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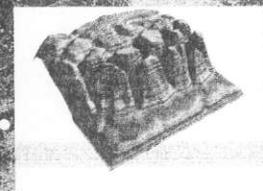
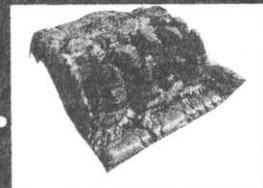
## FIELD TRIP GUIDES

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Volume II

**TRAVERTINES AND VOLCANIC LANDFORMS IN THE EASTERN  
PYRENEES MARGIN**

Lluís Pallí, David Brusi, David Soler, Carles Roqué, Rogelio Linares  
and Albert Cebrià

## TRAVERTINES AND VOLCANIC LANDFORMS IN THE EASTERN PYRENEES MARGIN

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### 1. Introduction

The province of Girona is located in the eastern part of the Pyrenees. The Pyrenean Range is an east-west trending orogen situated in the north-eastern border of the Iberian Peninsula, between the Mediterranean Sea and the Atlantic Ocean. These mountains are the result of the convergence of the Iberian and Eurasian continental plates during the Paleogene. The thrust sheets that form the orogen core (known as Axial Zone) are made up of Paleozoic sedimentary rocks that were metamorphosed and intruded by igneous bodies during the Variscan Orogeny, in Carboniferous and Permian times. The Mesozoic sedimentary cover was incorporated in several thrust units verging northwards and southwards of the Axial Zone, developing a fold and thrust belt.

The Catalan Coastal Range is similar to the Pyrenees in lithology, age and structure. Both ranges are linked in an area known as the Catalan Transversal System (Fig.1) This geologic unit is formed by several tilted blocks individualized by Neogene and Quaternary normal faults that display a horst-graben and half-graben structure. The main lithologies in the Catalan Transversal System are Eocene marls, siltstones, sandstones, conglomerates, limestones and evaporites. Some rift-type basins have developed in this area and have been filled by continental sediments since the Miocene. The Empordà Basin is the largest of these basins.

The Banyoles lacustrine complex was developed throughout the Quaternary at the boundary between the southern Pyrenean units, the Catalan Transversal System and the Empordà Basin.

Many volcanic exposures, mostly of basic composition, can be found related to the aforementioned extensional fractures. The most recent volcanic extrusions, which occurred during Quaternary times, crop out near the town of Olot. The interaction between fluvial dynamics, volcanic extrusions and tectonic activity has led to the sedimentation of fluviolacustrine deposits.

#### 2.1 Objectives

The Banyoles-Besalú lacustrine basin is a structurally-controlled discharge area of a karstic hydrogeologic system. Several geological, geomorphologic and paleontological evidences indicate that the lacustrine processes have been active in this area since the lower Pleistocene. The hydrogeological dynamics of the area, the lacustrine sedimentation and the paleontological and archaeological record reveal the complex environmental evolution of the system.

The fieldtrip has been designed to show the most interesting geological and geomorphologic sites related to the lacustrine system, its hydrogeological dynamics and the associated travertine rocks.

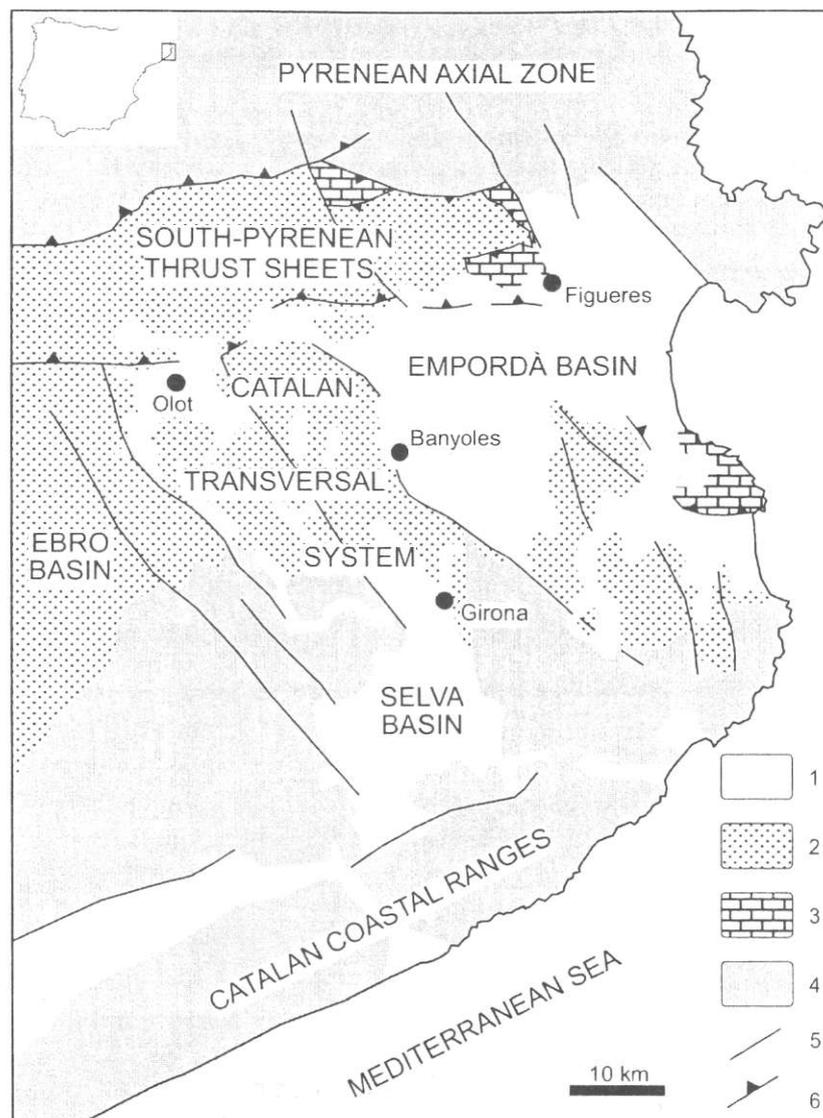


Figure 1.- Main structural units in the eastern pyrenean margin. 1: Quaternary and Neogene. 2: Paleogene. 3: Mesozoic. 4: Paleozoic. 5: Normal fault. 6: Thrust.

## 2. Banyoles lacustrine area

### 2.2 General aspects

#### 2.2.1 Geological context

The Banyoles lacustrine area is located along the boundary between two major morphostructural units: the Catalan Transversal System and the Empordà Basin. The Banyoles Lake (Estany de Banyoles in Catalan language) gives its name to the whole region, known as El Pla de l'Estany.

It is worth remarking that the lacustrine area is not just a wetland. As it is genetically related to a karstic aquifer, it is necessary to enlarge its limits to the perimeter of the Garrotxa-Banyoles hydrogeological system. The geological unit "Banyoles-Besalú lacustrine basin" defined by Julià (1980) does not refer strictly to a relief unit. Rather, this term might have been created to group all the geological features generated by the lacustrine dynamics in this sector under a single denomination. Thus, this unit can also be conceived as a morphodynamic unit which has been

acting as a discharge and sedimentation area since, at least, Middle Pleistocene times and which has been influenced by the geological and climatic changes occurred during this time span (Brusi, 1996).

To explain the dynamics of the basin, it is necessary to introduce the geological framework of the area first. Two main geological domains can be differentiated. One of them is formed by the Tertiary sedimentary rocks that host the hydrogeological system. The other one is made up of detrital and lacustrine sequences deposited in the basin.

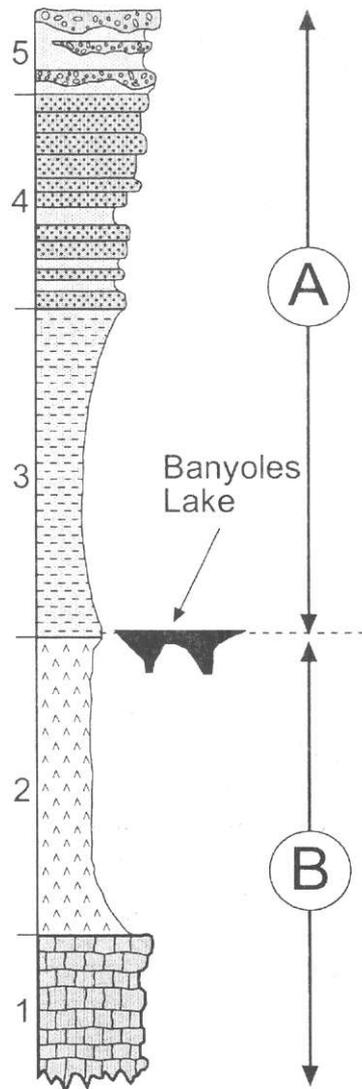


Figure 2.- Synthetic stratigraphic column of the Paleogene units involved in the Banyoles hydrogeological system (Brusi et al., 1987). A) Superficial units which crop out in the vicinity of the Banyoles Lake; B) Deep units deduced from a borehole located close to the lake; 1) Limestones; 2) Gypsum and anhydrite with marl intercalations; 3) Marly shales; 4) Sandstones; 5) Shales and conglomerates.

The Lower Tertiary sedimentary sequence is the pre-Quaternary rigid bedrock where the lacustrine area was formed. This bedrock does not play a passive role: on one hand it hosts the hydrogeological system that links the discharge area with the recharge areas located farther apart

to the north. On the other hand, the upper section of this sequence is intensely affected by karstic collapse phenomena that give rise to the lacustrine geomorphologies. It is not the purpose of this field-guide to describe thoroughly the stratigraphy of the area which has already been described by many authors, like Pallí (1972). However, it is possible to summarize the Tertiary stratigraphic column (Fig. 2). The upper limit of the Paleocene sequence can be found at 350 m of depth under the lacustrine area. This sequence, formed by continental conglomerates, siltstones and clays, constitutes the impermeable lower limit of the Eocene materials above: a limestone formation, 100 m thick, and an evaporitic level made up of gypsum and anhydrite of variable thickness. Right above these materials lays a formation made up of Eocene marls and clays, that ends up in a sandstone unit. These last two formations crop out and constitute the topographic relieves that host the lacustrine area. Unconformably overlying the Eocene bedrock, some fluvial and alluvial formations composed of gravels, sands, silts and clays, are found in the middle reach of the Fluvia River. These materials were deposited by the river and tributary alluvial fans in a subsiding area during the Pliocene and the Quaternary. The oldest of these materials are found interfingered with the lacustrine deposits in the eastern limits of the Banyoles-Besalú area (Solà et al., 1996).

The lacustrine formations are closely related to the location and evolution of the outlets of this hydrological system. These formations are made up of travertine, calcarenitic and clay facies formed under lacustrine conditions. The older deposits crop out in the northern area: Incarcà quarry, Bòvila Ordis and in several places across Pla d'Usall. Southwards the travertine deposits are younger and crop out in Lió, Els Tanyers, Les Estunes and through the Banyoles-Mata-Cornellà del Terri overflow travertine platform.

### 2.2.2 Hydrogeologic dynamics

The Banyoles hydrogeological system can be defined as a karstic complex characterized by a far recharge area mainly fed by rainwater, and by a tectonically-controlled discharge area. The altitude gradient between both areas enables the water in the aquifer to reach the required pressure to emerge in the discharge area enhancing the karstification processes. Old fluorescein tests carried out by Vidal-Pardal (1957) suggested that the water infiltrated through the thalweg of the Llierca River in the Alta Garrotxa area and "sprang up in the Banyoles Lake some days after". Many subsequent studies have completed this hypothesis. Sanz (1981, 1985) provided the geological and hydrogeological data that led to the model which best explains the behaviour of the system (Figs. 3 and 4). This model is still accepted today. Tritium and  $^{18}\text{O}$  isotopic studies of the water surging in the Banyoles Lake, Pla d'Usall and Sant Miquel de Campmajor, point towards a common origin for these waters. Also according to Sanz, recharge takes place in an area located between 700 and 900 m of altitude, in the Eocene limestones that crop out in the Alta Garrotxa area. Tritium percentage values indicate that the mean residence time of underground waters in the aquifer system can be up to 11 months. This hydrological model is supported both by geomorphologic evidences of karstification and by a conspicuous decrease in the discharge recorded by many fluvial streams.

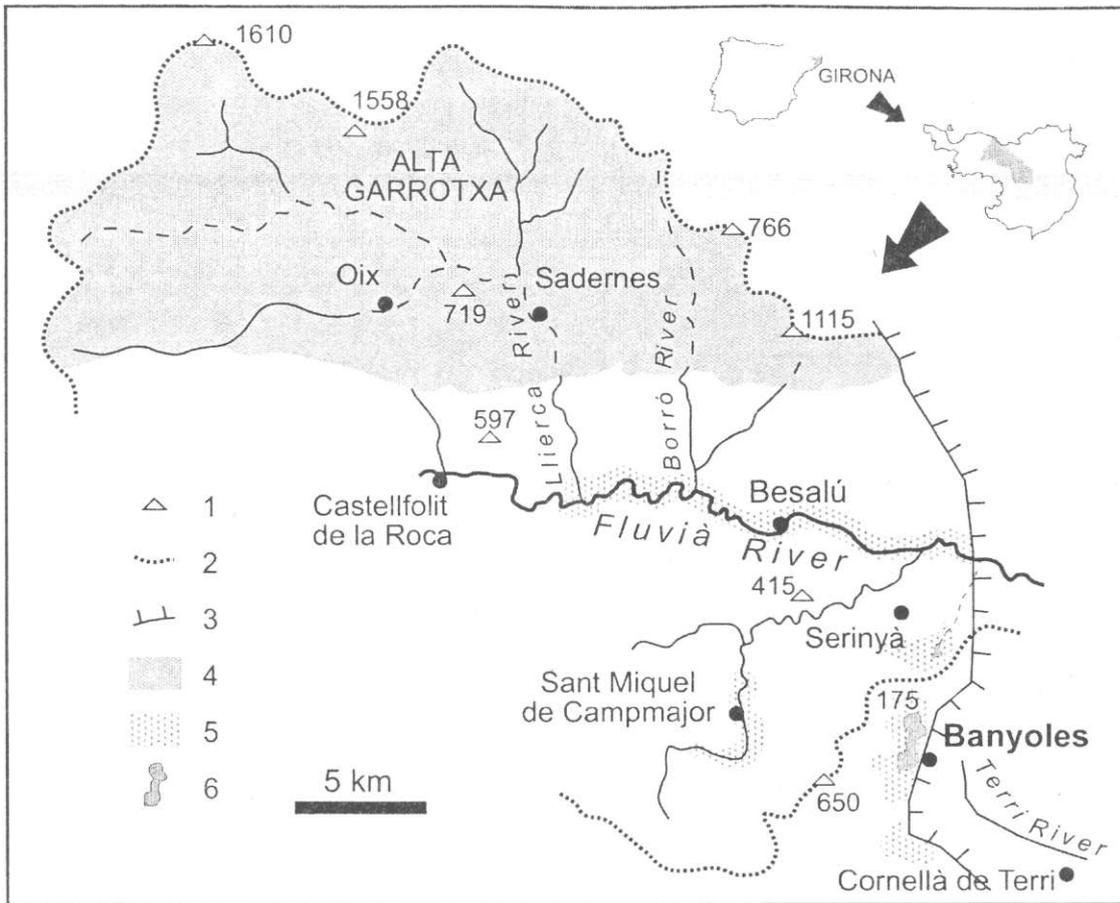


Figure 3.- Map showing the areas of recharge and discharge of the Banyoles hydrogeological system (after Sanz, 1985). 1) Geodetic benchmark; 2) Fluvià River drainage basin divide; 3) Normal fault; 4) Input areas to the hydrogeological system; 5) Output areas of the hydrogeological system; 6) Banyoles Lake.

The dynamics of the system could be summarized as a sequence of linked processes:

1. The water infiltrated in the Alta Garrotxa area feeds an aquifer that spreads southwards within the karstified levels of Tertiary limestones.
2. The system becomes artesian where any tectonic structure facilitates the upward discharge of the flow (Fluvià River valley). The confined flow can also continue among low permeability layers until it finds new fractures to rise up and create new flow paths by means of the dissolution of the Eocene evaporitic formations.
3. Gravitational collapses reach the topographic surface generating sinkholes which host ephemeral water bodies (ponds). The coalescence of some of these depressions led to the formation of the Banyoles Lake.

