Intra-Conference *Field Trip*

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Natural Park of La Garrotxa volcanic field: magmatic vs phreatomagmatic activity. The role of the basement to control the eruptive dynamics.

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Introduction

All the attendees to the Conference will visit the Natural Park of la Garrotxa Volcanic Zone. The volcanic landscape of La Garrotxa is one of the most singular scenic areas of Catalonia, a montane landscape articulated by the rivers Fluvià and Ter that possesses a series of outstanding morphological features generated by the area' s Quaternary monogenetic volcanism. The first stop of the field trip is a wonderful view of the Castellfollit de la Roca basalt cliff, which consists of two superimposed lava flows with well-developed columnar jointing. Of note too is the aesthetic and visual effect of the urban architecture of the Medieval village of Castellfollit de la Roca sits atop the volcanic outcrop (Fig. 1, #1).

Then, participants will visit the youngest part of La Garrotxa volcanic field (currently a natural protected area) visiting the Holocene volcanoes of La Pomareda spatter cone (Fig. 1, #2), Croscat cinder cone (Fig. 1, #3), Santa Margarida maar crater (Fig. 1, #4), which lie along a 3-km-long eruption fissure. These volcanic edifices exhibit a diversity of eruptive styles with strong evidence of vent migration during the same eruption and of the existence of different strombolian and phreatomagmatic phases. The last geo-stop of the field trip will be in Rocanegra cinder cone composed of Strombolian fallout deposits (Fig. 1, #5). The whole visit includes a 5 km easy walk through these volcanic sites. Several outcrops present in the area such as the quarry on the Croscat's northern flank are exceptional sites to discuss the evolution of this eruptive fissure and the role of the basement to determine different eruptive dynamics. The field trip will finish in the Medieval village of Santa Pau. Participants can visit its monastery and castle, built on a hillock in the centre of the village, and its square building that was constructed in different phases during the thirteenth-fourteenth centuries.

