2 Geological Setting of La Garrotxa Volcanic Field

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Situated in the northeast of the Iberian Peninsula, La Garrotxa Volcanic Field is part of the Catalan Volcanic Zone and one of the provinces of the Neogene-Quaternary alkaline volcanism associated with the European Rift System. It covers about 600 km^2 and lies between the cities of Olot and Girona (Fig. 2.1). This basaltic volcanic field contains over 50 cones (including both cinder and scoria cones), lava flows, tuff rings and maars dating from the Middle Pleistocene to the early Holocene, which rest either on upper Palaeozoic granites and schists or on sedimentary Eocene and Quaternary substrata. Available petrological and geochemical data indicate that this region consists of a suite of intracontinental leucite, basanites, nepheline basanites and alkali olivine basalts, which in most cases represent primary or near-primary magmas, their geochemical characteristics being very similar to analogous petrologic types found in other European Cenozoic volcanic zones.

La Garrotxa Volcanic Field embraces two geographically distinct zones, the larger area located in the north of the county of La Garrotxa, mostly corresponding to La Garrotxa Volcanic Zone Natural Park, and a southerly area that contains fewer but larger and more complex volcanic edifices (Fig. 2.1). Although both correspond to tectonically controlled depressions, the northern zone has substrata consisting of thick layers of Tertiary and Quaternary sediments, whereas the southern zone is underlain by unconsolidated Quaternary sediments in combination with the Palaeozoic basement.

Volcanic activity in La Garrotxa Volcanic Field is characterised by numerous small cinder cones built during short-lived monogenetic eruptions occurring along tectonic-related volcanic fissures. The total volume of extruded magma in each eruption was between 0.01 and 0.2 km^3 (DRE). Strombolian and phreatomagmatic episodes alternated in most of these eruptions and gave rise to complex stratigraphic sequences with a broad range of pyroclastic deposits. The eruption sequences differ from one cone to another and demonstrate that the eruptions did not follow a common pattern, particularly in cases of magma/water interaction. This complex eruptive behaviour is likely to be due to the differing stratigraphic, structural and hydrogeological characteristics of the substrata below each volcano rather than to any differences in the physicochemistry of the erupting magmas, which are generally fairly homogeneous throughout La Garrotxa Volcanic Field.

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

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

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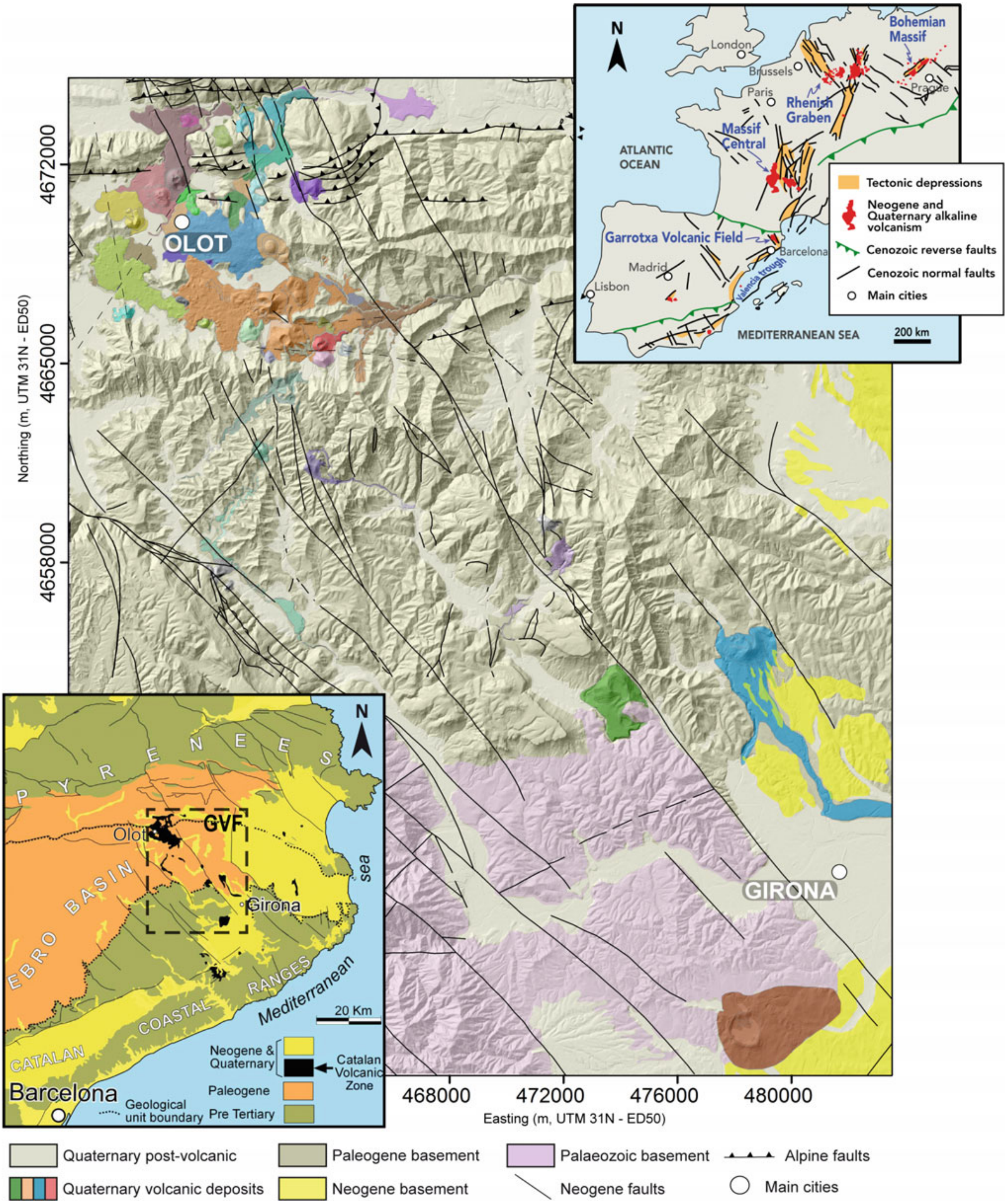

Fig. 2.1 Geological setting the study area. Inlet at the *upper right corner* structural map of the European Rift System. Inlet at the *lower left corner* geological map of the Ne of Spain. *Central image* geological map of La Garrotxa Volcanic Field

2.1 Geodynamic Context

The European Cenozoic Rift System extends from the coast of the North Sea to the Mediterranean and consists of the Spanish Valencia Trough, the Gulf of Lion and Massif Central in France, the Rhine, Ruhr Valley and Leine grabens in Germany, which straddle the river Rhine and cut across the Rhenish Shield, and the Eger Graben in the Bohemian Massif (Fig. 2.1). In the south it joins a Plio-Pleistocene volcanic chain crossing the Atlas ranges. This rift system evolved in the Alpine foreland during late Eocene to Recent times. The evolution of this European rift system is thought to be governed by the interaction of the Eurasian and African plates and by early phases of a plate-boundary reorganisation that may lead to the break-up of the present assembly of continents.

Widely distributed along an extensive rift system, the Cenozoic (Middle Miocene to present) alkaline volcanism in central and western Europe consists of four main volcanic areas: the Rhenohercynian (Germany), the western Panonian Basin (Eastern Europe), the Massif Central (France) and the Valencia Trough (Spain). The causal mechanism(s) of this rift system is poorly understood but seems to be related to the extension that affected the whole area following the Alpine tectonics, which was probably associated with the upwelling of a mantle plume beneath the European plate. This extension would thus explain the creation of a number of tectonic basins in which Neogene-Quaternary sedimentation and volcanism have occurred. Primitive mafic alkaline volcanic rocks derived from this volcanism have petrological and geochemical signatures that suggest the involvement of both lithospheric and asthenospheric mantle source components in their petrogenesis.

