

Short guide to Val d'Orcia field trip – May 27th and 28th 2022

Edited by:

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Regional geological setting

Finished in the Upper Oligocene, the closure by 'continental collision' of the Ligurian-Piedmont basin was followed by Sardinian-Corse block rotation counterclockwise about 35°, that started 30 to 28 million years ago (Late Oligocene). This block reached its present position in the Early Miocene, about 19 million years ago, and has been stationary ever since; during this phase, the Balearic Basin was formed (**Figure 1**).

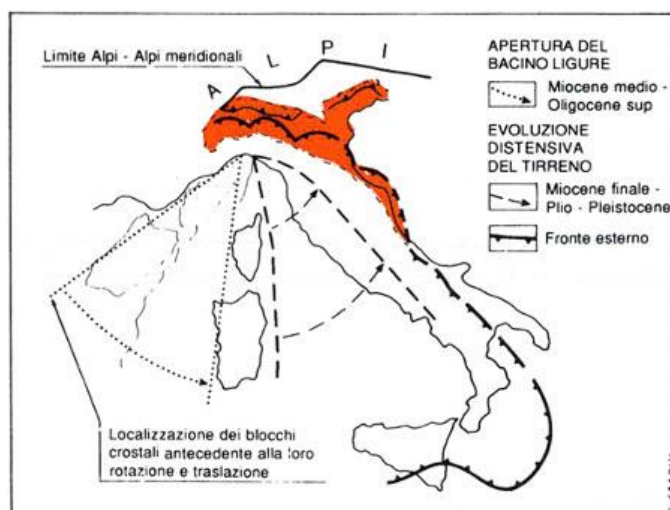


Figure 1 - Schematic paleo-geographic reconstructions of the Corsica-Sardinia block rotation.

At the same time, a new subduction process forms (east of the Sardinian-Corse block) with the associated formation of a volcanic arc. The retreat of the subduction line, known as rollback, results in the affected area forming a marginal basin due to the retreat of the Balearic arc. This happens between the Burdigallian (early Miocene) and the Pliocene (**Figure 2**).

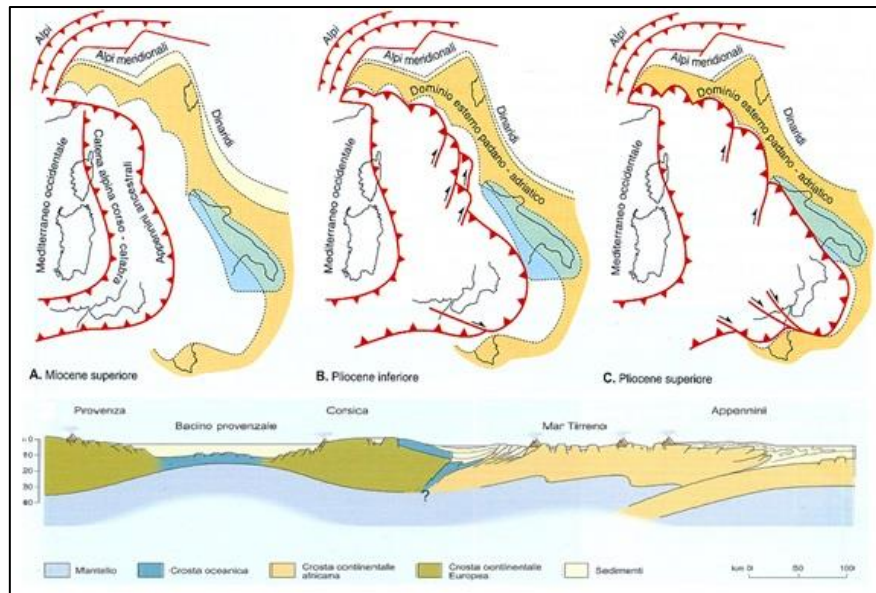


Figure 2 - Schematic paleo-geographic reconstructions illustrating the Burdigalian to Pliocene kinematic evolution of the Central Mediterranean area after the Early Miocene drifting and rotation of the Corsica-Sardinia block. The thick red line with unshaded triangles represents the different thrust fronts.

Finally, in the Pliocene, intense magmatic activity began, involving, along the Apennine line, a vast range from Mount Amiata to Campania (**Figure 3**).

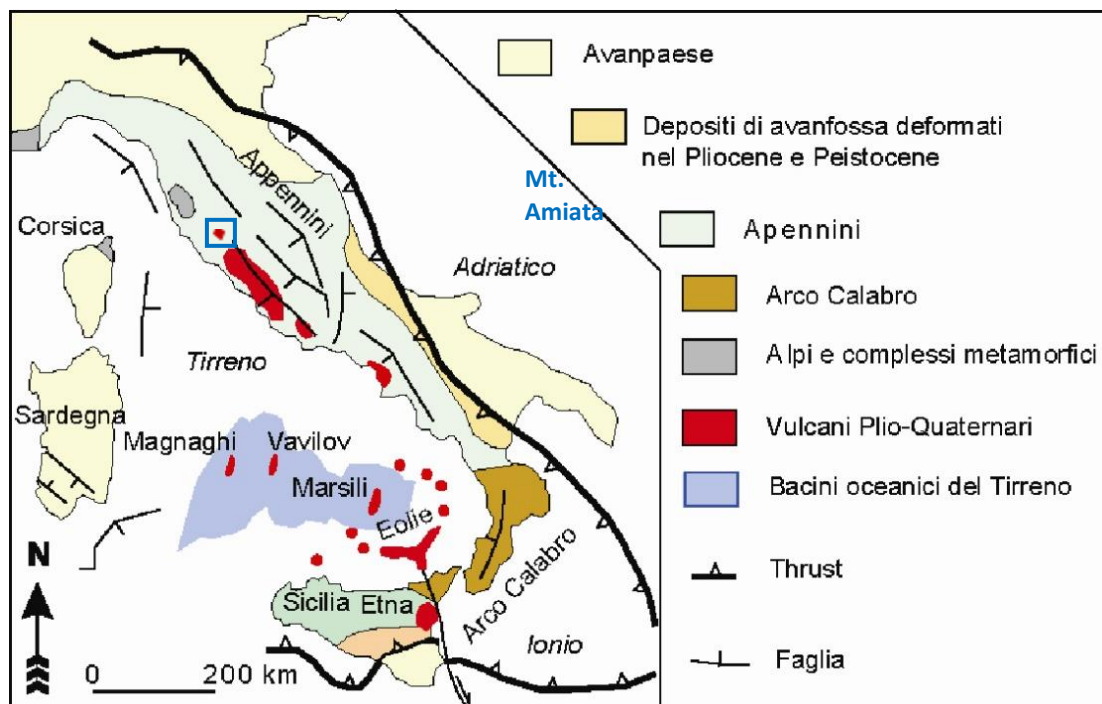


Figure 3 - Areas in red are Plio-Quaternary volcanoes. The light blue box indicates the area of Mount Amiata.

