. From here we can also access to informative signs spread throughout the CNMD and some small scattered outcrops of the tuff ring (Fig. 14). This viewpoint is very close to Can Argilera excavations (number '2' in top center picture in Fig. 13). Such site (see Figs. 15 and 16) is the most important in the Camp dels Ninots, but is only accessible during excavation works. Further information can be found in the conservation laboratory located in the future interpretation center AQUAE (a research and socialization centre, see Fig. 17) located at Carrer Sant Grau, hosting the exhibition 'Camp dels Ninots ara fa 3,5 Ma'.

The Camp dels Ninots Maar diatreme is located just SW of Caldes de Malavella village (see Fig. 13). The name of this location refers to the field (camp) where dolls (ninots) are found, which in fact are menilitic opal nodules with peculiar shapes that form as silicifications within lascustrine sediments. CNMD is also found along a border fault of la Selva Depression (see Fig. 5), as is the case of the La Crosa de Sant Dalmai volcano visited in stop 1 (see Fig. 1). In CNMD, volcanic features are hardly visible on surface, and its main interest is related to the maar lake and its paleontological content. The area was already the goal of several scientific investigation since Vidal (1882) who attributed them to a lacustrine origin the sediments at Camp dels Ninots, but no volcanic structure was considered. The work by Vehí et al. (1999) first identified lacustrine sediments to be the infill of a maar volcano.

Apart from lacustrine rocks, the geology around CNMD (see Fig. 13) also include two kinds of prevolcanic rocks: basement rocks (granites and few schists) of Late Carboniferous – Permian age and Pliocene arkose sands, clays and gravels of the La Selva Basin alluvial fan systems that may be up to 150 m thick (see details in ICC, 2006). Under a hydrological point of view, basement rocks and Pliocene sands contain a fractured rock and a porous aquifer, respectively. At CNMD the contact between these two geological units is a fault zone that recharges the Pliocene aquifer (see Folch and Mas-Pla, 2008). The geology of post volcanic rocks, include those infilling the maar diatreme (both igneous and lacustrine) and Pliocene (?) to Holocene surface formations. Among these last there is a slope wash layer that is generally less than 0.5 m thick has been dated by Optically Stimulated Luminescence (OSL) at 16.795 years BP (Gómez de Soler et al., 2012b). Also, to the North and West of the tephra ring Post volcanic sediments are recent gravels related to the present day fluvial network. Some 400 meters to the northeast of the tephra ring, recent travertines are also found.

As seen in Fig. 14, CNMD was built in two different substrates (i.e. soft and hard mixed setting) as a result of its location in a normal fault separating the Neogene sediments from the Paleozoic granites. In order to characterize the internal structure and post-eruption stratigraphy of the maar-diatreme, Oms et al., (2015) integrated geological mapping, core logging, description of the tephra ring outcrops and near-surface geophysics, including 9 transects of electric resistivity tomography and a gravity survey. The deeper part of the diatreme is excavated into granites and is relatively steep and symmetrical. The uppermost diatreme is asymmetrical because of mechanical contrast between granites and Pliocene sands. In surface, the resulting present-day crater has a diameter of 400 m.

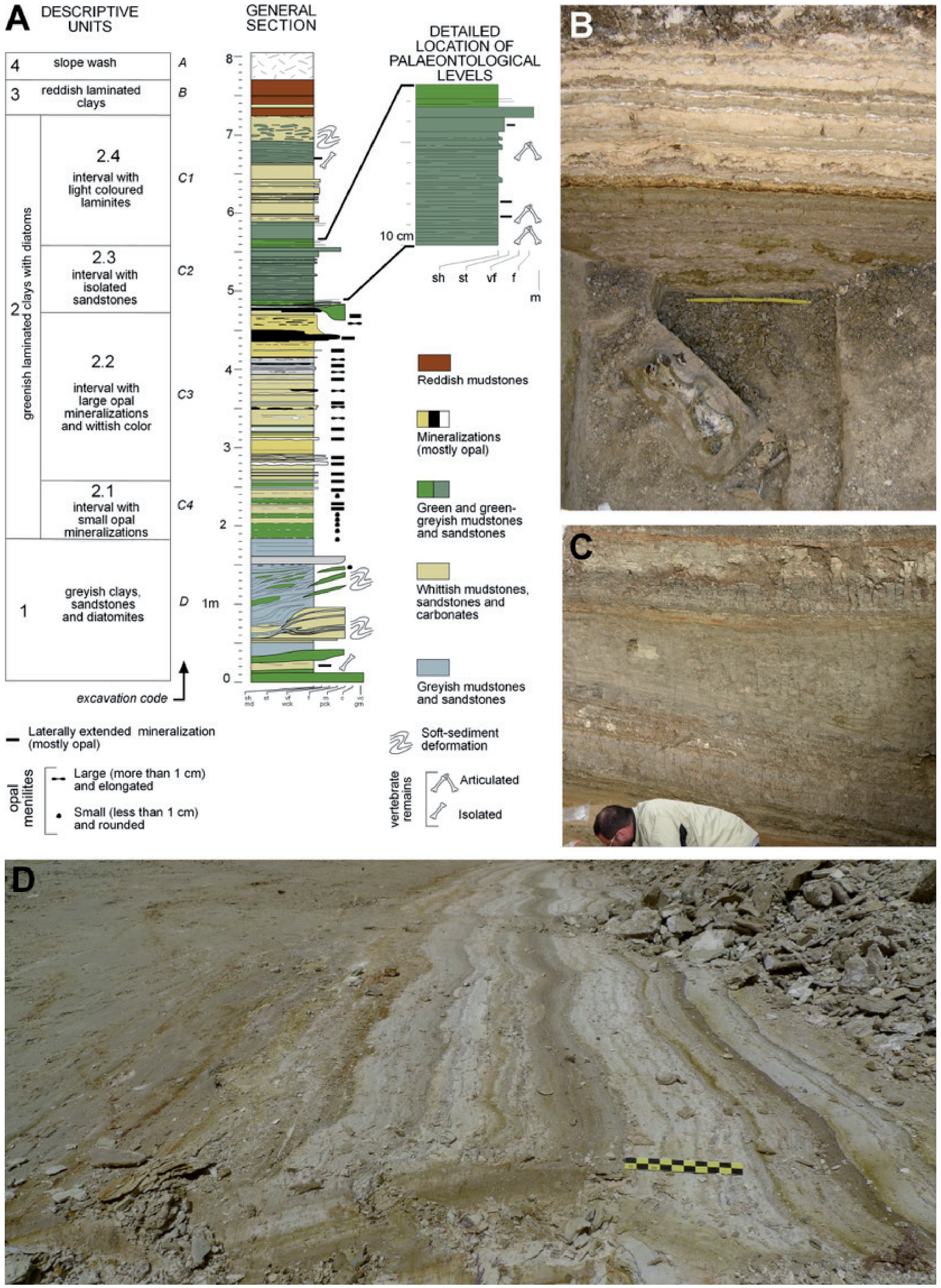

Figure 15. Lacustrine sediments at the Camp dels Ninots. A: Can Argilera section (Gómez de Soler et al., 2012a). B: section adjacent to Can Argilera, with laminated greenish claystones and whitish carbonates (rhinoceros femur isolated at the trench bottom, where a slump deposit is observed). C: laminated claystones and carbonates interrupted (middle of the picture) by a mass transport complex. D: laminated carbonates and claystones at the petrol station trench (bedding dipping to the left).