The Valencia Trough is a NE-SW-oriented Neogene basin located between the Iberian Peninsula and the Balearic archipelago offshore of NE Spain (Fig. 2.1). It has a complex geological history that contains two main stages of magmatism. During Early to Middle Miocene times, the area was subjected to compressional tectonics accompanied by calc-alkaline volcanism. This was followed by a period of extensional tectonics and mafic alkaline volcanism in the Middle Miocene to Recent times. The greatest concentration of Middle Miocene to Recent volcanism in the region is found in the Catalan Volcanic Zone (CVZ) in the NE Iberian Peninsula (Fig. 2.1), in which La Garrotxa Volcanic Field represents the most recent (0.7 Ma to early Holocene) episodes of this volcanism (Fig. 2.1).

The CVZ has traditionally been divided into three sub-zones based on the age of its volcanic rocks: L'Empordà in the northeast (>12–8 Ma), La Selva (7.9–1.7 Ma) in the south and La Garrotxa (>0.5–0.01 Ma) in the west (Fig. 2.1). The total volume of extruded magma seems to increase progressively from the early (L'Empordà) to later (La Garrotxa) episodes. Thus, a progressive and concomitant increase in the volume of magma generated, as well as an increase in the degree of partial melting, can be observed in the geochemistry of the rocks in the CVZ. Some volcanoes in La Garrotxa sub-zone contain ultramafic to mafic xenoliths. The xenoliths comprise pyroxenites (the most abundant), melanogabros, amphibolites and spinel lherzolites. Pressure and temperature estimates for these xenoliths suggest that they may have crystallised in magma chambers located at the crust-mantle boundary, which geophysical estimates locate at a depth ~30 km. These geophysical studies also indicate that the CVZ is characterised by a regionally thinned lithosphere, about 60–70 km thick, high elevations and a notable thermal gradient, suggesting that the area is affected not only by the topographic load of the Pyrenees but also by the opening of the Valencia trough. The local structure of the area is composed of a set of horst and grabens bounded by NW- and NE-oriented Neogene normal faults that have controlled the recent sedimentation and distribution of the area's volcanism.

2.2 Geological Characteristics of La Garrotxa Volcanic Field

The 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. 2.1). 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. 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. 3.1). As a consequence of the Alpine folding, the Neogene normal faulting system and subsequent erosion, the basement of each volcano varies. The oldest recognisable unit corresponds to the schist, gneiss, granodiorites and granites of Permo-Carboniferous age, which is unconformably overlain by the Eocene Formations that, from base to top, comprises: (1) the blue marls and gypsum of the Banyoles Formation; (2) the marls and brown sandstones of the Bracons Formation; (3) the red sandstones, mudstones and conglomerates of the Bellmunt Formation; (4) the glauconite sandstones and conglomerates of the Folgueroles Formation; and, finally, (5) the grey sandstones and marls of the Rocacorba Formation. Filling valley bottoms or the existing trough in the area and unconformably overlying the previous units lie

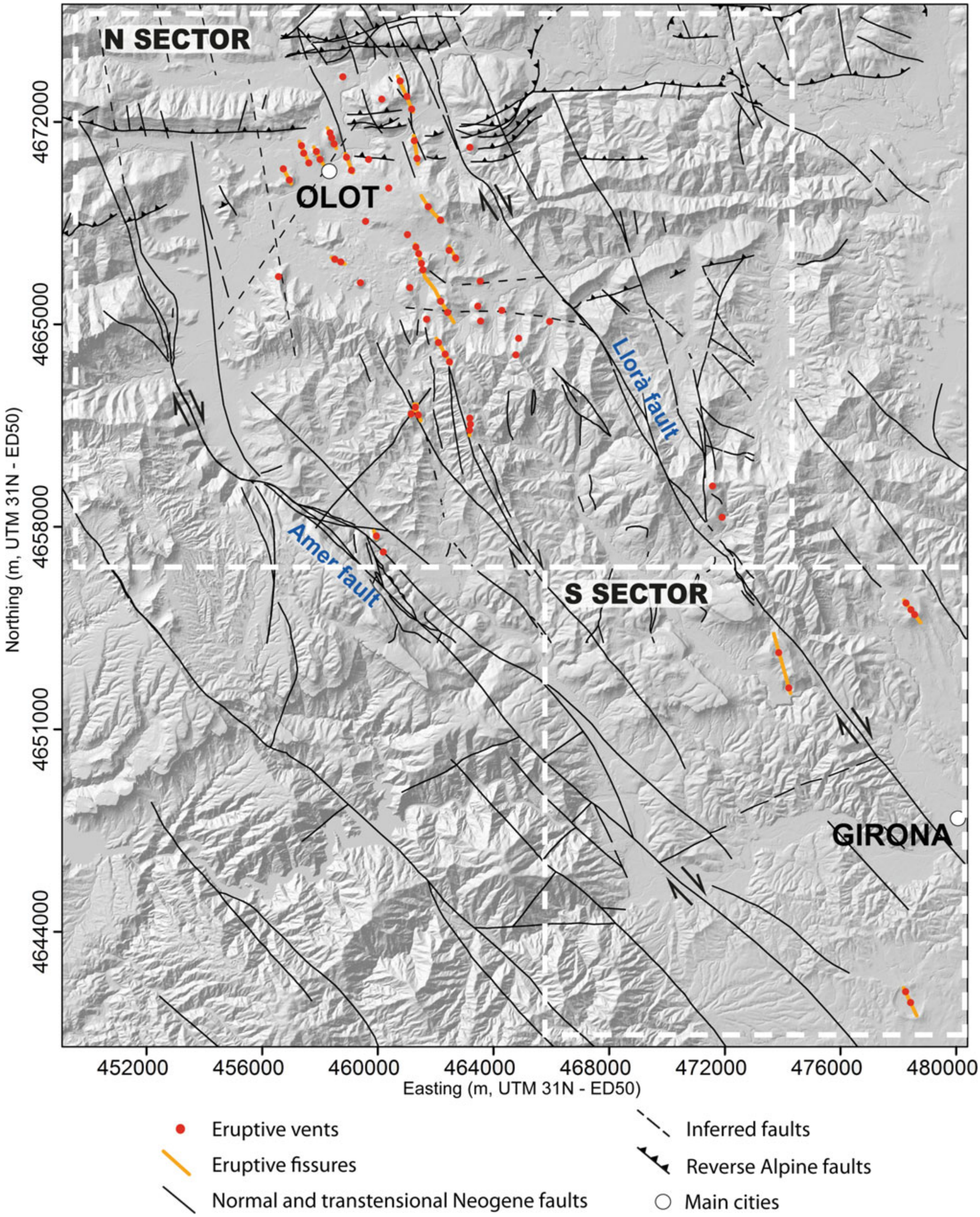

Fig. 2.2 Structural map of La Garrotxa Volcanic Field, with indication of all main structural elements including positions of vents and eruptive fissures (reproduced with permission of Elsevier)

unconsolidated gravels, clay and sands, and alluvial deposits, which, together with lava flows and pyroclastic products, form the Quaternary sequence. The Palaeozoic terranes, the Bellmunt Formation and the Quaternary deposits hold the main aquifers of the area, although the bases of the Folgueroles and Banyoles Formations may also act as aquifers in some sectors of the study area.

Due to the extensional tectonics following the Alpine compression in western Europe that were responsible for the formation of the European Rift System, NE Iberia developed a horst and grabens structure mainly limited by NE- and NW-oriented major faults. These faults show normal and trans-tensional movements and control sedimentation and volcanism. In particular, La Garrotxa Volcanic Field is bounded by two regional conjugated Neogene normal faults—the Amer Fault to the east and the Llorà Fault to the west—with a trans-tensional component. These two faults are responsible for the distribution of the area's volcanism and its seismicity, as well as the structuring of its fluvial network (Fig. 2.2).

2.3 Volcanism

The first volcanic episodes in the CVZ took place in the Empordà sub-zone and have ages older than 12 Ma. Since then, volcanism has been intermittent, producing an eruptive episode every several tens of thousands years up to the early Holocene. The age of these rocks suggests that a migration in the loci of the volcanism occurred, first southwards and subsequently towards the northwest, probably as a response to a migration in the focus of local tectonism. Thus, La Garrotxa Volcanic Field contains the most recent volcanism in the CVZ and is also the most tectonically active area, with historically high-magnitude seismicity.