Geological setting of the Monte Amiata

Monte Amiata (with a summit elevation of 1738 m a.s.l.) is the highest mountain in the Tuscany region and the second tallest volcano in Italy. It is probably the least known of the major Italian central volcanoes and volcanic complexes. It lies in the southernmost part of Tuscany, close to the boundary with Latium, only a few tens of kilometers to the north of the Vulsini volcanic complex.

The surrounding landscape is densely forested and consists of a series of roughly NW-SE trending ridges and valleys. Monte Amiata is a late Quaternary (300.000 years ago until 190-180.000 years ago) complex mainly formed of ignimbrite sheets and trachytic lava domes and flows, with subordinate more mafic lava flows erupted late in the activity. The volcanic area of Monte Amiata is roughly 85 km², the thickness of the volcanic pile reaching up to 600 m. It now hosts a water-dominated geothermal field, which is being exploited for the production of electric power since the early 1960s.

The knowledge of the geological setting of the Monte Amiata volcano and the geothermal area around it (**Figure 4**) mainly derives from mining and geothermal exploitation (Elter & Pandeli, 1991; Batini et al., 2003), from the interpretation of geophysical data (Brogi, 2004, 2006) and from fieldwork data (Brogi, 2004).

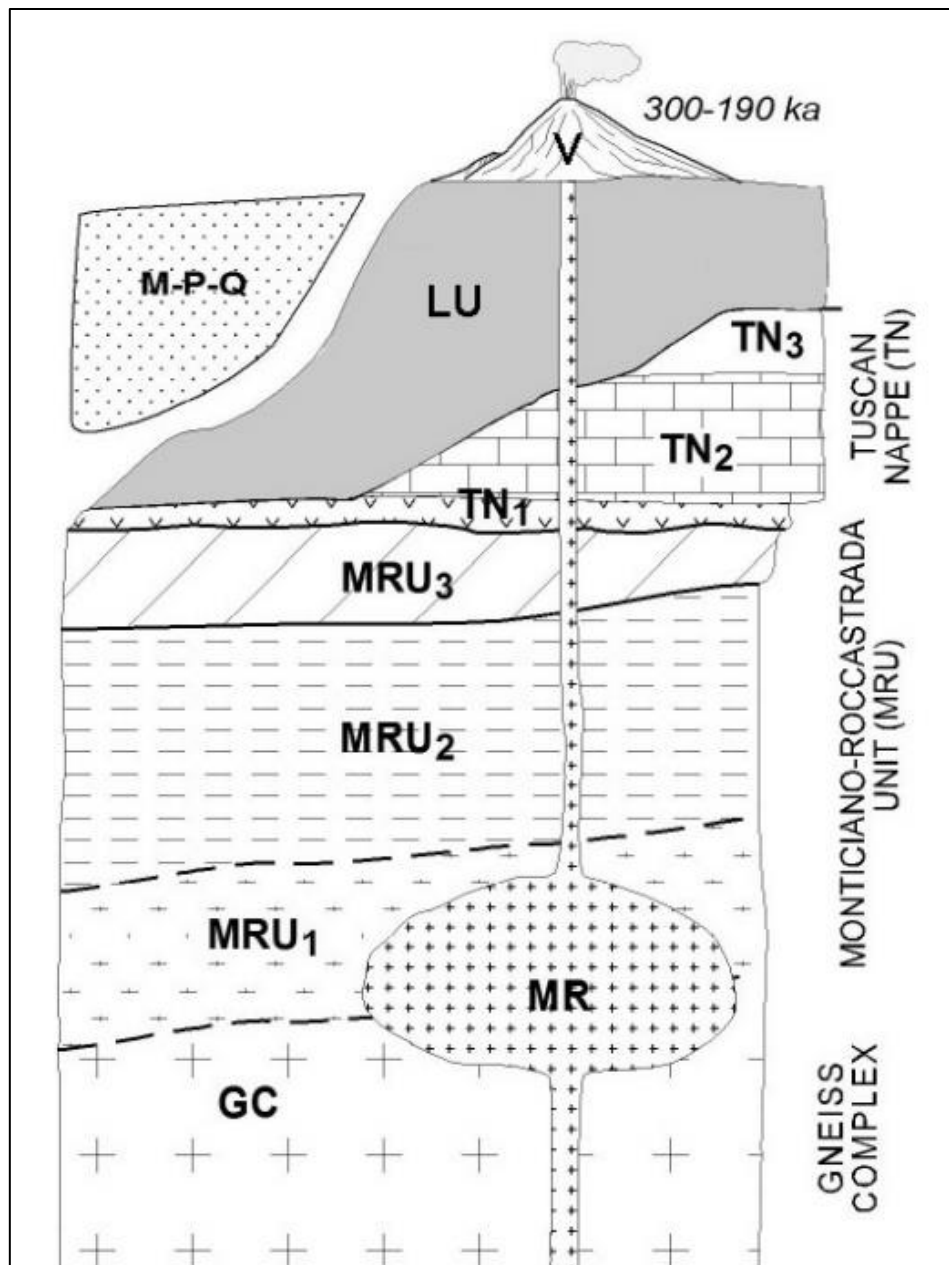


Figure 4 - Tectono-stratigraphic units in the Monte Amiata area (from Batini et al., 2003).