Tephra ring outcrops (see Oms et al., 2015 and Fig. 14) show generally poorly sorted, lithic rich medium-thick (10-30 cm) beds of lapilli and breccia with some thin (1-10 cm) beds of poorly sorted medium-coarse lapilli with weak lamination. These deposits are made of block- and lapilli angular and subangular prevolcanic lithic clasts (granite), some of which have partly or totally oxidized surfaces. Poorly vesicular juvenile scoria fragments are also found. The interstitial matrix is made of juvenile coarse lapilli to coarse ash and the same pre-volcanic accidental lithic clasts. The largest lithic clasts, up to 40-50 cm in diameter are angular to subangular granite blocks. Subordinate juvenile fragments are up to 50 cm as well. Laminated deposits consist of beds of poorly vesicular scoria of fine lapilli with subangular accidental lithic clasts (granites) up to a few centimeters in size. Within beds, planar and low-angle cross-laminae can be locally observed.

Four main lithologies observed at the trenches of CNMD lacustrine infill. First one is green-to-grayish mudstones that are generally laminated. They are formed by claystone submilimetric layers that alternate with similar sized dolomite layers. These clays contain abundant diatoms and some clastic grains. A second group are dark mudstones resembling the previous group but with rare dolomite laminae. A third group are whitish carbonates, both laminated or massive dolomite crystals of early diagenetic origin. They can be both indurated or rather loose, and few calcite layers are observed. A fourth group are opaline nodules that are usually dark in colour and irregularly shaped (planar and semi-spherical). Opaline nodules (Miró et al. 2016b) range from amorphous opal to cristobalite and tridymite opal, and usually appear as microspherules.

Sedimentary data obtained from trenches is complemented with scientific coring and logging, including those wells at Can Cateura (75 m, drilled in 2009, see Jimez Moreno et al, 2013), Can Pla 1 and Can Pla 2 (112.8 and 145 m, respectively, drilled in 2015). Can Pla wells contain borehole imaging and logging, which have been successfully combined to characterize volcanic deposits and sedimentary facies, especially in cases of low or no core recovery (see Bolós et al., 2016 and Miró et al. 2016a). The study of these boreholes and coring reveals interesting information to understand the igneous infill processes of the CNMD. The igneous infill includes a progressive transition from the dike intrusion to vesiculated magma to welded pyroclast and to country rock-rich breccia (the main section of the diatreme). Such rocks will shed light to diatreme formation models from the information of the inner diatreme deposits that suggest several inter-diatreme explosions in different depth levels during the maar eruption.

The maar crater contained a lake permanently isolated from the surrounding relief, and was deep enough to host anoxic bottom waters while its margins had shallower waters. These lake conditions preserved the remarkable Pliocene fossil record found in the lacustrine sediments. First paleontological from the lacustrine sediments at CNMD was reported by Vicente (1985), but recent research at this locality, starting in 2003, lead to the discovery of a large amount of Pliocene fossils. The macrovertebrates are the most impressive fossils (see Fig. 16) and are represented by tapirs (*Tapirus arvernensi*), bovids (*Alephis tigneresi*) and rhinoceros (*Stephanorhinus cf. jeanvireti*). Turtles are represented by the species Mauremys leprosa and *Chelydropsis cf. pontica*. The fossil assemblage is completed with amphibians like sharp-ribbed salamander (*cf. Pleurodeles sp.*), webbed newts (*Lissotriton aff. helveticu*s) and green frogs (*Pelophylax sp.*), the freshwater fishes of the group of cyprinids (*Leuciscus sp. and Luciobarbus sp.*) and isolated remains from rodent *Apodemus atavus* (Gómez de Soler et al., 2012a; Claude et al., 2014; Prikryl et al., 2016). All this fauna allows us to study the environment and the relationships between these different animal species. The coexistence of *Stephanorhinus cf. jeanvireti and Alephis tigneresi*, and the paleomagnetic data obtained from all the stratigraphic sequence of the maar, give us a normal polarity (Gauss) for all the sequence with two inverse changes (Kaena and Mammoth), with a sedimentation rate that took place in 200 ka, situating the fossils layers in 3.1 Ma, near the MN15 and MN16 transition (Jiménez-Moreno et al., 2013). The flora is abundant and is composed by vegetal macroremains as leaves imprints, fruits and trunks in the lacustrine clays and pollen remains captured in the sediment. These data correspond to a subtropical climate and landscape, plenty of laurisilva Forest. Pollen data from Can Cateura well (Jimenez-Moreno et al., 2012) provided an excellent record which is a reference one for the European Pliocene. Preliminary data on diatoms also shows a large potential for paleocological studies. The large amount and variability of the recovered paleobiotic assemblage and its good preservation, enable us to consider the site as a Fossil-Lagerstätte. Its exceptionality offers a unique opportunity to study an ecosystem during the Pliocene, and provides paleoenvironmental data for understanding the dynamics of climate changes developed until today.

Figure 16. Paleontological record at Camp dels Ninots. Top left: bovid Alephis tigneresi in anatomical connection excavated in 2011 at Can Argilera. Top right: The same species at pit 13 in Can Cateura (discovered in 2011 and excavated in 2017). Bottom: Camp dels ninots reconstruction by Mauricio Antón, with tapirs Tapirus arvernensi, bovids Alephis tigneresi and rhinoceros Stephanorhinus cf. jeanvireti.