Available data indicate that mafic volcanic products in the CVZ, like the parental magmas of the cumulate xenoliths, range from strongly silica-undersaturated to nearly silica-saturated compositions. This region comprises a suite of intracontinental leucite, basanites, nepheline basanites and alkali olivine basalts, which in most cases represent primary or near-primary magmas.

2.3.1 The Volcanoes of La Garrotxa Volcanic Field

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. 2.2). The main concentration of volcanic cones and edifices lies in the northern sector, which corresponds to La Garrotxa Volcanic Zone Natural Park, 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. During the Quaternary, volcanic activity occurred sporadically in the study area over a time period ranging from >500,000 years ago to about 11,000 years ago, with eruptive events occurring every 10,000–30,000 years.

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 (Fig. 2.3). The total volume of extruded magma in each eruption was small (0.01–0.2 km^3 DRE), suggesting that the amount of magma available to feed each eruption was very limited. 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.

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. 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. Examples of this type of activity include the volcanoes of Puigalós, Puig de Martinyà, San Marc, Roca Negra and Puig Subià (Figs. 2.4 and 2.5). 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 characterised by a succession of phreatic phases produced by vapour 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 behaviour, probably due to differences in the local substrata and its hydrogeological characteristics. Examples of this type of activity are the volcanoes of Santa Margarida, Croscat, Garrinada, Montsacopa, Can Tià and Cairat (Figs. 2.4 and 2.6) in the northern sector (Fig. 3.4), and the volcanoes of Puig d'Adri, Puig de Banya del Boc, Clot de l'Omera, Granollers and Sant Dalmai in the southern

Fig. 2.3 Landscape picture of the Croscat and Santa Margarida volcanoes, at the central part of the northern sector of La Garrotxa Volcanic Field (*Credit* Eduard Masdeu)

sector (Fig. 2.7). Table 2.1 summarises the eruptive sequences deduced for the volcanoes under study.

The variety present in the eruption sequences characterising the eruptive activity of this monogenetic volcanic field (Table 2.1) contrasts with the compositional monotony of its magmas (alkali basalts and basanites). The physicochemical characteristics of the magmas from most of the volcanoes in La Garrotxa Volcanic Field are very similar. They mainly correspond to leucite basanites, nepheline basanites and alkali olivine basalts, with a phenocryst (olivine, pyroxene, plagioclase) content up to 12 % and an aphiric-to-microcrystalline or microlitic groundmass. Ascent velocities of the order of 0.2 m/s have been calculated using the presence of large mantle-derived nodules and lower crust xenoliths in some of these magmas. Densities in the range 2700–2860 kg/m^3 and typical viscosities in the order of 10–10^2 Pa s have been calculated using standard methods based on crystal content and rock composition and assuming temperatures in the order of 1200–1300 °C. Despite the fact that some variations in the dynamics of the Strombolian episodes may be attributed to changes in magma flow conditions related to changes in the crystallinity and vesicularity (gas content) of the erupting magma, it is obvious that variations in magma physics are not the main factor behind the large diversity of eruption sequences recorded in this volcanic field.

In fact, as can be deduced from the sequences of deposits observed in each volcano, the differences in eruptive behaviour are related to the occasional interaction of the ascending magma with groundwater. Magma/water interaction is the main reason why so many of these volcanoes significantly deviate from the typical Hawaiian-Strombolian behaviour that characterises some of area's volcanoes and monogenetic basaltic volcanoes in general. The timing of the magma/water interaction and the way in which it occurred during the course of the eruptions differs considerably from one volcano to another. This contrasts with other monogenetic volcanic fields where eruptions seem to follow more constant patterns. In the present case, however, the large diversity of eruption sequences observed can be explained by variations in the stratigraphy and structure of the shallow geological basement beneath each volcano and the hydraulic characteristics of each aquifer.

Two main sedimentary aquifers have been identified that may have interacted with the magmas in La Garrotxa and thus given rise to a wide variety of phreatomagmatic episodes and eruption sequences. One aquifer is located at an average depth of a few hundred meters below the volcanic cones, while the other is much shallower, just a few dozen metres below the surface. The deep aquifer corresponds to Eocene continental sediments (the Bellmunt Formation), composed of conglomerates, feldspar-rich sandstones and red mudstones, while the shallow aquifer corresponds to Quaternary volcanic and alluvial deposits, mostly consisting of unconsolidated gravels, sands and clays, and volcanic products (lavas and pyroclasts) from former eruptions. A third aquifer played a significant role in some of the most important eruptions (Puig de Banya del Boc and Crosa de

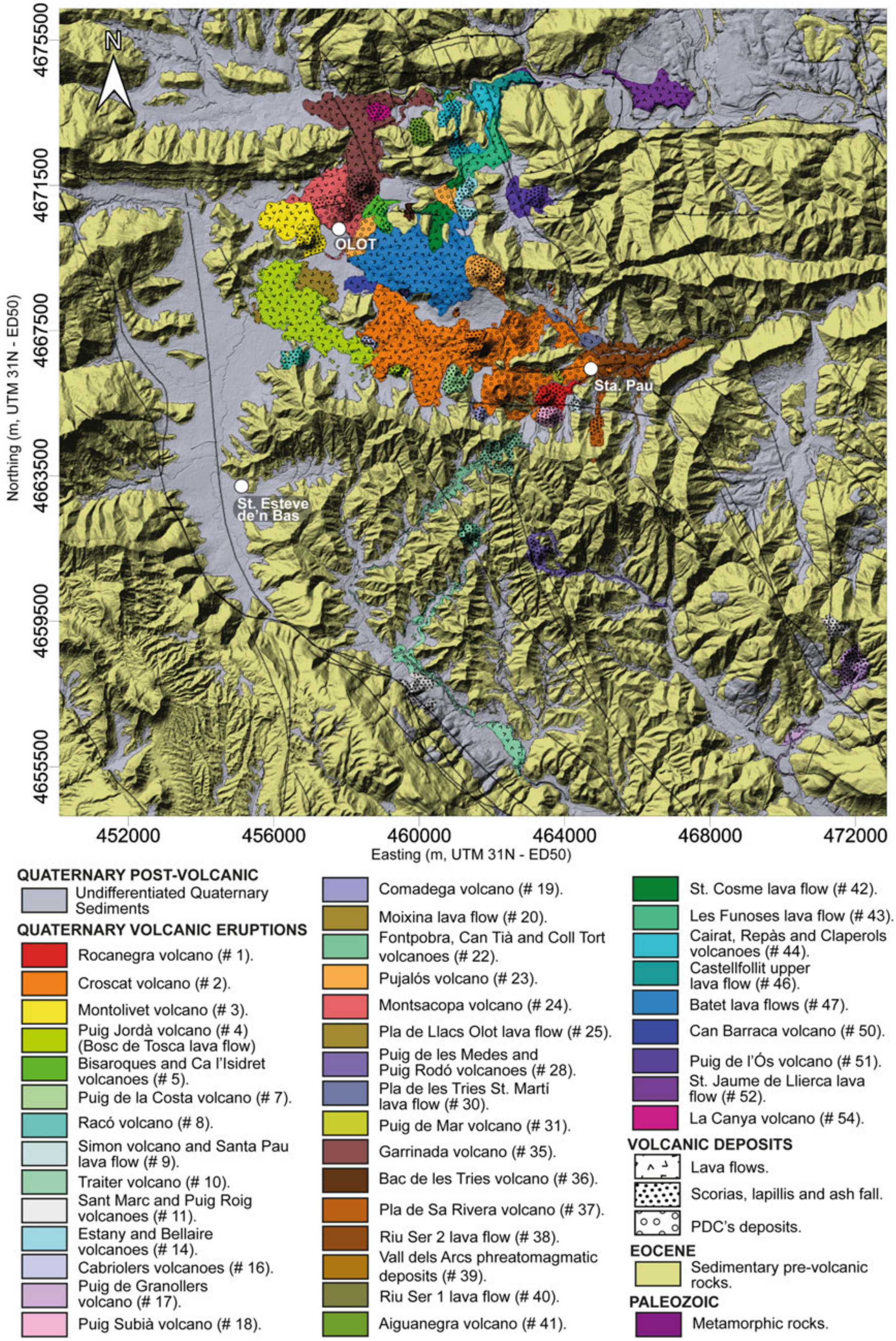

Fig. 2.4 Volcanic stratigraphy of the northern sector of La Garrotxa Volcanic Field, where all stratigraphic members (products of each single eruption) are identified with a different colours (reproduced with permission of John Wiley and Sons, Ltd.)