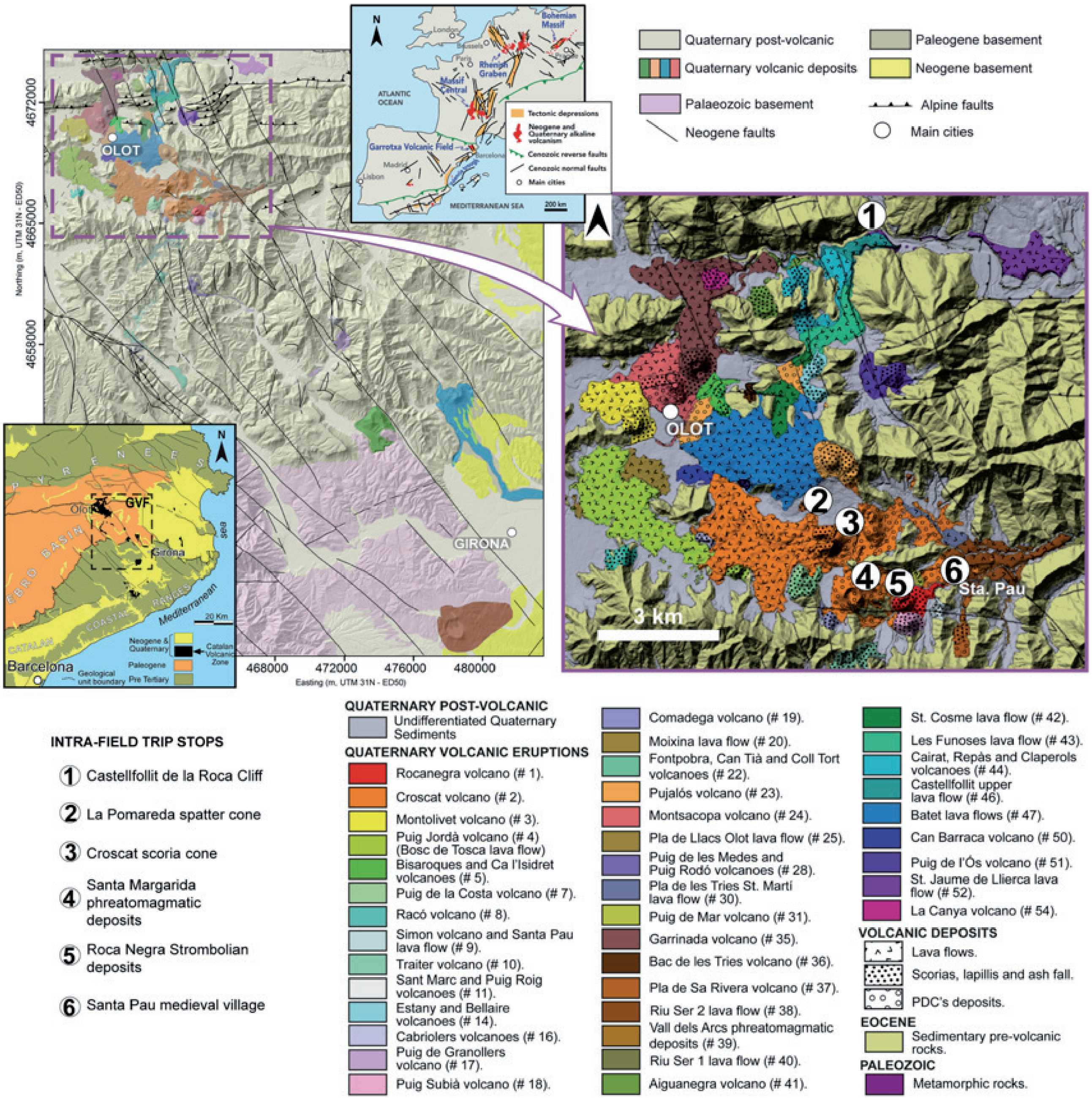

Figure 1. Left: Inlet at the upper right corner structural map of the European Rift System. Inlet at the lower left corner geological map of the NE of Iberian Peninsula. Central image geological map of La Garrotxa Volcanic Field. (modified from Bolós et al., 2015). Right: Detaied volcano-stratigraphyc map of the northern sector of the Garrotxa volcanic field with location of the stops. (modified from Bolós et al., 2014a).

Geological Settings

The Catalan Volcanic Zone (CVZ), which includes La Garrotxa Volcanic Field, is located in the NE corner of the Iberian Peninsula, and is limited by the eastern Pyrenees (north), the Ebro basin (west) and the Catalan Coastal Ranges (south) (Fig. 1). Its geological evolution is complex and includes the formation of a Palaeozoic basement, highly deformed by the Variscan orogeny, the sedimentation of a thick sequence of Mesozoic and Tertiary rocks, folding and faulting during the Alpine orogeny, and, finally, the Neogene-Quaternary extension that has controlled recent sedimentation and volcanism (Martí et al., 1992). Consequently, the lithostratigraphic units that outcrop in La Garrotxa Volcanic Field and form the basement of the volcanic edifices correspond to materials from the upper Palaeozoic, Eocene and Quaternary ages (Fig. 1). As a consequence of the Alpine folding, the Neogene normal faulting system and subsequent erosion, the basement of each volcano varies (Barde-Cabusson et al., 2014; Bolós et al., 2015).

La Garrotxa Volcanic Field hosts the youngest and best-preserved volcanic edifices in the whole CVZ. Over 50 volcanic cones are recognisable and can be grouped into two discrete areas, a northern sector corresponding to the upper basin of the river Fluvià and a southern sector located in the middle reaches of the basin of the river Ter (Fig. 1) (Bolós et al., 2014a). The main concentration of volcanic cones and edifices lies in the northern sector, which corresponds to La Garrotxa Volcanic Zone Natural Park that will be visit during the intra-conference field trip, while the southern sector holds far fewer but larger cones. The basement on which these monogenetic volcanoes stand differs between the two sectors. In the north, the volcanic rocks lie on Tertiary sediments, while towards the south they rest in some cases directly on the granites and schists of the Palaeozoic basement.

Volcanism in La Garrotxa Volcanic Field is characterised by the presence of small cinder cones constructed during short-lived monogenetic eruptions associated with widely dispersed fractures of short lateral extent (Martí et al., 2011; Bolós et al., 2015). The total volume of extruded magma in each eruption was small (0.01–0.2 km3 DRE), suggesting that the amount of magma available to feed each eruption was very limited (Bolós et al., 2014a). Strombolian and phreatomagmatic episodes alternated in most of these eruptions and gave rise to complex stratigraphic sequences composed of a wide range of pyroclastic deposits (Martí et al., 2011).

