SEISMICITY AND VELOCITY IMAGES OF THE ROMAN MAGMATIC PROVINCE

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ABSTRACT

Seismic tomography provides velocity images of the crust beneath Quaternary volcanoes and geothermal areas with a detail of 1-4 km. We describe the three-dimensional P-wave velocity structure of the upper crust beneath the adjacent Amiata and Vulsini Geothermal Regions, and beneath the Alban Hills Volcano (Central Italy), obtained by inverting local earthquake arrival times. In the three study areas, we find high-velocity anomalies in the upper 3-5 km of the crust revealing the presence of uplifted limestone units (metamorphosed at depth). The 3-D geometry of the limestone units (the main geothermal reservoir in the region) is clearly defined by the three-dimensional velocity pattern. Negative anomalies at 1 and 3 km depth identify Plio-Quaternary depressed structures, filled with low velocity clayey sediments. Earthquake hypocenters are confined in the high velocity carbonate units, in the upper 6-7 km of the crust. Abscence of seismicity beneath 6-7 km suggests ductile behavior of rocks and the presence of higher temperatures (> 400°C), probably generated by deep sub-volcanic bodies. We observe that the seismicity occurs within the uplifted limestone units (or in the metamorphic basement beneath Mt.Amiata). We also hypothesize that overpressured fluids within the seismogenic layer favors the earthquake generation.

Key words: seismicity, tomography, Roman Comagmatic Province

1. INTRODUCTION

The extensive development of local earthquake tomography and the presence of modem microseismic networks makes it possible to construct detailed images of the upper crustal structure beneath young volcanoes and geothermal areas (Eberhart-Phillips, 1986; Foulger and Amott, 1993; Chiarabba *et al*, 1994). The recovered velocity anomalies help to delineate the presence and geometry of intrusions, magma chambers, fluids enriched rocks (Evans and Zucca, 1993). In particular, numerous ray paths traverse the upper part of the crust (generally 5-7 km beneath volcanoes), illuminating objects as small as 1-4 km. In this paper, we present velocity tomograms of the Roman Comagmatic Province obtained from local events. The availability of several seismic refraction profiles and geologic information from several deep wells drilled in the region for geothermal research allow us to strongly constrain both the three-dimensional inversion and the interpretation of the obtained velocity model. Thus, we are able to define the geometry and extension of the limestone basement (the main geothermal reservoir of the region) in the first km of the crust. Deeper velocity anomalies represent the evidence of sub-volcanic or metamorphic rocks. The joint analysis of velocity tomograms and earthquake distribution led us to propose a schematic model for earthquake generation and on the rheologic behavior of rocks at depth. Our idea is that overpressured fluids are strongly linked with the seismogenic cycle, favouring the brittle behavior of rocks, up to 6-7 km depth. Below these depths the abrupt cut-off of seismicity suggests a ductile behavior of rocks probably due to high temperatures.

2. METHOD

Arrival times of body waves at a seismic network contain information about the velocity structure sampled by the seismic ray paths. Local earthquake tomography yields the three-dimensional velocity structure (defined as a discrete series of parameters) by inverting P- and S-wave arrival times at a dense local array (Thurber, 1983). We used the method developed by Thurber (1983) and successively modified by Eberhart-Phillips (1986). The crustal model is defined specifying the velocity values at the nodes of a three-dimensional grid (in our case, grid spacing is 4 km horizontally for the Amiata-Vulsini region, and 2 km for the Alban Hills). This technique consists of a simultaneous inversion of data to obtain both velocity parameters and earthquake location. The inversion is accomplished by minimizing the residuals, i.e. the differences between the observed arrival times and the theoretical ones (computed with a trial hypocentral location and a starting velocity model). The model parameters are perturbed iteratively, with a damped least-squares technique (see Thurber 1983, Evans and Zucca 1993, and Foulger and Amott 1993 for the details).

3. RESULTS

In the first part, we present the P-wave crustal structure of the Roman Comagmatic Province (RCP) Quaternary volcanoes, determined from local earthquake tomography. In the second part, we describe the main seismological features observed in the Tuscan-Latium volcanic areas.