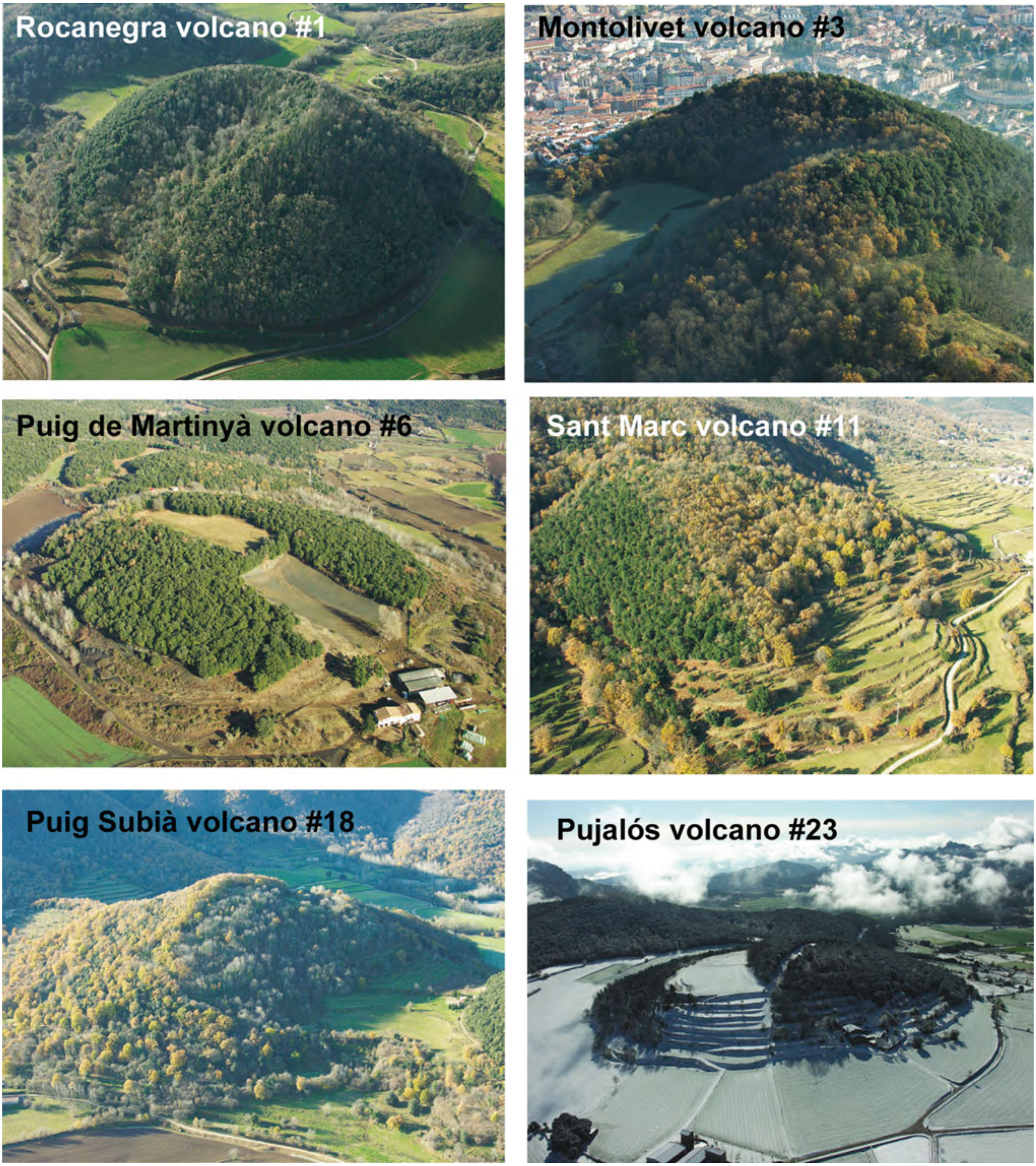

Fig. 2.5 Field pictures of some strombolian cones from the northern sector of La Garrotxa Volcanic Field (*Credit* Eduard Masdeu)

Sant Dalmai) and corresponds to highly fractured Palaeozoic rocks. The depth of this latter aquifer depends on the tectonics of each area and it may be a few hundred metres deep or lie at somewhat shallower depths.

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

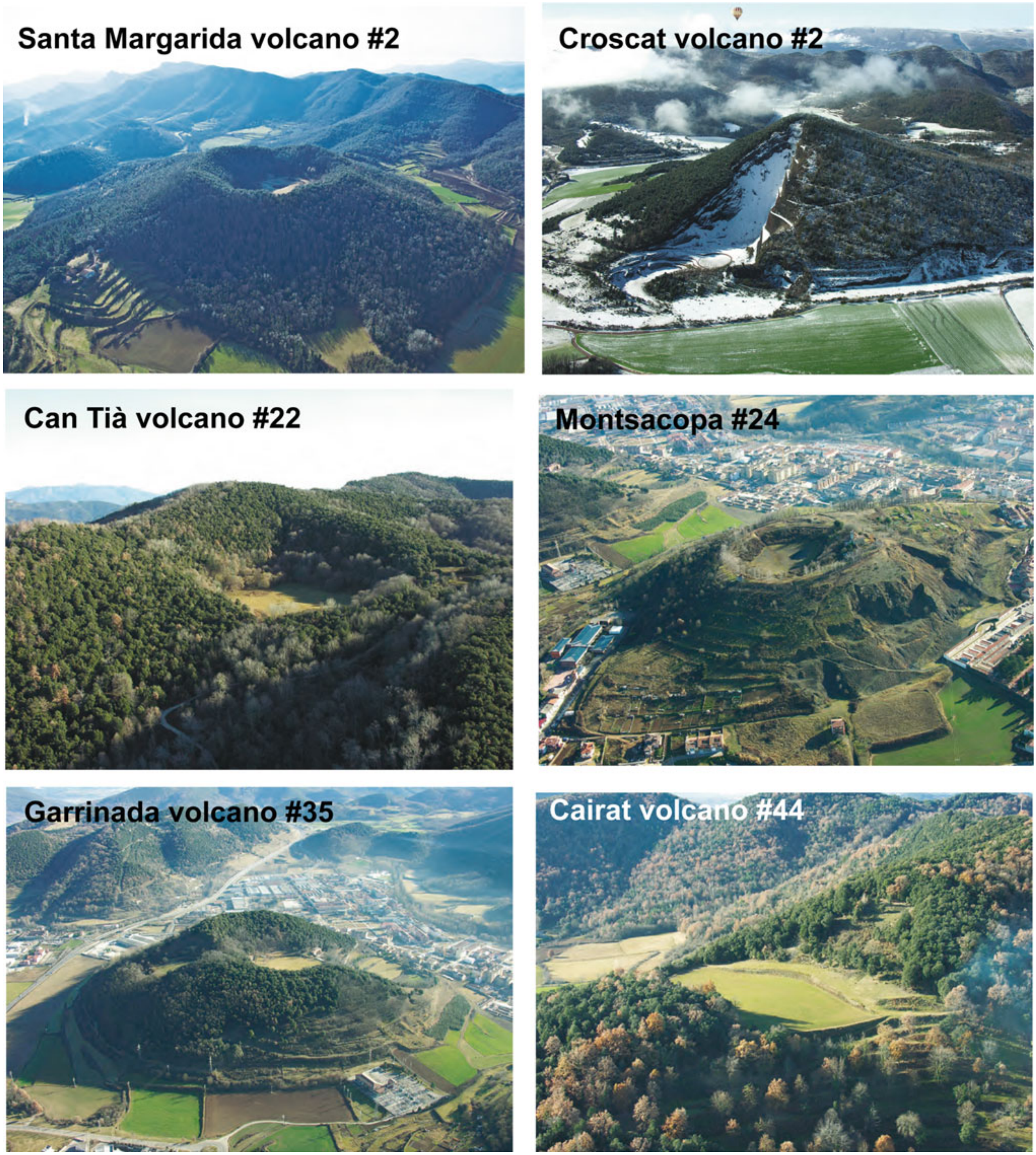

Fig. 2.6 Field pictures of some cones containing phreatomagmatic episodes from the northern sector of La Garrotxa Volcanic Field (*Credit* Eduard Masdeu)

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.