All the studied volcanoes were constructed during a single eruptive episode (i.e. they thus should be referred to as 'monogenetic') that commonly included several distinctive phases with no significant temporal separations between them. We can separate two groups of volcanic edifices: those that were built only by Strombolian activity and those that also experienced some phreatomagmatic phases (Fig. 2) (Bolós et al., 2016). In the first case, the volcanic edifices are symmetrical or horseshoe-shaped cinder cones constructed by the accumulation of scoria and lapilli, altered by occasional emissions of lava flows. Volcanic cones that experienced phreatomagmatic activity are much more complex, although morphologically they are still Strombolian in type. In these cases, the eruptive activity was characterized by a succession of phreatic phases produced by vapor explosions that only emitted lithic clasts from the substrata that alternated with both typical phreatomagmatic phases generating a wide diversity of pyroclastic density currents and fallout deposits, and typical Strombolian phases with explosive and effusive episodes. The sequences of deposits deducible from the resulting eruption sequences show substantial variations between cones, a sign of different types of eruptive behavior, probably due to differences in the local substrata and its hydrogeological characteristics that it is possible to recognize for their lithic types (Fig 2).

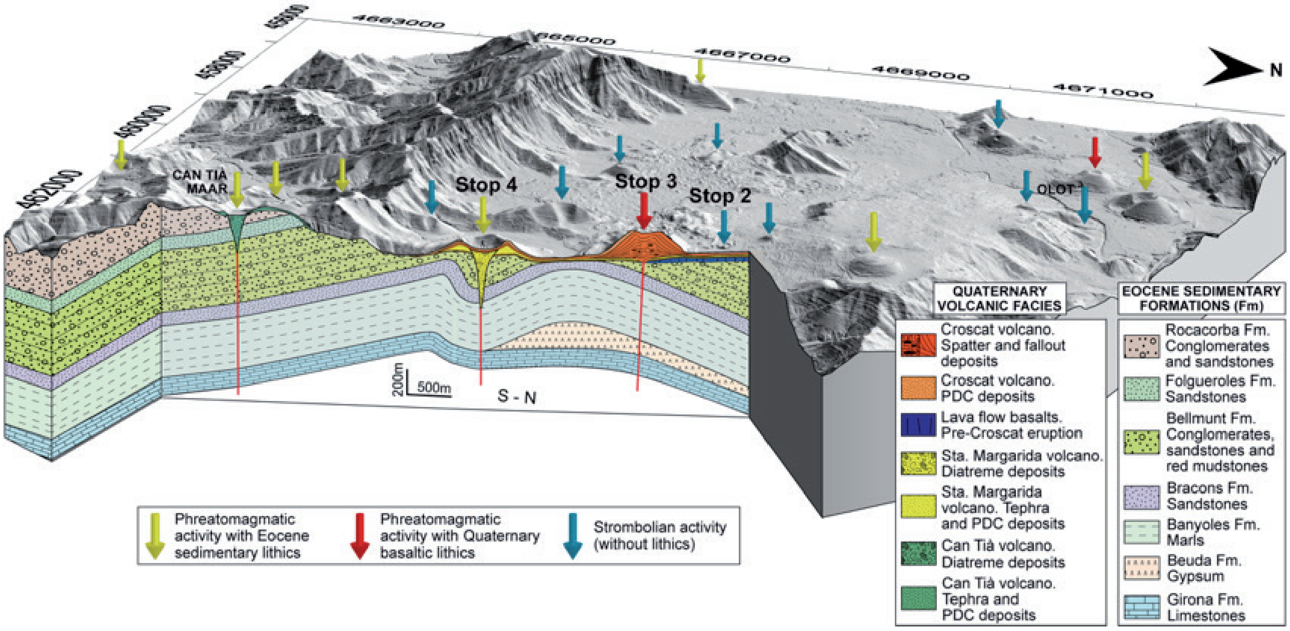

Figure 2. Geological cross section in a 3D block diagram showing the geometry and depth of the diatremes and volcanic successions of the GVF northern sector, as well as the sedimentary formations of the basement. The arrows show the location of the volcanoes divided in three main categories taking into account the rock-lithic presence/absence and their origin. Stop 2 and 3 corresponds to the volcanoes that we will visit during the intra-conference field trip. (Modified from Bolós et al., 2016).

In summary, the volcanoes of La Garrotxa Volcanic Field offer the opportunity to conduct different case studies that demonstrate how complex monogenetic basaltic volcanism may ensue in even a relatively small area if erupting magmas interact with the groundwater. This is particularly relevant when aquifers with different hydraulic characteristics are present, and when the structure of the terrain is complex due to local tectonics and/or differences in stratigraphy. The large diversity of eruption sequences deduced from the volcanoes in La Garrotxa reveal that most of the variables that have controlled them depend on local geology rather than on the magma, which can be considered as constant.

Field Trip

Castellfollit
de La Roca,
La Pomareda,
Croscat &
Santa Margarida,
Rocanegra
Santa Pau.

STOP 1: Castellfollit de La Roca Basalt Cliff.

