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Structural model of the Northern Latium volcanic area constrained by MT, gravity and aeromagnetic data

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Abstract
The results of about 120 magnetotelluric soundings carried out in the Vulsini, Vico and Sabatini volcanic areas were modeled along with Bouguer and aeromagnetic anomalies to reconstruct a model of the structure of the shallow (less than 5 km of depth) crust. The interpretations were constrained by the information gathered from the deep boreholes drilled for geothermal exploration. MT and aeromagnetic anomalies allow the depth to the top of the sedimentary basement and the thickness of the volcanic layer to be inferred. Gravity anomalies are strongly affected by the variations of morphology of the top of the sedimentary basement, consisting of a Tertiary flysch, and of the interface with the underlying Mesozoic carbonates. Gravity data have also been used to extrapolate the thickness of the neogenic unit indicated by some boreholes. There is no evidence for other important density and susceptibility heterogeneities and deeper sources of magnetic and/or gravity anomalies in all the surveyed area.

Key words *magnetotelluric sounding – gravity aeromagnetic – caldera*

1. Introduction

New high quality MT data are used jointly with the available gravity, aeromagnetic and borehole data to build up a simple well constrained large scale model of the shallow crust of the Vulsini, Vico and Sabatini volcanoes in Central Italy.

Several geothermal wells drilled throughout this area indicate the following schematic stratigraphic sequence (Funiciello *et al.*, 1979; Barberi *et al.*, 1993):

1) A volcanic Pleistocene-Holocene cover consisting of ignimbrites, other pyroclastic deposits and subordinate domes and lava flows.

2) A neogenic «neoautoctonous sedimentary cycle» (upper Miocene and Pliocene and seldom even lower Pleistocene) mainly consisting of sands, clays, conglomerates and Messinian evaporitic clay deposits. This formation is present only in some sedimentary basins and has not generally been found under the volcanic cover.

3) A «flyschoid complex», made up of clays, sandstones, marls and limestones (from middle Cretaceous to lower Miocene), of variable thickness (even more than 1000 m).

4) A «basal carbonatic formation», including limestones and marls from upper Triassic to Oligocene.

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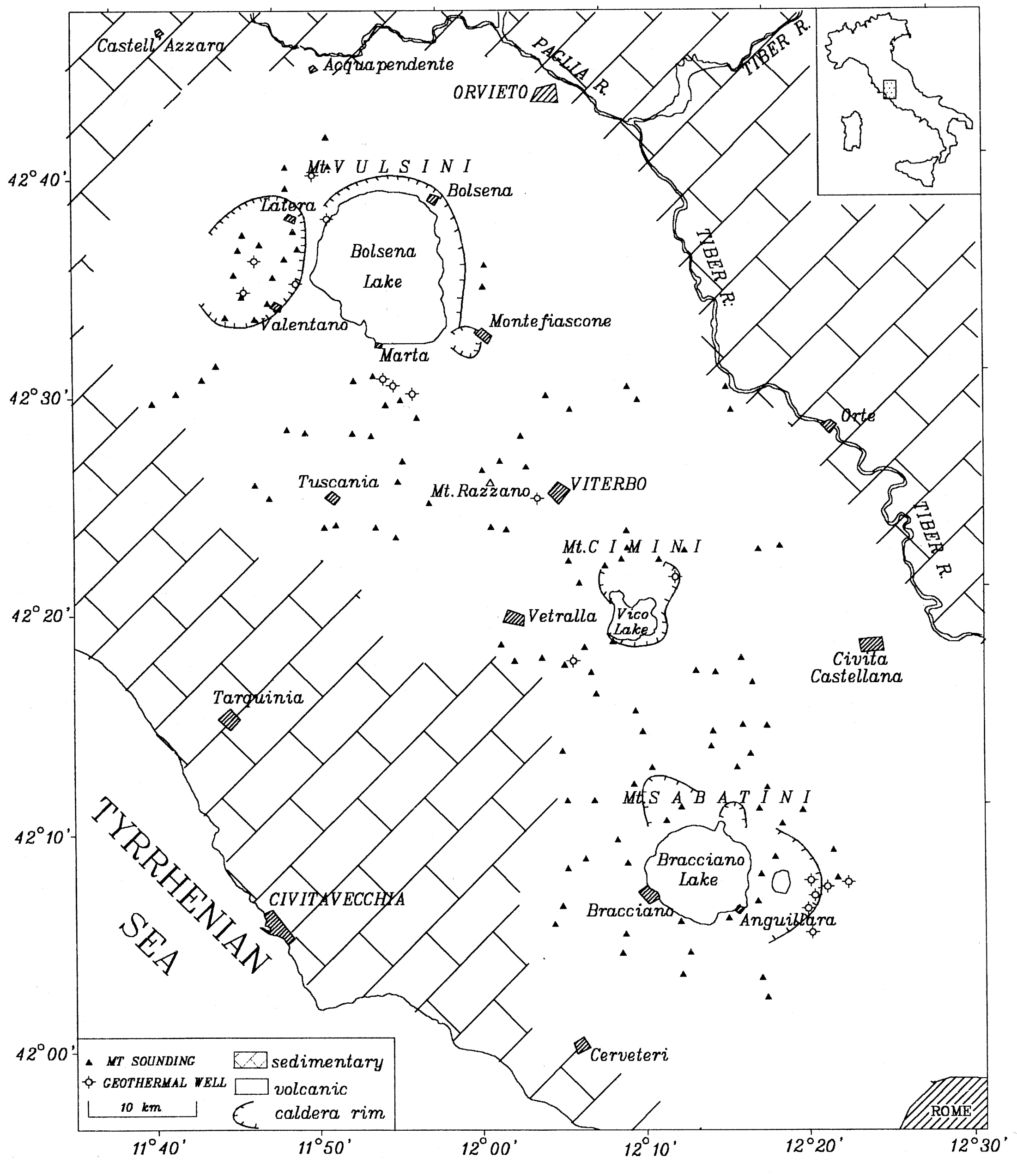