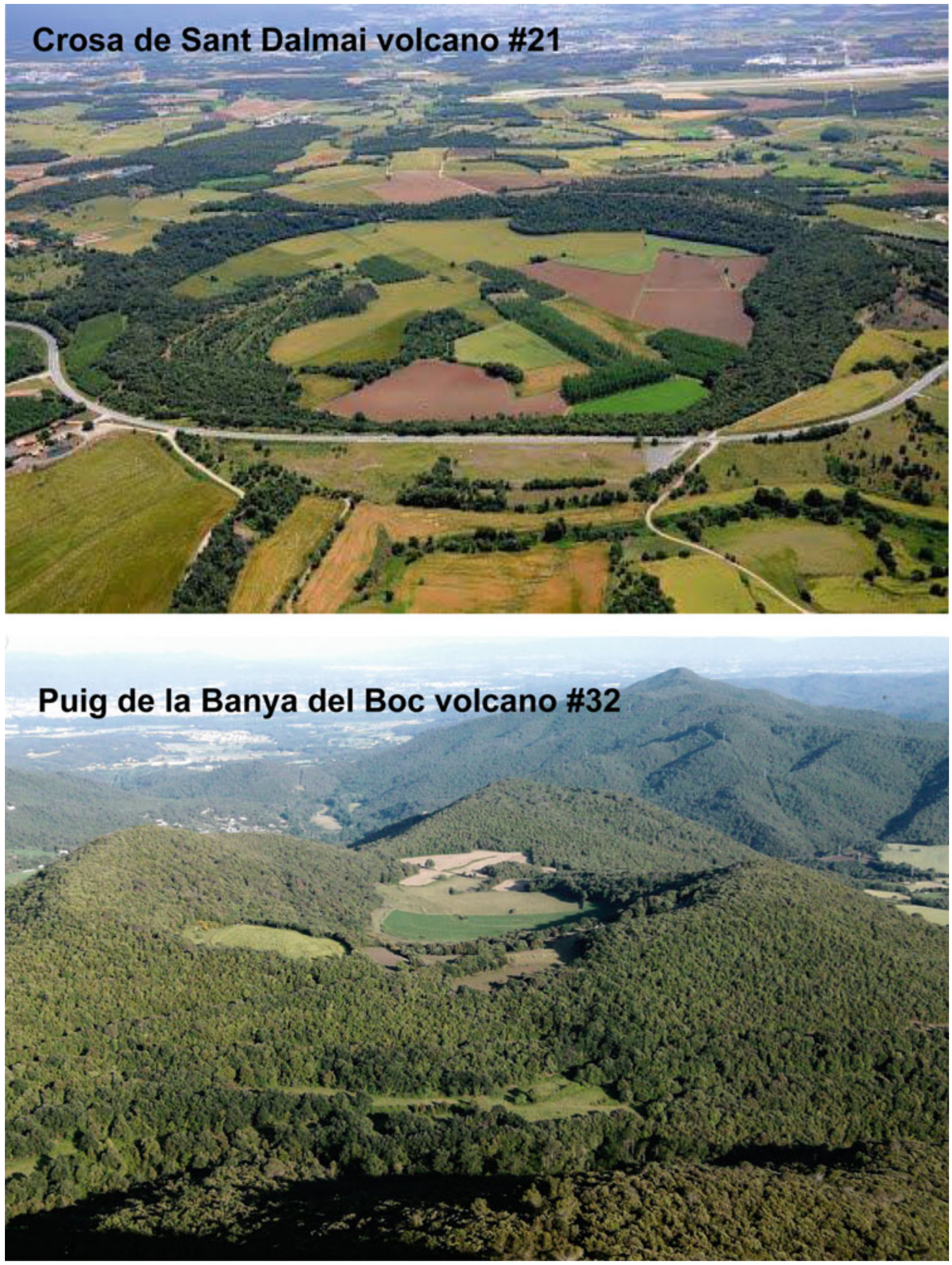

Fig. 2.7 Aerial views of La Crosa de Sant Dalmai and Puig de la Banya del Boc phreatomagmatic edifices from the southern sector of La Garrotxa Volcanic Field (*Credit* Eduard Masdeu)

Table 2.1 Summary of the different eruptive sequences deduced for the studied volcanoes

Volcano type	**Eruptive sequence** (from beginning to the end)
Puig d'Adri	Phreatomagmatic-Strombolian-Phreatomagmatic-Strombolian-Hawaiian
Crosa de Sant Dalmai	Phreatomagmatic-Strombolian-Phreatomagmatic-Strombolian
Santa Margarida-Croscat	Phreatomagmatic-Strombolian-Phreatomagmatic-Hawaiian
Garrinada	Hawaiian-Strombolian-Phreatomagmatic-Hawaiian
Can Tia	Phreatomagmatic-Strombolian-Phreatomagmatic
Montsacopa	Hawaiian-Strombolian-Phreatomagmatic
Puig de Banya de Boc	Phreatomagmatic-Strombolian-Hawaiian
Cairat	Phreatomagmatic-Strombolian
Clot de l'Omera	Phreatomagmatic
Roca Negra	Strombolian

2.3.2 Stratigraphy: The Volcanic Deposits

Volcanic terrains are characterised by the complex stratigraphic relationships of their products caused by, variously, extremely rapid depositional rates compared with conventional sub-aerial and submarine sedimentary environments, the friable character of many volcanic deposits that facilitates their rapid erosion, the contrasting influence of topography on the emplacement of volcanic products, and rapid changes in facies. Such complexity constitutes one of the main obstacles when attempting to reconstruct the geological evolution of volcanic areas. This is even more problematical in highly urbanised areas where construction modifies the original morphology of the area and hides many natural features, and where deposits are often lost to quarrying.

In the case of La Garrotxa Volcanic Field, an important part of the northern zone now lies beneath the city of Olot (almost 40,000 inhabitants), a highly industrialised and built-up area covering about 30 km^2. Deposits from five recent volcanic cones (Montolivet, Montsacopa, La Garrinada, Bisaroques and Ca l'Isidret) located in the heart of the city (Fig. 2.8) have been partially covered by or removed due to urban and industrial construction. Furthermore, a dense carpet of vegetation covers other parts of this volcanic field and thus the surface geology of the area is not always visible. Therefore, in addition to extensive fieldwork, a study of ephemeral outcrops and the stratigraphic logging of new wells and geotechnical drill holes, complemented by existing information gathered by recent geophysical studies of the substrata of this volcanic field, are required if we are to generate a comprehensive volcanic stratigraphy of the area that can identify the products of each eruption, their relative stratigraphy and their surface area.

The digital volcano-stratigraphic map of La Garrotxa Volcanic Field (1:2000) summarises all the stratigraphic members (i.e. all deposits from the same eruption) that can be identified in the region. Members are placed according to their relative stratigraphy from the youngest (top) to the oldest (bottom) (Fig. 2.4). Also given is an indication of whether the age is relative (i.e. established on the basis of observable stratigraphic relationships) or absolute (i.e. a geochronological—either isotopic or palaeontologic—date is available), as well as the corresponding reference source and the calculated erupted volumes (in Dense Rock Equivalent, DRE) when available.