The tectono-stratigraphic units in the area from top to bottom are (**Figures 4 to 6**):

- 1) the Volcanic complex (**V**): spreading out on $\sim 80 \text{ km}^2$ with an estimated volume of 19 km^3 , consisting of dacitic, rhyodacitic and olivine-latic rocks, mostly ignimbrites, containing mafic enclaves, erupted in a period ranging from 300.000 to 190.000 years ago (Ferrari et al., 1996 and references therein);
- 2) Neogene and Quaternary deposits (**M-P-Q**): they consist of Middle Miocene-Quaternary continental and marine sediments filling the tectonic depressions (Bonini & Sani, 2002);
- 3) the Ligurian Units (**LU**). They are composed by the remnants of the Jurassic oceanic basement and its pelagic sedimentary cover. They were thrust eastwards over the Tuscan Domain during the Latest Oligocene-Early Miocene;
- 4) the Tuscan Nappe (**TN**). It is related to part of the Late Triassic-Early Miocene sedimentary cover of the Adria continental paleo-margin. Its stratigraphic succession is made up of (from

bottom to top): evaporitic (Late Triassic, **TN1**), carbonate (Late Triassic-Early Cretaceous, **TN2**) and pelagic-turbiditic (Cretaceous-Early Miocene, **TN3**) successions. The Tuscan Nappe was detached from its substratum along the Triassic evaporite horizon (**TN1**) and was thrust over the outer paleo-geographical domains during the Late Oligocene-Early Miocene contraction;

5) the Tuscan Metamorphic Complex has been encountered only by deep boreholes (Elter & Pandeli, 1991) and it consists of very low-grade metamorphic successions ascribed to two groups: (i) the Triassic Verrucano Group (**MRU3**), made of continental metapelites, metasediments and metaconglomerates; and (ii) the Palaeozoic Group (**MRU2**), made of graphitic phyllites and metasediments of probable Carboniferous age, Devonian (?) hematite-rich and chlorite phyllites, metasediments with dolomite layers, and Late Permian fusulinid-bearing crystalline limestones and dolomites with intercalations of graphitic phyllite. The occurrence of the Micaschist Group (**MRU1**) and the Gneiss Complex (**GC**) at certain depth has been documented by xenoliths in the Quaternary lavas (Van Bergen, 1983);

6) magmatic rocks (**MR**) are assumed located around 6 km depth on the basis of geophysical interpretation (Bernabini et al., 1995).

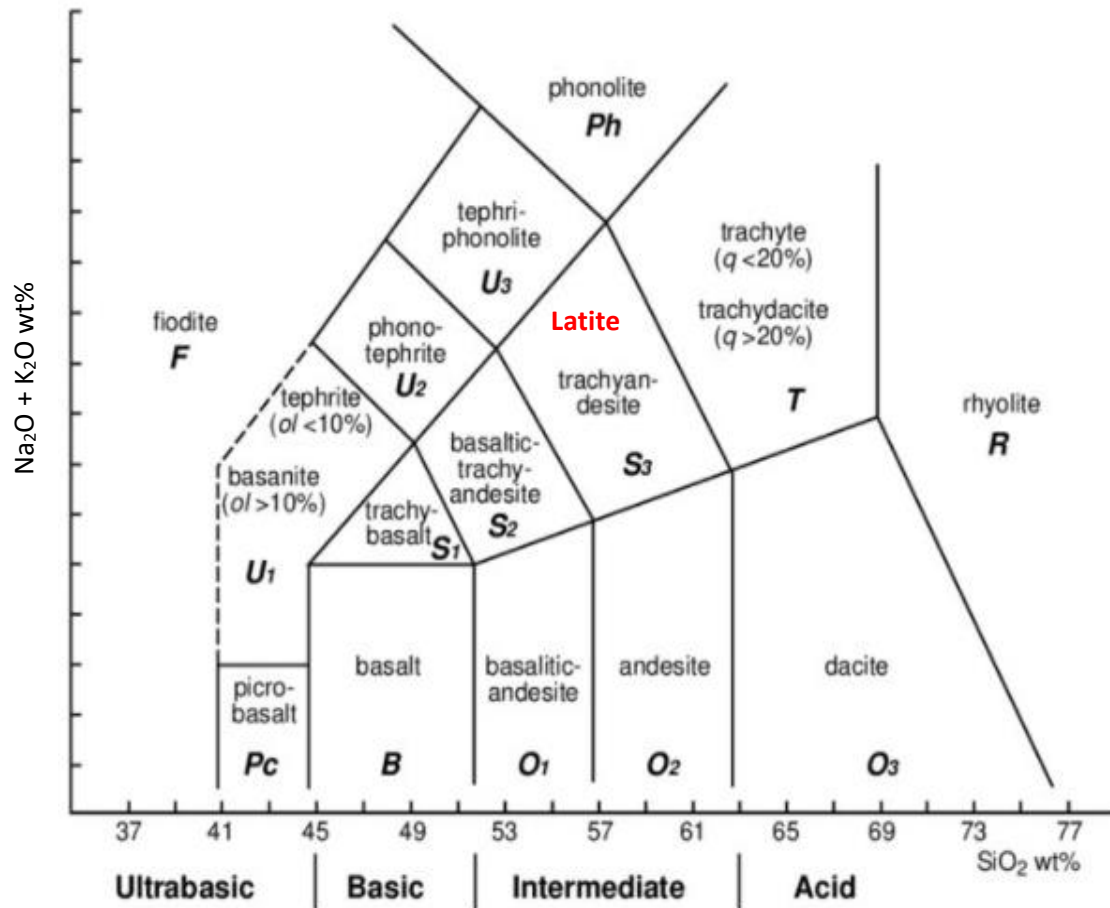


Figure 5 - Chemical classification of volcanic rocks (TAS: total alkali-silica diagram).

