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Geological Evaluation of the Base of the Mt. Amiata Volcanic Complex (Tuscany, Italy)

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ABSTRACT

The Monte Amiata volcano consists of acidic and intermediate products such as dacitic, rhyodacitic and olivine-latitic rocks containing mafic enclaves. This volcanic complex derived from the emplacement at a depth of about 6-7km of a broad anatectic magmatic intrusion, considered at the origin of the current geothermal anomaly of the two fields under the exploitation of Bagnore and Piancastagnaio. These volcanic rocks host an important phreatic aquifer in southern Tuscany. At its base this aquifer is confined by very low permeable rocks consisting of shales, sandstones and Ophiolite relics (Ligurian Units) which have recorded the whole tectonic history of the Northern Apennines orogenesis. Such rocks separate this aquifer from the geothermal reservoir hosted within permeable horizons at deeper levels. One of the most important items presently under discussion is the shape and origin of the base of the volcanic complex, i.e. the bottom of the volcanic aquifer. Borehole data, drilled for geothermal, water and mining purposes, have been integrated with geophysical interpretation of VES (Vertical Electrical Sounding) and EM soundings (Electro-magnetic) in order to reconstruct the geometry of the geological surface separating volcanites from underlying pre-volcanic rocks. The obtained surface has been compared with the DEM (Digital Elevation Model) of the surrounding area, by means of GIS (Geographic Information System) techniques, and with the geological setting of the volcanic substratum, revealing an abundance of information on the likely landform characterising the Monte Amiata geothermal region prior to the volcanic eruption. It has been highlighted that the morphology of the pre-volcanic substratum, hidden below the volcanic complex, fits well with the present landform in the surroundings of the volcano and the results are strongly influenced by the structural heritage deriving from the Neogene-Quaternary tectonic evolution of the Northern Apennines. As a whole, a good correlation has been observed between the morphological high locations and the laterally segmented geological bodies located at depth within the substratum as they have been hypothesized in literature. These geological bodies are related to the activity of Middle-Late Miocene low-angle normal faults which affected the Mt. Amiata region, as well as the whole inner Northern Apennines, after the building of the orogenic edifice. In conclusion, the geometry of the base of the Mt. Amiata volcanic complex seems to preserve a paleomorphology derived from the erosion of the prevolcanic uplifted substratum, thinned by extensional structures since Middle-Late Miocene.

1. INTRODUCTION

Over the past several years, the Mt. Amiata volcano-geothermal area has drawn the attention of the Italian scientific community for an environmental impact assessment concerning any interactions between the geothermal exploitation and the fresh water resources hosted in the volcanic rocks. In this view, an update of the geometry of the volcanic rock substratum and its interpretation was attempted.

Mt. Amiata is a Quaternary volcano located in Central Italy (Figure 1).

This area has been the subject of particular naturalistic interest since ancient times (Figure 2), and has become famous lately for the mining of mercury mineralizations (Arisi Rota et al. 1971) and for its geothermal resource (Cataldi, 1967). The latter has been industrially utilized for electricity production, at present almost 60MWe, for more than half a century in the Bagnore and Piancastagnaio geothermal fields, sited on the southern slope of the volcano.

The volcano rises to a maximum elevation of 1738 m in a gently hilly environment of 7-800m a.s.l. (Figure 3).

The volcanic rocks display good permeability, directly overlie a low permeable flyschioid substratum and host a wide aquifer utilized to supply water to the main cities of Southern Tuscany.

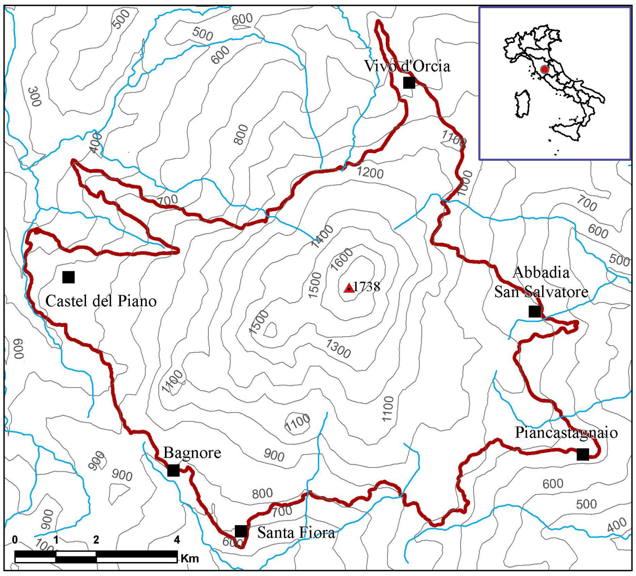

Figure 1: Geographic setting; the red line includes the volcanic complex.