The precision required to establish the stratigraphic relationships between the volcanic materials of the area decreases progressively with their age, as the younger materials are better exposed and preserved, and are located at shallower depths than older ones, often only accessible via boreholes and wells or at deep ephemeral outcrops. Due to incomplete exposure, some of the older units could have been overlooked.

The volcanic materials consist of lava flows and different types of fallout and pyroclastic density current deposits derived from Strombolian and phreatomagmatic eruptions. The calculated volumes shown in Table 2.2 are all minimum estimates of the DRE and represent the minimum volume of magma erupted in each case and, consequently, the magnitude of the eruption. Not all calculated volumes have the same degree of accuracy, since not all deposits are completely exposed. This implies that the record presented here is incomplete and should be treated with care if used in scientific studies. The volumes obtained lie in the range 0.01–0.03 km^3. However, a few eruptions (Croscat (2), Puig Subià (18), Crosa de Sant Dalmai (21), Puig de Banya del Boc (32), Garrinada (35), Puig d'Adri (45) and Puig de l'Os (51)) generated larger volumes, for example up to 0.2 km^3 in the case of Croscat.

Rather than being attributable to major tectonic events, the observed stratigraphic discontinuities and unconformities can be ascribed to either minor, inter-eruptive and syn-eruptive erosional and depositional episodes, to non-depositional hiatus corresponding to the non-uniform aerial distribution of the volcanic materials erupting from the vents, or—above all—to the fact that volcanic materials do not always emplace according to the principle of superposition, in particular when younger materials emplace on deeply eroded older ones. The style of the volcanism shows no significant variation along the stratigraphic succession and so the differences observed in the deduced eruption sequences (e.g. the alternation of Strombolian and phreatomagmatic phases) of the different members should be interpreted as due to local variations in the characteristics of the substrata rather than to any geological changes occurring on a major scale.

2.3.3 Structural Controls of the La Garrotxa Volcanic Field

La Garrotxa Volcanic Field is mostly controlled by two major Neogene faults, the Amer and Llorà faults. Both are oriented NW-SE, as are most of the major post-Alpine extensional faults that have defined a horst and graben structural pattern in NE Iberia. However, most of the eruptive fissures and secondary structural lineaments that control the precise location of the eruption centres of this volcanic field show a NNW-SSE trend that runs slightly obliquely to the main faults.

The pattern shown by the eruptive fissures and subordinated structural lineaments is compatible with a slight

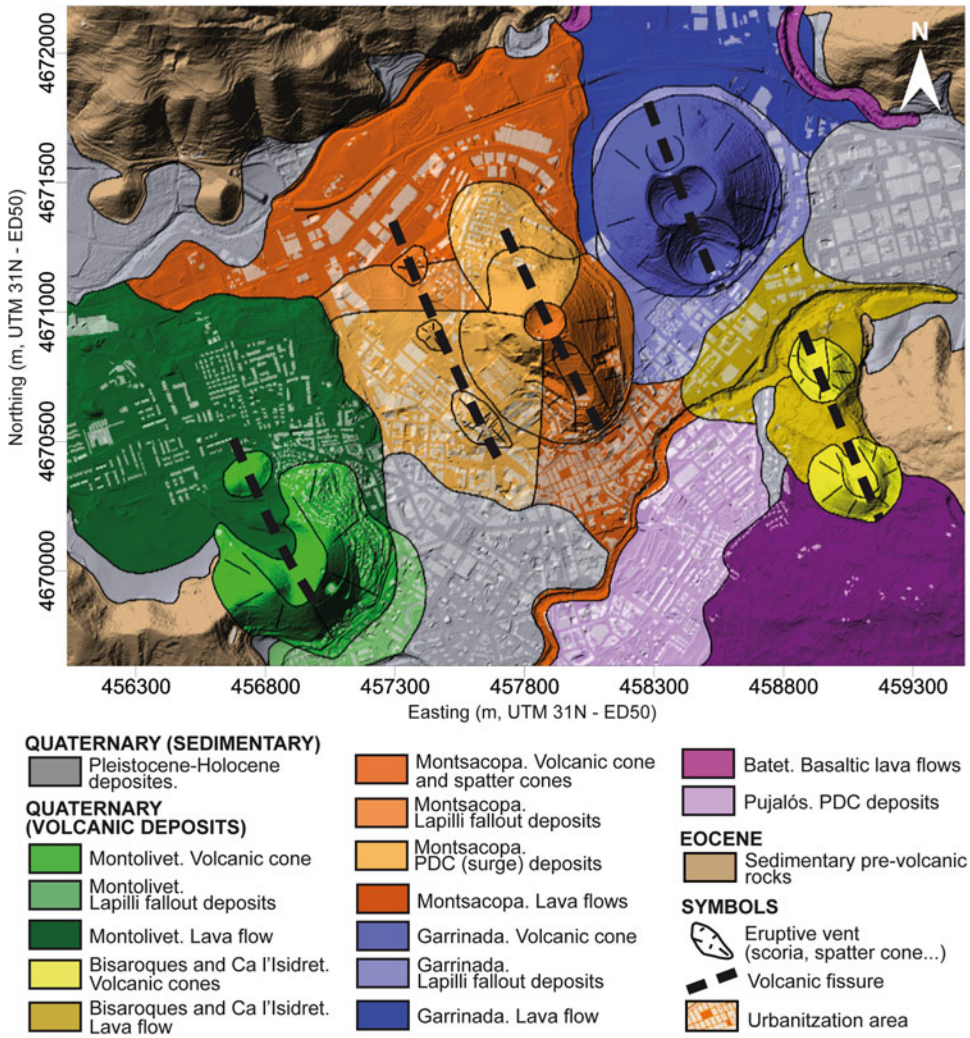

Fig. 2.8 Detailed geological map of Olot city (reproduced with permission of John Wiley and Sons, Ltd.)

dextral trans-tensional component in the two main faults and indicates that magma ascent in the uppermost crust and subsequent eruptions were controlled by these subordinated fissures. This structural configuration would have favoured the opening of these fractures and the transport of magma through them, at least in the final pre-eruptive stages. Similar behaviour has been described from other volcanic zones around the world. However, it is not clear how deep these fractures are nor what exactly their role was in transporting magma from deeper levels.

The presence of mantle-derived xenoliths and lower-crust cumulates suggests that the magmas that erupted in La Garrotxa Volcanic Field came either directly from the source region in the upper mantle or from intermediate reservoirs located at the base of the crust. No evidence exists for the presence of shallower reservoirs beneath this volcanic field. This is also confirmed by existing petrological and geochemical data that show the primitive or relatively poorly evolved character of these magmas. Therefore, what remains to be discovered is how deep the structures observed on the surface extend and how they were used by magma to reach the surface. It is worth noting that most of the area's freshwater springs are associated with relatively shallow stratigraphic or structural discontinuities, while the presence of high 222 Rn and CO_2 concentrations mainly occurs along the major Neogene faults (Fig. 2.9), thereby indicating that the deep circulation of these mantle-derived gases is permitted through these faults. Likewise, recorded seismicity also reveals that Neogene faults have been active recently, mainly linked to the Amer fault. Finally, the obtained magma ascent rates indicate that only a relatively short time was required for magmas to reach the surface, thereby suggesting the existence of preferential pathways for magma when ascending from source or accumulation regions up to the eruption sites.