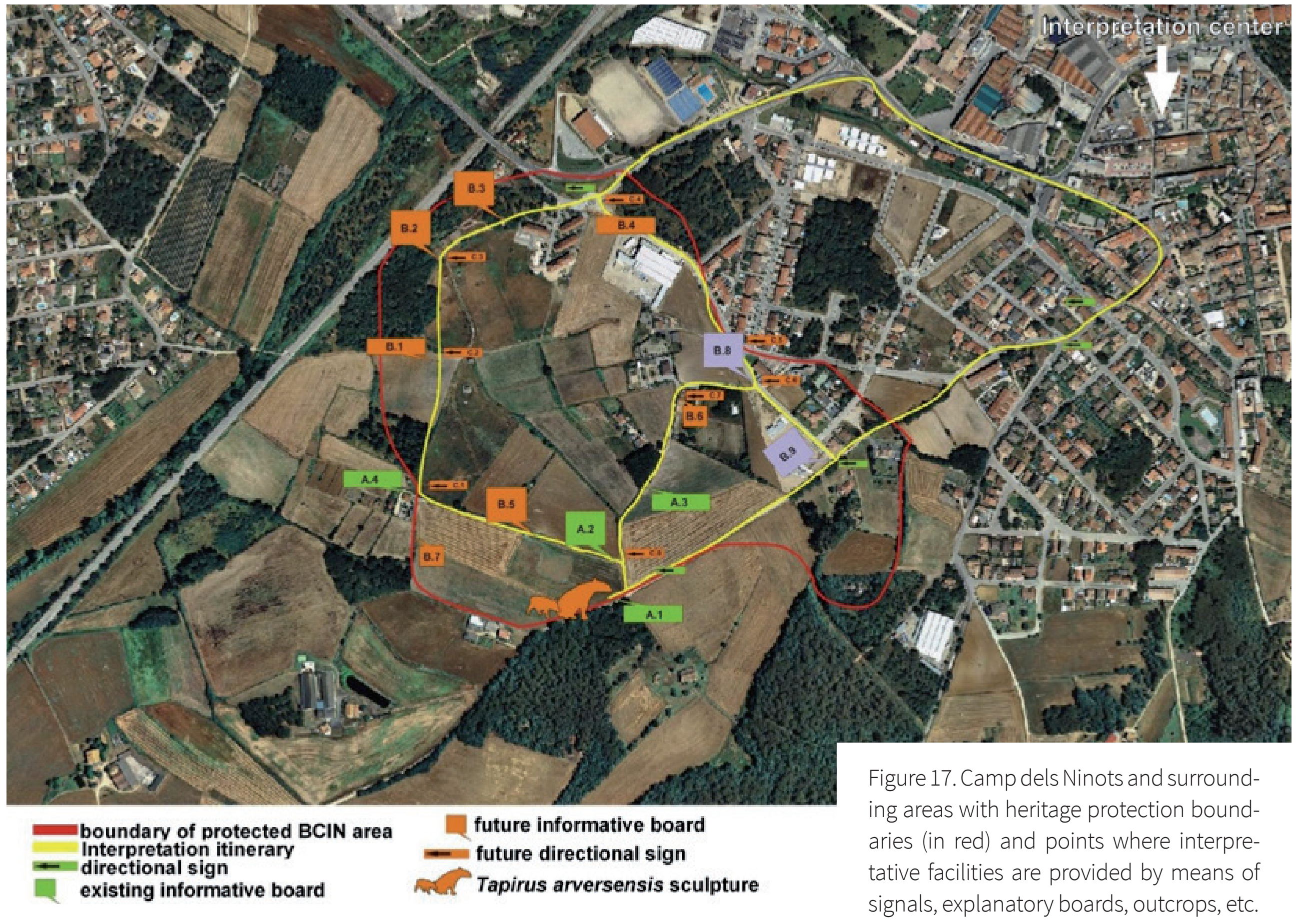

Figure 17. Camp dels Ninots and surrounding areas with heritage protection boundaries (in red) and points where interpretative facilities are provided by means of signals, explanatory boards, outcrops, etc.

DAY 2

Montsacopa complex scoria cone, Rootless volcanic cones, lava flows and Phreatomagmatic deposits of Cairat maar volcano.

STOP 4: Montsacopa complex cinder cone.

Montsacopa is one of the five volcanoes that stand inside the city of Olot. It rises right in the heart of the city, between the volcanoes of La Garrinada to the north-east and Montolivet to the south-west; on its summit stands the chapel of Sant Francesc, built in the nineteenth century, and two watch-towers. In this stop of the field trip, the group will visit Olot the bottom of the cone corresponding to a huge outcrop that was an old quarry, next to cemetery of Olot, and then, the group walk up to the phreatomagmatic crater at the top of this volcano (Fig. 18) (Barde-Cabusson et al., 2014; Bolós et al., 2014b).

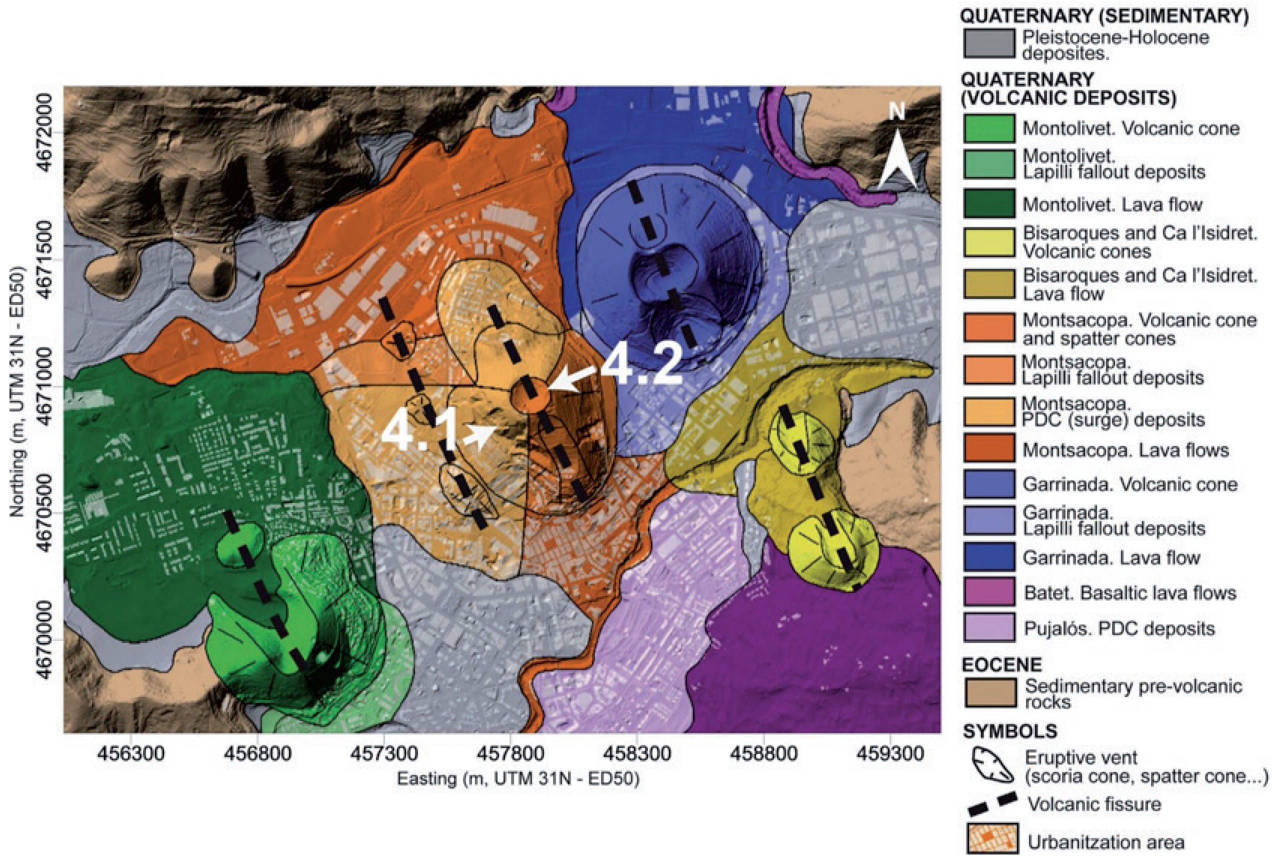

Figure 18. Geological map of the city of Olot and the location of the sub-stops.