Figure 2: Late 17th century painting of F. Nasini showing a Monte Amiata allegory.

Figure 3: Monte Amiata view (from South to North).

In the past the shape of the substratum was inferred on the basis of geologic/naturalistic observations only. (Marinelli, 1919). Mining activities together with geophysical surveys allowed a first scientific elaboration of this surface (Calamai et al. 1970). The recent acquisition of new geophysical data (Marrocchesi, 2003; IGG, 2006) together with new geological insights, have prompted for its updating.

2. GEOLOGICAL AND STRUCTURAL SETTING

The knowledge of the geological setting of the Monte Amiata volcano-geothermal area mainly derives from mining and geothermal exploitation (Arisi Rota et al., 1971; Elter & Pandeli, 1991; Batini et al., 2003), from the interpretation of geophysical data (Calamai et al., 1970; Gianelli et la., 1988; Orlando et al., 1994; Cameli, 1994; Brogi, 2004a, 2006) and from fieldwork data (Calamai et al., 1970; Decandia et al., 1993; Liotta and Salvatorini, 1994; Liotta, 1996; Brogi, 2004a, 2004b).

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

- The Volcanic complex (V), spreading out on ~ 80 km^2 with an estimated volume of $19km^3$, consisting of dacitic, rhyodacitic and olivine-latitic rocks, mostly ignimbrites, containing mafic enclaves, erupted in a period ranging from 300–190ka (Ferrari et al. 1996 and references therein). Petrographic and geochemical features, and the occurrence of mafic enclaves indicate mixing processes between anatectic and subcrustal magmas (Ferrari et al., 1996; Peccerillo et al., 2001 and references therein);

- Neogene and Quaternary deposits (M-P-Q). They consist of Middle Miocene–Quaternary continental and marine sediments filling the tectonic depressions (Calamai et al., 1970; Bossio et al., 1993; Liotta and Salvatorini, 1994; Liotta, 1994, 1996; Acocella et al., 2002; Bonini and Sani, 2002).

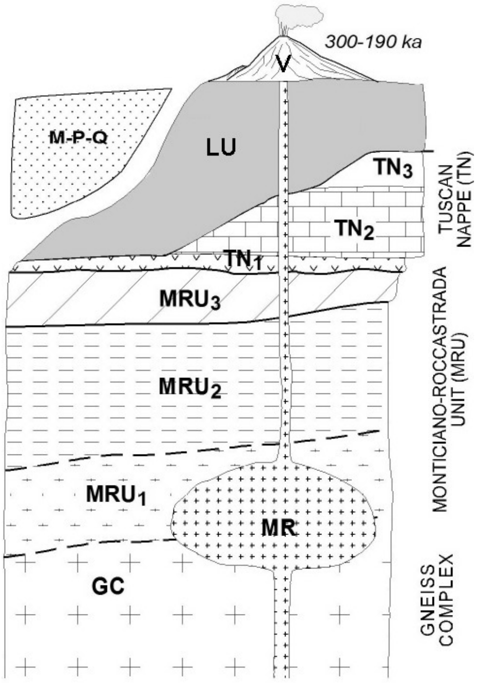

Figure 4: Tectono-stratigraphic units in the Monte Amiata area (from Batini et al. 2003, modified).

- 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.

- The Tuscan Nappe (TN). It is related to part of the Late Triassic–Early Miocene sedimentary cover of the Adria continental paleomargin. 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 paleogeographical domains during the Late Oligocene–Early Miocene contraction.

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

- Magmatic rocks (MR) are assumed to be located around 6km depth on the basis of geophysical interpretation (Bernabini et al., 1995).

The shallow aquifer is sited in the volcanic complex (V) while the geothermal reservoir is located in the calcareousevaporitic-metamorphic units (from TN2 to MRU2,). The two aquifers are separated by a low permeability barrier (LU, M-P-Q, TN3).

The substratum of the Monte Amiata volcano was affected by polyphased tectonics during the orogenic and post-orogenic evolution of the Northern Apennines (Brogi, 2008 and references therein). The deformational events and related structures taking place during the Cretaceous-Oligocene evolution gave rise to a tectonic pile and contractional structures such as thrusts, reverse faults, east-verging folds (Calamai et al., 1970; Bettelli, 1985; Pandeli et al., 1988; Brogi and Lazzarotto, 2002; Pandeli et al., 2005; Brogi, 2006a). Nonetheless, extensional and transcurrent structures have dominated the tectonic framework of the study area since the Middle Miocene (Brogi, 2008; Brogi and Fabbrini, 2009). Particularly, the deformation developed since the Middle Miocene drove the geological setting of the Monte Amiata area. Low-angle normal faults showing staircase geometry produced the Tuscan Nappe lateral segmentation, giving rise to areas where the uppermost Ligurian Unit directly overlies the Late Triassic evaporites (Brogi, 2004).