3.1 P-wave velocity models

Vulsini Volcano and adjacent region

Figure 1 shows the P-wave velocity model for the Amiata-Vulsini volcanic areas (from Chiarabba *et al.*, in press). In the first two layers (1 and 3 km depth), the geometry of the high velocity limestone units is clearly visible. Low velocity zones correspond to depressed grabens, filled by Quaternary sediments and flysch sequences. Our reconstruction is in good agreement with the deep-well data (Buonasorte *et al.*, 1988). The 4.6 km/s isoline marks the top of the limestone units, and may be successfully used to define the buried carbonate structure (see Figure 2). A deep high velocity anomaly (Layer 4) is probably related to a metamorphic uplifted lower crust present beneath the Radicofani graben at 7 km depth. The body is truncated southward by the northern border of the Bolsena structure, revealing a regional transiction between the strongly uplifted Tuscan Province and the collapsed Latium structure. Beneath Mt. Amiata Volcano, we observe a high velocity anomaly from 1 to 5 km depth, related to the metamorphic basement.

Alban Hills Volcano

The main observed feature is a high velocity body extending from 1 km depth beneath the western side of the volcano to 5 km depth beneath the central cone (see Figure 3). This anomaly can be related to an uplifted carbonate structure, probably metamorphosed at depth, and intruded by volcanic dikes (see also Chiarabba *et al.*, 1994; Cimini *et al.*, 1994).