This volcano consists of a single, regular-shaped cinder cone (Fig. 18 and 19). The construction of this cone involved an initial Strombolian phase and a final phreatomagmatic phase whose deposits are well exposed in the quarry behind the cemetery (Stop 4-1) (Fig. 18 and 20) (Martí et al., 2011; Bolós et al., 2014b).

Figure 19. Photograph of the Montsacopa volcano. Credit Pep Callís.

The succession of deposits in this outcrop is composed of a lower, 20-m-thick dark unit formed by well-stratified scoria with alternating layers and different grain sizes, some including centimetric-sized bombs. It is topped off by a 15-m-thick upper brown-to-pale unit formed of thinly stratified pyroclastic surges and fallout deposits with a high content of lithic clasts (Fig. 20).

Figure 20. Field photographs showing Montsacopa deposits and their stratigraphic relationships. Top: onformable 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).

We identified from direct and indirect methods (Fig. 21) (Bolós et al., 2014a, b), that the construction of this volcano resulted from a multi-vent eruption. In total we identified up to five different vents at Montsacopa: a central cone and crater, which was the only previously known cone, two other vents whose products are mostly covered by those emitted from the main crater, and scoria deposits that were generated by two further vents (Fig. 21). This multi-vent eruption included Strombolian and phreatomagmatic phases that generated a large variety of deposits, including fallout, ballistic ejecta, pyroclastic density currents and lava flows.

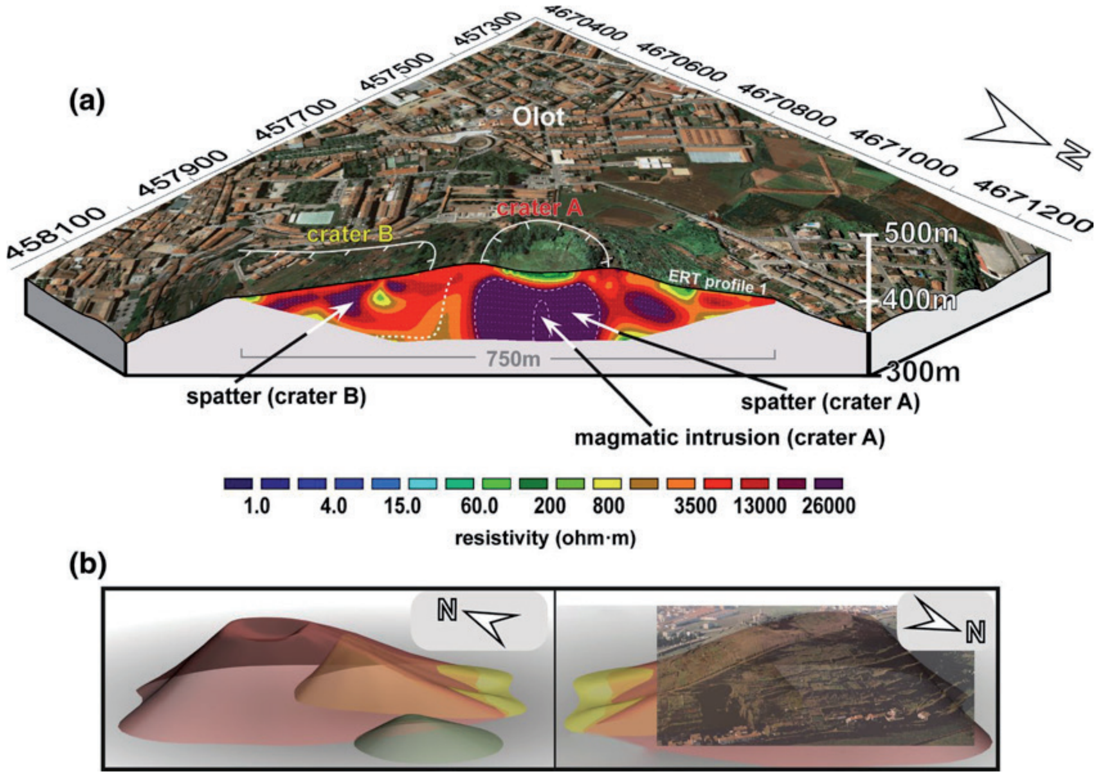

Figure 21. Orthophotograph overlaid on a 3D block diagram of ERT profile 1 corresponding to Montsacopa volcano (RMS error 5.7 %). b 3D interpretation model showing the overlapping cones inside the edifice. Coordinates in UTM—31 N—ED50. (Bolós et al., 2014b).

The stop 4-2, the group will walk around the crater lip enjoying the excellent views of La Garrinada, Montolivet and Bisaroques, three of the other volcanoes in Olot. To the north-east stand the three craters of La Garrinada (Stop 8): at the base of this volcano the first crater, part of a tuff ring that formed during a phreatomagmatic phase, is visible. This crater is almost completely covered by the cinder cone constructed during the subsequent Strombolian phases, which also gave rise to the other two craters that appear on top of the volcanic edifice, one on the southern side and the other on the northern side. Montolivet lies to the south-west of Olot and consists of a cinder cone embedded in the slopes of the mountain of La Pinya with a crater opening north-eastwards. Bisaroques to the south-east sits on the northern slopes of the Batet plateau and, like Montolivet, has a horseshoe-shaped crater (Fig. 18).

STOP 5: Rootless volcanoes and tumuli lava field of Bosc de Tosca.

Tossols is the local name that refers "rootless volcanic cones". The name refers to the fact that, rather than corresponding to a fissural conduit through which magma rises and provokes an eruptive episode, they are the product of the interaction between a lava flow and an area of humid sediments. Tossols are an uncommon phenomenon on Earth, only appearing on very few lava flows, and to date have been described from Iceland and the United States (Planagumà and Bolós, 2016; Bolós et al., in prep.). Curiously, certain morphological formations on frozen sediments on the planet Mars have also been described as rootless volcanic cones, a discovery that suggests that the conditions needed to form them are highly complex (Planagumà and Bolós, 2016). Rootless volcanic cones form when a lava flow runs over a wetland or area of marshes. The humid sediments heat up as they come into contact with the lava and generate steam. The steam then rises up under the lava flow through the fractures that appear as the lava cools and provokes small-scale eruptions that deform the surface of the lava flow (Fig. 22) (Bolós et al., in prep)