As a whole, there are three Tuscan Nappe sequences that are discontinuous geological bodies (extensional horses in Figure 5) that have been reconstructed in the subsurface of the Mt. Amiata area mainly integrating fieldwork data, well logs, seismic line interpretation (Figure 6). They are composed of the Triassic-Early Miocene stratigraphic sequence, or of part of this. The geological bodies show elliptical shapes and NNE-SSW orientation (Brogi, 2004b, c, d).

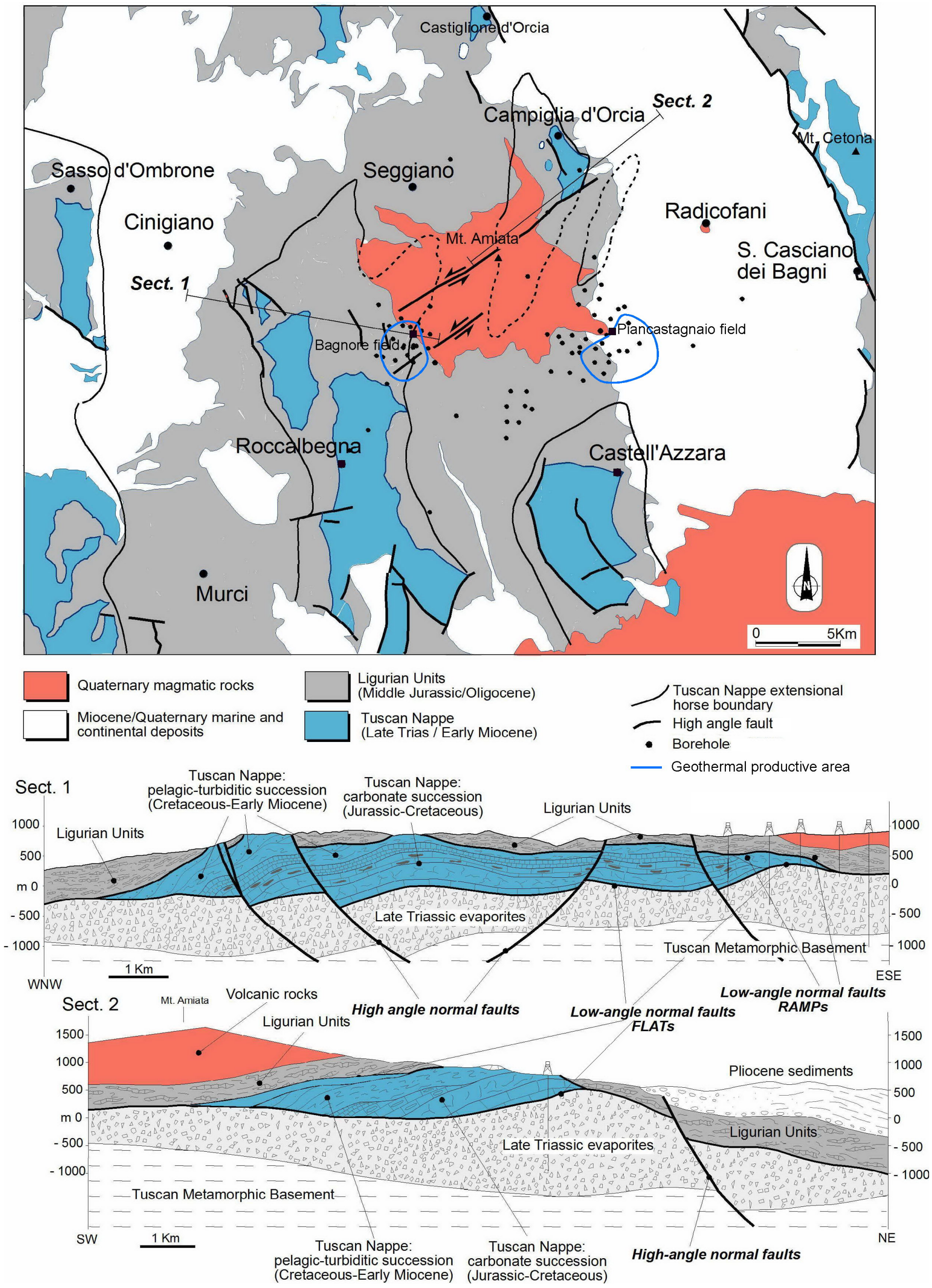

Figure 5: Tuscan Nappe geometry and geological sections across two main Tuscan Nappe geological bodies (from Brogi, 2008, modified).