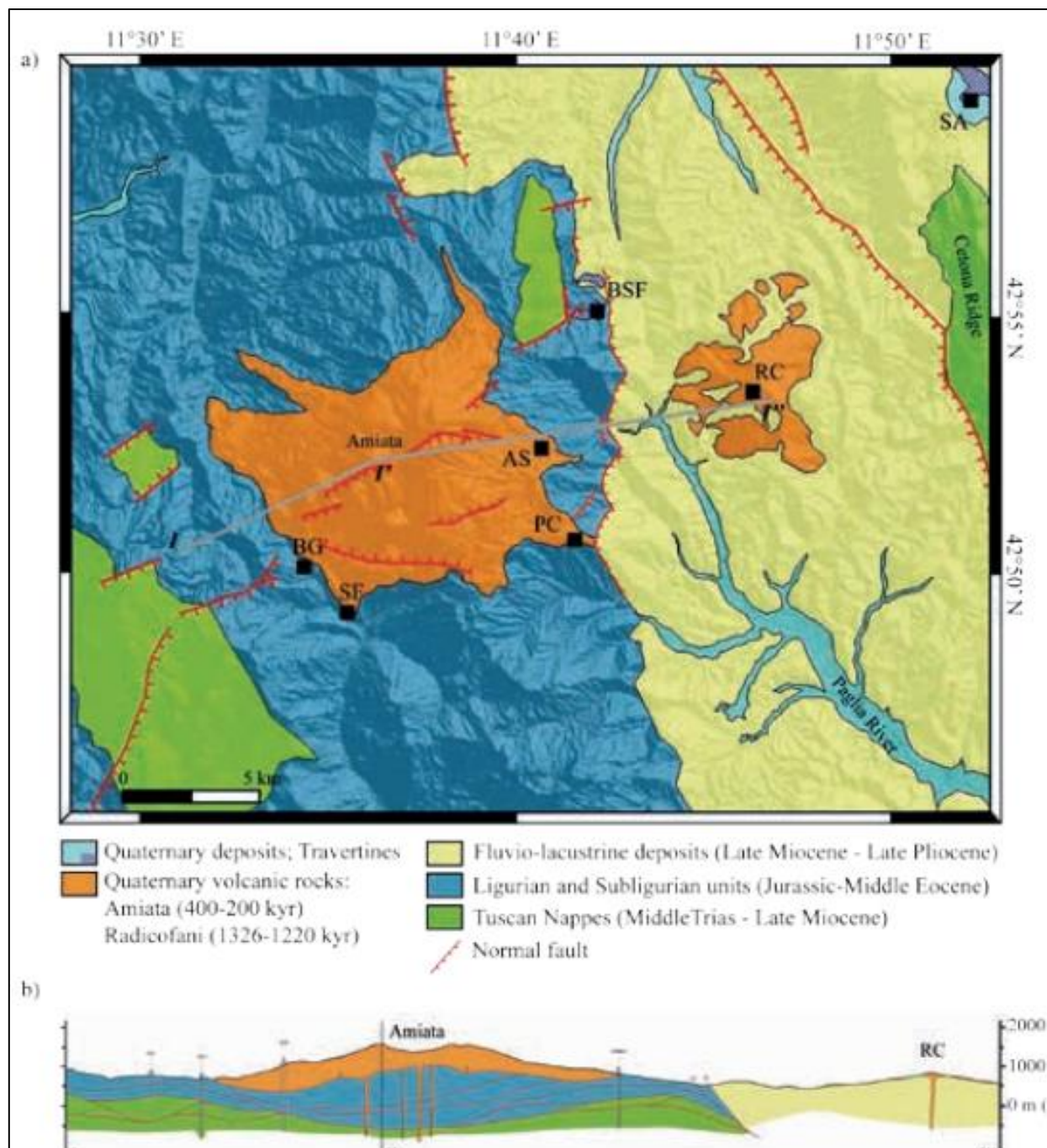


Figure 6 - A) Geological sketch of Mt. Amiata and surrounding area: BG-Bagnore; SF-Santa Fiora; PC-Piancastagnaio; AS-Abbadia San Salvatore; BSF-Bagni San Filippo; RC-Radicofani; SA-Sarteano. B) Schematic cross-section along grey line (I-I'), modified from Marroni et al., 2015.

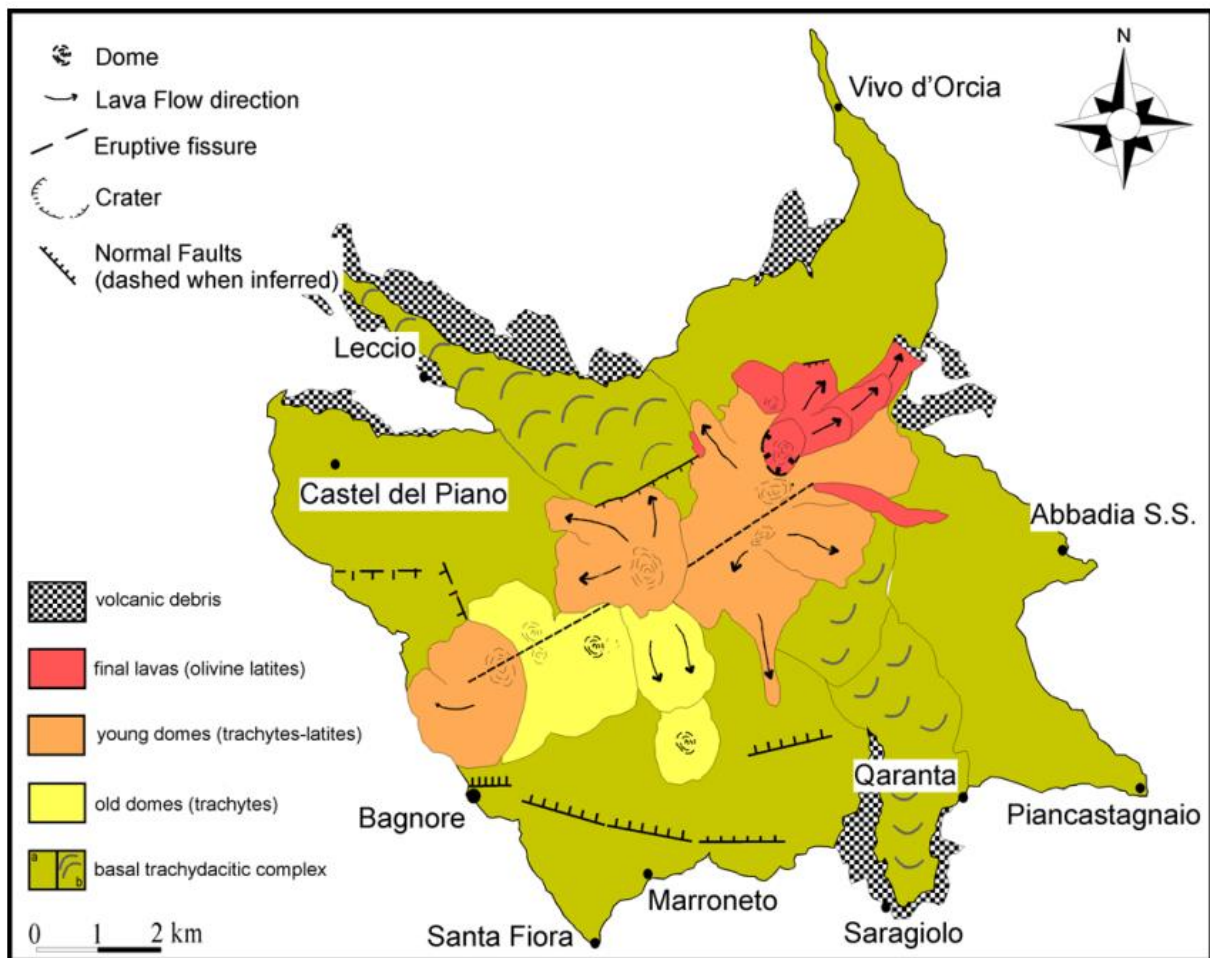


Figure 7 - Geological sketch map of the Mt. Amiata volcano, from Ferrari et al., 1996.