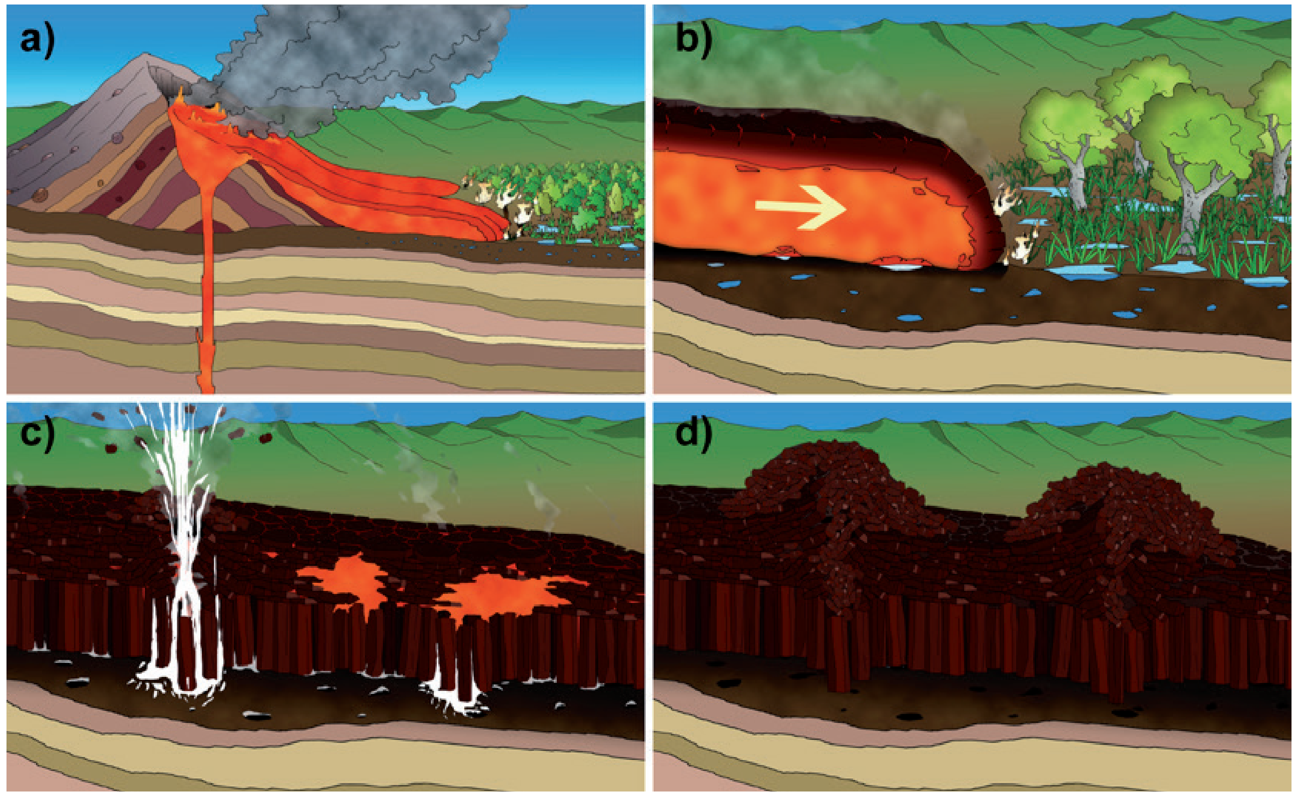

Figure 22. Formation and evolution of the rootless volcanic cones (tossols) (Planagumà and Bolós, 2016).

La Garrotxa volcanic field has around 40 superficial lava flows, mostly with aa morphology (i.e. malpais with rough surfaces and block lavas), although there are also some pahoehoe morphologies (smooth lava flows) in areas such as Batet de la Serra. Of these 40 lava flows, only five have morphologies that can be associated with rootless volcanic cones (tossols), and all have three elements in common: i) they erupted in periods of much cooler climate than the current period, ii) extend over a relatively flat area due to the barrage effect of other lava flows, and iii) they are less than 25,000 years old. Other lava flows with rootless volcanoes may exist but could have been eroded away or buried underneath other lava flows or sedimentary deposits generated by the barrage effect that lava flows have on local rivers. In all, 230 tossols have been identified, and just on the Bosc de Tosca lava flow—situated between the volcano of Puig Cabrioler and the river Fluvià—there are around 110 tossols (Fig. 23, green lava flow). As well, tossols have formed all along the lava flow emitted by the volcano of Puig Jordà that has been dated at the Fonts de Sant Roc as being around 17,000-years old (Planaguà and Bolós, 2016; Martí et al., 2017b, c).