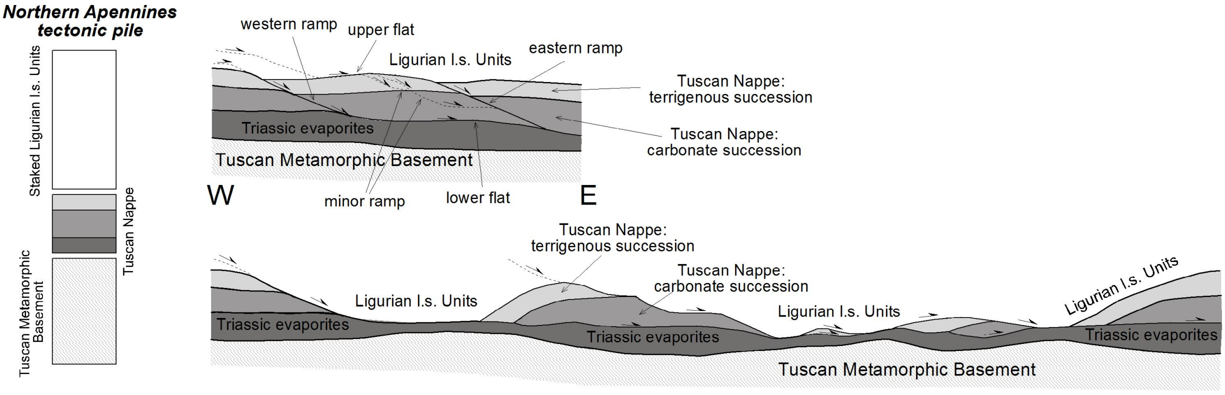

Figure 6: Schematic evolution of the lateral segmentation of the Tuscan Nappe related to development of low-angle normal faults (From Brogi, 2004d).

All the Tuscan Nappe geological bodies are delimited by two detachments, the uppermost of which is located at the base of or within the Ligurian Units, whereas the lowermost one occurs within the Triassic evaporites of the Tuscan Nappe. Subsidiary, detachments occur within the Cretaceous-Oligocene marly-clayey horizon ("Scaglia Toscana" Fm., TN_3 in Figure 4) or at the base of it. As a whole, flats are connected to ramp segments mainly located in the Mesozoic carbonates or, secondarily, in the Oligocene-Early Miocene turbiditic sequence. In section the Tuscan Nappe bodies show asymmetrical profiles, characterised by steeply dipping western and gently dipping eastern margins (Brogi, 2004 b, c, d).

These structures were dissected by high-angle faults mainly consisting of SW-NE striking sub-vertical faults, characterised by strike- and oblique-slip kinematics with a predominantly left-lateral movement (Brogi and Fabbrini, 2009). Two main shear zones of cartographic relevance affecting also the volcanites have been recognized in the area (Figure 5); they are referred to the Pleistocene. The northern strike-slip fault can be associated to the fissural eruption originating the volcano (Ferrari et al. 1996). The southern one affected the volcanites slightly north of the Santa Fiora springs.

The volcanic products show an asymmetrical distribution with respect to the feeding fissure: wider in the south-eastern area with respect to the north-western one (Figure 5). This feature can be put in relation to the existing morphology before the eruption that was most depressed southward.

3. HYDROGEOLOGICAL SETTING

The Volcanic Complex (V) is characterized by a high secondary permeability (1-10 Darcy estimated from hydraulic considerations), while the Neogenic and Quaternary deposits (M-P-Q), the Ligurian Units and the argillitic/terrigenous parts of the Tuscan Nappe (TN3) are characterized by low permeability. This permeability distribution is directly reflected by the hydrographic net; in the Volcanic Complex the drainage density is much lower than the surroundings.

The presence of a low permeability substratum beneath permeable rocks has allowed for the infiltration water to be stored within the volcanic rocks forming an important phreatic aquifer. This aquifer feeds more than 150 springs with an estimated total flow of about 2000 l/s (Figure 7) and it is tapped to supply water to the main Southern Tuscany municipalities.

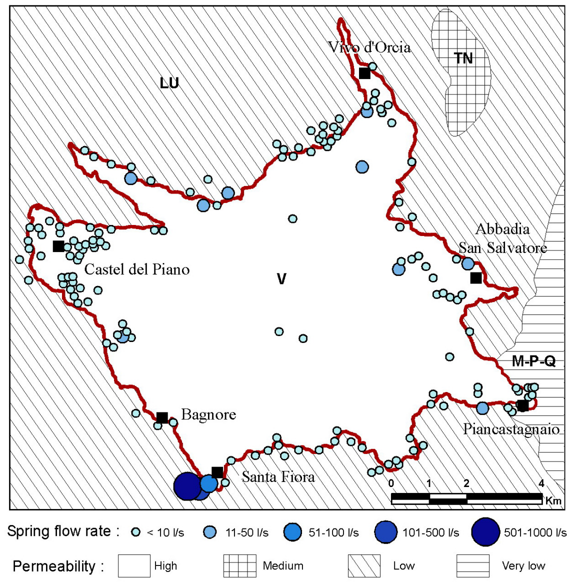

Figure 7: Hydrogeologic schematic map.