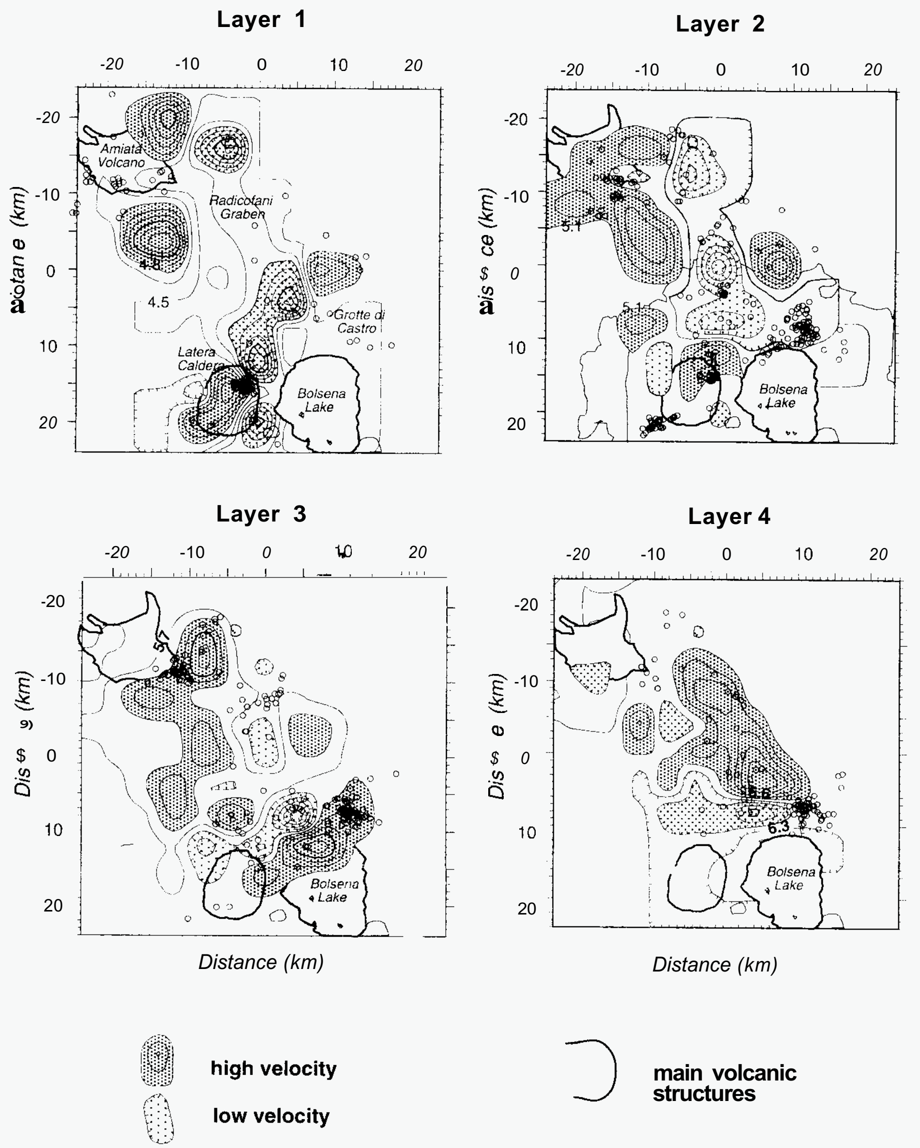

Figure 1: Earthquake hypocenters and velocity structure of the Mt. Amiata-Vulsini area at 1 km depth (Layer 1), 3 km depth (Layer 2), 5 km depth (Layer 3), and 7 km depth (Layer 4). Solid lines indicate the Amiata Volcano, the Latera Caldera, and the Bolsena Lake depression.

Seismological features may be evident from analysing the microseismic data recorded with dense local networks (Buonasorte *et al.*, 1987; Amato *et al.*, 1994; Chiarabba *et al.*, in prep.). We observe an intense seismic swarm activity both in the Vulsinian and Alban Hills area, whereas the Sabatini Volcano seems to be aseismic (Figure 4).

Vulsini and Amiata Volcanoes

Sparse clusters of epicenters are recognizable, distributed over the whole area (Figures 1 and 4). **A** cluster is present beneath Castel Giorgio (GC), north of Bolsena Lake. This structure has been active mainly during February 1992, with thousands of earthquakes recorded in a few days. The hypocenters are confined between 3 and 7 km, within carbonate rocks, at the edge of a deep high-velocity body, apparently of sub-volcanic origin.

A second seismic area is Piancastagnaio (PC), south-east of Mt. Amiata. The hypocenters are confined between 3 and 6 km depth. The seismogenic layer coincides with a high-velocity metamorphic basement. At greater depth, we observe a cut-off of seismicity. where temperatures higher than 400 C are expected.

The Latera (L) caldera is characterized by low magnitude earthquakes (less than 2) with hypocenters confined in the upper 3 crustal km. The events occur on a NW-SE normal fault inferred from tomography. bordering the carbonate horst prcaent at 1 to 3 km depth beneath the caldera.

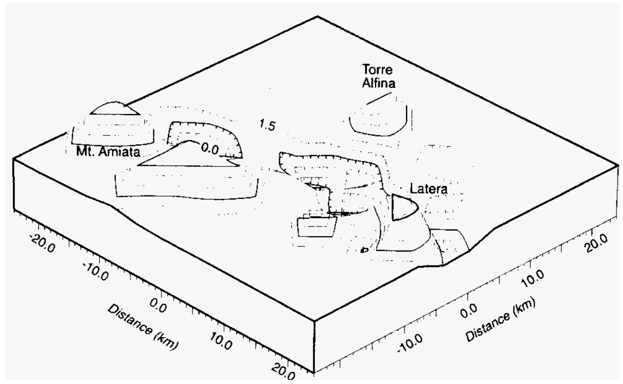

Figure *2:* Depth (km) of the Vp=4.6 km/s isoline in the studied region. In our interpretation, based on deep well data, this line marks the top of the marly-limestone Meso-Cainozoic units, containing the geothermal reservoir, from Chiarabba ***et al.***, in press.