From an observation point located on the old road from Olot to Girona, there is an excellent view of the Castellfollit de la Roca basalt cliff, which consists of two superimposed lava flows with well-developed columnar jointing (Fig. 3). The village of Castellfollit de la Roca sits atop a volcanic outcrop between the rivers Turonell (to the south) and the Fluvià (to the north) about seven kilometres from the city of Olot. To reach Castellfollit from Girona, take the N-260 road through Banyoles and on past Besalú. The basalt scarp and village can be viewed at 45 km at the junction of the road to Oix. Park here and follow Natural Park itinerary 13 down to the river Fluvià. After 500 m, cross the river on a wooden footbridge and head towards the foot of the cliff for closer views of the basalt columns (Fig. 3).

This cliff is the result of the emplacement of two lava flows along riverbeds and their subsequent erosion by the rivers Fluvià and Turonell. This outcrop—50 m in height and 1 km long—reveals the internal structure of a lava flow (Fig. 3). It has been eroding away for thousands of years, mostly as a consequence of erosion by the river Fluvià; however, the process of frost weathering (freezing-thawing), which is all the more effective given the existing jointing, is also relevant. The cracks in the cliff are weak points where weathering is concentrated, which eventually leads to the crumbling and fall of the blocks. They are then carried off by the river's periodic spates, thereby preventing the fallen blocks from building up and stabilising at the bottom of the cliff.

The base of the cliff consists of layers of Eocene sandstone and marl lying underneath gravel composed of many limestone, sandstone and, exceptionally, basalt pebbles. On top, there is a 40-m-thick layer of black and grey basalt. About nine metres 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 clearly 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 metre thick and again has columnar jointing but with columns that are only 30 cm in diameter.

b. The upper part has four layers: (1–3) the first three are 5–9-m thick and display obvious columnar jointing; (4) the final layer near the top is about 9-m thick and has well-developed spheroidal weathering.

Around 217,000 years ago a lava flow from the volcanoes on the Batet plateau flowed down and then along the old Fluvià valley to beyond where now stands the town of Sant Jaume de Llierca. Then, some 192,000 years ago, a second lava flow emitted by the volcanoes around Begudà flowed down the Turonell valley as far as Castellfollit de la Roca. In both cases differential cooling of the lava gave rise to a succession of layers in its interior. The time elapsed between these two lava flows was marked by the development of a soil and the emplacement of sedimentary materials, which form the deposit that is clearly visible between these two flows. The rivers Fluvià and Turonell overcame these obstructions to their courses once they had begun to erode away the contact zone between the basalt materials and the sedimentary rocks.

The medieval village of Castellfollit de la Roca was constructed on top of these lava flows using, above all, rocks and stones from the flows themselves as building materials.

Figure 3. Photograph of the village of Castellfollit de la Roca. Credits © Turisme de la Garrotxa.

STOP 2: La Pomareda spatter cone.

The volcanoes of Pomareda, Croscat and Santa Margarida (Fig. 1 and 2) are the most significant edifices in the northern sector of La Garrotxa Volcanic Field and hence also in the La Garrotxa Volcanic Zone Natural Park. After seven kilometres, park in the Àrea de Santa Margarida car park on the right. From here, follow Natural Park itinerary 15 to Can Passavent which goes around Croscat volcano to the north. At Can Pelat, we take to the right track to the Canova road. About twenty metres along, on the left, is the outcrop and the Stop 2 of the field trip. The Pomareda spatter cone is located on the Massandell plain in Can Genís side, is an old volcanic rock quarry where the materials from la Pomereda were extracted. On the quarry walls, the group will see successions of lapilli fallout deposits and spatters covered by a lava flow (Fig 4).

The Pomareda (Stop 2) - Croscat (Stop 3) - Santa Margarida (Stop 4) from an alignment as the result of a single eruptive episode occurring along a 3-km-long fissure system described by Martí et al. (2011).