Fig. 1. Simplified geological sketch map with locations of MT soundings (filled triangles) and deep boreholes. The map shows the main caldera rim and the outcropping area of the sedimentary rocks.

In this framework, aeromagnetic data have been used to compute the thickness of the volcanic cover, MT data have been used to compute the depth to the top of the sedimentary resistive basement (flysch or carbonates), gravity data have been used to compute the depth to the top of the carbonate basement and to extrapolate the thickness of the neogenic unit indicated by the boreholes.

The Vulsini, Vico and Sabatini volcanoes constitute the northernmost extension of the potassic Roman comagmatic Province, characterized by high-K magmas, which were active up to a few thousand years ago (fig. 1). This area has been the site of very complex geological processes during the Neogene with repeated subsidence episodes involving the development of sedimentary basins and important differentiated uplift phenomena. Geophysical, stratigraphical and structural studies show that volcanic and tectonic activity was controlled by three main fault systems (NW-SE, NE-SW and N-S), which often are hidden below the Pleistocene volcanic cover (Faccenna *et al.*, 1994). The NE-SW system has been interpreted as a transfer fault of the NE-SW striking extensional system. This tectonic pattern gave rise to the formation of several NNW-SSE trending structural highs and lows of the sedimentary basement (Buonasorte *et al.*, 1987 and Barberi *et al.*, 1993).

The structural lows constituted the basins where neogenic and quaternary sediments piled up. The most important structural high is the Castell'Azzara-Mt. Razzano ridge, consisting of Cretaceous limestones and Tertiary flysch.

An intensive widespread magmatic activity affected this region from the Pliocene. Volcanic centers migrated with time from W to E (Civetta *et al.*, 1978) accompanying the evolution of the NE migration of the extensional tectonics (Cavinato *et al.*, 1994). The composition of the erupted magmas changed towards less evolved terms (Barberi *et al.*, 1993), which are characteristic of the final stage of activity.

All this area is characterized by high heat flow (up to 350 mW/m^2) as pointed out by the researches of the ENEL (National Electric Board) – AGIP (National Oil Authority) joint project for the exploitation of geothermal energy. Mongelli *et al.* (1989) point out the existence of a high regional heat flow corresponding to a major crustal thinning (Nicolich, 1989). Local thermal anomalies are observed in correspondence of the main volcanic complexes and they may be linked to magmatic bodies intruded in the crust.

2. Geophysical data

2.1. *Magnetotelluric data*

The magnetotelluric survey consisted of about 120 soundings, located in the area of exploration geothermal permits, in Central Italy (Latera, Bolsena, Cimini, Tuscania and Sabatini permit in the Northern Latium volcanic area). The survey was carried out by Geosystem s.r.l. (Milano) by appointment of UNOCAL (Santa Rosa, California).