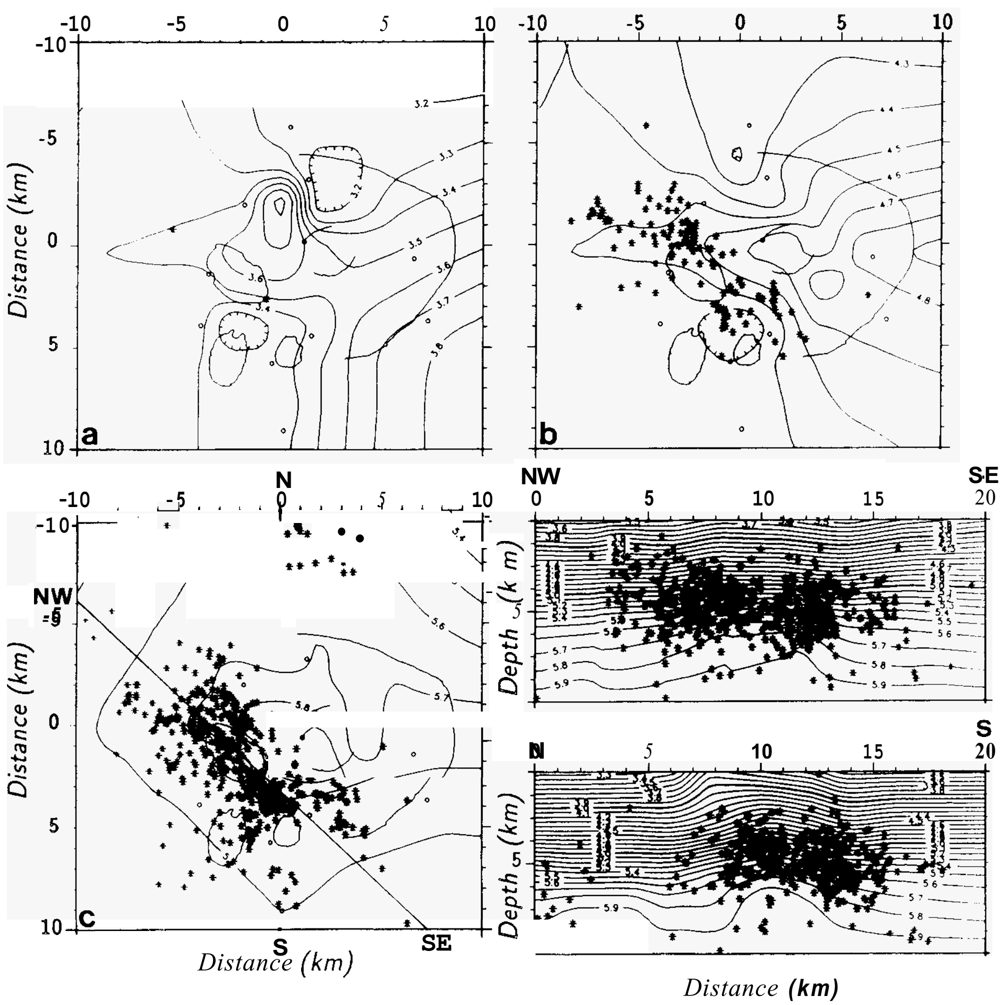

Figure *3:* Earthquake hypocenters and velocity structure of the Alban Hills area at 1 **km** depth (a), 3 km depth (b), and 6 km depth (c), from Chiarabba ***et** al.* (1994). Solid lines indicate the caldera rim, the central cone, and the phreatomagmatic craters.