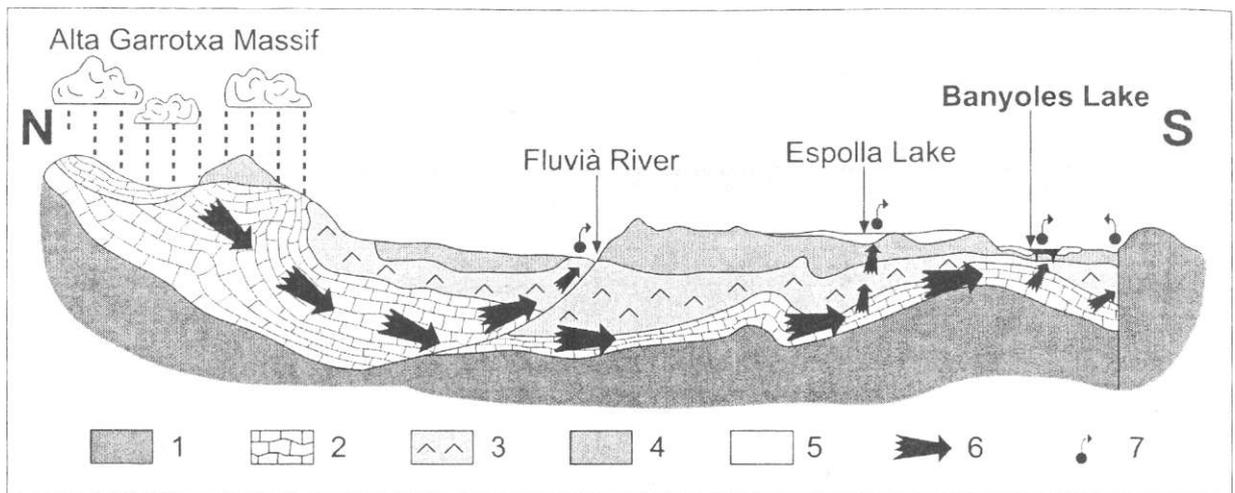


Figure 4.- Simplified cross section showing the structure of the Eocene materials and main groundwater flow paths (after Sanz, 1985). 1) Shales, sandstones and conglomerates; 2) Karstified limestones; 3) Gypsum and anhydrite; 4) Marly shales; 5) Travertine and other quaternary lacustrine deposits; 6) Groundwater flow; 7) Spring area.

## 2.2.3 The Travertines

### 2.2.3.1 Origin of the term

The most common sedimentary deposits in the Banyoles lacustrine basin are travertines. The term *travertine*, according to Chafetz and Folk (1984), comes from the phonetic evolution of the Latin expression *lapis tiburtinus* or Tibur (present day Tivoli town, located near Roma) stone, where different types of lacustrine limestones crop out and are mined. The word travertine is used to designate carbonate deposits, at any diagenetic stage, formed in continental environments. They are often related to carbonate-rich springs, whether they have a thermal origin or not. The term *tufa* is normally used as a travertine synonym, but it usually has a more restricted meaning and is reserved to designate those travertines that have high porosity and low density. The travertine origin is related to the physical, chemical and biological mechanisms of calcium carbonate precipitation due to organic and/or inorganic processes.

### 2.2.3.2 Travertine genesis in the Banyoles lacustrine area

The high salinity of the underground waters and the CO<sub>2</sub> release have been the main controlling factors of travertine precipitation in the Banyoles lacustrine area. Fossil fauna and absolute dating indicate that travertine sedimentation has been continuously occurring since the lower Pleistocene (Julià and Bischoff, 1993). The continental carbonate formations crop out in a roughly north-south elongated area extending from the Fluvià River to Serinyà, Banyoles and Cornellà de Terri.

The spatial distribution, depositional model and precise temporal evolution of these formations have been established by several authors (Julià, 1980; Brusi, 1993 and 1996). The research of these authors has included geological mapping, detailed study of outcrops and delimitation of the underground extension of the travertine formations.

Up to six different travertine depositional morphologies and sedimentary facies can be identified: carbonate muds, calcarenite travertines, macrophyte facies, stromatolithic facies, pisolitic and oncolitic facies and breccia travertines.

1. Carbonate muds are accumulations of grey and white coloured calcite crystals, that usually form very thick, unconsolidated deposits. Older formations are frequently cemented. In the Banyoles area these facies can be found in La Draga and near the lake (Fig. 5). They also crop out in Bòvila Ordis and in Incarcà quarry. Its origin is related to the filling of depressions due to intense calcite precipitation in the spring areas.

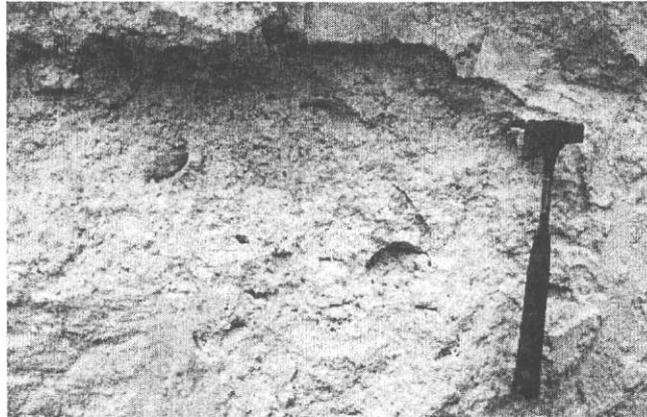


Figure 5.- Massive carbonate muds with bioturbation structures, La Draga, Banyoles.

2. Calcarene travertines have some features in common with carbonate muds, but they have medium to coarse sand grain size. They are commonly found interbedded among other facies (Fig. 6). They are interpreted as deposits produced by turbulence phenomena within travertine pools bounded by natural dams.

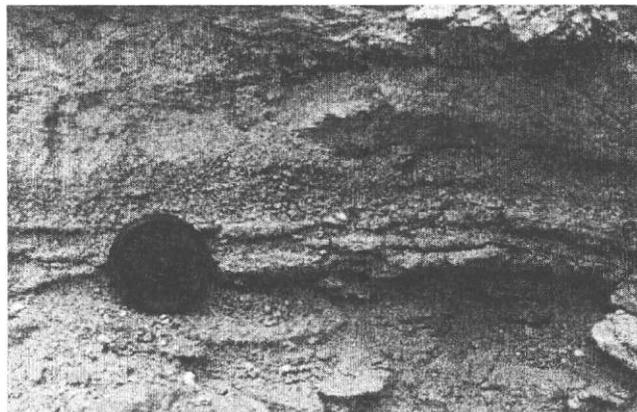


Figure 6.- Calcarene sands showing cemented laminae.

3. Macrophyte facies are carbonate deposits precipitated on vegetal cells of different kinds (*bryophyta*, *hepatophyta*, *cyperus*, reeds, tree leaves). They are usually highly porous and have cylinder-shaped cavities and casts which may help to identify the encrusted plants (Fig. 7). They are formed in shallow and emerged littoral environments or in travertine pools.

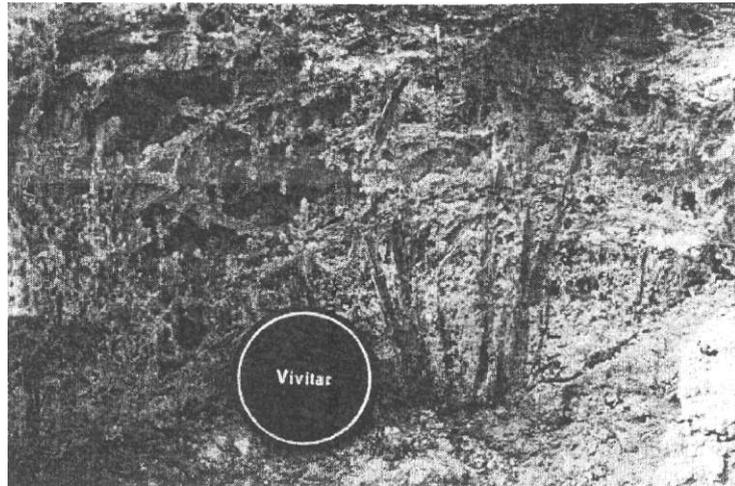


Figure 7.- Macrophyte travertine facies, Les Rodes square, Banyoles.

4. Stromatolitic facies are those laminated deposits formed by calcite precipitation within algae and cyanobacteria cells. These deposits are characterized by rhythmic sequences of spongy and compact layers, related to seasonal changes in precipitation. Planar laminated stromatolitic travertines show subhorizontal layers of metric to decametric extent (Fig. 8). They are related to littoral lacustrine environments and overflow areas. Hemispherical stromatolitic travertines are formed by the stacking of stromatolitic laminae (Fig. 9). Similar morphologies, observed in currently active environments, indicate that they form in bands along shallow lacustrine littoral areas. In waterfall stromatolitic travertines, laminae are wavy and stepped (Fig. 10). They are characteristic of tilted surfaces developed both over bedrock scarps and on inclined surfaces of the travertine dike fronts.

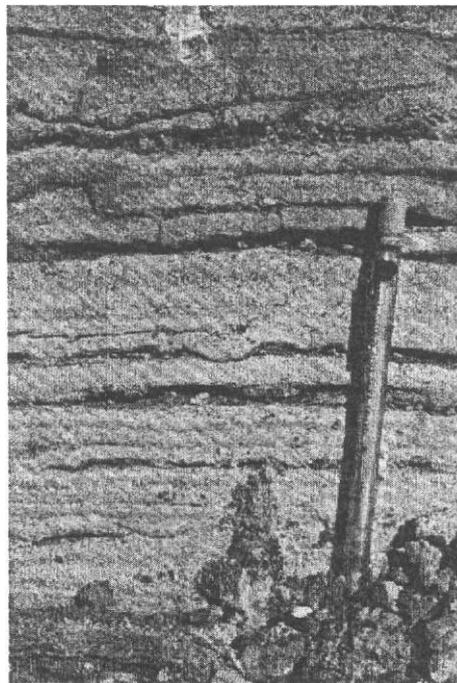


Figure 8.- Planar, laminated, stromatolitic travertine facies related to overflow lacustrine platform environments, Pla de Mata travertine quarries, Mata.

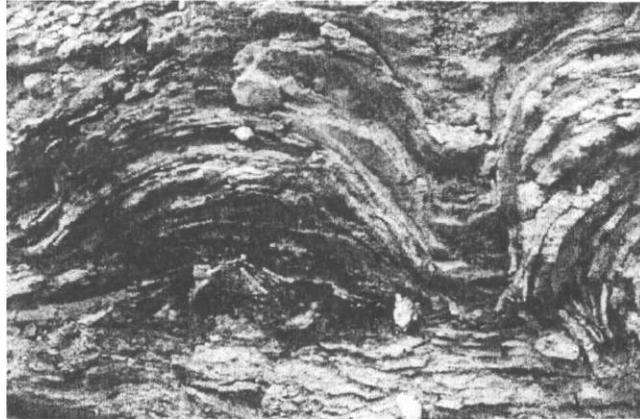


Figure 9.- Hemispherical, stromatolitic travertine facies, La Draga, Banyoles

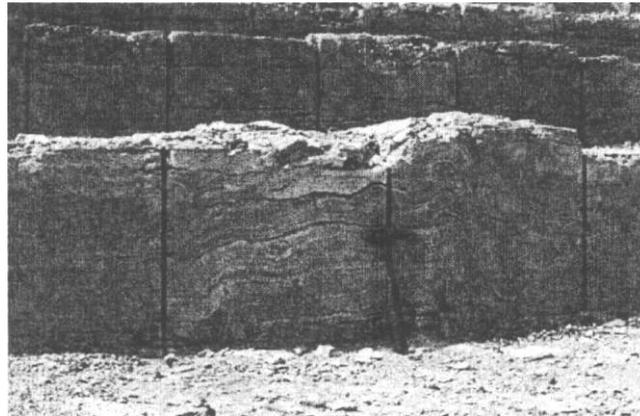


Figure 10.- Ondulated laminae in waterfall travertine, Pla de Mata travertine quarries, Mata.

5. Pisolitic and oncolitic facies consist of isolated spherical or ellipsoidal morphologies with a concentric, laminated internal structure. Pisolites are small pearls from 2 mm to 3 cm in diameter, while oncolites have larger diameters. They usually appear in high-turbulence environments, within some travertine pools and at the base of some cascades or damming-dikes, where particles move freely, enhancing the growth of successive laminae (Fig. 11).



Figure 11.- Pisolitic and oncolitic facies related to travertine pool fillings, Porqueres.

6. Breccia travertines are accumulations of travertine clasts, commonly intercalated within other facies. The clasts are fragments of slabs or boulders of a wide variety of sizes coming from former deposits (Fig. 12). They are evidence that destructive and constructive processes occur simultaneously in travertine environments.

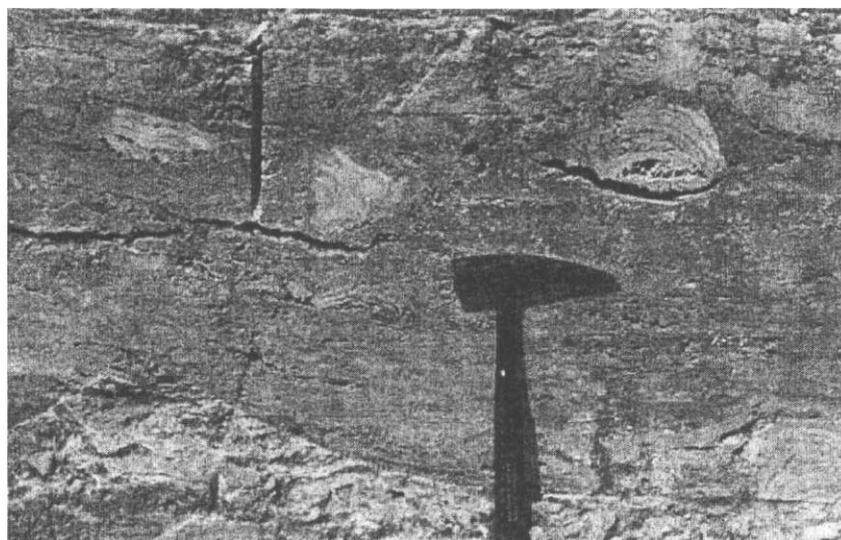


Figure 12.- Lithoclast-breccia facies with irregular travertine clasts embedded in cemented detrital levels, Pla de Mata travertine quarries, Mata.

A depositional model can be established thanks to the integration of lithological, tectonic and geomorphologic observations and their relationship with the internal variability of the travertine deposits. The different travertine facies have formed under changing conditions, which are influenced by bedrock stability, water depth, depositional slope and input of terrigenous material.

A synthetic model has been suggested to explain travertine formation in the area (Brusi, 1993), where different sedimentary environments have been individualized according to their hydrodynamic characteristics (Fig. 13):

1. Spring areas in unstable bedrock (lakes and pools).
2. Littoral lacustrine margins (passive and overflow platforms).
3. Overflow slope.
4. Lacustrine overflow valleys.
5. Valleys where fluvial sedimentation prevail.

It is important to point out that subsidence of the topographic surface due to gypsum karstification has a great influence on travertine formation. Karstic collapses not only determine the appearance of lakes fed by subaqueous springs, but also control the location and discharge of active springs, define the overflow areas and modify the characteristics of the substratum (Brusi et al., 1987).

Paleontological data indicate that lakes have been present in the area since the Upper Pliocene-Lower Pleistocene (Incarcal and Ordis sites). However, travertine sedimentation in Banyoles is much more recent.  $^{230}\text{Th}/^{234}\text{U}$  datings indicate that travertine sedimentation areas have migrated

spatially and that travertine formation began 120.000 years ago and remains active today (Brusi, 1993).

#### 2.2.4 Paleontological and archaeological record

There are numerous paleontological and archaeological sites in the Banyoles-Besalú lacustrine basin which have provided an abundant fauna of mammals ranging in age from the Pliocene to the present (Galobart et al., 1996; Galobart et al., 2002; Nadal et al., 2002; Sana, 2002; Soles and Maroto, 2002) (Fig. 14). This paleontological richness is due to the presence of lacustrine environments that facilitate the preservation of organic remains and to the existence of travertine shelters and alluvial deposits.

The prehistoric archaeological sites in the area, known since the 19<sup>th</sup> century, bear a continuous and high quality record (Soler et al., 2001). Excavations of Paleolithic remains have taken place in three sites: Reclau caves, Bora Gran d'en Carreras and Pla d'Usall (Brusi et al., 2002).