Ferrari et al. (1996) subdivide the activity of Monte Amiata (**Figure 7**) in two main phases (The Basal Trachydacite Complex, **BTC**, and Domes and Lava flow Complex, **DLC**) and a final third phase when olivine latitic lava flows were emitted (**OLL**).

The deposits of the first phase are a lower massive unit evenly distributed around the volcano, and an upper unit that forms two distinct tongues and consists of loose blocks. The volume of the **BTC** is estimated by Ferrari et al. (1996) at 13.5-18 km³. The overlying **DLC** unit consists of lava domes and short viscous lava flows, which were K/Ar dated at 207+/-10 and 190+/-23 ka. Ferrari et al. (1996) distinguish nine dome and flow units, all except one lying on a fracture orientated ENE-WSW. The final **OLL** lava flows form two small lobes distinctly different in terms of mineralogy and chemical composition from the earlier erupted products. The longer of these two flows, named Ermeta lava, has a length of 2.5 km.

Although Monte Amiata does not exhibit any signs of forthcoming activity, there is continuing seismicity in the area (a seismic swarm occurred as recently as 1977). Among the various events that occurred was the earthquake of November 3, 1948, which had as its epicenter the mountainous area straddling the provinces of Grosseto and Siena, reaching a magnitude of 5.03 on the Richter scale and VI-VII on the Mercalli Scale. Other seismic events affecting the Amiata area, however, had as their epicenters the localities of Arcidosso, Santa Fiora, Abbadia San Salvatore and Piancastagnaio.

Hydrogeological setting

Up to the middle part of the twentieth century, the major interest in Monte Amiata was related not to its volcanological aspects but to its natural resources: drinking waters (**Figure 8A, 8B**), diatomaceous earths, earth pigments and mercury ore-minerals.

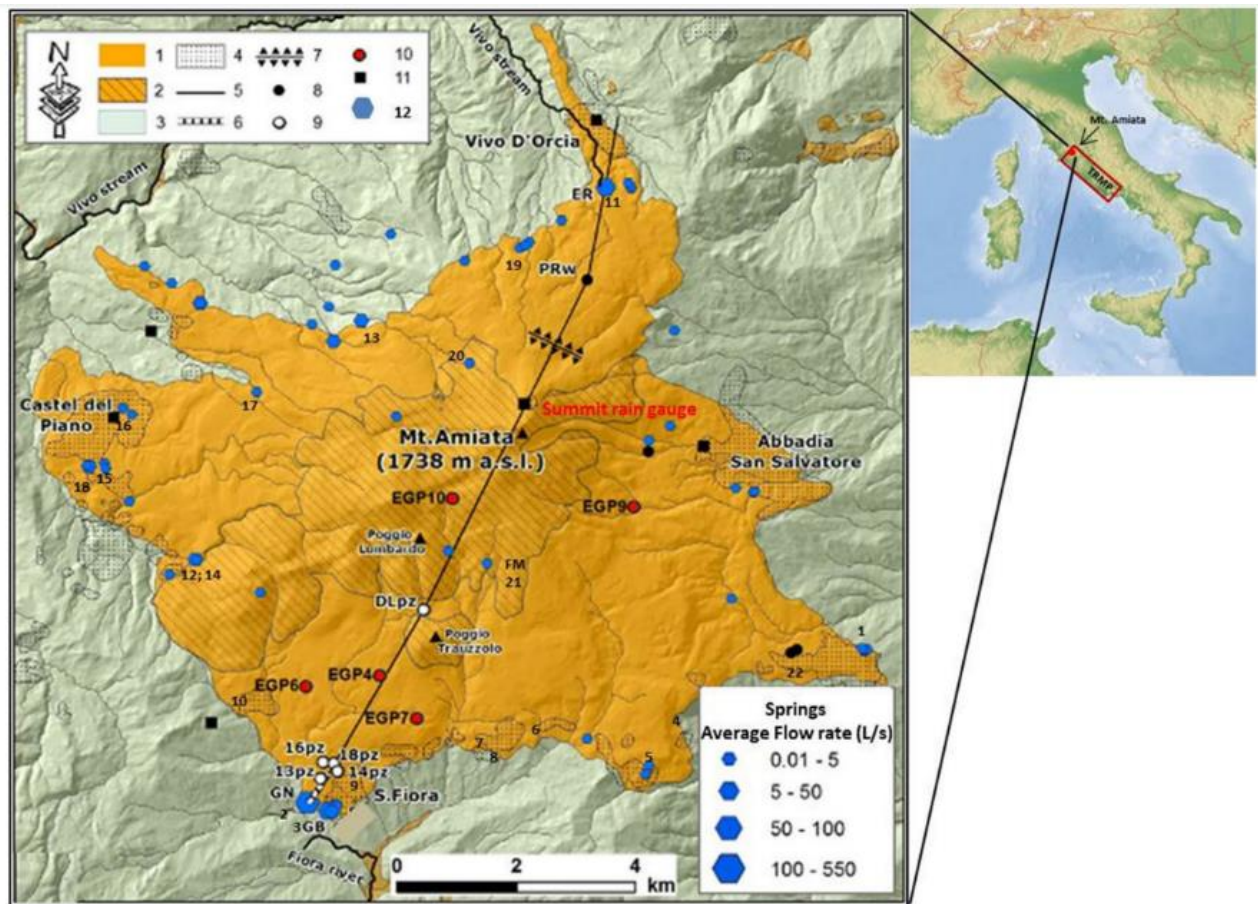


Figure 8 (A) - Hydrogeological sketch of Mt. Amiata (from Magi et al., 2019). Legend: (1): rocks with medium-high permeability; (2): rocks with medium permeability; (3): rocks with low to very low permeability; (4): BTC, volcanic complex; (5): DLC, volcanic complex; (6): watershed; (7): groundwater divide between Galleria Nuova (GN) and Ermicciolo spring (ER) systems; (8): drinking water pumping well; (9): piezometers; (10): EGP piezometers; (11): weather stations; (12): springs used for an isotopically based comparison (see text).