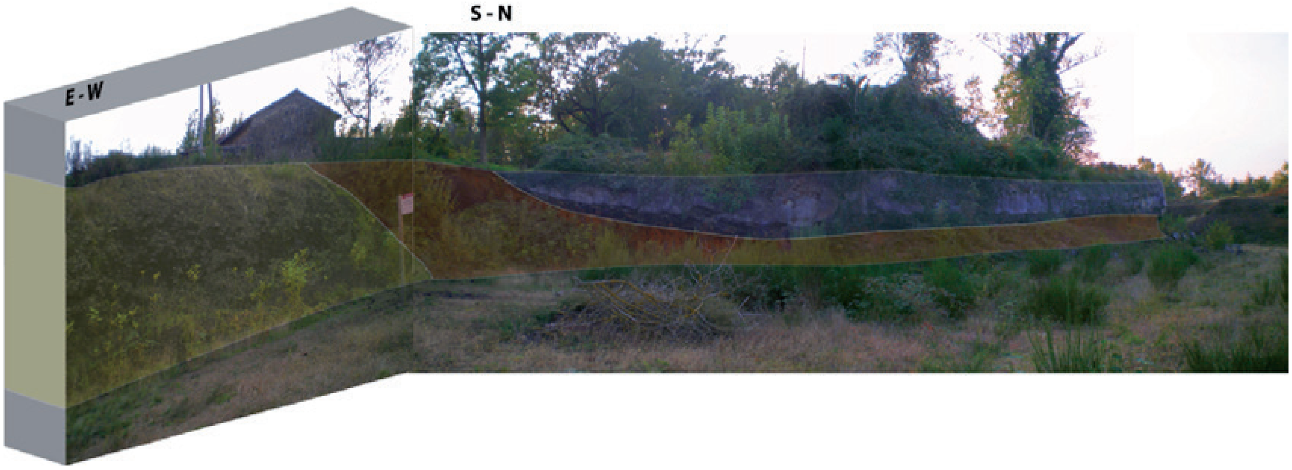

Figure 4. Panoramic view of the Pomareda outcrop (Stop 2). Yellow: spatter deposits, red: fallout deposits and blue: lava flows.

The lava flow of the upper part is dated at 11,500 years old and it is emplaced with channel-shaped, about two metres thick. Its internal structure displays columnar jointing with undefined-size scoria clasts. Below the lava flow, we can see a Strombolian fallout deposit with well classified lapilli. At the base of the sequence we observe a spatter facies. The scoria of this massive deposit is welded and continuous towards the northwest part of the outcrop (Fig 4 and 5).

Figure 5. Spatter facies of the Pomareda volcano (Stop 2). Credit Xavier Bolós.

Pomareda spatter cone forms a smaller edifice than Croscat. Martí et al. (2011) and Bolós et al. (2014b) suggest that the magma flow rate—and thus the intensity of the eruptive activity—was lower at this point on the fissure. Croscat and Santa Margarida edifices, built on the same eruptive fissure, is a complex volcano with several vents and several eruptive phases including violent Strombolian and phreatomagmatic episodes.

In the Pomareda spatter cone, we started to implement the use of geophysical surveys, especially the ERT method published in Bolós et al. (2014b). 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 as the case of this stop or other volcanic facies (Fig. 6) (Barde-Cabusson et al., 2013; Bolós et al., 2014b). 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 Bolós et la., 2012; 2014b; Barde-Cabusson et al., 2013; 2014).