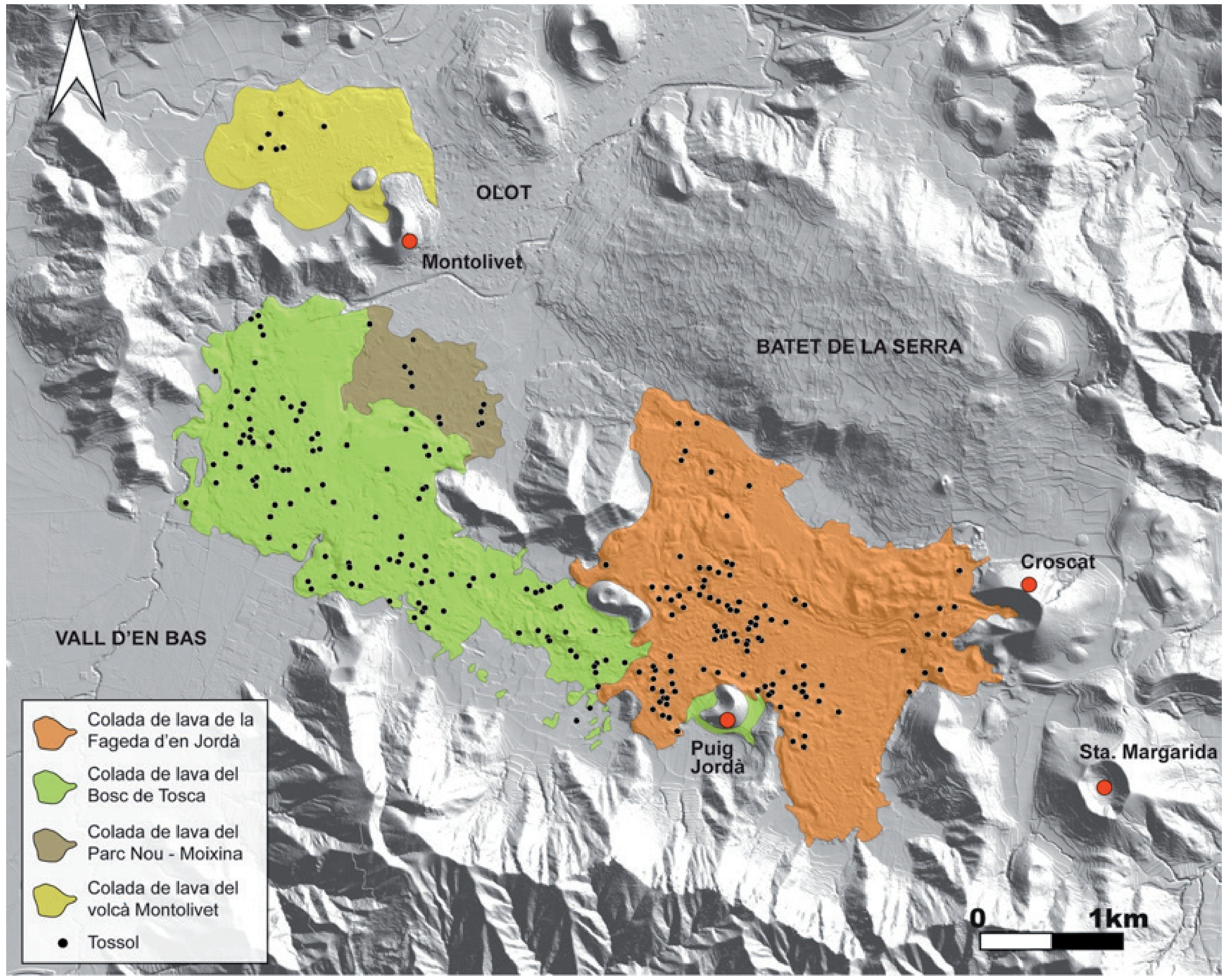

Figure 23. Lava flows with rootless volcanic cones in the Garrotxa volcanic field. Black dots corresponds to rootless volcanoes (tossols). (Planagumà and Bolós, 2016).

The lava flow on which the Fageda d'en Jordà stands was generated by effusive emissions from the fissural eruption that formed the volcanoes of Croscat, Santa Margarida, Turó de Can Xel and several small associated spatter cones (Fig. 23, orange lava flow). The eruptive activity had different explosive Strombolian and phreatomagmatic phases, and a final effusive phase caused by the degasification of the magma. This effusive phase gave rise to an aa- type lava flow that spread across the marshy plain created by the barrage effect of older lava flows in the area. This lava flow is characterized by a profusion of small hillocks, of which 103 are tossols. Most are distributed in the distal part of the lava flow, furthest away from the crater. The Montolivet lava flow crosses and forms the plain known today as Pla de Dalt (Fig. 23, yellow lava flow). The date of this eruption is unknown, although a relative date has been calculated based on the fossil fauna found under a layer of pyroclasts thought to have originated from this volcano. This fauna was typical of the region at about 9500–18,000 years ago. This lava flow spread across a flat valley generated by the barrage effect of the different lava flows that exist in and around Olot. In all, seven tossols have been identified that had already been mapped at the beginning of the nineteenth century. The structure of these tossols is very similar to those from the Bosc de Tosca (Stop 5).

The origin and age of the Parc Nou-La Moixina lava flow are unknown. It lies partially underneath the Puig Jordà lava flow and thus must be at least 17,000-years old. In all, 10 tossols have been catalogued from this lava flow (Fig. 23, brown lava flow).
On all of the studied lava flows, the rootless volcanoes are a material resource that has been quarried for the rocks they contain. This provided local inhabitants with a good supply of stone that could be worked into blocks that were lighter than other local rocks due to the vesiculation (large pores) present in these volcanic rocks (Fig. 24).

Figure 24. Inlet at the upper an example of rootless volcanic cone (tossol) in the area. The lower picture corresponds to facia-type of the inner part of a rootless volcanic cone. (modified from Planagumà and Bolós, 2016).

The first attempts to build using rocks of this sort date from the seventeenth and eighteenth centuries and include the Collell bridge and the enlargements of certain farm- houses permitted by the economic prosperity of the time. These rocks were used almost to the end of the nineteenth century and, for example, the Fonts de Sant Roc (1883) were built from stone extracted from the inside of a tossol.

Consequently, most tossols were converted into quarries that were then used to supply stone for the building of houses and public buildings. One of the best sites in the area for seeing tossols is the Bosc de Tosca (formerly known as Vora Tosca or Malatosquera), an area situated to the south of the city of Olot and north of Les Preses, and part of the La Garrotxa Volcanic Zone Natural Park. Its volcanic nature (it lies on the lava flow emitted by the volcano Puig Jordà) makes it unique in the Catalan countries. The Parc de Pedra occupies a small part of the Bosc de Tosca and consists of a labyrinth of paths, dry-stone walls, small pastures, and stone huts whose aspect changes with the seasons. Via the execution of a European LIFE environmental project, the town council of Les Preses managed to rehabilitate this area, thereby restoring, respecting and consolidating the work that had been carried out there 150 years ago (Planagumà and Bolós, 2016; Bolós et al., in prep.)

STOP 6: Rootless volcanoes and tumuli lava field of Bosc de Tosca.

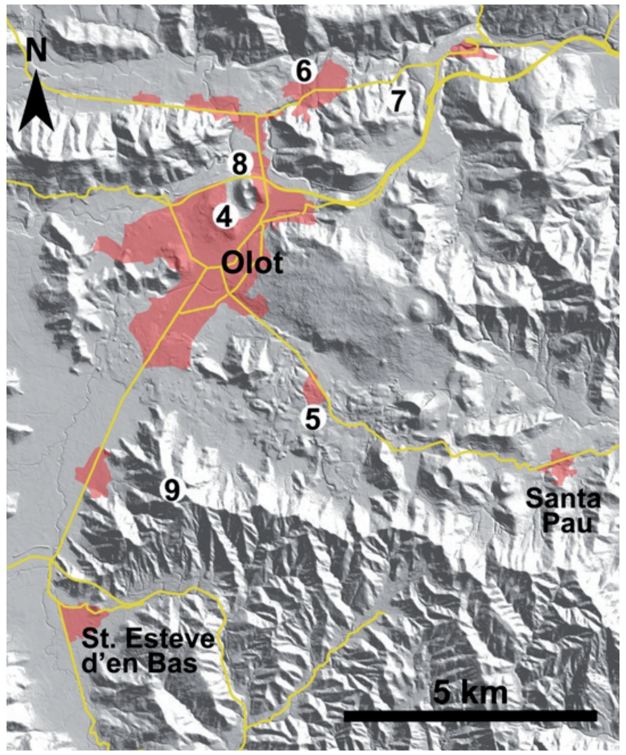

Figure 25. Location of the stops 4 to 9 around the city of Olot. Stop 6 corresponds to the Sant Joan Les Fonts outcrops.

To reach Sant Joan les Fonts from Olot, take the GI-522 road towards La Canya or, if coming from Girona along the N-260, turn right towards Sant Joan just after Castellfollit de la Roca (Fig. 25). To get to the outcrops on foot, follow Natural Park itinerary 16 from the main square in Sant Joan, which is also where you should park.

This Stop (number 6) consists of three separate outcrops near the town of Sant Joan les Fonts that exhibit different aspects of basaltic lava flows: El Boscarró (Fig. 26, left photo), a former basalt quarry that was abandoned in early twenty-first century, stands above the right bank of the Riera de Bianya; the Fontfreda cliff quarry lies alongside the same riera (stream); finally, on the left bank of the river Fluvià at Molí Fondo, water erosion has uncovered another sequence of lava flows (Fig. 26, right photo).

Figure 26. Left: photograph of El Boscarró quarry. Credit Pep Callís. Source Documentation Centre, Garrotxa Volcanic Zone Natural Park. Right: Molí Fondo outcrop with a blaster morphology. Credit Eduard Masdeu.