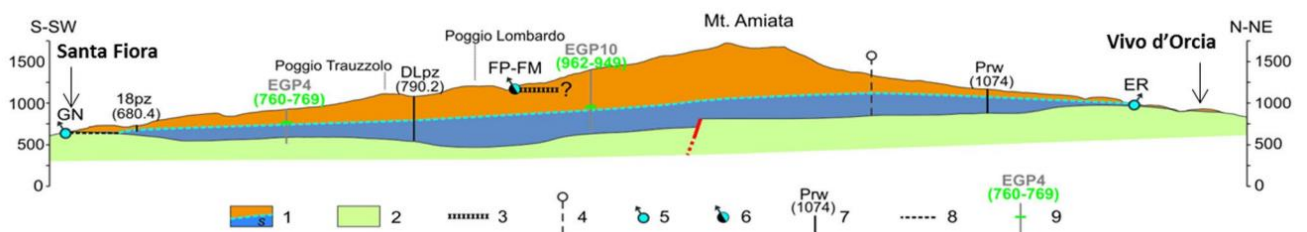


Figure 8 (B) - Hydrogeological cross section of the Mt. Amiata aquifer reconstructed by subsurface data. Legend: (1) saturated thickness of the volcanic aquifer; (2) sedimentary impervious substratum (Ligurian Units I.s.); (3) aquitard level; (4) hydrogeological watershed; (5) main springs (GN: Galleria Nuova and ER: Ermicciolo; Fig. 1); (6) springs emerging from a locally perched aquifer; (7) wells and/or piezometer monitored by SIR-Tuscany Region (between

brackets the levels referred to a survey carried out in 2011 are also reported); (8) drainage tunnel (GN); (9) piezometers installed by Enel Green Power Ltd. (between brackets the level range of the phreatic aquifer since the date of installation are reported). From Magi et al., 2019.

The Monte Amiata volcanics host one of the most important groundwater body of Tuscany. The aquifer is mainly unconfined (Doveri et al., 2012) and its impervious substratum is principally made up of shale belonging to the Ligurian Units. Groundwater is drained by several springs (more than 150 according to Barazzuoli et al., 1995) that are distributed all around the volcanic edifice, generally close to the contact between volcanic rocks and substratum. Two major groups of springs (**Figures 8A, 8B**) are located in the southern (close to Santa Fiora) and northern (close to Vivo d'Orcia) parts of the volcanic complex. The first group is represented by Galleria Nuova, Galleria Bassa, Carolina and Peschiera springs, and it has an average flow rate higher than 700 L/s (**Figure 9** - from Doveri et al., 2012). The second group is essentially represented by the spring named Ermicciolo, which has an average flow rate of about 100 L/s (**Figure 9**). Most springs are tapped for supplying drinking water over a wide and densely populated area that encompasses the Siena and Grosseto districts and part of the Arezzo and Viterbo districts. The shaly substratum plays also the role of cap-rock respect to a regional evaporitic-carbonate reservoir, which at places hosts thermal waters. Downward, the hydrogeological succession ends with a Palaeozoic basement, which is mainly impermeable, excluding fractured zones that are exploited by deep geothermal wells (deeper geothermal fields, at Bagnore and Piancastagnaio).

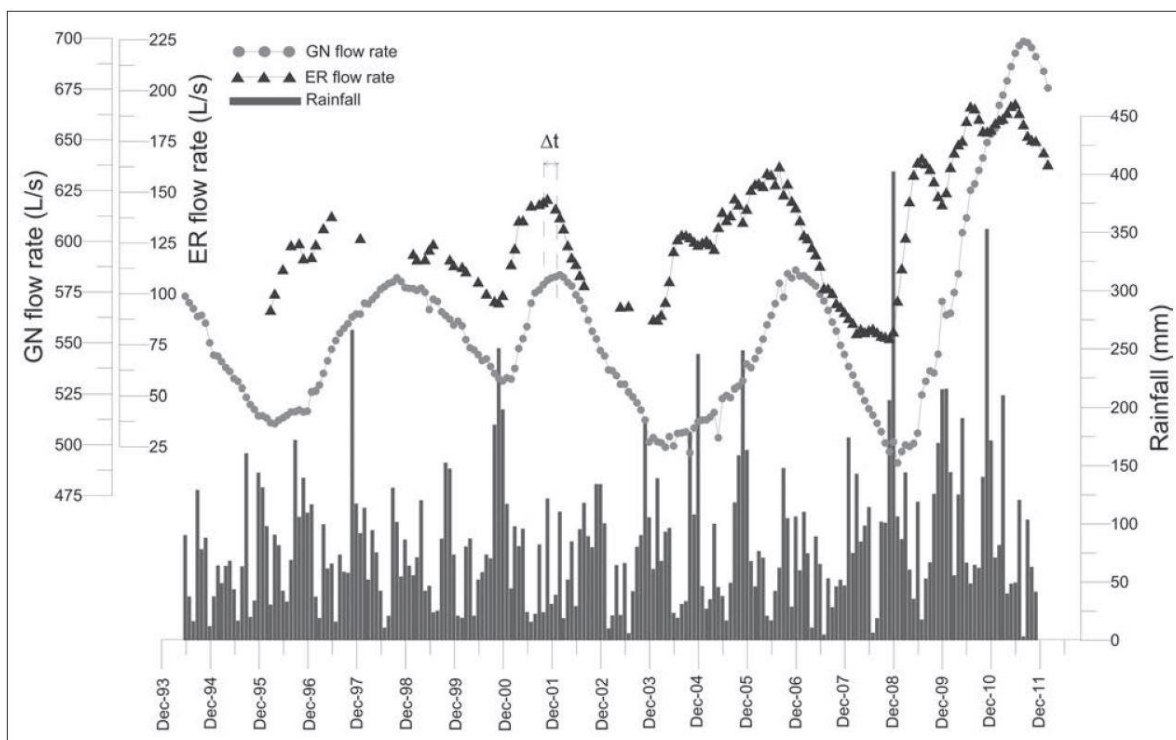


Figure 9 - Monthly flow rates of GN and ER springs compared with the monthly average rainfall of the Mt. Amiata area. “ Δt ” is the recurrent temporal shift between maximums or minimums of GN spring with respect to that of ER.

Geothermal reservoir around Mt. Amiata

3D integrated modelling allows the reconstruction of the shallow geothermal reservoir geometries (**Figure 10** - from Fulignati et al., 2014). **Figure 10A** evidences the irregular shape of the top surface of Ligurian cover units and highlights the sharp deepening of this surface that occurs in

correspondence of the western master fault of the Radicofani basin. In **Figure 10B** the top surface of carbonate fractured shallow reservoir is shown. This has a complex geometry due to the tectonic framework of the area, particularly characterized by an important uplift caused by the emplacement (between 130 and 300 ka) of the low-density intrusion that constituted the Mount Amiata volcano feeding system.