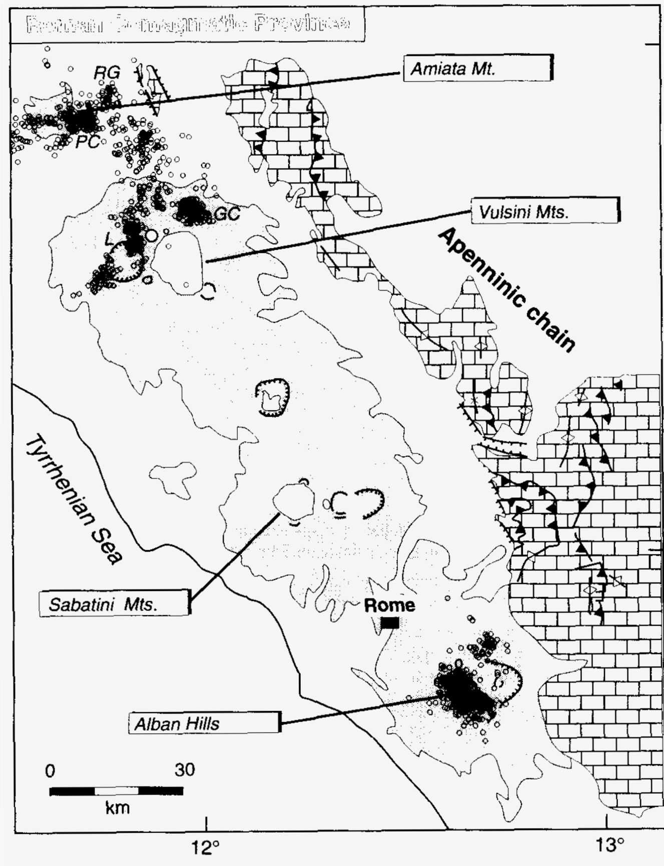

Figure 4: Geologic sketch of the Roman Comagmatic Province. The main volcanoes are indicated. We plot the seismicity for the Vulsini-Sabatini volcanoes (data span from 1977 to 1992), and for the Alban Hills volcano (data are relative to the 1989-1990 seismic swarm).

Beneath the Radicofani Graben (RG), earthquakes are confined between 3 and 6 km depth, within carbonate **rocks** at the top of a deep high-velocity anomaly interpreted as a high metamorphosed crust or intrusive body (Chiarabba ***e? al.***, in press). **A** strong seismic refractor, probably related to a fluid filled crustal level (the "**K** Horizon"), has been observed at 7 km depth (Orlando *et al.*, 1991). In the top 2 km of the Graben, where low-velocity anomaly indicates the presence of Plio-Pleistocene sediments, no seismicity occurs.

<u>Alban Hills Volcano</u>

The earthquake epicenters delineate a 6 x 12 km^2 seismic zone in the western side of the volcano, elongated in a NW-SE direction (see Figures 3 and **4).** This area coincides with the area where the most recent phreato-magmatic activity took place at 0.027 Ma (De Rita *et al.,* 1988). The central part of the volcano appears to be aseismic, as well as the eastern side. The seismicity is confined between 3 and **6** km depth (Figure 3). Two main clusters are recognisable, one north of Albano Lake and a second between Nemi and Albano Lake (see Amato ***et** al.,* 1994).

A synoptic representation of the seismogenic structure has been proposed by Chiarabba ***et** al.* (1994). Earthquake hypocenters occur within the high-velocity body located in the western side of the volcano between 1 and 6 km depth (Figure 3). The seismic layer is mainly composed by uplifted Meso-Cainozoic limestones. Below 6 km depth the limestones may be thermo-metamorphosed by a close thermal source hypothesised by Amato andValensise (1986) and Cimini ***et** al.* (1994).

4. DISCUSSION AND CONCLUSIONS

This paper emphasises the contribution of seismologic studies, and particularly of local earthquake tomography, to the definition of the deep structure beneath the main geothermal fields of the Roman Comagmatic Province. First, the pattern of velocity anomalies (constrained by independent geologic information) identifies the 3-D geometry of the carbonate structure beneath Vulsini and Alban Hills volcanoes. Since limestone rocks represent the main geothermal reservoir in this region, our proposed methodology seems to be a robust and inexpensive tool to explore the RCP geothermal resources. Furthermore, the presence of deep sub-volcanic bodies can be indicative of deep high heat sources, located beneath the shallow limestone units. The ductile behavior of rocks observed below 6-7 km depth suggests a high thermal environment.

We propose a model in which the overpressured fluids within the limestone units play an important role for the earthquake generation in the RCP. A high fluid pressure within the seismogenic layer, sustained by a strong fluid circulation, and a plausible thermo-metamorphism of the buried limestones, represents the triggering mechanism for the seismic swarm activities, as suggested by seismological evidence. The high fluid pressure decreases the shear resistance within the brittle layer, favoring earthquake occurrence. According to this model, the shallow uplifted carbonate structure is fractured and largely permeated by fluids, and represent a primary target for geothermal research.

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