Almost all the springs are radially located on the edge of the volcanic rocks where the Ligurian Units outcrop (Figure 7). This contact follows an irregular trend with elevations variable between 370m, north-westward, and 1150m a.s.l., northward. Most of the springs have a flow rate lower than 50 l/s except a southward group of springs, at an elevation of 650m a.s.l., characterized by a total flow of about 850 l/s. These springs are commonly known as "Sorgenti del Fiora".

4. THE BASE OF THE VOLCANIC COMPLEX

The more reliable data, utilized to outline the base of the Volcanic Complex, are the drilling stratigraphic columns which traverse the entire thickness of the volcanic rocks. These data derive from nine geothermal wells, one water borehole (Consorzio per l'acquedotto del Vivo, 1974), 42 mining pits (DBGM), and about ten piezometers (Celico et al., 1988, Ramella & Baldini, 1966). The afore mentioned information covers very small and localized areas when compared to the entire volcanic complex surface (Figure 8). Therefore, data have been integrated with the results of geophysical surveys.

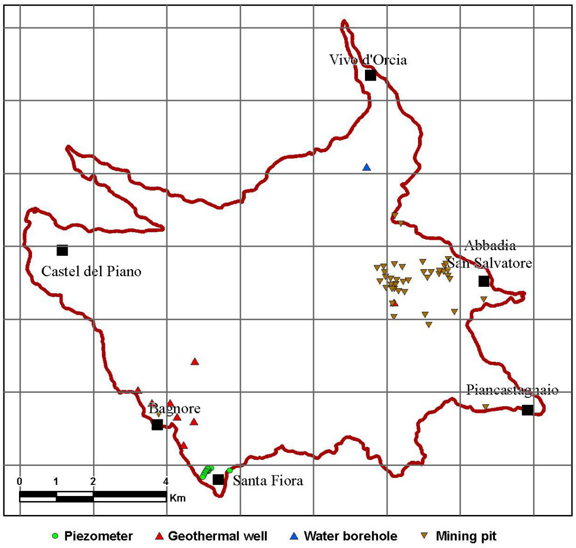

Figure 8: Drilling location inside Volcanic Complex outcropping.

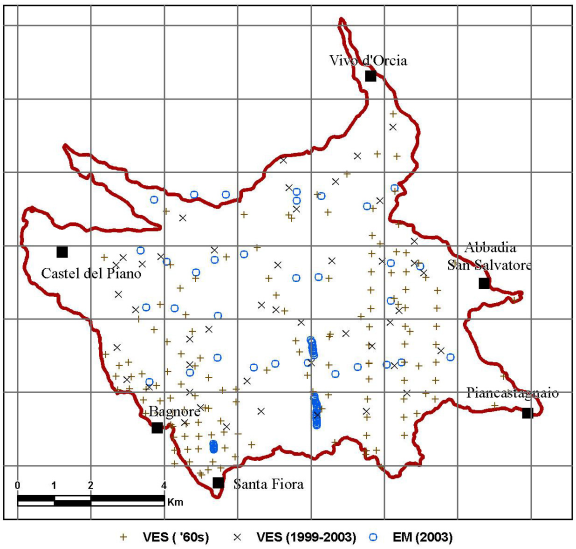

Figure 9: Geophysical sounding location.

A total of 199 Vertical Electric Soundings (VES Schlumberger) were available, 153 of them belonging to a survey performed in the ’60s by Enel for geothermal purposes and 46 surveyed between 1999 and 2003 by the Grosseto provincial administration for studies related to the M. Amiata shallow aquifer vulnerability (Marrocchesi, 2003). Additional data coming from the interpretation of 64 Electro-Magnetic soundings (EM), performed for hydrogeologic purposes on behalf of the Tuscany regional administration (IGG, 2006), were utilized. In Figure 9 the location of the utilized soundings is shown.

The availability in the same area of a large amount of geo-scientific information such as stratigraphic columns, geophysical soundings (VES and MT) and chemical-physical aquifer parameters (TDS, porosity, etc.), allows a good electrical characterization of the two main geological units, also in accordance with Archie's law. The volcanic complex (V) displays high resistivity values (500-2000ohm.m), while the argillitic substratum shows a sharp resistivity drop (5-30ohm.m). To this end it is worthwhile underlining that the electrical conductivity of a rock is basically driven by its water content, that is not necessarily related to its permeability. Thus the volcanic aquifer, although permeable, results electrically resistive because of its rather low porosity and low TDS. For the same reason argillitic impermeable formations result conductive, since they are characterized by high micro-porosity soaked by stationary water.