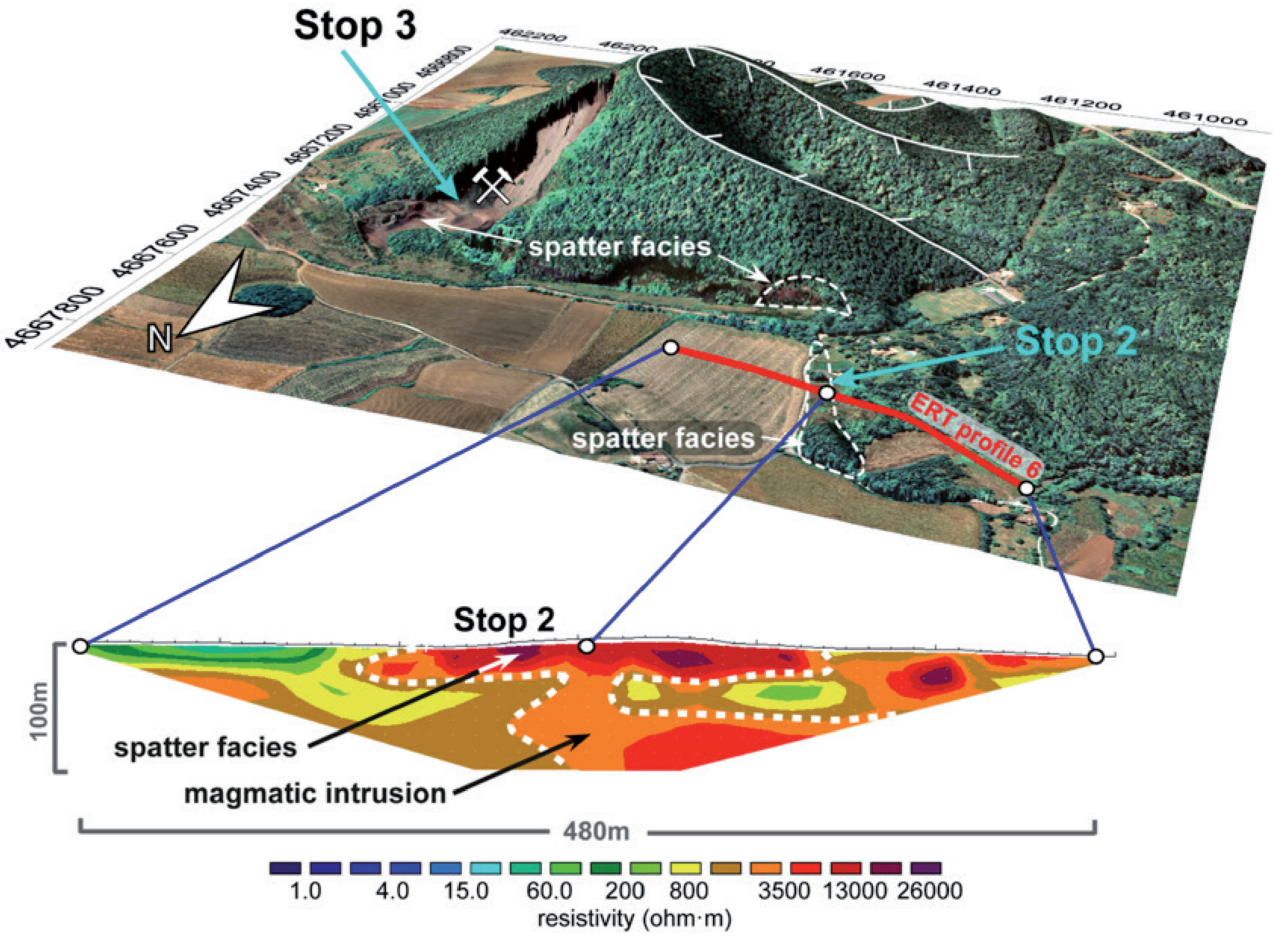

Figure 5. Top: orthophotograph overlaid on a digital elevation model with the location of ERT profile 6 corresponding to Pomareda volcano (red line). Bottom: ERT model (RMS error 5.5 %). Coordinates in UTM—31 N—ED50. (Modified from Bolós et al., 2014b).

STOP 3 and STOP 4: Croscat cinder cone and phreatomagmatic deposits of Santa Margarida maar volcano.

The volcanoes of Croscat and Santa Margarida (Fig. 6) are the most significant edifices in the northern sector of La Garrotxa Volcanic Field and hence also of the Natural Park of La Garrotxa. Croscat lies halfway between Olot and Santa Pau in a relatively flat area, with the Corb-Finestres mountain ridge to the south, Sant Julià del Mont to the north-east, and the Batet basalt plateau to the north. The quarry on its northern flank is an exceptional site that reveals the internal structure of this cinder cone and it will be the most important stop of the field trip. To reach the information centre (Can Passavent) next to the quarry, take the GI-524 road from Olot towards Santa Pau. After seven kilometres, park in the Àrea de Santa Margarida car park on the right. From here, follow Natural Park itinerary 15 to Can Passavent. During the field trip the attendees will visit this outcrop after the Pomareda Stop (number 2).

Figure 6. Photograph of the Croscat and Santa Margarida volcanoes. Credit Xavier Bolós.

In operation from the late 1950s to the early 1990s, the quarrying carried out in the flank of Croscat has revealed an about 150-m-high and 500-m-wide outcrop of pyroclastic materials (Fig. 7). On the right-hand side, the quarrying was executed in great terraced steps to help stabilize the volcanic material. However, the middle and the opposite side are less stable and landslips are more frequent. The different layers of scoria made up of irregular, highly vesicular juvenile fragments, for the most part lapilli-sized, are easy to spot. The slope of these layers increases in gradient from the centre to the outside of the cone. The alternation of layers is concentrated at the base of the sequence, where bombs are more abundant. The materials are mostly dark grey or black, although in the area closest to the centre of the edifice they are reddish and ochre. In the lowest part of the quarry there is a reddish layer of welded scoria, which corresponds to the first episode in the cone-building phase of the volcano. If you follow the path back to the information centre, on top of the succession of black Strombolian pyroclastic deposits there is a 2-m-thick laminated layer of finer pale-brownish material that corresponds to phreatomagmatic material deposited at the end of the volcano's explosive activity (Martí et al., 2011) (Fig. 7).