The oldest evidences of human occupation in the area are as old as Late-Middle Paleolithic (end of Middle Pleistocene). Pre-Neanderthal settlements (*Homo heidelbergensis*) have been found in Mollet Cave (Reclau caves). Recent Middle Paleolithic (Upper Pleistocene) is well recorded in Arbreda Cave (Reclau caves). It is also preserved in some superficial sites in Pla d'Usall. A human jaw was found in 1887 in the travertines of Pla de la Formiga (Banyoles). Originally, There were doubts about its Neanderthal or Pre-Neanderthal origin (Maroto, 1993). Recent datings have given an age of 45,000 years, characteristic of *Homo neanderthalensis* (Julia and Bischoff, 1993).

The Upper Paleolithic is recorded in Reclau caves (Arbreda, Reclau River, Pau and Mollet sites) and in Bora Gran d'en Carreras, where *Magdalenian*, the last Upper Paleolithic culture, is also found. From this site comes a collection of tools made of bones and horns of *cervus* (awls, needles, harpoons, spatulas...) and thousands of small flint tools.

The post-Paleolithic prehistoric sequence is also well recorded in the area. The early Neolithic is recorded in the exceptional lacustrine village of La Draga, next to the Banyoles Lake. Neolithic remains have also been collected in Reclau caves and in Mariver Cave (Martís). The end of the Neolithic and the Metal Age are recorded in several sites such as Reclau caves, Encantats Cave (Margenera) and Encantades Cave (Martís). They consist mostly of sepulchral remains.

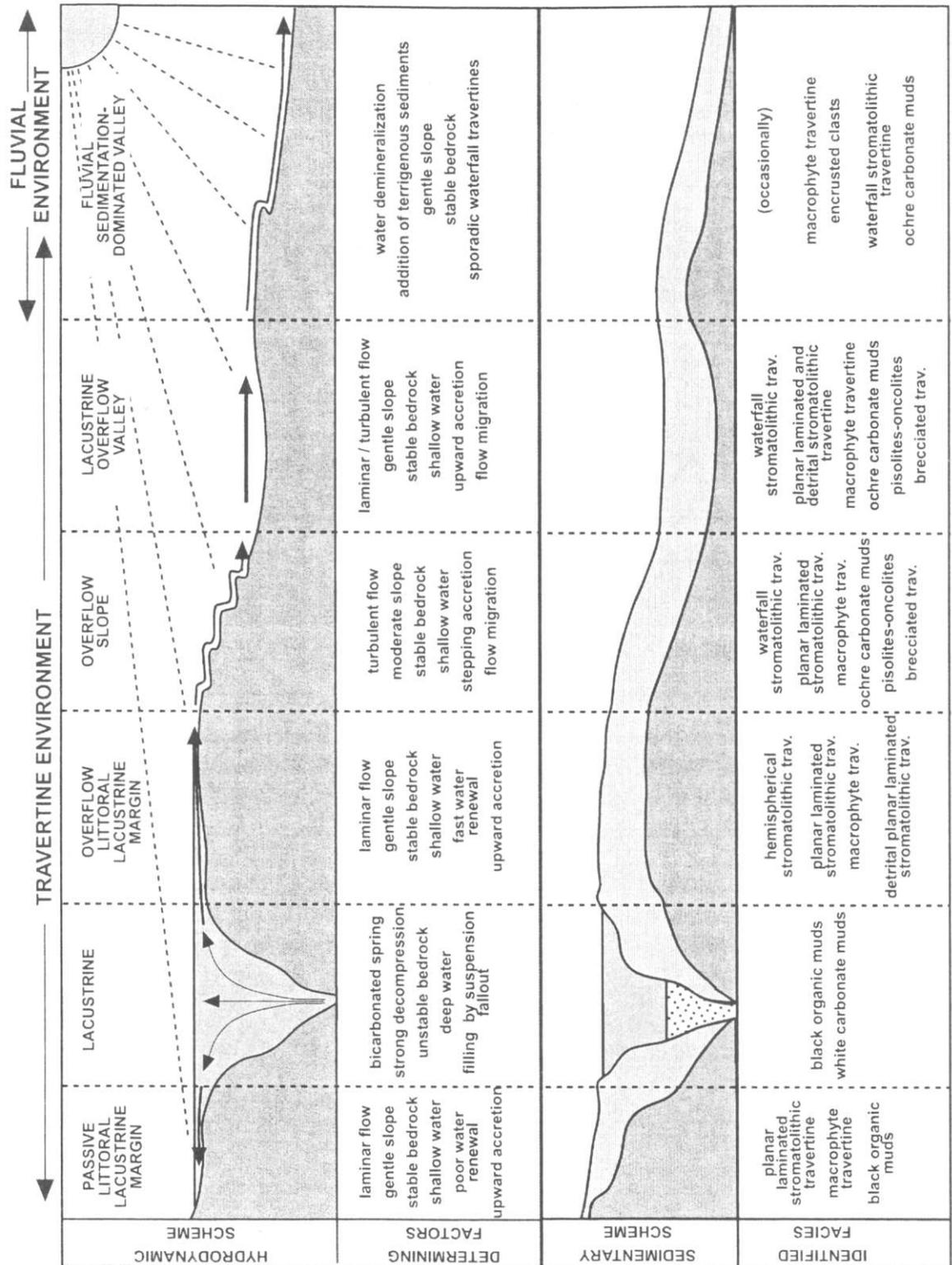


Figure 13.- Sedimentary depositional model for the travertine deposits in the Banyoles Lake area (after Brusi, 1993).

**Stop1. Puig de Sant Martirià.** Puig de Sant Martirià is a hill located northeast of the Banyoles Lake and provides a good viewpoint over the area. The hilltop can be accessed by an unpaved trail that starts in the kilometre 1.3 of the GIP-5121 road from Banyoles to Esponellà.

PERIOD	CLIMATE CURVE	ABSOLUTE AGE	BIG MAMMALS FAUNA	SITE	ARCHEOLOGY
HOLOCENE		11 k.yr.	PRESENT-TIME deer wild boar	Vilauba La Draga	ANCIENT WORLD, NEOLITHIC...
UPPER		40 k.yr.	LATE QUATERNARY horse donkey deer roe deer aurochs bison ibex cave bear cave lion panther cave hyena wolf	Bora Gran Reclau Viver Pau Arbreda	UPPER PALEOLITHIC
PLEISTOCENE		128 k.yr.	MIDDLE QUATERNARY primitive elephant Prairie rhinoceros Mosbach horse deer "praearctos" bear hyena Lunel-Viel wolf	Pla de la Formiga/Mata Arbreda	MIDDLE PALEOLITHIC
MIDDLE PLEISTOCENE		700 k.yr.	OLD QUATERNARY Archaic elephant Etruscan rhinoceros Stenon horse Archaic hippopotamus Sabertooth cat short muzzel hyena	Mollet	LOWER PALEOLITHIC
LOWER PLEISTOCENE		1,8 M.yr.	VILLAFRANCHIAN Auvergne mastodon Borson Mastodon Etruscan rhinoceros	Bòvila Ordís Incarcal	?
PLIOCENE		5 M.yr.		Cornellà del Terri	

Figure 14.- Summary table for the big-mammals fossils recovered in several paleontological and archaeological sites in the Banyoles-Besalú area (after Brusi et al., 1992 and 2002).

*Features to observe*

The wide panoramic view from Puig de Sant Martirià makes it easier to introduce the lacustrine system and the most outstanding aspects of the aforementioned Banyoles hydrogeological system.

To the north, the south-Pyrenean morphostructures stand out from the Alta Garrotxa area. In the foreground lies Pla d'Usall (showing a flat morphology) which constitutes the geological evidence of former lacustrine stages.

To the south, the whole lacustrine basin with the Banyoles Lake and several smaller ponds can be seen. The Banyoles Lake has a roughly 8 shape elongated in a north-south direction, and its banks have a natural lobed geometry. All these evidences indicate that the same subsidence processes that have originated the ponds (estanyols in Catalan language) are responsible for the geometry of the lake.

Many studies have tried to elucidate the lake bottom geometry and to elaborate a bathymetric map. In 1987, Moreno and Garcia located 13 points where water springs up in the bottom of the lake by means of echosounding methods (Fig. 15). The main lake geometric parameters measured by the same authors (Moreno and Garcia, 1989) before the lake was modified to host the canoeing competitions during the 1992 Olympic Games, were as follows:

Maximum length:	2,150 m
Maximum width (North lobe):	775 m
Maximum width (South lobe):	725 m
Minimum distance between lake-banks:	235 m
Perimeter:	6,650 m
Maximum depth:	46.40 m
Average depth:	14.40 m
Surface area:	111.70 hm <sup>2</sup>
Volume:	16.12 hm <sup>3</sup>

There are six main depocentres and many other smaller ones in the bottom of the lake. Below a certain depth, most of the depressions are occupied by suspended sediments due to the pressure of the water emerging from the lake floor. The bathymetric map locates the floor of these depressions at the top of the suspended load instead of on the substratum.

To assess the water budget in the Banyoles Lake it is necessary to determine its drainage basin first. Rainwater that falls in this basin flows towards the lake through six streams located mainly in its western side. Apart from direct rainwater, the lake also collects water coming from some other springs, ponds and crop fields.

The lake outputs, located in the eastern margin of the system, flow into the Terri River. Before the construction of the Banyoles Monastery in 812, water used to overflow the south-eastern margin of the lake, originating a marshy area. Several centuries ago, six irrigation ditches were dug to drain the lake and to use the water for agricultural, industrial and domestic purposes. Nowadays two underground pipes act as artificial drains in case of emergency. Another output in the hydrological budget is the water diverted from the lake to provide drinkable water to the nearby urban areas.

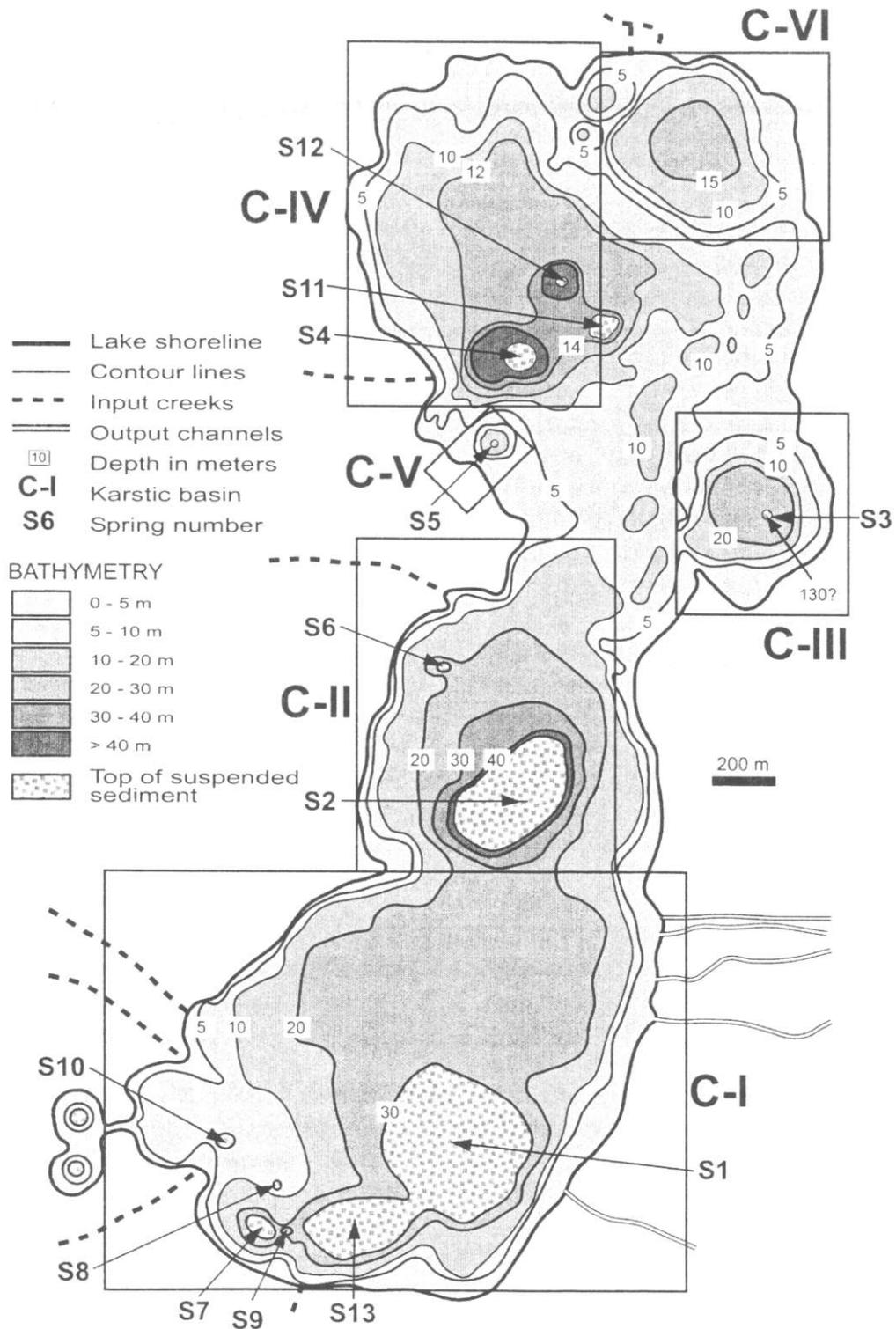


Figure 15.- Bathymétrie map of the Banyoles Lake (after Moreno and Garcia, 1989).

Water level in the lake remains fairly invariable during the year. This implies that inputs and outputs of water must be equal, and that the volume of water must remain constant. Apart from

evapotranspiration, direct rainfall and gains/losses through the Quaternary deposits bordering the lake; it can be accepted that both the inputs due to superficial waters from springs and those due to surging waters have to be roughly equivalent to the volume of water drained by channels and water supply extractions.

The following table provides the mean annual discharge values of the creeks and channels flowing into and out of the lake, measured in  $\text{m}^3$  /day (Brusi et al., 1990):

Riera de Lió	6,700	Rec de Ca n'Hort	7,100
Riera de Can Morgat	6,650	Rec de Can Teixidor	9,300
Riera Castellana	700	Rec Figuera d'en Xo	11,300
Riera dels Tanyers	325	Rec Major	12,500
Riera Marquès	1,025	Rec de Guèmol	4,300
Riera del Vilar	1,025		
Riera de les Tunes	500	Water extractions	6,000
<b>Total Input</b>	<b>17,625</b>	<b>Total output</b>	<b>58,500</b>

As the water input is smaller than the water output, it follows that there must be underground water feeding the lake. It has been estimated that 40,000  $\text{m}^3$  of water spring daily from the lake floor (400-600 l/s). The volume of water entering the lake from the streams constitutes the third part of the total discharge of underground waters in the lake. Most of the water flowing along the streams also has a karstic origin. Both waters emerging from the lake floor and superficial waters coming from the streams continuously renew the water stored in the lake. The renewal time of the water in the lake is longer than 200 days, however this estimation does not take into account the permanence time of water in certain depressions.

**Stop 2. Riera Castellana ponds.** In the western side of the Banyoles Lake, near Castellana creek (Riera Castellana in Catalan language), there are three ponds fed by subaquatic springs. This site can be reached from the road that contours the lake, following an unpaved trail that starts next to Masia de Can Sisó (masia is a Catalan word for cottage).

#### *Features to observe*

Ponds present a subcircular morphology in plan view, slightly modified by human action, and a typical funnel-shaped or bowl-shaped cross-section. They constitute one of the most outstanding evidences of the artesian behaviour of the aquifer system and the dynamics of dissolution processes in the area. The land subsidence, which leads to the formation of the ponds, can be explained as a consequence of the underground pressurized water flow along a confined aquifer. Water rises to the surface through faults affecting the tertiary bedrock. Gypsum, existing in a considerable thickness at depth, is preferentially dissolved and generates voids whose size depends on the magnitude of the underground flows. The cavities grow until their roof cannot stand the weight of the materials above. Then a gravitational collapse occurs, leading to the formation of funnel-shaped sinkholes. Ponds form when water emerges in these depressions (Fig.

16). The high sulphate content of the sourcing waters, usually higher than 500 mg/l, is an evidence of the aforementioned dissolution of gypsum.

There are several ponds near the Riera Castellana mouth. Sisó pond (Estanyol d'en Sisó) shows seasonal variations in the water colour related to changes in the kind of bacteria living there. Nou pond (Estanyol Nou) formed after a gravitational collapse that took place in November 1978. A spring is also found in the right margin of Riera Castellana.