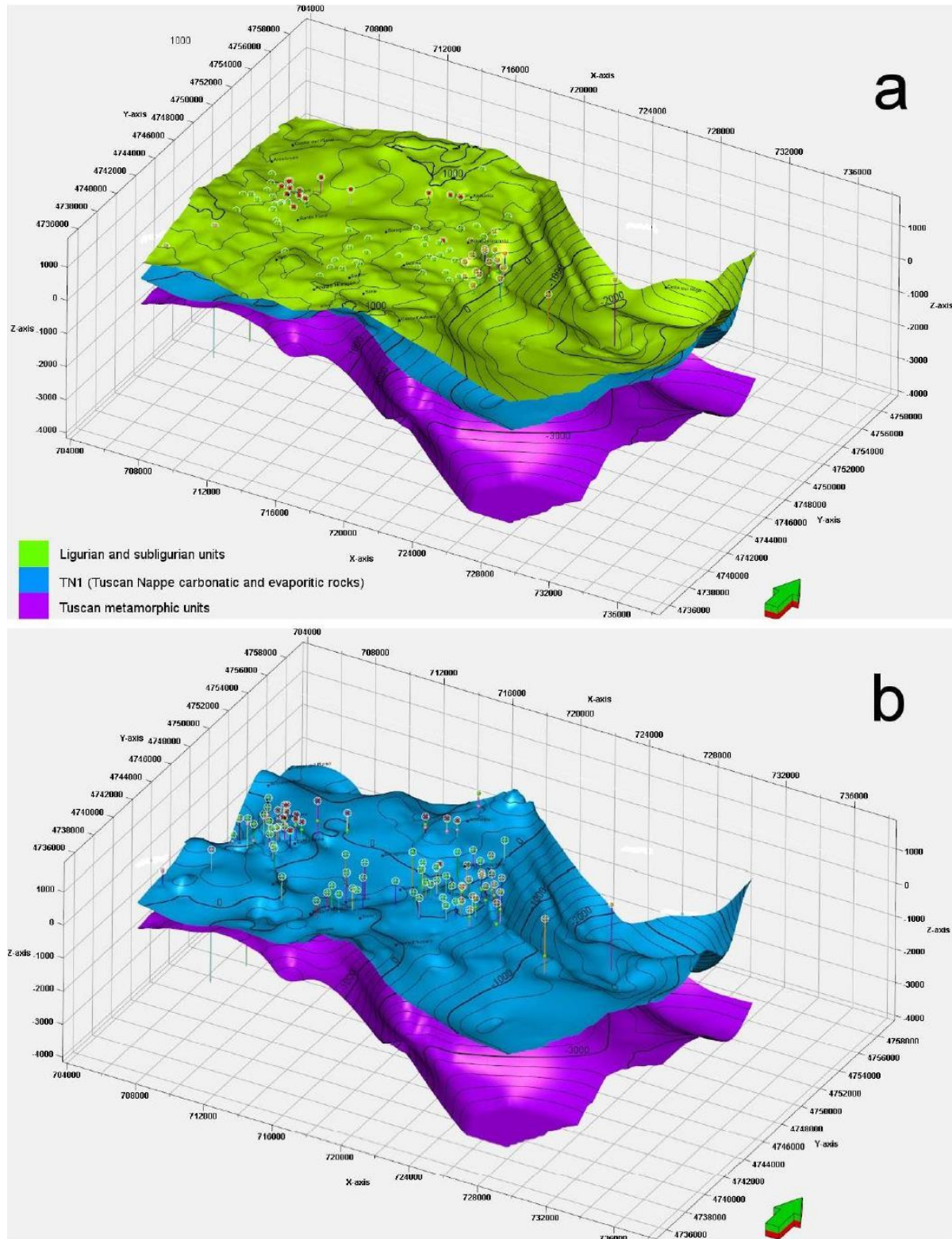


Figure 10 - 3D subsurface horizons of the Mt. Amiata area. (a) Green = top of cover formations (Ligurian units); (b) Blue = top of shallow geothermal reservoir.

In the northern side of Mt. Amiata, the reservoir outcrops in Bagni S. Filippo area (**Figure 11** - circled in red), this represents one of the recharge zones of the geothermal fields. The carbonate units deepen abruptly (more than 30° dip westward) reaching about 1000 m of deepening westward. Shallow reservoir outcrops also in Selvena-Castell'Azzara hills and deep northward toward the volcano edifice (Fulignati et al., 2014). This represents another probable recharge area of the geothermal systems. The top surface of the reservoir shows structural highs in correspondence with the Piancastagnaio, Bagnore and Poggio Nibbio geothermal fields and Bagni S. Filippo and Bagno Vignoni low-temperature hydrothermal system, where thermal and gas pools are widespread.