In light of this evidence, the Llorà fault can be judged to have played the most important role in conducting magma from the source region, either to the base of the crust where magma occasionally accumulated (underplating) and differentiated, or directly to much shallower levels where it was

Table 2.2 Volcanic stratigraphy and volume estimates of La Garrotxa Volcanic Field

Time period	Relative Stratigraphy (from younger to older)	Age	Member	Description	DRE (Km^3)	Source
Holocene	1	Relative	Rocanegra volcano	These deposits overlie the Croscat volcano (# 2) phreatomagmatic deposits and are not covered by the Croscat volcano fallout.	0,01	(1)
Upper Pleistocene	2	11.5–13 ka	Santa Margarida – Croscat – Pomareda eruptive fissure		0,18	(2) (3)
	3	Relative < 18000	Montolivet volcano	These deposits overlie those of Montsacopa volcano (# 24), which in turn overlay La Garrinada (# 35) volcano deposits.	0,02	(4)
	4	17.1 ka	Puig Jordà volcano	Lava flow with rootless volcanoes, locally known as Bosc de Tosca.	0,03	(2) (3)
	5	Relative	Bisaroques and Ca l'Isidret volcanoes	Young aspect and poorly eroded materials overlying La Garrinada (# 35) volcano deposits.	0,01	
	6	Relative	Puig de Martinyà volcano	There is a paleosoil that separates these deposits from the Croscat volcano (# 2) deposits.		
	7	Relative	Puig de la Costa volcano (Lava flow below Croscat volcano member (# 2))	Several lava flows were recognised in the Croscat borehole below the Croscat and Puig Martinyà (# 6) deposits. The uppermost lava flow can be stratigraphically correlated with the Puig de la Costa volcano, so it should be younger than 30 ka.		
	8	Relative	Racó volcano		0,02	
	9	28.1 ka	Simon volcano and Santa Pau lava flow	Santa Pau lava flow could be related to the Simon volcano according to its location and stratigraphic position.		(2)
	10	30 to 46.3 ka	Traiter volcano		0,03	(2)
	11	Relative	Sant Marc and Puig Roig volcano			
	12	Relative	Lava flow below Bosc de Tosca	Appears underlying the Bosc de Tosca (Puig Jordà volcano (# 4)) lava flow and Racó volcano (# 8) deposits.		
	13	Relative	Pla de Massandell borehole upper lava flow			
	14	Relative (< 45 ka)	L'Estany and Bellaire volcanoes		0,02	(1)
	15	Relative	Pla de Massandell borehole lower lava flow			
	16	Relative	Cabriolers volcanoes			
	17	Relative	Puig de Granollers volcano		0,03	
	18	Relative	Puig Subià volcano	Its deposits appear below the Santa Pau lava flow (# 9).	0.1–0.2	
	19	Relative	Comadega volcano	Underlying deposits from Croscat and Santa Margarida (# 2) and other volcanoes deposits in the Santa Pau area.		
	20	Relative	La Moixina lava flow			
	21	43–120 ka	Crosa de Sant Dalmai volcano		0,13	(1) (5)
	22	73.5 ka	Fontpobra, Can Tià and Coll Tort volcanoes		0,03	(2)
	23	Relative	Pujalós volcano		0.03–0.07	
	24	Relative	Volcà del Montsacopa	Its deposits overlay La Garrinada volcano (# 35) and are covered by thus from the Bisaroques and Ca l'Isidret volcanoes (# 5).	0.02–0.06	
	25	Relative	Pla de Llacs lava flow			
	26	Relative	Pla d'Olot lava flow	Below Pla de Llacs (# 25). Only observable in boreholes.		
	27	Relative	Pla d'Olot lava flows	Undetermined number of lava flows that fill the Olot depression.		

(continued)

Table 2.2 (continued)

Time period	Relative Stratigraphy (from younger to older)	Age	Member	Description	DRE (Km^3)	Source
	28	100 ka	Puig de les Medes and Puig Rodó volcanoes		0,02	(2)
	29	Relative	Lava flow in borehole at Croscat northern flank			
	30	110 ka	Pla de les Tries lava flow			(2)
	31	110 ka	Puig de Mar volcano			(6) (2) (7) (6) (2) (7)
	32	121 ka	Puig de la Banya del Boch and Clot de l'Omera volcanoes			(2) (3)
	33	Relative	Olot 2 lava flow	Only observable in boreholes.		
	34	Relative	Olot 1 lava flow	Only observable in boreholes.		
Middle Pleistocene	35	133 ka	Garrinada volcano		0,08	(2) (8)
	36	Relative	Bac de les Tries volcano	Deposits observable below la Garrinada volcano (# 35).		
	37	Relative	Pla sa Ribera volcano			
	38	Relative	Riu Ser lava flow 2	Appearing above the Riu Ser lava flow 1 (# 40).		
	39	Relative	Vall dels Arcs phreatomagmatic deposits	Underlying the Riu Ser lava flow 2 (# 39).		
	40	Relative	Riu Ser lava flow 1			
	41	150 ka	Sant Joan les Fonts lava flow and Aiguanegra volcano			(8)
	42	Relative	Sant Cosme lava flow (from Batet)	Above the Funoses lava flow (# 42).		
	43	Relative	Les Funoses lava flow	Above the Castellfollit lava flows (# 46 and # 47).		
	44	Relative	Cairat-Repàs-Claperols eruptive fissure			
	45	168 ka	Puig d'Àdri volcano		0,09	(9)
	46	192 ka	Castellfollit de la Roca upper lava flow			(8)
	47	217 ka	Castellfollit de la Roca lower lava flow			(8)
	48	Relative	Batet upper lava flows			
	49	247 ka	Batet middle lava flows			(2)
	50	Relative	Barraca volcano	These products are covered by the Batet lavas (# 48 and # 49).		
	51	250 ka	Puig de l'Ós volcano		0,02	(8)
	52	Relative	Sant Jaume de Llierca lava flow			
	53	Relative	Batet lower lava flows	Lava flows identified in a borehole at the Batet high		
	54	Relative	La Canya volcano			
	55	590–700 ka	Sant Joan les Fonts lava flows	The oldest lava emission recognised in this volcanic field.		(8)

RS, relative stratigraphy (from younger to older)
Source: (1) Burjachs (1985), 14C dating. (2) Guérin and Valladas (1980), thermoluminiscence dating of volcanic plagioclases. (3) Guerin and Benhamou (1985), thermoluminiscence dating of volcanic plagioclases and K/Ar isotopic dating. (4) Bolos (1925), relative dating by biostratigraphy. (5) Pedrazzi et al. (2014), U–Th and 14C dating. (6) Mallarach (1981, 1982, 1998), relative dating by stratigraphy. (7) Donville (1973), K/Ar isotopic dating. (8) Lewis (2000), Ar/Ar isotopic dating. (9) B. Gómez (personal communication, 2014), thermoluminescence (TL) dating of sediments