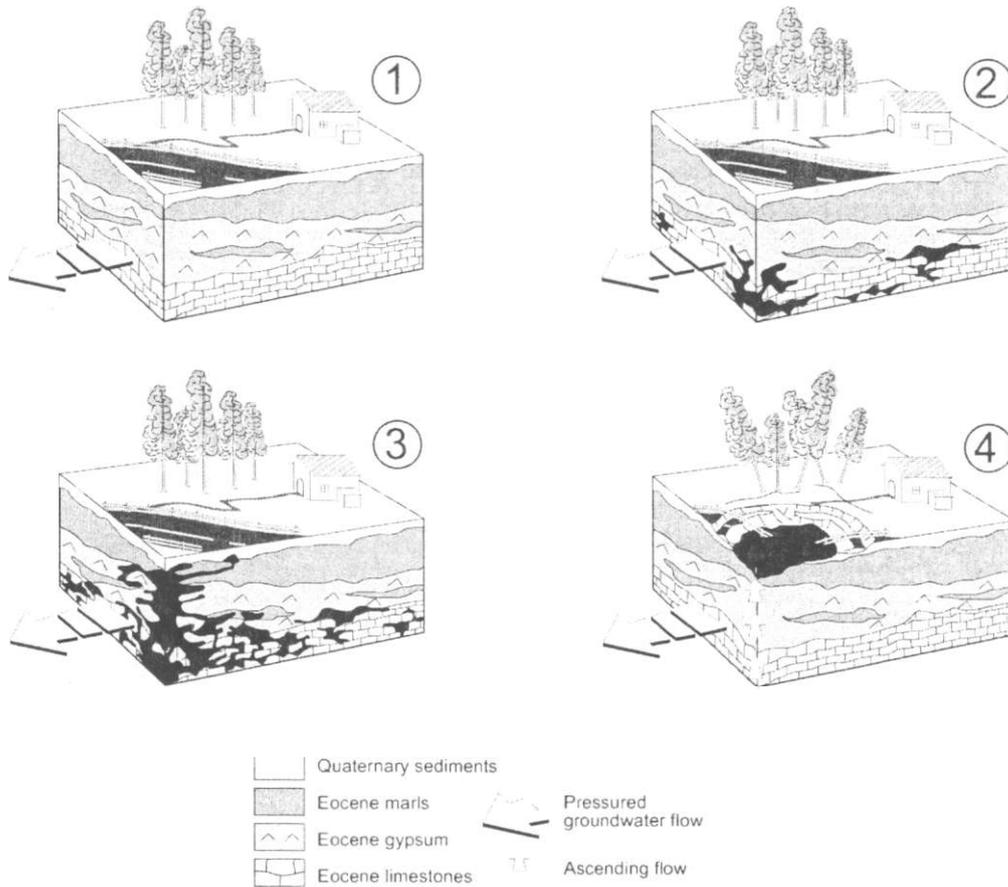


Figure 16.- Idealized scheme of the formation of a karstic pond in the Banyoles area (after Brusi et al., 1987).

Similar ponds can be found in the southern margin of the Banyoles Lake. Vilar pond, Cendra pond and Montalt ponds stand out. Vilar pond is formed by the coalescence of two depressions.

**Stop 3. Les Estunes travertines and cracks.** This outcrop is located on the left side of the GI-524 road, which links Banyoles and Olot through Santa Pau. The stop point is situated 250 m after the junction to Pujarnol.

#### *Features to observe*

In Les Estunes (also known as Les Tunes), a travertine deposit whose top is 10 m above the present lake level can be observed. A sequence of travertine facies can be seen in several outcrops. These deposits have been interpreted as the result of carbonate precipitation related to existing springs to the east of this location, in the littoral margin of a former lake. The travertine

*Travertines and volcanic landforms*

platform is disrupted by many cracks which are slightly affected by karstification. In some places it is possible to walk inside these cracks. Their origin has been related to the tilting of travertine panels.

The sedimentological characteristics of these travertine deposits are described here from top to bottom (Fig. 17):

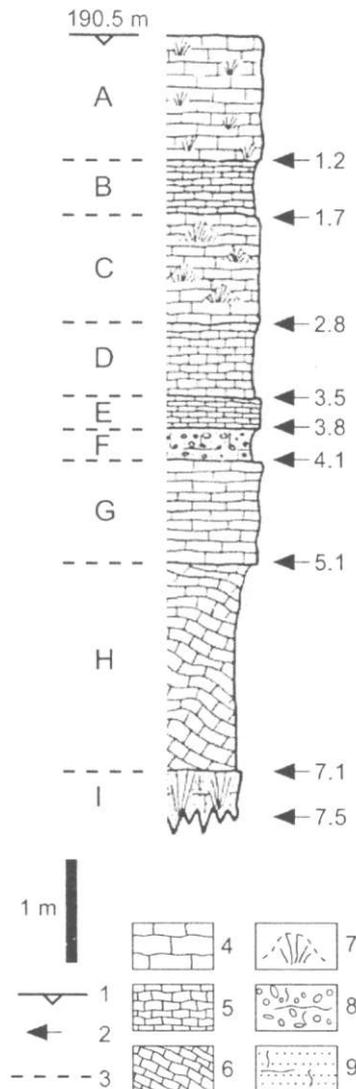


Figure 17.- Stratigraphic section of Les Estunes travertines (after Brusi, 1993). 1) Absolute topographic elevation of the top of the section; 2) Relative depth; 3) Facies contact; 4) Coarse to medium laminated, stromatolitic travertine; 5) Fine laminated, stromatolitic travertine; 6) Ondulated, stromatolitic travertine; 7) Macrophyte travertine; 8) Breccia travertine; 9) Carbonate mud.

- A. 0.00-1.20 m: Travertine made of encrusted vascular plants, stems of *typha* (*sp.*) being the most common, with a vertical or slightly radial orientation. Tree leaves prints can be seen occasionally at the top of the level.
- B. 1.20-1.70 m: Planar, laminated, stromatolitic travertine with conspicuous bioherm layers.

- C. 1.70-2.80 m: Macrophyte travertine with many vertical casts.
- D. 2.80-3.50 m: Laminated, stromatolithic travertine intercalated with compact layers and spongy layers, with an average thickness higher than 2 cm.
- E. 3.50-3.80 m: Homogeneous, thin-laminated, stromatolithic travertine, with rhythmical subhorizontal laminae up to 1 cm thick.
- F. 3.80-4.10 m: Detrital and brecciated travertine strongly cemented although with a porous appearance. Clasts are smaller than 2-3 cm.
- G. 4.10-5.10 m: Compact, subhorizontal, coarse-laminated, stromatolithic travertine.
- H. 5.10-7.10 m: Wavy-laminated, stromatolithic travertine.
- I. 7.10-7.50 m: Macrophyte travertine with vertical encrusted stems which can reach 30-40 cm of length and 3 cm in diameter.

**Stop 4. Reclau Caves, Serinyà Prehistoric Caves Park.** Reclau caves, which are included in the Serinyà Prehistoric Caves Park, are located 5 km to the north of Banyoles, in the east side of the C-66 road from Girona to Olot. The park is 500 m south of Serinyà.

#### *Features to observe*

These caves, which host several prehistoric sites, are found in a travertine cliff close to the Serinyadell River and its narrow fluvial terrace. Reclau caves are spring and waterfall travertine structures that form natural shelters which in turn are affected by karstification phenomena (Julià, 1980). In this area, notably influenced by the Serinyadell River incision, carbonate-rich flows coming from Pla d'Usall descended abruptly forming waterfall- travertines.

Travertine genesis was controlled by the quick migration of the active springs. The travertine front shows a relatively simple overall structure but a complex geometry in detail. Waterfall travertine facies were permanently modified by erosive processes and by the migration of the active flow. This fact determined the coalescence of many erosive and depositional morphologies.

Very compact and laminar deposits are common. These deposits sometimes generate small terraced pools filled with detrital facies. Incrustation facies of different types of macrophytes and microphytes, characteristic of waterfall and splash zones (*bryophyta*, *hepatophyta*, *cyperus*, *typha*, reeds, tree leaves) are also very common. Remains of fresh water fauna usually appear within these deposits. Accretion of these morphologies created overhangs. Some of these overhangs were big enough to be used as shelters by humans. These cavities and the high porosity of the waterfall facies contributed to increase the complexity of the travertine deposits. Breccias, terrigenous fillings and even travertinization flows which grew upwards, are found in the cavities. Secondary travertinization and recrystallization within cracks and pipes are also common, and so is the slight karstification of the travertines.

All the paleontological sites are located along the 200 m long travertine cliff. From north to south, the most important sites are Reclau Viver Cave, Mollet Cave and Arbreda Cave. Arbreda Cave stands out from the rest. It was discovered in 1972 and it has been systematically excavated since 1975 (Fig. 18). It has yielded a prolific archaeological sequence ranging from the Middle to the Upper Paleolithic (Upper Pleistocene). Mollet Cave contains a lower level with remains of the Middle Paleolithic (Middle Pleistocene). These remains constitute the oldest record of human occupation in the area. Reclau Viver Cave, excavated *ca.* 1940, supplied an archaeological sequence from the Upper Paleolithic and the prehistorical Holocene (Neolithic and Bronze Age).

The remains in all these caves record a time period ranging from 200,000 years ago (early Middle Paleolithic) to 3,000 years ago (the end of the Bronze Age) (Brusi et al., 2002).

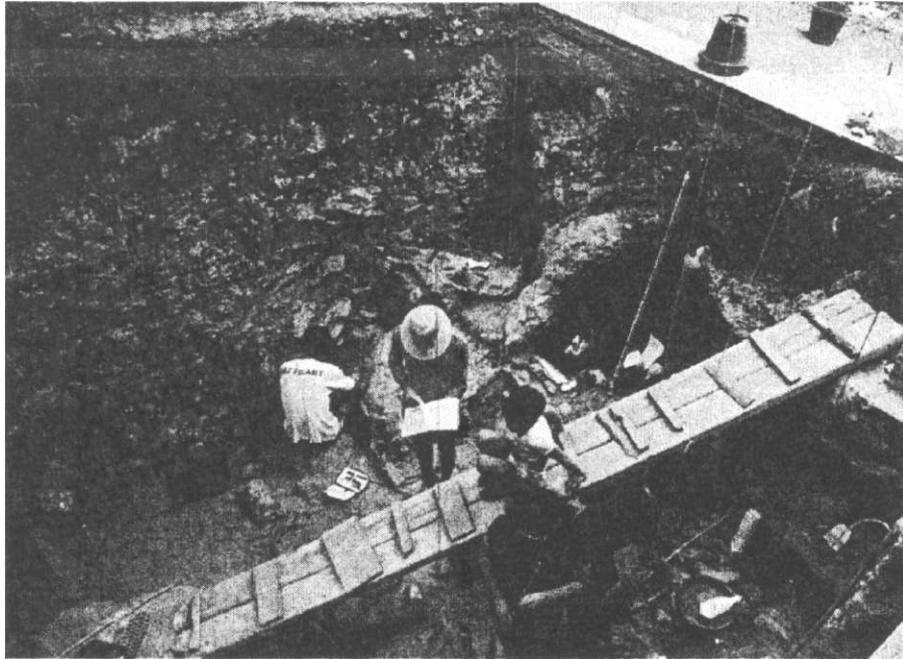


Figure 18.- Arbreda cave (Reclau caves, Serinyà) during an archaeological campaign in the Upper Paleolithic levels (J. Maroto photo).

This place was set up in 1996 as a public archaeological park compatible with further research activities. Among the offers of the park, stand out a film which introduces the visitors to the caves and to the Paleolithic period and a display of human life in the area 18,000 years ago. Apart from that, the three main caves can be visited by means of signposted paths.

### **3. Garrotxa volcanic zone**

#### *3.1 Objectives*

The general purpose of this part of the field trip is to show the most outstanding features of the Quaternary volcanism in north-eastern Catalunya. An itinerary across the Garrotxa Volcanic Zone (GVZ), which hosts the most recent and best preserved volcanoes of the Iberian Peninsula, is proposed.

#### *3.2 General aspects*

##### *3.2.1 Volcanic context*

The Catalan volcanic field was described for the first time more than 150 years ago (Bolós, 1841; Gelabert, 1904; Calderón et al., 1907). It is geodynamically related to other volcanic areas occurring in western Europe. Since the Upper Miocene, post-Alpine extensional tectonic conditions generated an intraplate rift that spreads along more than 1,100 km from the North Sea and the Rhine Basin to the Mediterranean coast of the Iberian Peninsula. Within this rift zone, several graben formed in response to the displacement of large north-eastern to south-western trending normal faults. One of the main structural features is the Valencia trough, which extends from the Mediterranean margin of the Iberian Range to the eastern Pyrenees.

Three volcanic regions can be individualized within this trough: the Valencia, the Columbretes Islands and the Catalan volcanic fields (Fig. 19). The last one includes many volcanoes entirely located in the province of Girona. Here, magma rose up through north-western to south-eastern trending normal faults, perpendicular to the main rift faults, originating many eruptive events.

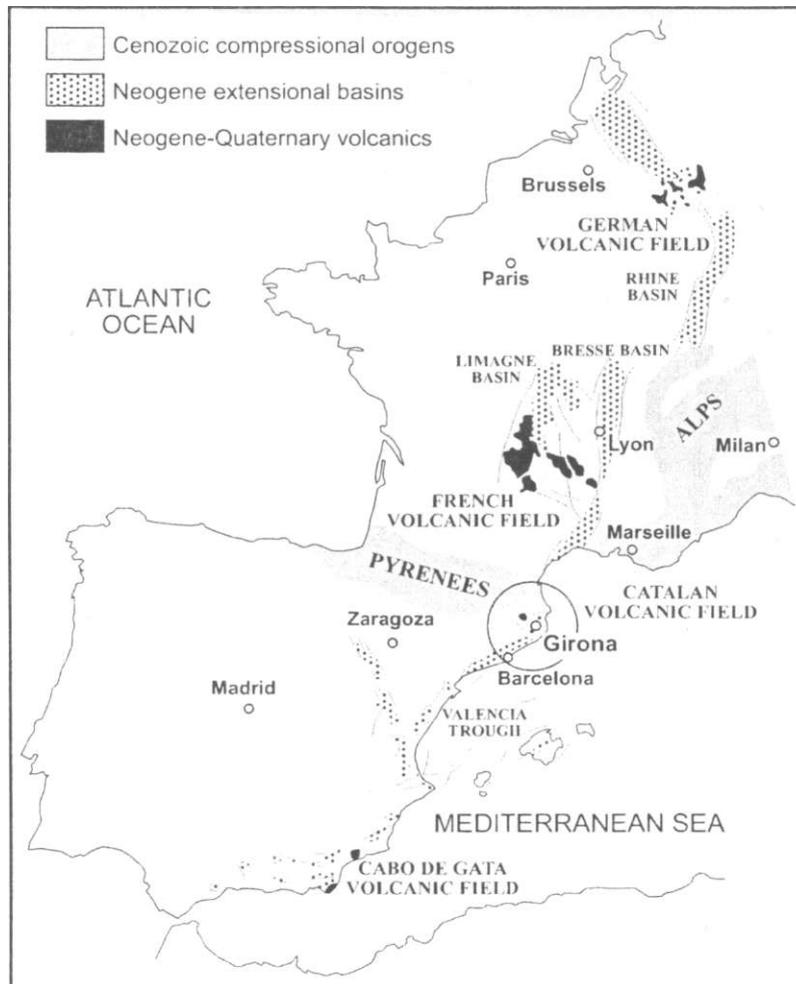


Figure 19.- Location of the Catalan Volcanic Field within the Neogene-Quaternary rift system of Central-Western Europe.

### 3.2.2 Age of the volcanism

Although scarce, geochronological data show that volcanism in Girona was active from the Pontian (Upper Miocene continental stage) until relatively recent times (the latest volcanic eruption took place ~10.000 years ago). According to datings by several authors, volcanism began in the Empordà region, then moved towards La Selva region and eventually focused in The Gironès and Garrotxa regions (Guardia, 1964; Donville, 1973; Guérin *et al.*, 1985) (Fig. 20). With more than 40 (Pallí, 1981; Ferrés *et al.*, 1998; Mallarach, 1998), the GVZ, particularly the Olot volcanic area, hosts the highest number of volcanoes of the Catalan Volcanic Field. Most of these volcanoes are very well preserved and are included in the Garrotxa Volcanic Zone Natural Park (Fig. 21).