The Riera de Bianya flows into the river Fluvià at Sant Joan les Fonts. Erosion by these watercourses has uncovered three superimposed lava flows that run along the former beds of these rivers. The extraction of basalt rocks from quarries in the early twentieth century enables us today to interpret the relationships between these three lava flows and their internal structures, and to reconstruct their emplacement history.

At El Boscarró different types of jointing are visible in the most recent of the three lava flows emplaced along the Fluvià valley. Five layers can be distinguished here: the lowest has columnar jointing with 5- or 6-sided columns, 20–40 cm in diameter and 2–3-m high. The second and fourth layers have slab jointing, while between them in the third layer there is massive material with a few cooling cracks. The fifth and final layer, just below the soil level, is far more altered due to its proximity to the surface and has a marked spheroidal structure. North-west from the quarry face, the Riera de Bianya follows the contact zone between the volcanic materials and the reddish Eocene sedimentary materials.
At El Molí Fondo, the first and oldest lava flow lies on the bed of the river Fluvià. To the right of the weir, which was built on this first lava flow, the blue-grey basaltic lava exhibits a degree of columnar jointing. If you walk down-stream along the left bank of the river, the slabs underfoot correspond to the base of the second lava flow. In places rocks stick out and reveal the rough cinder base. On the cliff next to riverbed the remains of this second lava flow with columnar jointing is visible. On top of this lava flow there is a layer of sediment consisting of sandstone and basalt pebbles in a silt matrix. Finally, the third Boscarró lava flow sits on top of this alluvial layer.

The Fontfreda cliffs correspond to the third lava flow, the same one as is visible at El Boscarró. The lowest layer has clear columnar jointing with columns that are over three metres in height, and an area of lenticular jointing above. Unlike at El Boscarró, the transition between these two layers is here obvious.

The geological history of these three outcrops can be deduced from the emplacement of the lava flows. The first lava flow, emitted by the volcanoes on the Batet plateau, followed the old bed of the river Fluvià and filled in part of its basin. However, the river's erosive power gouged out a new riverbed in the lava flow at the same time as it deposited sediments on its surface. Many thousands of years later, the riverbed was occupied by a second lava flow whose origin has not yet been determined. Over time, sedimentary materials (silt, sand and pebbles) were deposited on top of this second lava flow and once again grew to form a river terrace. Finally, about 133,000 years ago a third lava flow from the volcano of La Garrinada was emplaced on top of these fluvial sediments. This lava flow ground to a halt just past the town of Sant Joan les Fonts.

El Molí Fondo was once a paper mill and its history is closely linked to that of the town of Sant Joan. Although the factory dates back to 1723, its most important transformation took place in 1841, when it was purchased by Pere Capdevila. He undertook a large series of reforms and introduced continuous paper milling that signalled the start of the factory's industrial production. Inside El Molí Fondo there is a permanent exhibition that tells the story of this important example of the industrial heritage of the county of La Garrotxa.

STOP 7: Phreatomagmatic deposits of the Cairat maar volcano.

The Pleistocene Cairat maar volcano is located on the eastern flank of the eroded Eocene anticline that limits the Olot depression at the north–east. The Cairat is a maar-type volcano with a crater of 120 m of diameter excavated in the sedimentary Eocene substrate. It is one of the few examples in the studied area nearly exclusively composed of phreatomagmatic deposits (Martí et al., 2011). The pyroclastic deposits that form this volcanic edifice were preferentially emplaced to the north and south of the crater. The characteristics of the deposits and the nature of the abundant lithic clasts they content suggest that most of the eruptive activity of the Cairat volcano involved interaction of the erupting magma with groundwater from the main Eocene aquifer (Martí and Mallarach, 1987). The succession of pyroclastic deposits of the Cairat volcano is composed of a 20 m thick succession of lithic rich explosion breccias and lapilli-sized fallout, and pyroclastic surge deposits (Fig. 27) (Martí et al., 2011).

Figure 27. Phreatomagmatic deposit successions of an outcrop of the Cairat maar.

The main characteristic of this succession of deposits is the presence of abundant lithic clasts from the Eocene sedimentary basement, which in this area is formed (from top to base) by the Banyoles Formation (blue marls), the Bracons Formation (grey sandstones and lutites), and the Bellmunt Formation (red sandstones and lutites). These lithic clasts range in size from a few centimetres up to 2 m. Although the distribution of the largest blocks is rather irregular they tend to concentrate towards the base of the sequence and in some lithic-rich units in the middle and upper parts. Some of the lithics from the Bellmunt Formation are deeply hydrothermally altered. Juvenile fragments are less abundant than lithic clasts and correspond to poorly vesicular scoria lapilli, a few cauliflower bombs, and blocky shaped ash fragments (Fig. 28) (Martí et al., 2011).

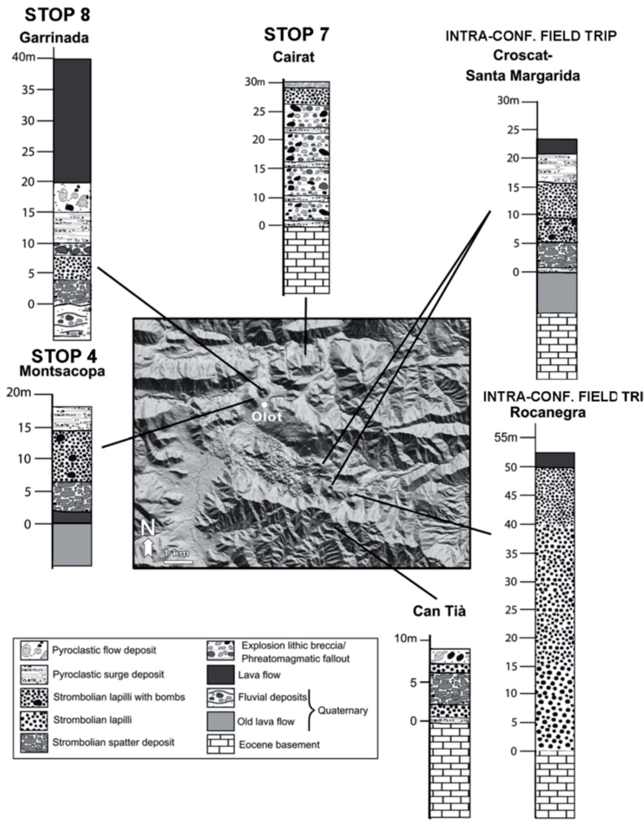

Figure 28. Synthetic stratigraphic sections of some volcanoes of the region (Modified from Martí et al., 2011).