This clear resistivity differentiation strongly contributes to the reliability of the volcanic substratum detection by means of VES. These latter were processed with a specific software (WinGLink®) to obtain, through automatic 1D inversion, the best fitting between surveyed data and computed ones (Figure 10).

As in southern Tuscany the resistivity of geological formations is well known (Albo et al., 1974), when automatic inversion did not yield a definite model, it was possible to constrain some resistivity values, especially those of the conductive substratum.

No new processing was performed for EM, but the original interpretation made by the surveyor (IGG, 2006), was directly utilized.

All the available information was then interpolated on a regular grid considering the elevation of the edge of the volcanic rocks as well. In this manner the *boundary effect* of the automatic contouring was considerably reduced. The base of the Volcanic Complex was then superimposed on a DEM image of the area by means of GIS (Geographic Information System) techniques, for evaluations on morphological relationships (Figure 11). The intersection between these surfaces allowed a precise computation of the Volcanic Complex volume which was 19.2km^3.

5. GEOMORPHOLOGIC CONSIDERATIONS

The Volcanic Complex base contour (Figure 11) shows an uneven morphology. The most elevated areas (900-1000m) are north-east sited, while the more depressed ones (600m) are south-west located. From a morphological point of view these areas depict ridges and valleys largely consistent with the surrounding drainage net. In detail a northward extension of the Fiora river valley is speculated, completing its headwater area (dashed line in figure 11). Therefore, the Volcanic Complex base can be roughly considered as a paleomorphology preserved, during the last 200-300ka, under the volcanic products. For an accurate comparison between this surface and the morphology outside the volcanic rocks, it should be taken into account that the latter, has undergone a continuous erosional processes up to now. This occurrence combined with different erosion velocities of the volcanic rocks with respect to the flyschioid ones, has locally induced topographic inversion phenomenon. A clear example is given by the Vivo d’Orcia area where the volcanic deposits that filled a paleo-valley, nowadays form a watershed between two small valleys (Mazzuoli e Pratesi, 1963, Ferrari et al., 1996, Marinelli, 1919).

The Miocenic Tuscan Nappe segmentation (Brogi, 2004) affects the main morphological trends. In fact, the geological bodies made by piles of rocks of the more or less complete Tuscan Nappe “horses”, are tougher than the laminated parts. The first areas generally form the ridges while the latter correspond to valleys.