### 3.2.3 Magma characteristics

The volcanic materials in the GVZ have alkaline-basic composition. They consist mostly of basalts and basanites with low silica content and low sodium and potassium average content (Tournon, 1969). The basalts contain small olivine, pyroxene, plagioclase and alkaline-feldspar (sanidine) phenocrysts, within a microcrystalline to vitreous matrix with abundant magnetite, biotite and amphiboles. The basanites are very similar to basalts, but have lower silica content and have small feldspathoid crystals (leucite, analcime and nepheline).

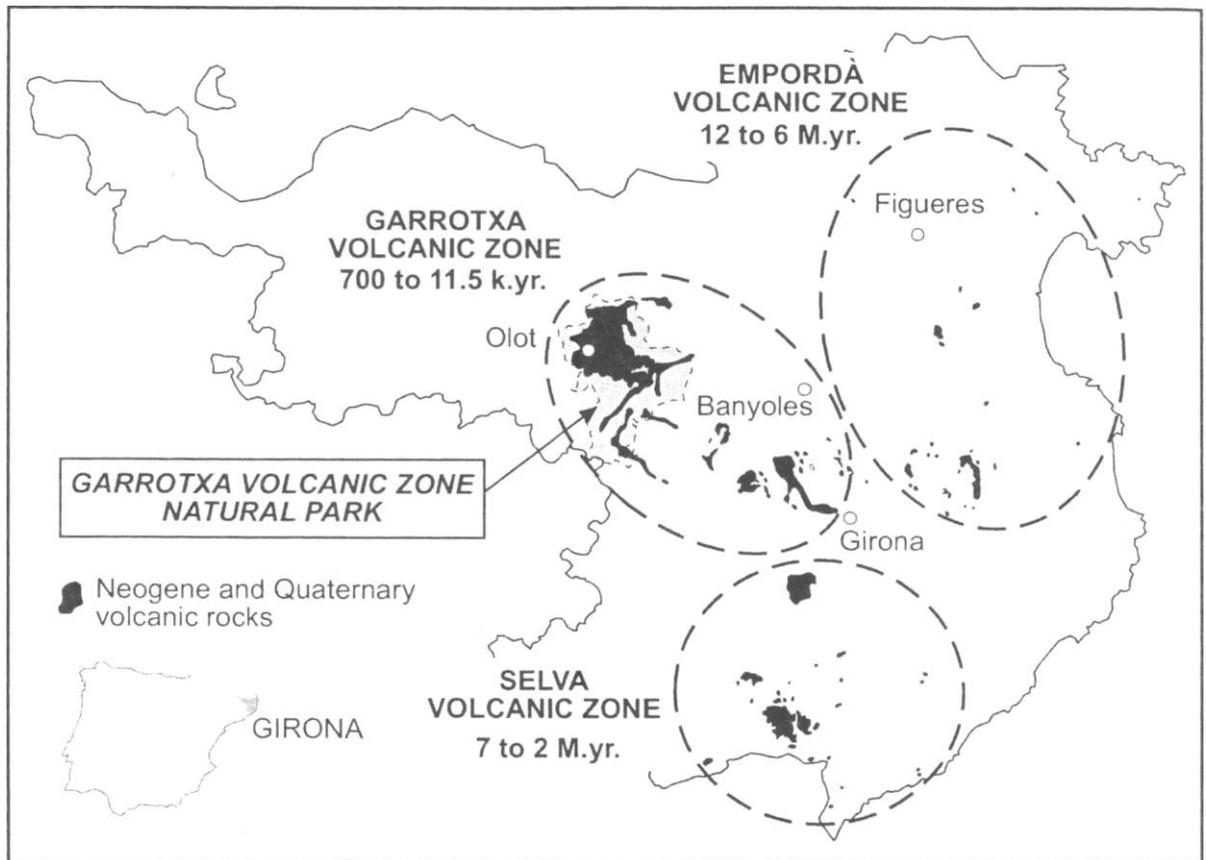


Figure 20.- Age and distribution of the Neogene and Quaternary extrusive rocks in the three volcanic zones of the province of Girona (adapted from Palli and Roqué, 1996).

Magmas rose up very fast from the source area (asthenospheric mantle) to the surface in one single eruption and there was no magmatic differentiation. The study of ultrabasic xenoliths incorporated in the ascending magma allowed to estimate in 0.2 m/s the velocity of the rising magma (Martí et al., 1992). Taking into account that crust thickness in this area is around 30 km, the rise of the magma from the lower crust to the surface lasted one day and a half (Gallart et al., 1984).

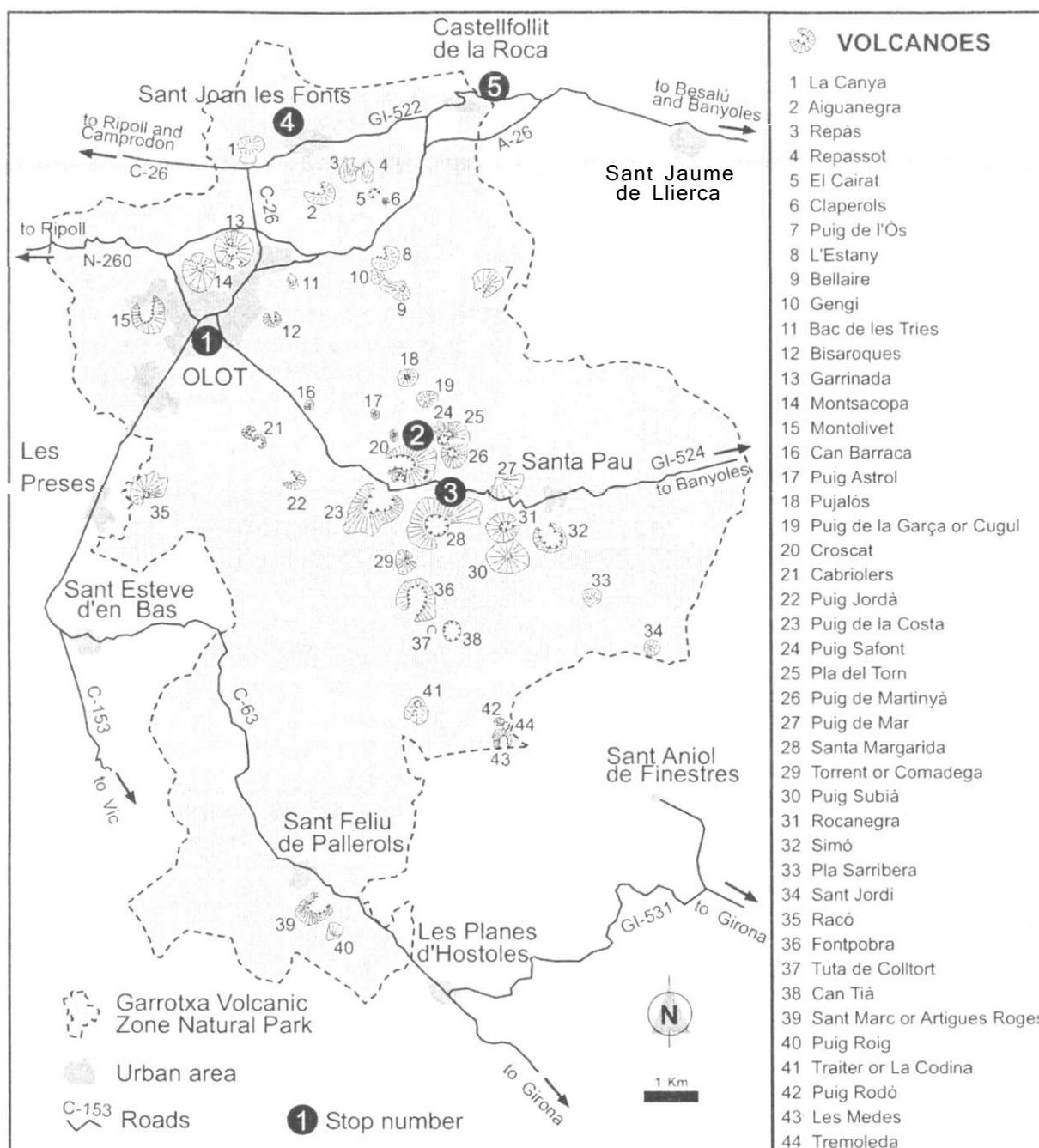


Figure 21.- Volcanoes in the Garrotxa Volcanic Zone Natural Park and fieldtrip stops.

### 3.2.4 Eruptive activity

Different types of eruptive activity (effusive and explosive) took place depending on the volatiles content of the magma and on whether it interacted with water along its way up or not.

#### 3.2.4.1 Effusive activity

It consisted of a continuous and quiet emission of lava from the eruptive vent, since the pressure exerted by the gas in the volcanic chimney was not strong enough to throw it to the atmosphere. This type of eruptive activity was characterized by basic, gas-poor magmas. Gas-poor magma

could be the result of both previous eruptive events leading to degasification (explosive or fumarolic stages), or initial composition of the magma.

Lava descended along pre-existing valleys, creating lava flows. Due to the low viscosity of the basic magmas in the GVZ, they reached long distances before they solidified. The lava flows of Croscat, Pla Sarribera and La Canya volcanoes, with trajectories sometimes longer than 10 km (Pallí, 1981), are good examples of this kind of effusive activity (Fig. 22).

When lava flowed over water-saturated ground, water in the substratum evaporated and steam escaped as bubbles through the lava layer. Rising gas produced incipient explosions on the top layer of the partially solidified lava. This resulted in the formation of blisters: slag protuberances, several meters high (tossols in Catalan language). These formations are known as hornitos if they have an outlet hole.

#### 3.2.4.2 Explosive activity

It was characterized by fragmentation and ejection of the magma, in a more or less violent way, through successive explosions triggered by rapid gas expansion. Although explosive activity can be of different types, only strombolian and phreatomagmatic phases have been documented in the GVZ.

- Strombolian activity, characteristic of basic magmas, consists of periodical explosions separated by variable time spans (seconds to hours), caused by the arrival of gas bubbles to the magma surface that pull out the outermost fragments of magma and throw them to the atmosphere with a parabolic trajectory. During spells between explosions the top of the magma solidifies, as a result gas pressure increases, and the cycle can start again.
- Phreatomagmatic activity is characterised by its high violence, being the result of the interaction between magmatic materials and underground water. The high temperature of melted materials turns water into vapour very fast. Sudden expansion of the vapour overpressurizes the aquifer, triggering a sequence of violent explosions which fragment the magma and the rocks surrounding the magmatic pipes, thus producing high-speed pyroclastic flows.

Even though the volcanoes in the GVZ underwent a single eruption, most of the eruptions consisted of a few eruptive phases. This is due to variations in gas proportion of the magma and presence or absence of underground water. Usually, when there was no influence of external water, the eruption had one or several phases of strombolian activity and a later phase of effusive activity due to the decrease in the gas content within the magma (Croscat volcano is a good example). However, the existence of underground water triggered phreatomagmatic activity which intercalated with strombolian phases to form polyphasic volcanoes, such as Santa Margarida volcano.

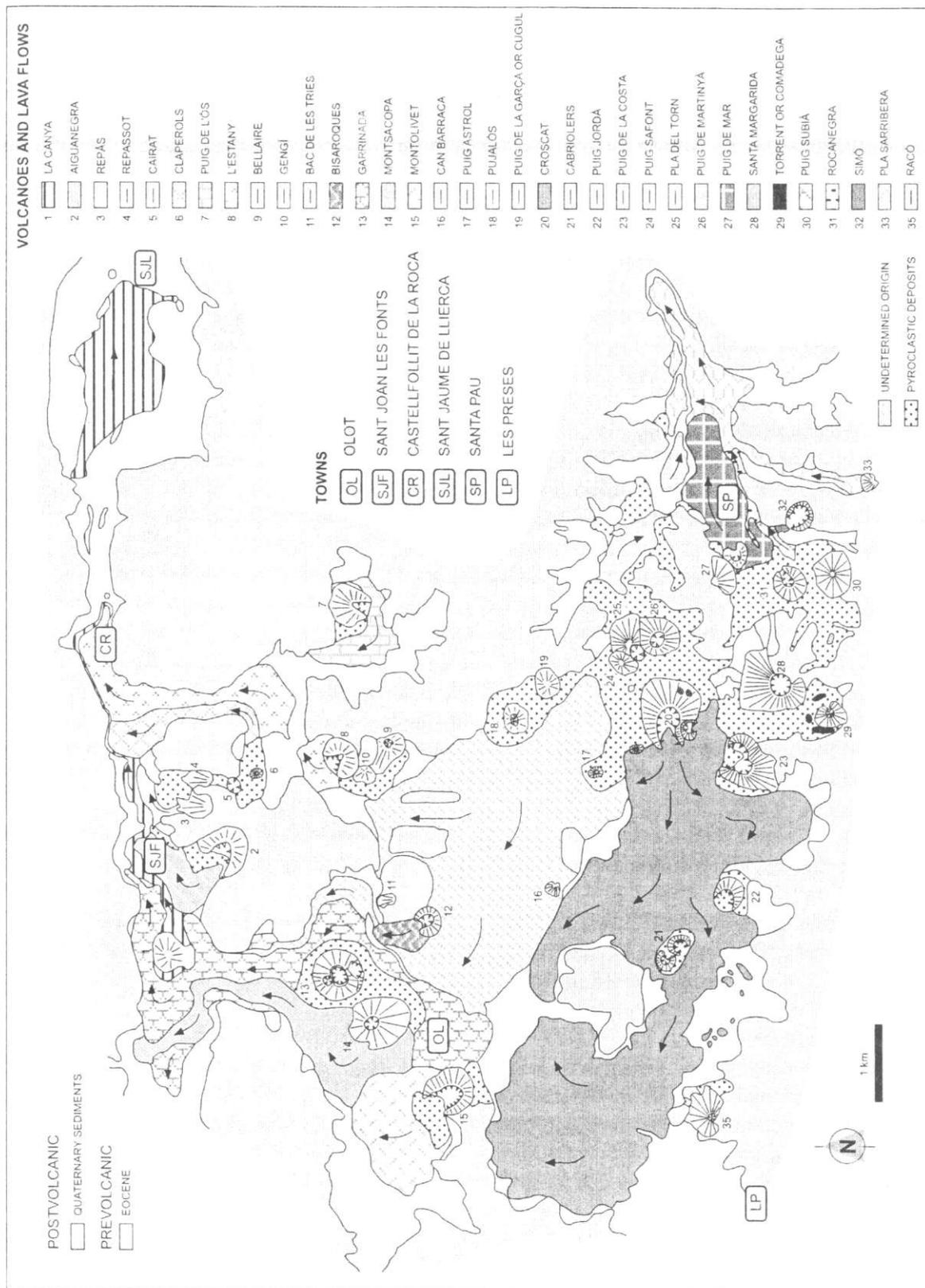


Figure 22.- Volcanoes and lava flows in the surroundings of Olot (modified after Palli, 1981).

### 3.2.5 Volcanic materials

The different eruptive events expelled out solid, liquid and gas products. Solid and liquid materials formed two types of volcanic deposits: massive and volcanoclastic.

#### 3.2.5.1 Massive materials

After the cooling and solidification of lava, compact rock bodies of homogeneous composition developed. They display different geometries, morphologies and internal structures. These features depend on the magma composition, original viscosity, cooling temperature, volume of erupted material, terrain slope and characteristics of the substratum materials. Lava flows can be classified in two groups depending on their general aspect:

- Smooth lava flows (or *pahoehoe*) display a regular and slightly wavy surface. The existence of turbulent flows in their interior can produce creases and folds in the surface, which are perpendicular to the flow direction, resulting in the formation of ropy lavas.
- Rough lava flows (or *aa*) display an irregular surface, composed of blocks formed by the continuous fragmentation of the cooled lava crust while the lava is still flowing. If this movement takes place over steep slopes, larger boulders may break from the crust, generating boulder lava flows.

When lava flows cooled down, they contracted and an internal system of joints was developed. If a lava flow is stopped, cooling is slower and joints perpendicular to the surface may form, leading to pentagonal and hexagonal prisms. If a lava flow is still moving and cooling is faster, then joints form parallel to the lava flow direction, and slabs are individualized. Some lava flows display a secondary spheroidal jointing, related to the weathering of its outer surface. Retraction joints facilitate spherical, "onion-skin" weathering, resulting in the formation of rounded blocks of different sizes. In areas where lava flows are permanently in contact with water, mineral weathering produced whitish stains and ovoid grains which may be as big as a hazelnut.