Figure 7. Photograph of the Croscat quarry.
Credit Xavier Bolós .

The Strombolian activity in Croscat generated two main lapilli fallout units: the lower one overlies conformably the basal spatter cones and consists of a several-metres thick, poorly stratified, coarse lapilli deposit with several bomb and scoria beds; the upper unit constitutes most of the volume of the cone and is composed of a thick (several tens of metres), well-stratified-to-thinly-laminated, medium-to-fine-grained lapilli deposit with a few bombs and scoria fragments. This upper lapilli unit also corresponds to most of the intermediate-to-distal outcrops lying to the east of the volcano that are identifiable at distances over 5 km. This unit also covers the Pomareda scoria and spatter cones, as well as the phreatomagmatic deposits and basement of Santa Margarida, which explains this latter volcano's false aspect of a cinder cone. At the top of the upper lapilli unit there is a phreatomagmatic deposit that extends for several kilometres to the east, which changes from planar to cross-bedded stratification in the proximal to distal facies. In its final eruptive phase, Croscat emitted a lava flow, not visible from the main quarry, that breached its western flank. It covered an area of 5 km2, has an average thickness of more than 10 m and travelled west for 10 km. The total volume of magma (DRE) emitted during the Pomareda, Croscat and Santa Margarida eruption was in the order of 0.2 km3 (Martí et al., 2011; Bolós et al., 2014a).

Back at the Santa Margarida car park, take Natural Park itinerary 4 and after 200 m turn right up towards the crater of Santa Margarida. However, to best understand this volcano's structure and materials, continue straight on along the road to Mas El Cros and into the eastern sector of the volcano. Pyroclastic deposits outcrop on the right-hand side of the road, the best sequence of which appears 400 m past the junction (Fig 1, Stop 4 and Fig. 8).

Santa Margarida is a phreatomagmatic volcano that sits on Eocene rocks. Its crater is circular, about 350-m wide and 70-m deep. Its cone is not formed entirely of volcanic materials, however, and its southern inner rim contains pre-volcanic rocks due to the fact that its crater is embedded into the substrate. In the middle of the crater stands a Romanesque chapel, which has been heavily restored in more recent periods.

The Stop 4 of the field trip consists in an outcrop along the road to Mas El Cros where three types of volcanic materials, sloping successively from right to left, are visible. On top of a silty soil, which corresponds to the pre-volcanic substrate, lies a layer of compacted ash. On top of this there is a layer of black juvenile fragments and fairly rounded reddish-brown lithics. Next, there is a layer of lithic and juvenile lapilli-sized fragments, which predominate. They are black and slightly rounded in shape and have little vesiculation; the lithics are mostly red sandstone. Finally, at the top of the sequence there is a deposit—a fine-grained scoria fragment with no stratification—that closely resembles the previous layer but without any lithic (Martí et al., 2011).

The volcanoes of Croscat and Santa Margarida represent two different phases of the same eruption (Martí et al., 2011; Bolós et al., 2014a, b). Along with the spatter cone of La Pomareda (Stop 2), located a couple hundred metres north-east of the base of Croscat, they lie along a 3-km-long eruption fissure oriented NNW-SSE. The eruption started at the southern end of the fissure with a vent-opening phreatomagmatic phase that created the explosion crater of Santa Margarida on top of the Eocene basement. This first eruptive phase generated a massive lithic-rich pyroclastic flow deposit, visible on the eastern flank of Santa Margarida, along with several widespread beds of medium-to-coarse-grained, dilute pyroclastic surges and associated fine-ash deposits, which covered most of the area and formed the unit on which the Croscat succession was built up. This phreatomagmatic phase was followed by a short Strombolian phase that generated a thin, lithic-rich, coarse lapilli fallout deposit that overlaid the previous deposits in the vicinity of the crater. Immediately after these first two phases, the eruption progressed through the central and northern sectors of the fissure extruding basaltic magma and generating massive spatter and occasionally rheomorphic- welded scoria agglomerates, which formed the first cone-building deposits of Croscat and La Pomareda (Fig. 5 and 8). No more magma was emitted during this and the subsequent phases from the Santa Margarida crater. Thereafter, the eruption was concentrated in the central part of the fissure and changed from fissural (Hawaiian) to central conduit (Strombolian) activity, and the rest of the Croscat cinder cone was constructed (Fig. 8).