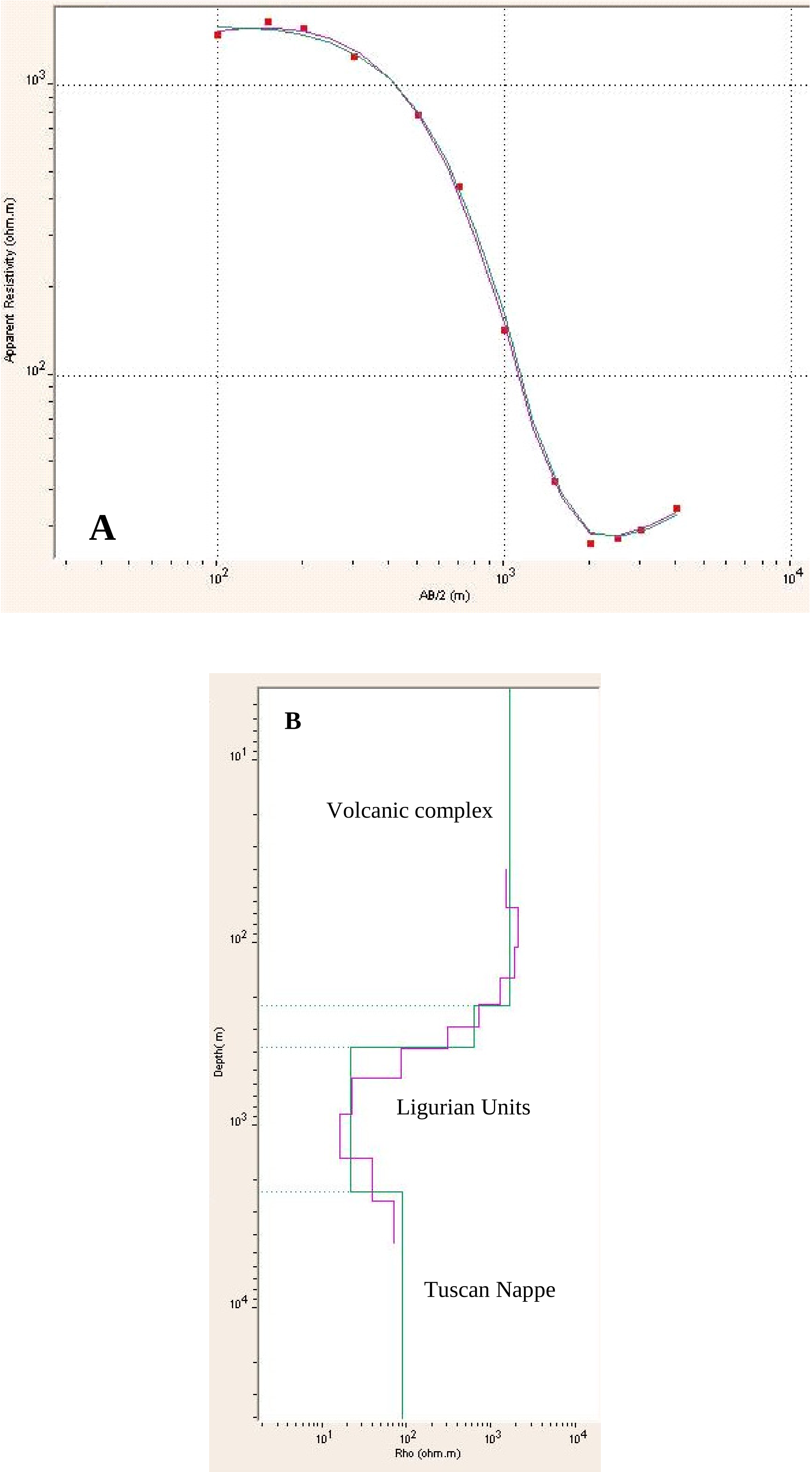

Figure 10: VES modelling display: A) measured data (red dots) and computed ones (curves), B) detailed automatic model (violet colour) and 1D model (green colour).

The gentle counterslope of the base of the vulcanites (40-50 m) north of the Fiora springs (Figure 12, sect. BB') as pointed out by detailed investigations for the spring catchments (Ramella & Baldini, 1966) can be ascribed to the afore mentioned regional strike-slip Plio-Quaternary tectonic which interests also the Volcanic Complex (Brogi and Fabbrini, 2009).

It is worth noting that considering both the relatively small volcanites volume (19km^3) and the depth of the magmatic chamber estimated by gravimetric modelling, at 6-7km (Bernabini et al., 1995 e Orlando et al. 1994), it is very unlikely that large volcano-tectonic events could have taken place.

This hidden morphology determine the underground water flow primarily southwards where about 50% of the total spring outflow is concentrated (Fiora springs). This particular point is sited in the lower elevation of vulcanites in the southern hillside, in correspondence of the Santa Fiora river paleovalley floor.

A precise Volcanic Complex base mapping (Figures 11, 12) is also useful for the estimation of the hydraulic resources, particularly as it concerns the permanent reserves (Rappuoli, 1992).

6. CONCLUSION

The Volcanic Complex base reconstruction shows a good correlation with the morphology external to the area covered by volcanics. It also accounts for a principal southwards subterranean flow in correspondence of Santa Fiora springs and in line with its homonymous valley.

The proposed interpretation of this surface reveals a possible pre-volcanic paleomorphology whose main lineaments derive from the Miocene regional Tuscan Nappe tectonics. On the contrary no important recent (<300ka) volcano-tectonic feature has been revealed by this study such as those mentioned by some authors to justify a supposed interference between shallow aquifer and geothermal reservoir (Delcroix, et al. 2006).