#### 3.2.5.2 Volcanoclastic materials

Volcanic explosive activity resulted in accumulations of volcanic materials mixed with fragments of country rocks. The fragments resulting from this kind of activity are known as pyroclasts. They are classified according to their origin into young and lithic pyroclasts.

- Young or essential pyroclasts come from the magma erupted onto the surface. They can be dense or vesicular.
- *Accidental lithic pyroclasts* come from the prevolcanic sedimentary, metamorphic or igneous bedrock
- *Accessory lithic pyroclasts* come from the fragmentation of magmas solidified during previous phases of the same volcano.

According to their particle size, three categories of pyroclasts can be distinguished:

- Ash, less than 2 mm in diameter.

- Lapilli (greda in Catalan language), from 2 to 64 mm in diameter.
- Bombs (rounded) and blocks (angular) when diameters are larger than 64 mm. The bombs that were ejected before they had completely cooled down adopted rounded or ellipsoidal shapes during their aerial trajectory. Usually, they show a quartered surface due to faster solidification and retraction in the outermost parts of the bombs (bread-crust bombs).

Accumulations of volcanoclastic materials are generically known as pyroclastic deposits or tephra. Several types of pyroclastic deposits are common in the GVZ.

- Scoria deposits. They are formed by young, vesicular pyroclasts of lapilli or greater size.
- Volcanic tuff. This term is used to designate compact deposits due to welding or secondary cementation.
- Pyroclastic fall deposits. They are formed by the free or parabolic fall of material expelled from the eruptive vent. They usually form laterally continuous layers that cover the pre-existing topography and whose thickness decrease as the distance to the eruptive vent increases. Since strombolian eruptions did not eject materials to a high altitude, pyroclasts accumulated next to the vent. On the other hand, phreatomagmatic eruptions expelled great amounts of lithic and young pyroclasts with a horizontal displacement more important than in the strombolian activity.
- Pyroclastic flow deposits. They are the result of laminar, gaseous, dense, gravity-controlled flows which contained great amounts of high-temperature pyroclasts. They move downhill very fast and close to the topographic surface, filling valleys and gullies. These deposits are compact, heterometric and heterogeneous in lithology.
- Pyroclastic surge deposits. These materials are the result of turbulent, gaseous flows with a small percentage of pyroclasts. They move downhill at a very high speed and close to the land surface, filling valley bottoms. Due to their high energy, they sporadically could surpass topographic obstacles moving uphill. These well sorted deposits often show conspicuous unidirectional sedimentary features.

### 3.2.6 Volcanic edifices

Depending on the type of eruptive activity and its evolution through time, and on whether they are the result of a single eruption or several of them, volcanoes are classified into monogenetic and polygenetic categories.

All the GVZ volcanoes are monogenetic. They are formed by a single eruption which led to the construction of a cone and a crater. Cones are positive relieves of pyroclastic deposits, variable in height, width and slope. Craters are negative relieves defined by a circular or subcircular depression where explosions and extrusion of volcanic materials took place. In some cases lava flows partially destroyed the cones and created horseshoe-shaped craters (Croscat volcano being a good example). This morphology can also be due to either an inclined volcanic chimney or to wind-driven differential accumulation of pyroclasts. Other volcanoes have craters with no morphological expression (for example, Puig Subià volcano). Some others show two (Traiter volcano) or even three (Garrinada volcano) superposed craters produced in different phases of a unique eruption.

Many of the volcanoes are found in a lineal, straight arrangement. Fissure-related vents are the most accepted interpretation of this reality. The most common volcanic edifices in the GVZ are

pyroclastic and scoria cones formed by strombolian activity. Volcanic edifices derived from phreatomagmatic activity are less common.

- Up to 27 strombolian pyroclastic cones have been identified. They usually show a circular or slightly elongated shape in plan view. Two facies of pyroclastic deposits can be distinguished in these volcanoes. The external facies consist of lapilli layers with blocks which radially contour the eruption vent and have a dip of 15° to 30°. The more complex inner facies contain welded pyroclastic and crater-fill deposits of layered lapilli and bombs, which in turn are intruded by chimney dikes in the innermost parts of the vent. These deposits have an average dip of around 25° to 35°.
- Ring shaped tuff volcanic edifices are also present in the area, but they are not as widespread as strombolian edifices. They differ from the pyroclastic cones in height, nature of materials and crater dimensions. As they are mainly the product of phreatomagmatic activity, tuff rings are lower, display more gentle slopes (up to 10°), and they are composed of a mixture of young and lithic pyroclasts.

Most of the volcanoes in the GVZ were formed by strombolian and phreatomagmatic phases belonging to a single eruption. This fact has resulted in polyphasic edifices where several morphologies interfere with each other. As a consequence, original volcanic geometries are sometimes difficult to identify.

The particular orographic configuration of Olot area is responsible for its especially moist climate, since humid, prevailing Mediterranean winds are trapped there. A mean annual precipitation of 1,040 mm and an average annual rainfall of 98 days are combined with the absence of an extremely dry season. This climate contributes to the preservation of an edaphic cover that has helped to protect the volcanic structures from erosion. The original slope of 35° of most of the cones has been flattened to 22° to 26°, evolving into a concave-convex slope. Only in those edifices placed on the slopes of former relieves (such as Puig de Mar, Pla Sarribera and Repàs volcanoes) and in the oldest ones (La Canya volcano), the original crater does not remain and displays eroded slopes.

**Stop 1. Museu dels Volcans (Volcanoes Museum)** Torre Castanys (Castanys' Villa) is a Modernist building located in Santa Coloma Avenue, 17800 Olot, which hosts the Volcanoes Museum and the head office of the Garrotxa Volcanic Zone Natural Park.

#### *Features to observe*

The permanent display shows the origin and dynamics of earthquakes and volcanoes, the seismic activity recorded in the region and its volcanism, known through the study of the main volcanic structures (Fig. 23). Some panels should be remarked:

Panel number 7: Geological cross-section of the Garrotxa region.

Panel number 8: Garrotxa geology.

Panel number 12: The Catalan volcanism and its relationship with the European rift system.

Panel number 13: Montsacopa, a strombolian volcano.

Panel number 14: Santa Margarida volcano.

Panel number 15: The lava flow of Croscat volcano.

Panel number 16: The cliff of Castellfollit de la Roca.

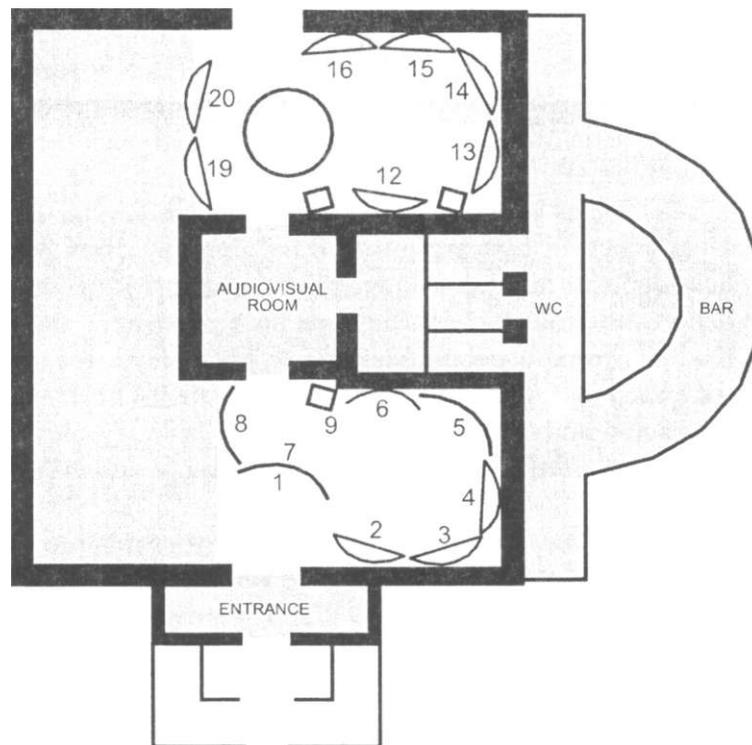


Figure 23.- Museu dels Volcans (Volcanoes Museum) plan view showing reference numbers of the display panels (see text for details on the most interesting ones).

**Stop 2. Croscat Volcano.** The GI-524 road from Olot to Santa Pau goes around the southern side of the main volcanic structure of Croscat volcano, one of the most visited of the Garrotxa Volcanic Zone Natural Park. Since motorized access to the main volcanic outcrops is restricted, it is necessary to park in the kilometric point 6.5 of this road. It takes 15 minutes to get to the information centre located in Can Passavent (Passavent House). The large outcrop visible in an old lapilli quarry, restored in 1995, gives us a unique opportunity to observe the internal structure of a volcanic edifice.

*Features to observe*

Croscat volcano is a pyroclastic volcanic cone with a horseshoe-shaped crater open to the west due to the extrusion of a lava flow which blurred its original conical shape (Fig. 24). The volcanic cone has a maximum basal diameter of 1,200 m and a height of 170 m. These features make croscat volcano the highest volcano of the Iberian Peninsula. The crater is 650 m long and 350 m wide. There are five adventive cones surrounding the main volcanic edifice: Can Xel, Pomareda, S'Agonia and two other unnamed small cones (Fig. 25).

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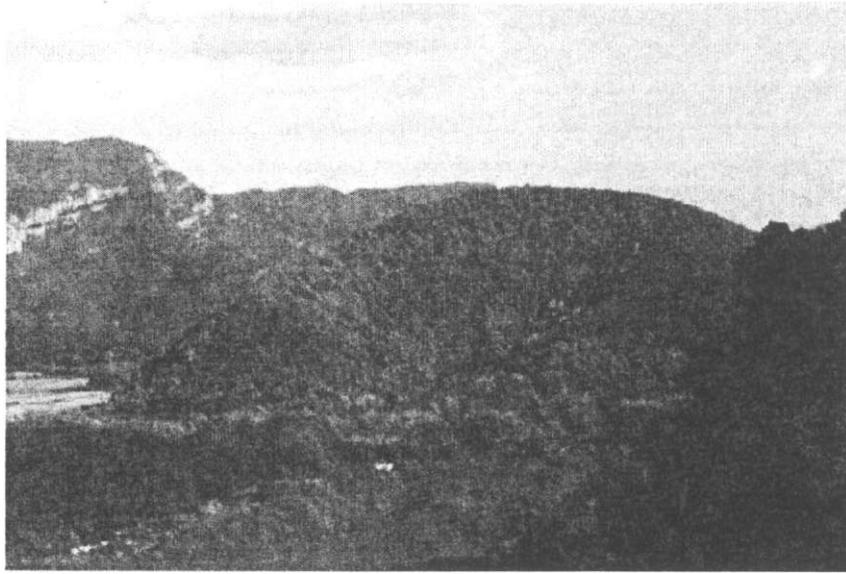


Figure 24.- View of croscat volcano and its horseshoe-shaped crater completely covered by forest.

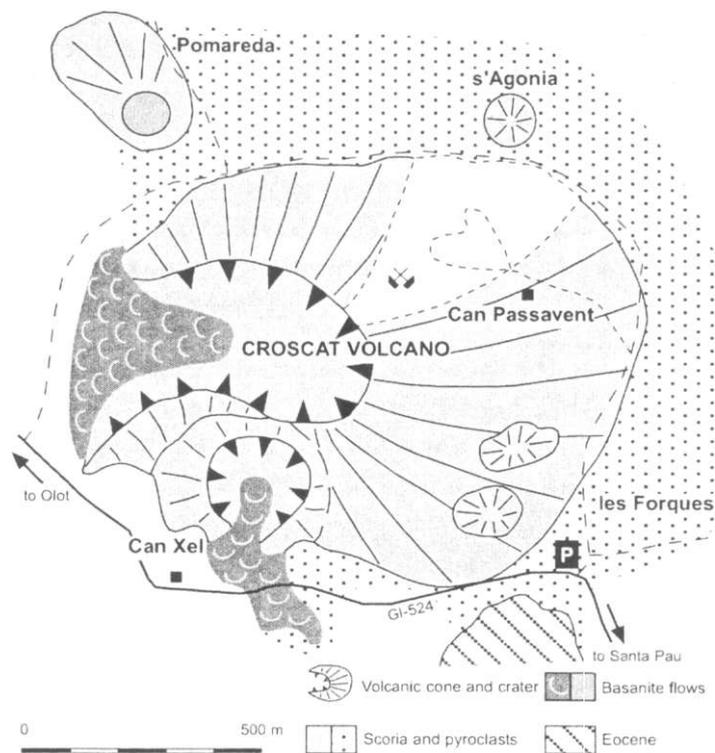


Figure 25.- Simplified geologic map of croscat volcano and its adventive cones (modified after Mallarach, 1998).

Former mining activity in the north-eastern flank of the volcano was active until the beginning of the nineties and has left an outcrop 150 high and 500 m wide (Fig. 26). This large scar, and other smaller ones in the vicinity which had been used as urban waste dumps, have been partially restored since 1995. Nevertheless, the main front is considered to be the most exceptional outcrop of the inner parts of a volcanic edifice not only in the GVZ, but in the whole Catalan Volcanic Field. Consequently, it has been preserved because of its high scientific and pedagogic value.

The internal structure of the cone consists of pyroclastic layers made up of alternating irregular and vesicular lapilli, scoria blocks, scattered volcanic bombs and some ash layers. The dip of pyroclastic layers decreases in distance, since volcano slope increased during its eruption. Dominant colours of the pyroclastic deposits are black and grey. However, reddish colours can be seen close to the vent, which could be related to thermal alteration by hot rising gases during the last stages of the eruption.

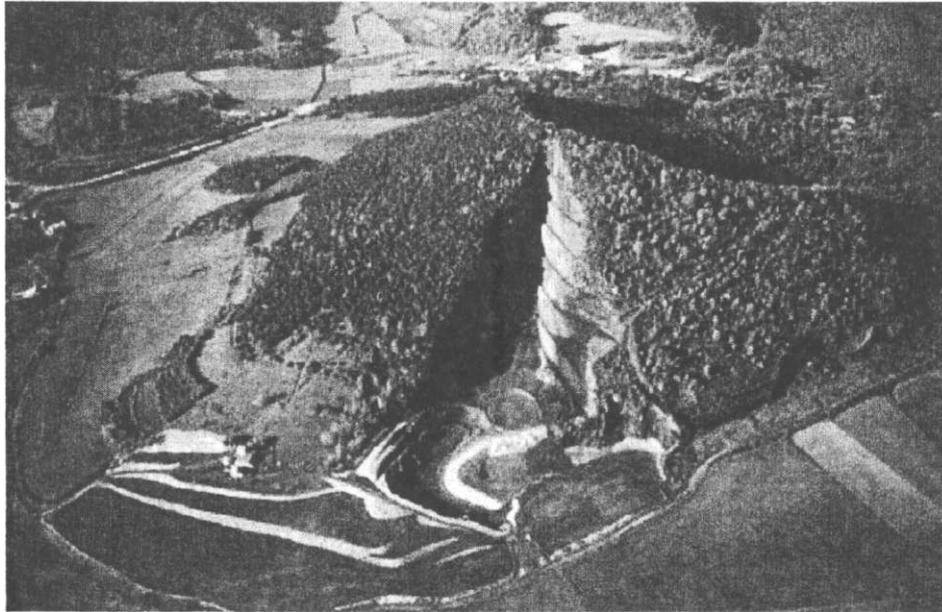


Figure 26 - Aerial view of Croscat volcano from the northeast. Nowadays the base of the old quarry scar and other restored former extraction areas are accessible for the public (Garrotxa Volcanic Zone Natural Park photo).

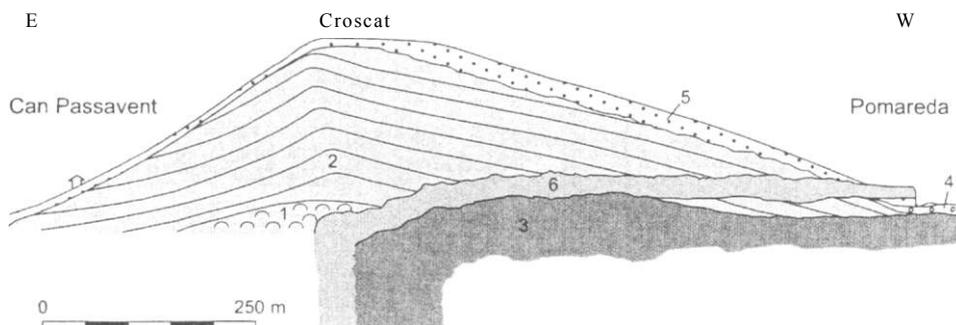


Figure 27.- Schematic geologic cross section of croscat volcano. Numbers refer to the eruptive phases cited in the text.