The eruptive activity of the Cairat volcano mostly produced lithic breccias, with a massive emplacement of ballistic blocks, and some more energetic episodes that generated thinly bedded, pyroclastic density currents (Martí et al., 2011). The location of the vent at a hill's crest, with steep slopes at both sides, conditioned the accumulation of volcanic materials which were affected by continuous sliding until they redeposited on a more stable slope. This implied a continuous syn-depositional remobilisation of the original pyroclastic products deposited on the highest parts. At the northern side the products of this continuous debris avalanching were channelised inside a pre-existing gully where they eroded and incorporated part of the non-volcanic sediments that existed there. This also contributed to the large variety of lithic fragments found in these pyroclastic deposits and the chaotic aspect of some of the units. However, it is still surprising the relative significant amount of lithics from the Bracons and Banyoles formations, both older and located stratigraphically deeper than the Bellmunt Formation, the stratigraphic unit that constitutes the main aquifer in this area (Martí et al., 2011). The reason for the appearance in the deposits of this volcano of lithic clasts from stratigraphic levels located below the aquifer that interacted with the erupting magma is purely tectonic, as in this particular site the action of an Alpine thrust caused the inversion of the stratigraphic succession (Martí et al., 2011; Bolós et al., 2015).

DAY 3

Phreatomagmatic deposits the Garrinada volcano and the landscape overview of the Garrotxa Natural Park.

STOP 8: Phreatomagmatic deposits of the Garrinada maar volcano.

It is a fissural cone with three vents aligned in NNW-SSE direction. The cone is 800 m in diameter and 116 m in height. It is the largest and best-preserved cone in the Olot city. The cinder cone lies on a structural flat surface corresponding to the top of the younger lava flow at the Olot plain, which was probably related to the same vent that generated the Garrinada cinder cone (Fig. 18) (Gisbert et al., 2009).

The characteristics of the deposits suggest that the eruption started and progressed for a while being purely magmatic. However, at about the middle the eruption changed into phreatomagmatic due to the interaction of magma with a shallow aquifer located in the Quaternary unconsolidated sediments, as it is evidenced in both cases by the characteristics of the resulting deposits and the nature of the lithic clasts included (Gisbert et al., 2009; Martí et al., 2011). This phreatomagmatic activity produced in both cases several lithic-rich explosion breccias, and pyroclastic density current deposits that represent different magma/water ratios (Gisbert et al., 2009) and at the final stage returned to the magmatic activity with the emission of several lava flows (Fig. 28 and Fig. 29) (Martí et al., 2011).

Figure 29. Phreatomagmatic deposit successions of the Garrinada volcano. (Credit Gisbert et al., 2009).

The substratum of the Garrinada volcano is only known through indirect studies, since the Olot plain is highly urbanized and no important fluvial (Fluvià river) erosive incisions exist on the lava flow and sediment succession that constitutes the Olot valley filling. Most of the available information comes from boreholes, geophysic surveys, and ephemeral outcrops in urbanized areas (Bolós et al., 2014a). Several lava flow intercalations have been detected between marly sediments (mostly lacustrine), pyroclasts and epiclasts, and the coarse deposits of the Fluvià river terraces, showing up to more than 100m of Quaternary sediments overlying the Eocene substratum (Gisbert et al., 2009). These volcano sedimentary successions constitute an excellent multilayer aquifer, with several confined or semiconfined aquifers at the deepest levels that allow to explain the important phreatomagmatism activity of this volcano.

STOP 9: Xenacs landscape overview.

Puig Rodó (909 m a.s.l.) stands at the far western end of the Serra del Corb ridge where you will also find the Xenacs Recreation Area, one of the best viewpoints over La Garrotxa volcanic zone. From here there are excellent views over the main axial Pyrenees, the pre-Pyrenees and the sub-Pyrenees, as well as most of the Olot trough and Vall d'en Bas (valley).

To get there, take the C-152 from Olot and, about 300 m after passing through Les Preses, turn left up a minor road (Fig. 25 - Stop 6). After about 5 km of climb, park in the recreation area's car park. From here, take the signposted path to the Puig Rodó viewpoint. The road up is closed to coaches and to other vehicles on weekdays, but you can apply for a permit from Les Preses Town Council. Alternatively, walk up to Xenacs following Natural Park itineraries 10 and 11, which start from Les Preses.

The track to Xenacs affords good views over the Vall d'en Bas (1) (Fig. 30). This agricultural plain was once a lake: the lava flow that issued from Croscat ran down to the bed of the river Fluvià and obstructed its course, thereby forming a natural dam and lake. Over time, the sediments caused by the erosion of the surrounding slopes silted up the lake, a process that was culminated in the eighteenth century when the plain and its lagoons and marshes were drained for farming.
From Puig Rodó, you can see where Croscat's lava flow spread across the landscape by looking for the wooded areas, mostly corresponding to the D'en Jordà beechwood, which covers this lava flow (2) (Fig. 30).

On a clear day you can see most of La Garrotxa, as well as parts of El Ripollès to the west and El Pla de l'Estany, L'Alt Empordà and the Mediterranean Sea to the east. If you look northwards, you can appreciate: a. Axial Pyrenees (3) (Fig. 30): the mountains in the background, whose highest peaks are covered by snow for most of the year, are made up of ancient Palaeozoic rocks. b. Pre-Pyrenees and sub-Pyrenees (L'Alta Garrotxa) (4) (Fig. 30): chains of mountains between 1000 and 1500 m a.s.l. running south of the Axial Pyrenees. They mostly consist of Eocene rocks that were intensely folded and affected by faulting during the Alpine orogeny. c. The mountains of the Sistema Transversal: these are the closest peaks and include the Serra del Corb (5) (Fig. 30), and are composed entirely of Eocene rocks. They consist of a series of raised and sunken blocks, the product of a system of normal faults. The Collsacabra mountains to the south-west and Puigsacalm (6) (Fig. 30) to the west are the highest peaks in this sector. The low-lying area in the foreground to the north is the Olot trough (7) (Fig. 30). Also visible are the volcanoes of Montsacopa, La Garrinada, Les Bisaroques, Puig Cabrioler, Puig Astrol, El Pujalòs, Puig de la Garça, Croscat, Puig Jordà, Puig de la Costa and Santa Margarida.

The depression bordered by L'Alta Garrotxa to the north, the Serra del Corb to the south, Sant Julià del Mont to the east and Collsacabra and Puigsacalm to the west is known as the Olot basin or trough. In the background and surrounding this depression of tectonic origin stands the majority of the volcanoes in La Garrotxa.

The valleys are all U-shaped since they were filled in by the lava flows emitted during the volcanic eruptions or by sediments that built up in the lakes formed behind the vol- canic barrages. From Puig Rodó you can see almost the whole of the northern sector of La Garrotxa volcanic zone, including 14 of the (8) 40 volcanoes in the Natural Park (Fig. 30). A characteristic feature of the volcanic edifices is their conical shape with craters that are either circular or horseshoe-shaped. They are covered in woodland and almost always stand out from the croplands that encircle their bases. Note also the Batet plateau (9) to the north-east (Fig. 30), which is formed by a superimposition of successive lava flows from the region's oldest—and so now most heavily eroded—volcanoes (Martí et al., 2017c).

Figure 30: Aerial view from Xenacs with the Pyrenees in the background. Credit Pep Callís. Source Documentation Centre, Garrotxa Volcanic Zone Natural Park

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