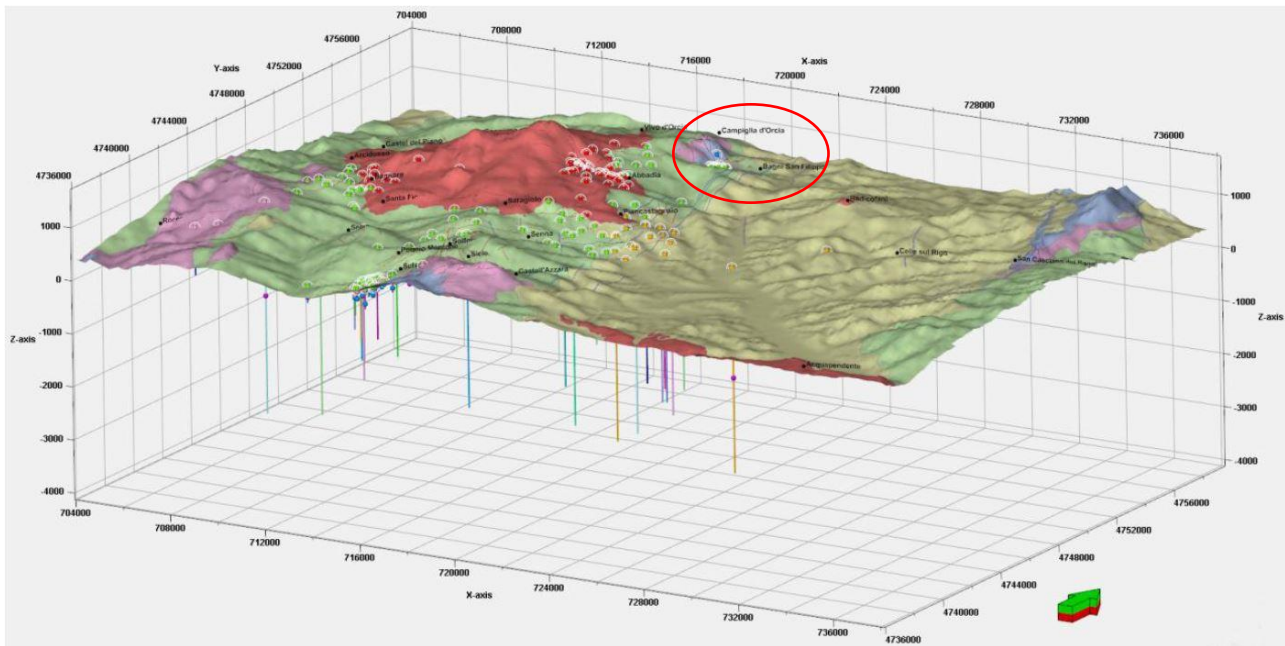


Figure 11 - 3D Map of the Mt. Amiata area with the representation of terrain surface level.

Another important area where the shallow geothermal reservoir (made by Tuscan nappe carbonatic and evaporitic rocks) outcrops is the famous Bagno Vignoni area. Recently, geological studies, carried out to assist the realisation of the new geological map of Tuscany (1:10.000 scale), highlight that the collisional structures, consisting of imbricate thrusts and related minor structures within the Tuscan Nappe, crop out in the Bagno Vignoni area, located on the northern side of the Mt. Amiata geothermal area, along the Orcia river (further north of Bagni San Filippo).

The geological evidence attests to, for the Bagno Vignoni area, a similar Tuscan Nappe tectonic setting as inferred for the other areas around Mt. Amiata (Brogi et al., 2005). The contacts between the different tectonic units correspond to low-angle extensional detachments, or low-angle normal faults. These tectonic contacts were later displaced by high-angle normal faults, mainly NNW-SSE oriented, which, in the Bagno Vignoni area, caused upwelling of hydrothermal fluids and related thermal springs and travertine deposition (Brogi et al., 2005). The Tuscan Nappe is typified by repetitions of its stratigraphic succession, corresponding to overthrust Tuscan Nappe subunits. These have been detected in the “il Poggione” hill and on the northern side of Bagno Vignoni village (**Figure 12A, 12B** - from Brogi et al., 2005).

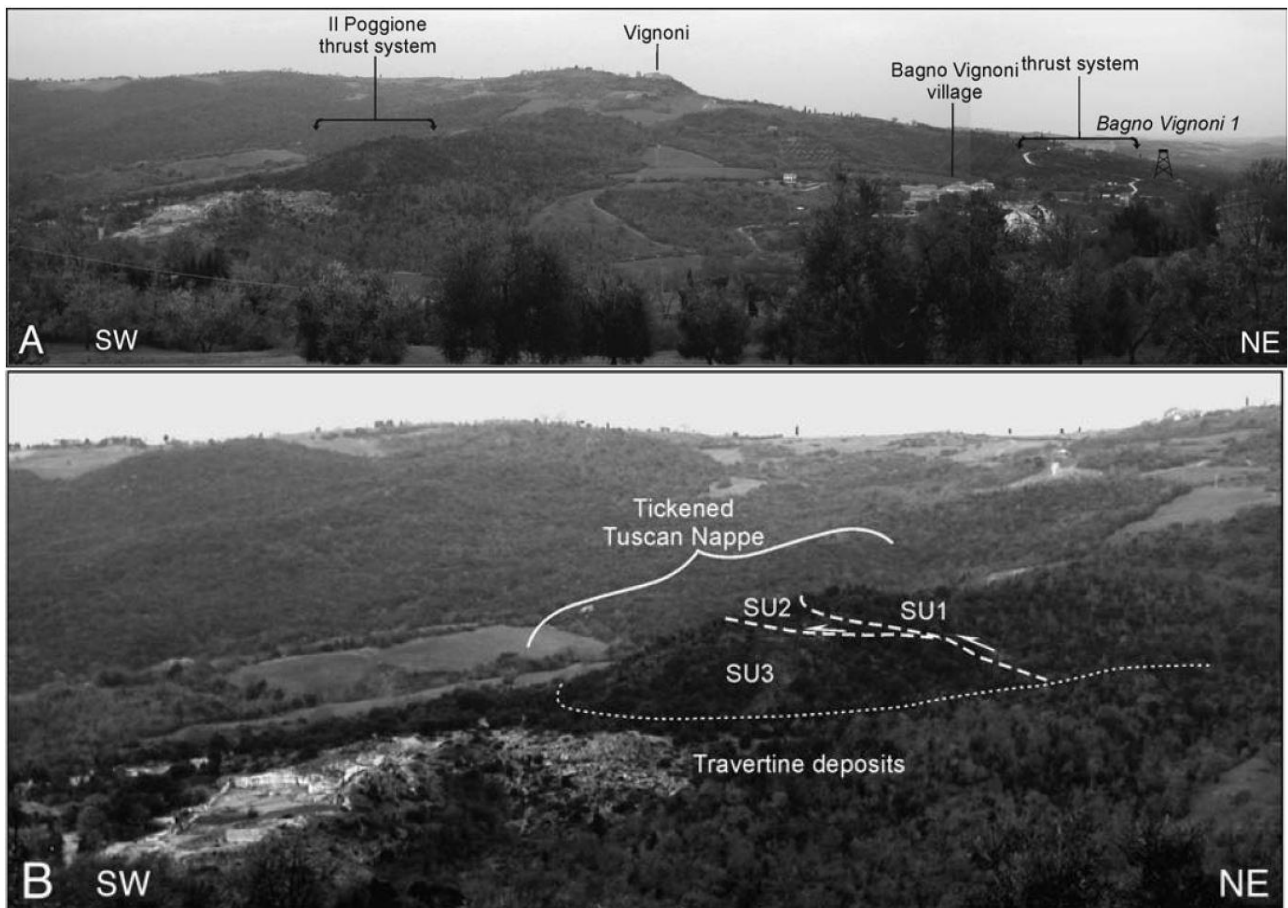


Figure 12 - Panoramic view of the Bagno Vignoni area (A) and detail of the «il Poggione» thrust system (B). SU1, SU2 and SU3 indicate the Tuscan Nappe tectonic subunits.

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