The following eruptive phases have been deduced for croscat volcano and its adventive cone Pomareda (Fig. 27) (Ferrés, 1996):



Figure 28.- Basanite lava flow over lapilli deposits at Pomareda (Crosca's adventive cone), which is the youngest dated lava flow in the whole Catalan Volcanic Field.

- A first phase of low explosive strombolian activity formed a welded slag deposit (tuna in Catalan language) near the vent. It shows an easily recognizable red colour and can be seen in the lowest part of the main outcrop.
- A second phase of highly explosive strombolian activity ejected great amounts of lapilli, ash and blocks that built the main volcanic cone. Successive explosions took place during this eruptive phase, which formed layers of different grain size.
- During a third effusive phase, almost simultaneous to the former stage, a rough, aa-type basanite lava flow was extruded. As a consequence, the original cone was partially destroyed. The lava flow covered a distance of 7 km to the west with a maximum width of 2 km. The Fluvià River and many other smaller streams were dammed, creating a 10 km<sup>2</sup> lake which flooded the Bas valley to the southwest. In addition to this, as lava went over rivers and water saturated terrains, blisters (tossols in Catalan language) and hornitos formed. More than 150 tossols have been identified in the Crosca lava flow, some of them reaching more than 25 m in height and 150 m in basal diameter. Irregular and size variable lava blocks, black in colour, protrude over the flow surface. Other visible morphologies on the slaggy lava surface are pressure ridges, waves and progression folds parallel and perpendicular to the flow direction respectively. The age of the lava flow, dated by thermoluminescence, is 17,100±1,600 years B.P. (Guérin et al., 1985).
- A fourth strombolian phase, which has been recorded in the Pomareda adventive cone, created a 5 m thick volcanic agglomerate made up of young vesicular blocks and lapilli. It forms a strongly welded, dark coloured deposit.

- In the fifth highly explosive strombolian phase, lapilli, ash and large volcanic bombs were expelled. This phase was probably short, fast and without interruptions. These materials finished the construction of the Croscat cone. Winds coming from a western direction transported a great part of these materials, which covered several of the nearest pre-existing relieves with a 1 to 4 m thick lapilli and ash layer. This can be observed in Les Forques plain, Safont, Pla del Torn, Martinyà and Santa Margaida volcanoes, among other locations.
- The sixth and last effusive phase emitted a small basanite lava flow up to 2 m thick from the Pomareda adventive cone (Fig. 28). It covered less than 1 hectare in area. This small flow covered and welded former pyroclastic deposits. The age of this flow is  $11,500 \pm 1,100$  years B.P. (Guérin et al., 1985). This is the most recent volcanic eruptive event dated in the Catalan Volcanic Field.

**Stop 3. Santa Margarida Volcano.** One km away from the 2<sup>nd</sup> Stop, following the GI-524 road to Santa Pau, there is another parking area which is the starting point for the visit to Santa Margarida volcano. A 30 minutes walk is required to reach the crater. Halfway up, in Can Caselles (Caselles House), the Eocene sedimentary bedrock crops out. In order to observe the volcanic materials and their depositional sequences, it is necessary to follow an unpaved trail to Can Collellmir for about 500 m from the parking lot.



Figure 29.- Aerial view of Santa Margarida volcano, taken from the north.

*Features to observe*

Santa Margarida is a polyphasic volcano generated by both phreatomagmatic and strombolian phases. Although the volcanic cone is 150 m high and has a basal diameter of 1,200 m, it is covered by a maximum of only 85 m of volcanic materials. The volcanic edifice is irregular because part of it was built over a pre-existing relief. What seems to be a conventional cone with a circular crater is, in fact, a more complex structure composed mainly of volcanic materials but also of Eocene bedrock affected by the eruption (Figs.29 and 30). This is evidenced by the outcrops of Eocene rocks (sandstones, conglomerates and siltstones) appearing in the south-eastern border of the crater, and the boulders detached from it. This crater is 70 m deep and has a maximum diameter of 400 m.

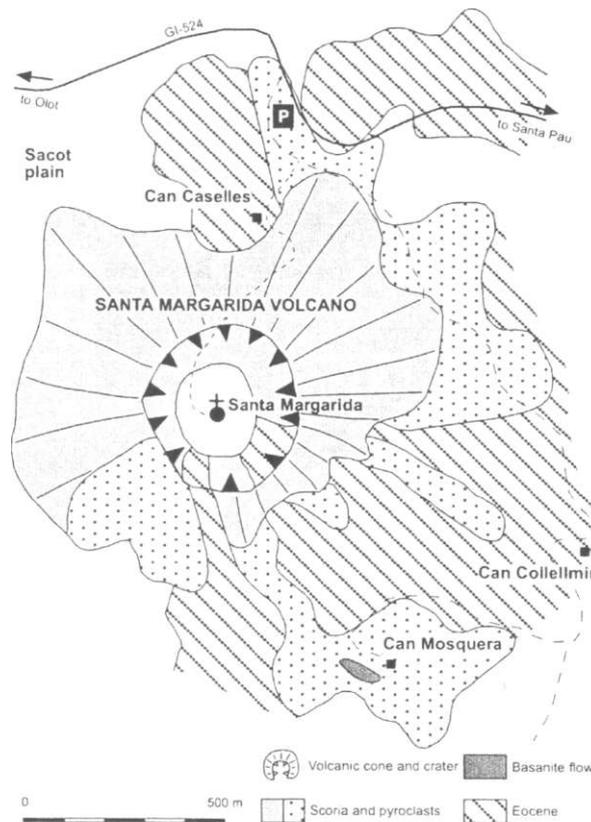


Figure 30.- Simplified geologic map of Santa Margarida volcano and its volcanic materials (modified after Martí et al., 2000).

There is a Romanesque hermitage on the crater floor. It was damaged by the two strong earthquakes that affected the region in 1427 and 1428. It was rebuilt during the 19<sup>th</sup> century.

Four eruptive phases have been identified (Fig. 31) (Martí et al, 2000):

- A first low explosive strombolian phase built a pyroclastic cone made up of scoria, lapilli, volcanic bombs and ash.
- A second brief and highly explosive phreatomagmatic phase partially destroyed the recently created cone. Violent explosions, triggered by the interaction between magma and underground water, generated wet pyroclastic surges. Lithic clasts, mainly red

sandstones, were detached from the walls of the volcanic chimney and were expelled mixed with young, black pyroclasts including large rounded blocks. The deposition of these materials took place especially in the southern and eastern flanks of the volcano.

- A third phase was characterized by moderate phreatomagmatic activity, leading to dry pyroclastic surges expelled radially from the eruptive vent. The extruded materials were composed of rounded, slightly vesicular young pyroclasts and of Eocene lithic pyroclasts of lapilli size. The crater acquired its final shape during this phase.
- Finally, it can be interpreted that during the last stages of activity a small basanite lava flow extruded in the southernmost flank of the volcano. This might be considered as a fourth modest effusive phase. The outcrops attributed to this lava flow are almost completely concealed.

Most of the volcano is covered by a massive, black lapilli layer. It corresponds to the pyroclastic fall deposit related to the 5<sup>th</sup> eruptive phase of Croscat volcano, located only 1.5 km to the northwest. It has a neat contact with the underlying deposits. Considering that there is no evidence of soil development before the deposition of the Croscat pyroclastic materials, and considering the lack of alteration of the uppermost Santa Margarida deposits, it may be inferred that the time span between both eruptions was considerably short.

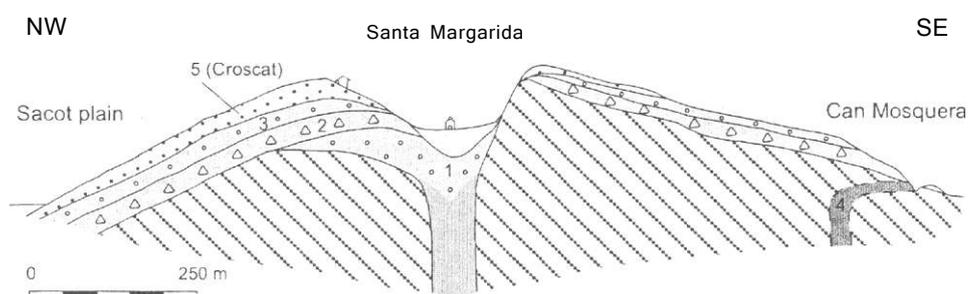


Figure 31.- Schematic geologic cross section of Santa Margarida volcano. Numbers correspond to the eruptive phases described in the text.

### Visit: Santa Pau

Santa Pau is a small village that preserves most of its original Middle Age configuration. It has been declared Artistic Historical Monument by the regional government (Generalitat de Catalunya). Its origins lay on the erection of an old castle which was later surrounded by the construction of what is now known as the Old Village (Vila Vella in Catalan).+

The Castle stands high in the centre of the village. This voluminous building has a squared floor and was built in several stages between the 13<sup>th</sup> and the 17<sup>th</sup> centuries. The main gate and the homage tower are located in the northern wall of the castle. Once inside the castle we find the parade-ground. It is surrounded by the rooms that hosted the stables, the prison, the gunsmith's and the servants' lodgings. A large staircase leads to the noble's floor.

The construction of the Santa Pau main porched square known as Firal dels Bous (which could be translated as Oxen Fairground), began in the 14<sup>th</sup> century. It is headed by the church (16<sup>th</sup> century) and has a triangular shape. Its buildings, adjacent to the old wall, show gothic characteristics of different styles. Their typical structure is as follows: a porched ground floor, a first floor used as main living space and a wooden loft used as a granary.

Several defensive towers, lintels showing noble's coats of arms and many Renaissance balconies and windows are just a few of the attractions that make Santa Pau a place worth visiting.

**Stop 4. Molí Fondo and Boscarró quarry, Sant Joan les Fonts** San Joan les Fonts, located about 4.5 km north of Olot, is crossed by the Fluvià River which meets the Bianya stream there. This site can be reached following the C-26 road from Olot and the GI-522 road after the village of La Canya. To get to this place from Besalú, Banyoles and Girona it is necessary to follow the A-26 road until Castellfollit de la Roca, and then take the GI-522 road. A trail which starts in the eastern side of Sant Joan les Fonts church goes to Boscarró quarry, an old basalt quarry, and to Molí Fondo in the Fluvià riverbed. Signposts indicate access to both sites.

#### *Features to observe*

Three superposed lava flows have been exposed by the river erosion at Molí Fondo (Fig. 32):

- The lower basaltic lava flow crops out in the riverbed and below the foundations of a small dam. It has an observable thickness of 5 m. It displays weak columnar jointing and superficial neat spheroidal weathering. This lava flow is believed to have come from La Canya volcano, and to have followed the Fluvià River valley for more than 10 km. It has been dated as being  $217,000 \pm 35,000$  years old.
- The intermediate basaltic lava flow is 5 m thick and overlays the previous flow. There is not any visible discontinuity between them. It displays columnar jointing in its upper and lower parts, and lenticular jointing in its middle part. Small dome-shaped, slaggy protuberances are found related to lava flow blistering. This flow was possibly originated in the nearby Aiguanegra volcano.
- A fluvial terrace made up of pebbles of basalt and Eocene sedimentary rocks, with sandy and silty matrix, crops out over the aforementioned lava flows. It has a maximum thickness of 2 m which varies laterally until it almost disappears.
- The upper basanitic lava flow shows an alternation between columnar and lenticular jointing. The uppermost levels contain elongated vesicles that mark the flow direction at the time it stopped. The origin of this flow is Garrinada volcano, located near the town of Olot. Datings indicate that it is  $133,000 \pm 12,000$  years old.

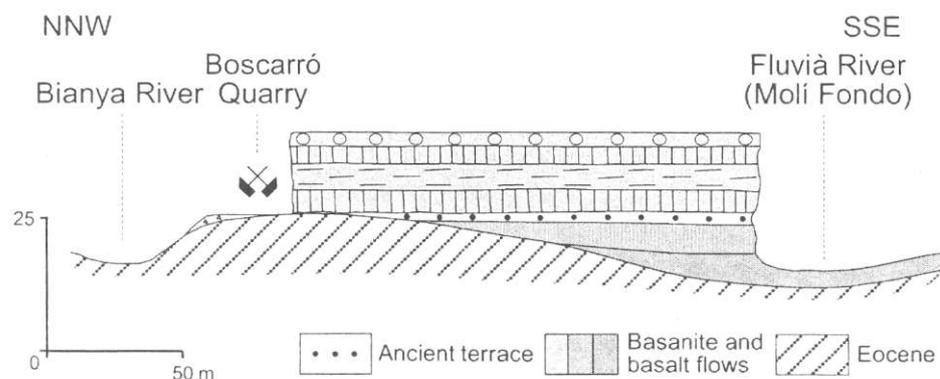


Figure 32.- Cross section showing the three superposed lava flows observed in Molí Fondo and Boscarró quarry, Sant Joan les Fonts.

The internal structure of this upper basanitic lava flow can be better observed in the nearby Boscarró quarry, located a few meters north of Molí Fondo next to Bianya stream. This quarry remained active until the beginning of the 20<sup>th</sup> century. At this 15 m high outcrop several basic jointing types can be distinguished. From bottom to top we find (Fig. 33):

- A total thickness of 4 m of hexagonal and pentagonal prisms 20 to 40 cm wide and 2 to 3 m high, individualized by columnar jointing.
- A level of lenticular jointing slabs, with a total thickness of 2 m.
- A massive columnar jointing level up to 1 m thick, with a few cooling cracks.
- An upper level of 2.5 m of rounded blocks generated by spheroidal weathering.

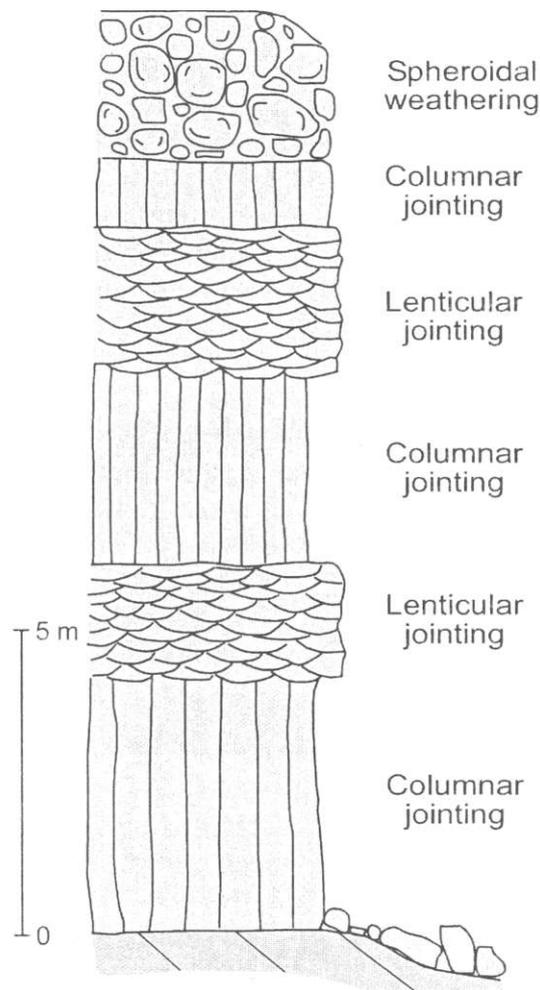


Figure 33.- Different retraction and weathering habits in the upper Boscarró quarry basanite lava flow.

**Stop 5. Castellfollit de la Roca cliff.** Castellfollit de la Roca is located 7 km northeast of Olot. It is reached by the A-26 road, formerly N-260. Part of the village is placed over a spectacular vertical cliff, 1 km long and 50 m high, composed of two superimposed lava flows (Figs. 34 and 35).