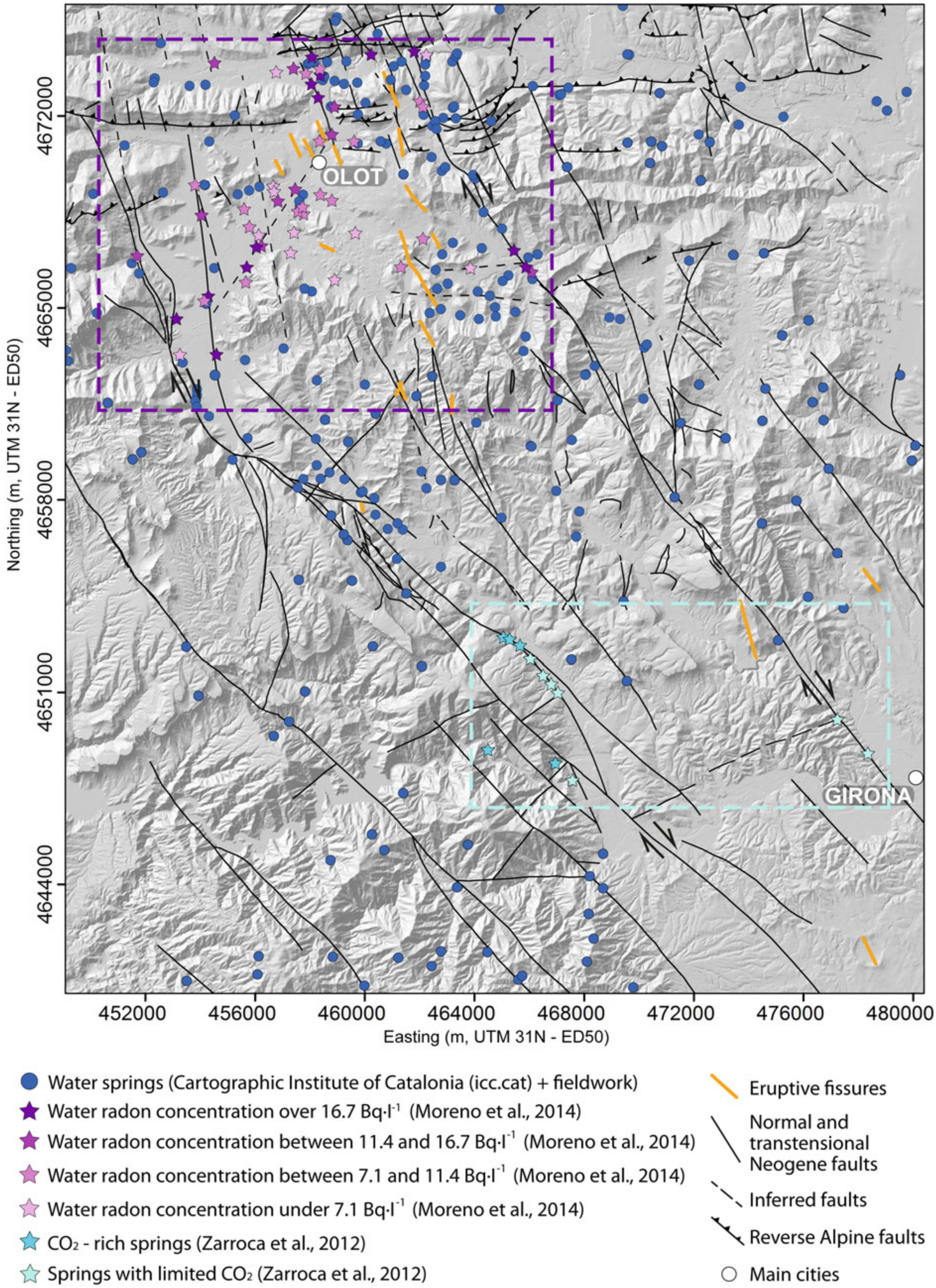

Fig. 2.9 Location of the main water springs and gas emission sites at La Garrotxa Volcanic Field (reproduced with permission of Elsevier)

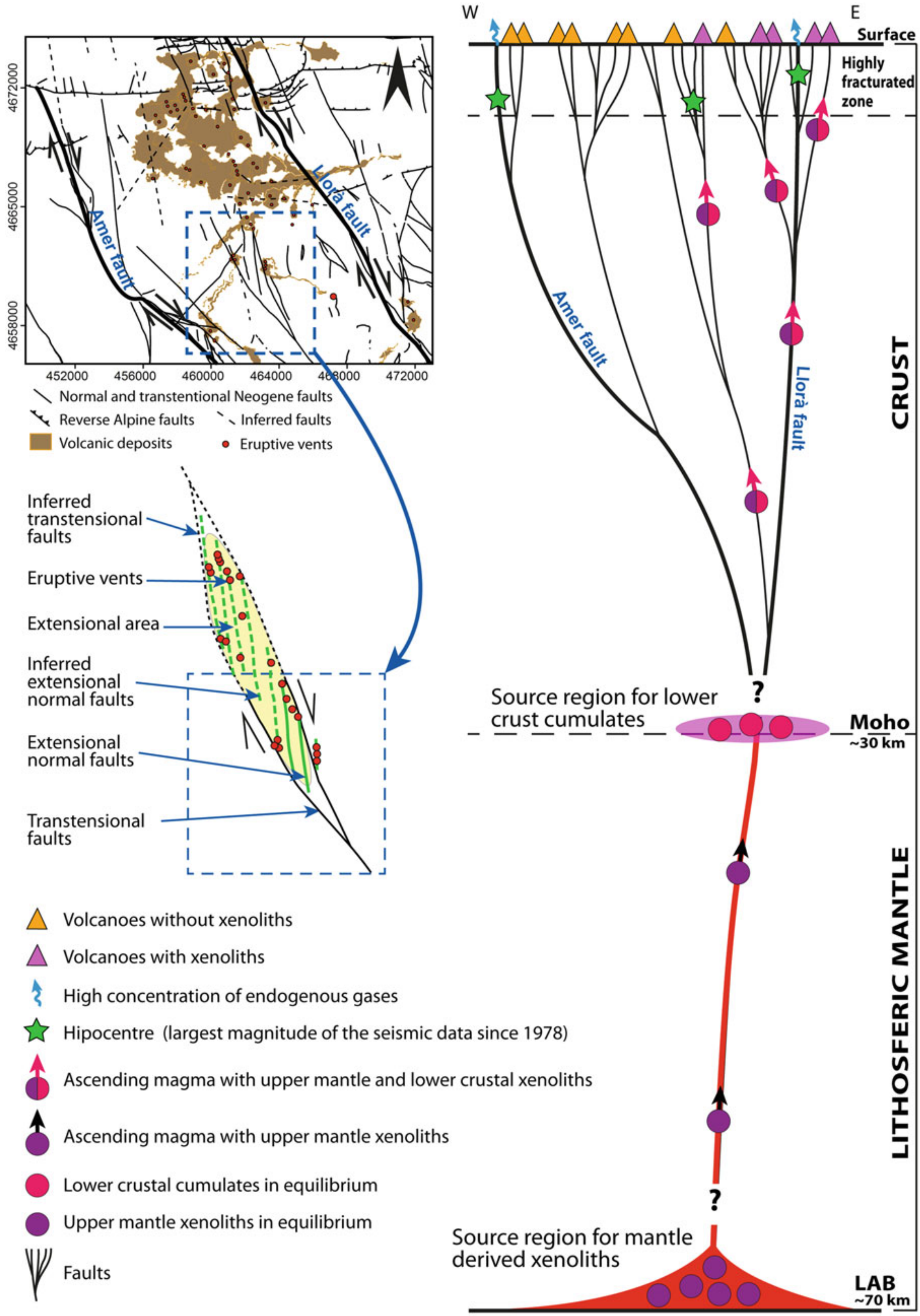

Fig. 2.10 Conceptual model of the magmatic plumbing system at La Garrotxa Volcanic Field (reproduced with permission of Elsevier)

captured by the subordinated fractures that allowed it to erupt to the surface. As indicated by the presence of lower-crust cumulates and the location of vents and eruptive fissures, the extraction of magma from the lower crust reservoir(s) was mainly controlled by the Llorà fault and, to a lesser extent, by the Amer fault, which would have acted as a conjugate major fault reaching down to the base of the crust. Shallow subordinated fractures to the Amer fault would have also captured the ascending magma in its last stages and have controlled its eruption to the surface (Fig. 2.10). The fact that the mantle-derived xenoliths and the largest lower-crust cumulates are restricted to the vents related to the Llorà fault is strong support for this model. Likewise, the volcanoes associated with this fault generated the largest erupted volumes of all volcanoes in this volcanic field, which also suggests that the Llorà fault was the main magma pathway.

The reason why magma eruptions have occurred through different NNW-SSE eruptive fissures during the history of La Garrotxa Volcanic Field—despite the constant and common feeding system at depth—seems to be related to the role played by these subordinate shallow fractures. They captured magma during the final stages of its ascent to the surface and so determined the point of each eruption. The shallow character of these fractures suggests that the local stress field, which was mostly controlled by the movement of the two main (Llorà and Amer) faults, only made a weak contribution. Under these circumstances, these shallow fractures could be easily sealed by residual magma that solidified within, thereby making it easier for a new eruptive episode to open a fresh fracture than to reuse a previously sealed one. This would also suggest—in accordance with the intermittent character of this volcanism—that each eruptive episode corresponds to an intermittent reactivation of the main fault system every 10,000–30,000 years. These tectonic reactivations would permit the ascent of deep magma and the opening of subordinate fractures in the uppermost crust, which would then erupt on the surface each time in a different location in the volcanic field.

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