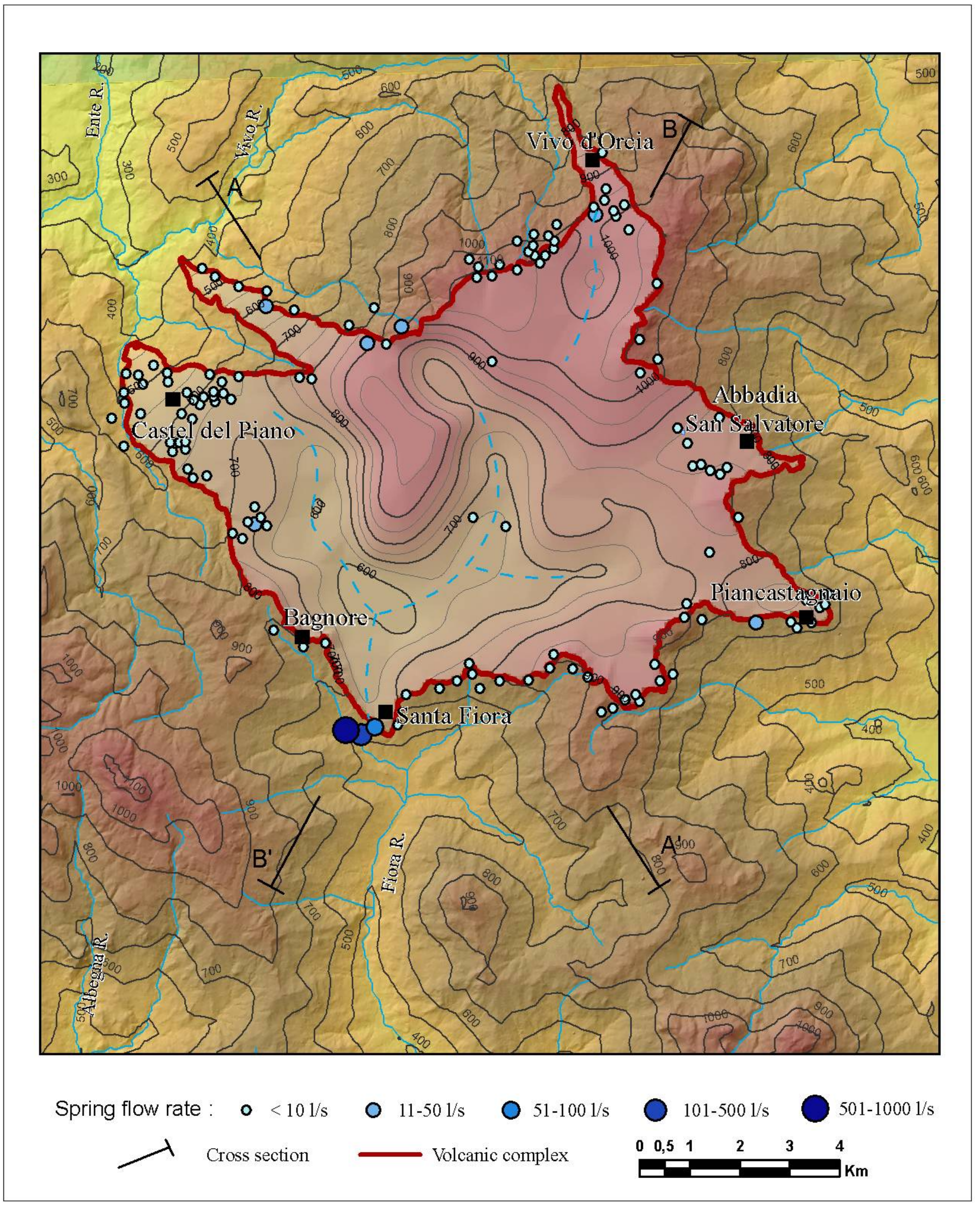

Figure 11: Base of the Vulcanic Complex superimposed on a DEM image.

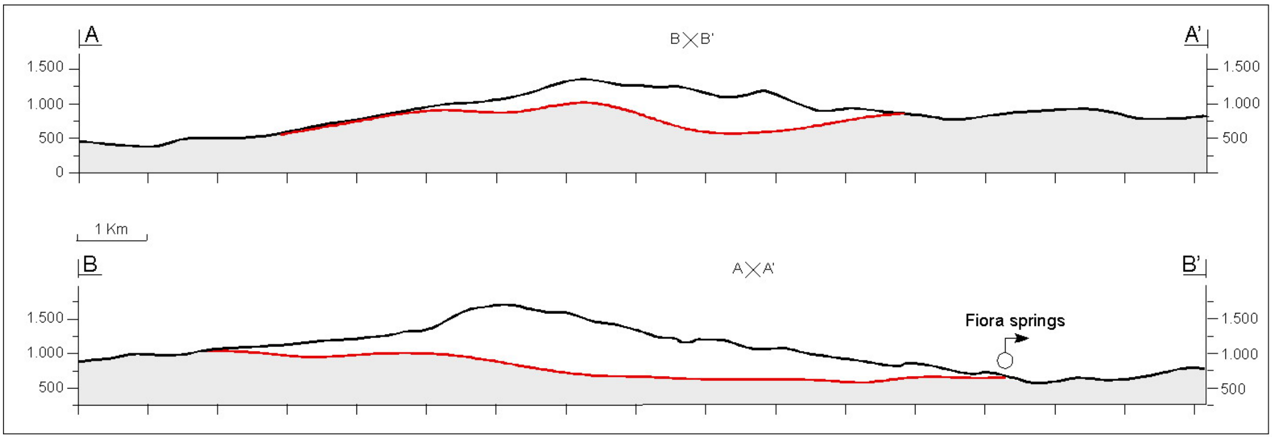

Figure 12: Morphological cross sections.

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