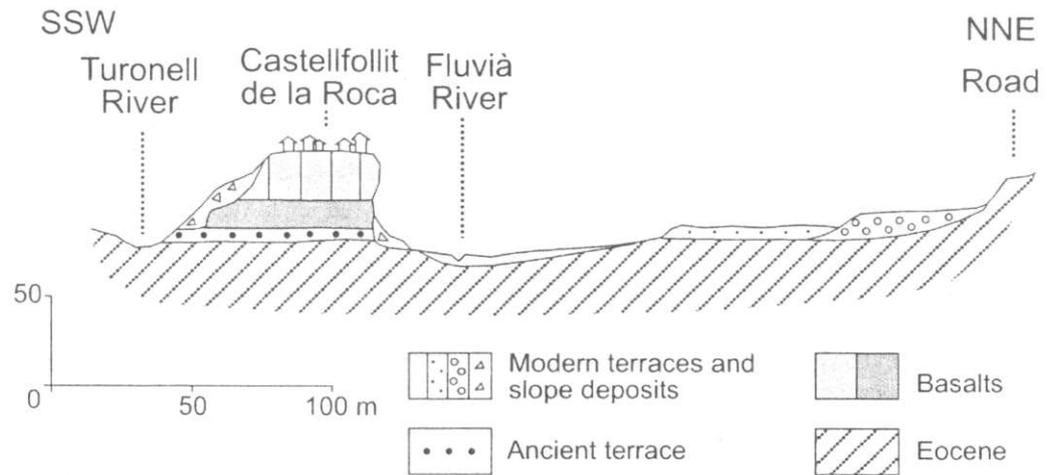


Figure 34.- Castellfollit de la Roca cross section (adapted from Pallí and Trilla, 1976).

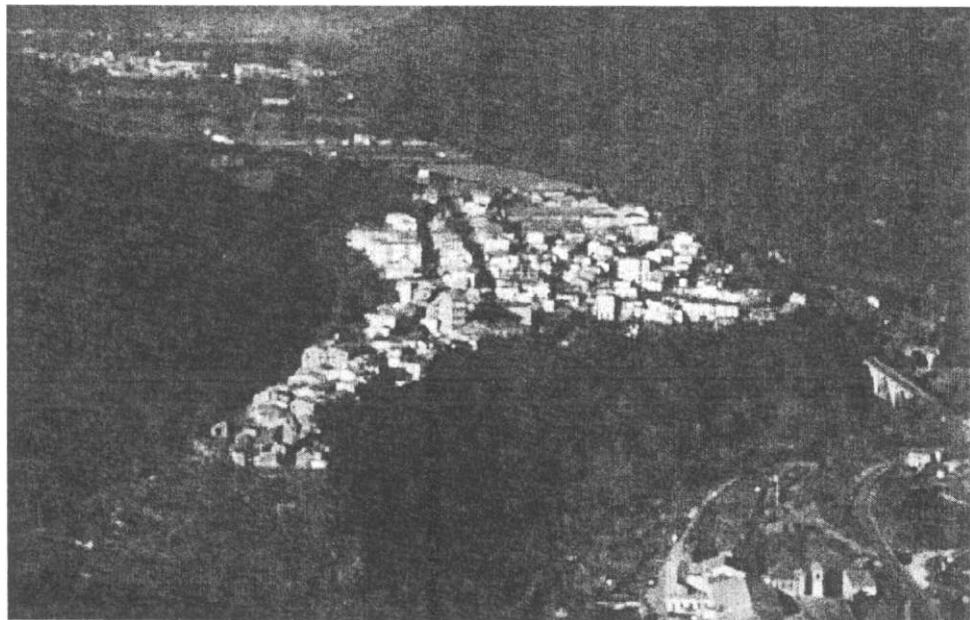


Figure 35.- The village of Castellfollit de la Roca, built over two lava flows, standing on the cliff exposed by the Turonell and Fluvià rivers downcutting (Garrotxa Volcanic Zone Natural Park photo).

The kilometric point 45 of the aforementioned road provides a good general view over the outcrop. To have a closer view, visitors can go down to the Fluvià River, walking along a trail that starts 100 m before this point. Then they can cross a wooden bridge and get to the base of the cliff.

#### *Features to observe*

The lava flows followed the old Fluvià and Turonell riverbeds. Subsequent fluvial erosion, mainly in the contact between the lava flows and the underlying sedimentary materials, as well as gelifraction processes, have formed the cliff, where the internal structure of the lava flows can be seen (Figs. 36 and 37). From bottom to top, the sequence of materials in the cliff is as follows:

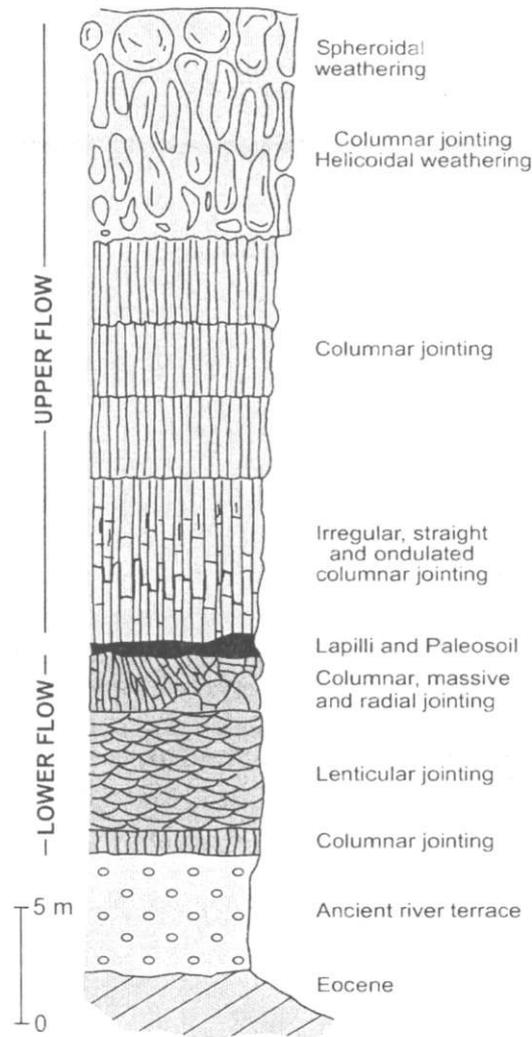


Figure 36.- Section of Castellfollit de la Roca cliff, Fluvià river side, where two basaltic lava flows overlay an old fluvial terrace (adapted from Palli and Trilla, 1976).

- An ochre-blue sedimentary serie of Eocene sandstone and marls.
- An old fluvial terrace, 5 m thick, unconformably overlying the former deposits. It consists of heterometric pebbles of limestone, sandstone and calcarenites in a sandy or silty matrix. Some weathered basaltic pebbles have been also identified.
- A lower basaltic lava flow, 8.5 m thick. It can be correlated to the lower Molí Fondo lava flow in Sant Joan les Fonts. Three different morphologies can be distinguished:
  - 1.5 m of vertical prisms up to 0.8 m high.
  - 5 m of horizontal lenticular slabs.
  - 2 m of small, vertical prisms that laterally display rose-like and massive patterns.
- A pyroclastic lapilli layer underlies a dark soil. This weathering profile is 1.8 m thick and records the time span between the two lava flows in the cliff.
- An upper basaltic lava flow, 28 m thick. Its origin lies probably to the south, in the Estany volcano group. According to datings it is  $192,000 \pm 25,000$  years old. Three main patterns are distinguished from bottom to top:

- 8 m of irregular prisms up to 2 m high. The lower ones have a sharp planar surface. The upper ones overlap each other and have a wavy surface.
- 10 m of well-defined vertical prisms, up to 3 m high.
- 10 m of massive lava. The lower part displays a helicoidal aspect. The upper part is strongly weathered and shows spheroidal jointing, a concentric type of flaking and a superficial granular disintegration.

Nowadays the erosional processes remain still active in the sedimentary materials at the base of the cliff, triggering rock falls from the upper units. Several large rockfalls occurred in the 1970s, with a total volume of fallen material estimated in 3,000 m<sup>3</sup> (Pallí and Trilla, 1976).

### **Visit: Besalú**

The town of Besalú was the capital of the county of the same name from the government of the first count Odiló (811-823) until the government of Bernat III (1111). Since the latest one died without issue, the county lost its independence and was inherited by his uncle Ramon Berenguer III count of Barcelona. Later on, the town was the capital of several administrative divisions: Vegueria de Besalú (1226) which comprised up to 29 villages, Corregimiento (established in 1716) and finally Alcaldía Mayor (19<sup>th</sup> century).

The Jewish communities of Besalú and Girona were the most important ones in the eastern regions of Catalunya. Although the earliest documented cites regarding the Jewish community of Besalú date from the 13<sup>th</sup> century, it seems reasonable that it already existed in the 9<sup>th</sup> century. It lasted until the end of the 15<sup>th</sup> century. Catalan kings Jaume I (1229) and Pere IV (1342) protected the community during its most brilliant times. The best preserved Jewish site of this period is the Besalú *Migve*. This building was devoted to ritual baths for spiritual purification and preparation for any important event in Jewish life. It is considered unique in the Iberian Peninsula, and it is the third most important of Europe. This Romanesque style building covers an area of 25 m<sup>2</sup>, and has a 36 steps staircase that descends to a 4 m" rectangular pool. Travertine was used to construct this building. Water to fill the pool came from a nearby natural spring.

Only the Sant Pere Church remains from the former monastery built in 977 by the Count-Bishop Miró. It is of Romanesque style and has a broad and original ambulatory which distinguishes it from other Romanesque temples of Catalunya. The church has sculptured capitals and many tombs of abbots and of noble families from Besalú. The upper part of the bell tower is of Baroque style.

There are other interesting sites in the town. Sant Vicenç Church (12<sup>th</sup> to 13<sup>th</sup> centuries) shows the transition between Romanesque and Gothic styles. The gate of the old Sant Julià Hospital (12<sup>th</sup> century) still maintains some Romanesque arcades. The Sant Jaume Church (12<sup>th</sup> century) belonged to Sant Pere Monastery. The Old Bridge (11<sup>th</sup> to 20<sup>th</sup> centuries) which crosses the Fluvià River, is the result of many restorations through history. The Castle gate, the old tower and the apse of Santa Maria Church are the remains of the former Count Palace, located on the uppermost part of the town. Some parts of a wall built between the 10<sup>th</sup> and the 14<sup>th</sup> centuries survive. Numerous noble civil buildings such as Casa Cornellà (Romanesque), Cúria Reial (transition between Romanesque and Gothic), City Hall (16<sup>th</sup> century) and Can Zafont (15<sup>th</sup> to 16<sup>th</sup> centuries) among others can be found in the lanes and squares of medieval appeal. The whole Besalú County town was declared Artistic Historical Monument in 1966.

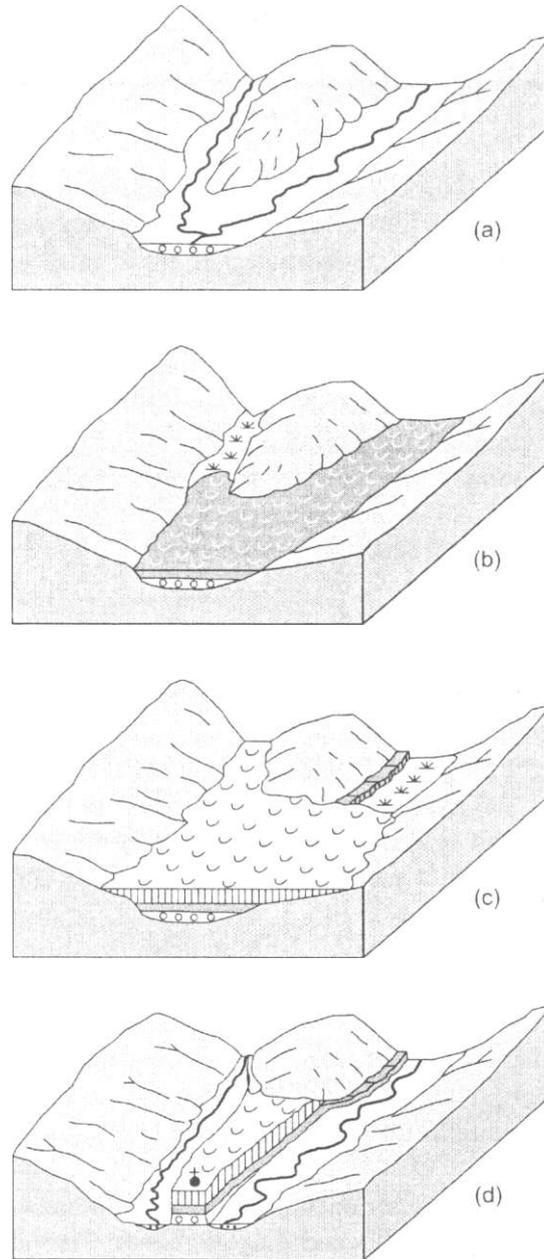


Figure 37.- Schematic diagram showing the stages in the formation of the Castellfollit de la Roca cliff (adapted from Pujadas et al., 1997).

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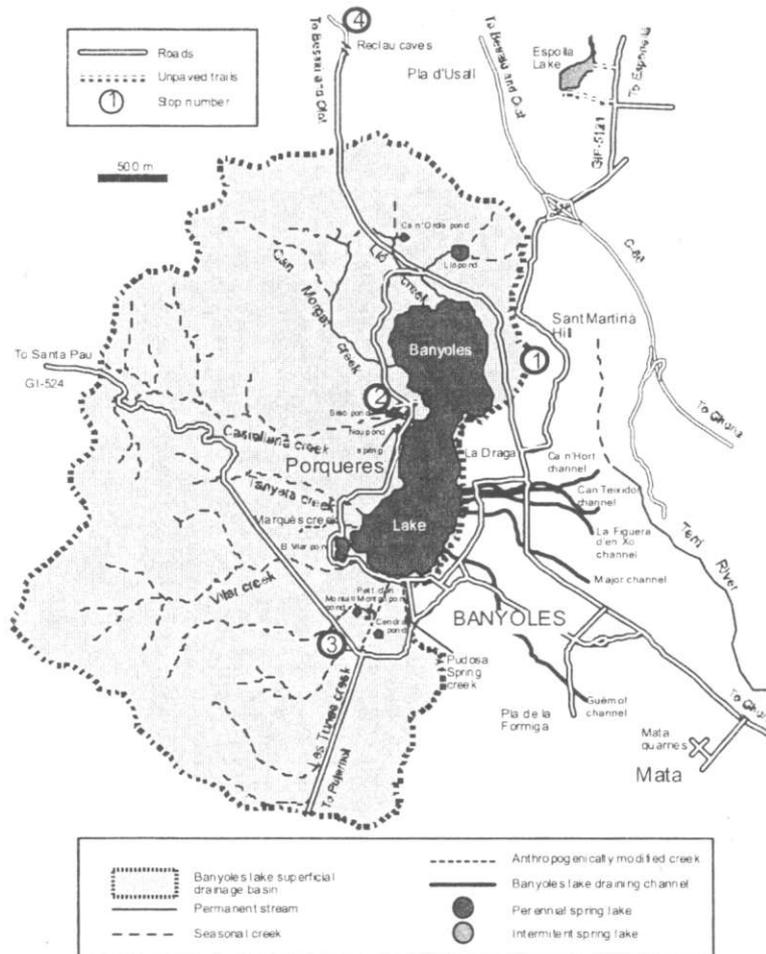
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### First day (12<sup>th</sup> September)

The fieldtrip starts in a panoramic viewpoint where a geographic and thematic introduction to the area can be made (1<sup>st</sup> Stop). The rest of the stops have been selected in order to observe some of the most representative geomorphologic features (2<sup>nd</sup> Stop), geological materials (3<sup>rd</sup> Stop) and paleontological and archaeological sites of the area (4<sup>th</sup> Stop) (see Figure below).



### Second and third day (12<sup>th</sup> and 13<sup>th</sup> September)

The stops of the field trip are located along the Fluvià River basin (1<sup>st</sup>, 4<sup>th</sup>, and 5<sup>th</sup> stops) and in Santa Pau valley (2<sup>nd</sup> and 3<sup>rd</sup> stops). All of them are located less than 6 km away from the town of Olot. The main accesses to this town are the roads N-260, A-26, C-63 and C-153 (see Figure 21).

The 1<sup>st</sup> Stop is the Volcanoes Museum (Museu dels Volcans or Casal dels Volcans in Catalan language), which is set in the town of Olot, close to the C-153 Olot-Vic road. Croschat Volcano (2<sup>nd</sup> Stop) and Santa Margarida Volcano (3<sup>rd</sup> Stop) are easily accessible, since the itineraries are well indicated by signposts. To visit them it is necessary to follow the GI-524 road, from Olot to Santa Pau. Molí Fondo and Boscarró quarry (4<sup>th</sup> Stop) are located in Sant Joan les Fonts following the GI-522 road. The cliff (cingle in Catalan) of Castellfollit de la Roca (5<sup>th</sup> Stop) is located 3 km away from Olot following the A-26 road towards Besalú and Banyoles.