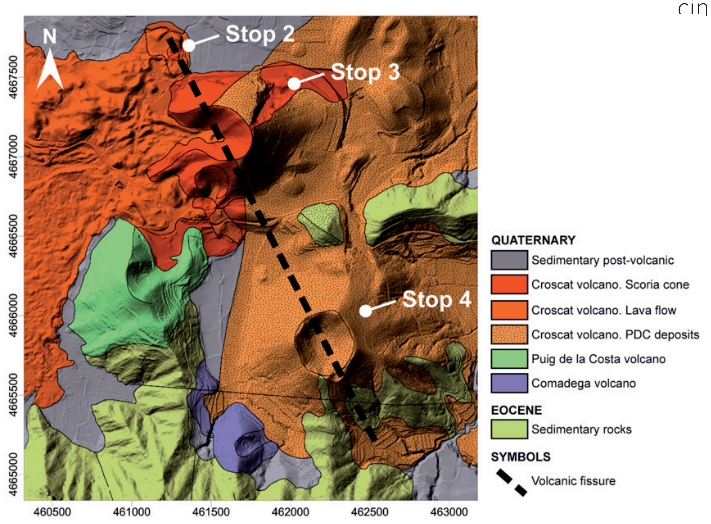

Figure 8. Volcano-stratigraphic map of the area (Bolós et al., 2014a). See cross-section of the eruptive fissure in Figure 2.

STOP 5: Rocanegra Strombolian cone.

Rocanegra cinder cone is composed of Strombolian fallout deposits (Fig. 9) that overlie the Croscat volcanic sequence. This suggests that the Rocanegra volcano is younger than the Santa Margarida-Croscat-Pomareda, so Rocanegra would be the youngest volcano of the whole volcanic field.

The main outcrop from Rocanegra volcano (Fig. 1, #5) is located in the southwest of Santa Pau village. From this medieval village, take Camí de les Fages path. About 2 km after the junction with the path to Santa Margarida, the outcrop of Rocanegra is on the left of the pathway from where the volcanic material was quarried. During the field trip, the participants will access to this stop from Santa Margarida after walking about 2 km to Santa Pau village.

The succession of deposits in this outcrop is composed of, a 10-m-thick dark unit formed by well-stratified scoria with alternating layers of different grain size, some including centimetric-sized bombs (Fig. 10).

In this deposit there are a large number of ultramafic to mafic xenoliths including pyroxenites, melanogabbros, amphibolites and spinel lherzolites, of which the pyroxenites are the most abundant (Llobera, 1983; Neumann et al., 1999; Galán et al., 2008; Bianchini et al., 2007; Bolós et al., 2015). Pressure and temperature estimates suggest that the pyroxenites, melanogabbros and amphibolites may have crystallised in magma chambers located at the crust–mantle boundary (Neumann et al., 1999), which, according to geophysical estimates, is located at a depth of ~30 km (Fernández et al., 1990; Gallart et al., 1984, 1991); on the other hand, the spinel lherzolites may derive from the source region in the asthenospheric mantle (Bianchini et al., 2007). Bolós et al. (2015) identified the presence of ultramafic xenoliths in the volcanic deposits along the main faults to explain the deepest fractures in the volcanic field and also to estimate magma ascent velocities that are about 0.2 m/s.

Figure 9. Aerial view of the Rocanegra volcano. Credit Eduard Masdeu.

Figure 10. Outcrop of the Stop 5. Strombolian deposits of the Rocanegra volcano.

STOP 6 (cultural stop): The Medieval village of Santa Pau.: Rocanegra Strombolian cone.

The field trip will finish at the Medieval village of Santa Pau. Participants can visit its monastery and castle, built on a hillock in the centre of the village, and its square building that was constructed in different phases during the thirteenth-fourteenth centuries.

Figure 11. Santa Pau Medieval village. Author. Pep Callís. Source Documentation Centre, Garrotxa Volcanic Zone Natural Park.

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FES/
FUNDACIÓ
D'ESTUDIS
SUPERIORS
D'OLOT

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

ICTJA
INSTITUT DE CIÈNCIES DE LA TERRA JAUME ALMERA

IGUM
INSTITUTO de GEOFÍSICA
Unidad Michoacán

Commission on
Monogenetic Volcanism

CVL
IAVCEI
Commission on Volcanic Lakes

Ajuntament d'Olot

Parc Natural
de la Zona Volcànica
de la Garrotxa

Generalitat de Catalunya
Departament de Territori
i Sostenibilitat

IPHES
Institut Català de Paleoecologia
Humana i Evolució Social

OPGC
Observatoire
de Physique du Globe
de Clermont-Ferrand

lmv
Laboratoire Magmas et Volcans

AJUNTAMENT DE
CALDES DE MALAVELLA

ACGAX
IMATGES

Diputació de Girona