A Phoenix Geophysics Ltd. real-time MT system was used to collect data at the stations shown in fig. 1. The system (MT16) allowed the recording of 16 channels simultaneously. A 10 component survey was planned, using 5 channels as a reference stations (Gamble *et al.*, 1979). The two stations, were 2 km apart and were connected by cable. The horizontal magnetic components of each station was used as reference for the other one. Four iron-cored induction (MTC60) coils were used to measure the horizontal components and two air loops to measure the vertical components of the geomagnetic field variations over six decade ranges (from 320 Hz to 0.00061 Hz). The electric potential variations were measured using unpolarizable lead-lead chloride electrodes forming 100 m long dipoles. Using a cross-shaped layout, the two components of the electrical field were recorded in a north-south and east-west direction. The signals were filtered and amplified by a processor unit located at the center of the sensor array, after which they were sent to an HP 9000 computer via a 16-bits A/D converter. The computer provided real-time analysis of the data and displayed continuous updates of all the MT parameters. Average recording time was about 24 h; it was changed according to signal strength and cultural noise.

The MT data were acquired at 40 discrete frequencies equally spaced in logarithmic scale, using 7 data points per decade. The data, transformed by DFT (Discrete Fourier Transform) coefficient in high frequency range (320-2.5 Hz) and by a cascade decimation in low frequency range (2.5-0.00061 Hz) (Wight and Bostick, 1980), were cross-multiplied with their complex conjugate to produce auto and cross-power. The latter were further used to compute the impedance tensor, from which apparent resistivity and phase were derived as a function of frequency.

Three MT curves typical of the surveyed area, are presented in fig. 2. The two curves of each plot are computed along the major and minor axes of anisotropy, determined by the azimuth which maximizes $|Z_{xy}|^2 + |Z_{yx}|^2$, where Z is the impedance tensor (Vozoff, 1972). These axes of anisotropy, for two-dimensional structure, correspond to the B-polarization (magnetic field parallel to the regional strike) and E-polarization (electric field parallel to the regional strike) modes respectively. For most of the soundings the two apparent resistivity curves are coincident within the errors. For periods less than 10 s skew is < 0.2 and tipper (computed from the vertical and horizontal magnetic components) is < 0.3 at most stations. This indicates that local structures can be approximately one-dimensional, and 1D modelling can be safely used. Only about 10% of soundings have apparent resistivity, skew and tipper indicative of a pronounced 2 or 3D structure. Some soundings show a static shift effect. It was accounted for in the sites where resistivity DC soundings exist, according to the method proposed by Capuano *et al.* (1988) and Sternberg *et al.* (1988).

MT apparent resistivity and phase curves were inverted using the rotationally invariant impedance (determinant of the tensor)

$$Z_{\mathrm{inv}} = \sqrt{Z_{xx}\, Z_{yy} - Z_{xy}\, Z_{yx}}$$

a method which was suggested by Berdichevsky and Dmitriev (1976) for reducing the effect of local electrical structure. The invariant impedance has been shown (Ingham, 1988) to provide valid results even in cases of 3D structures.

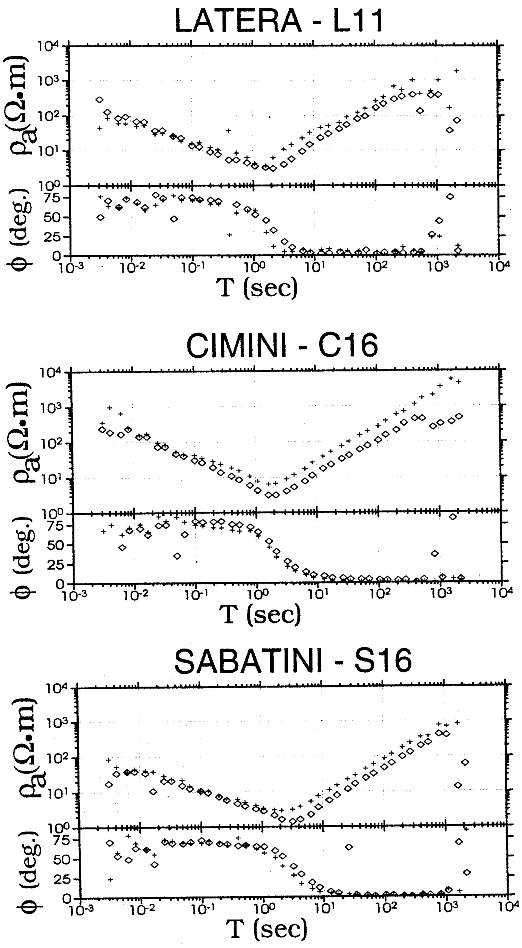
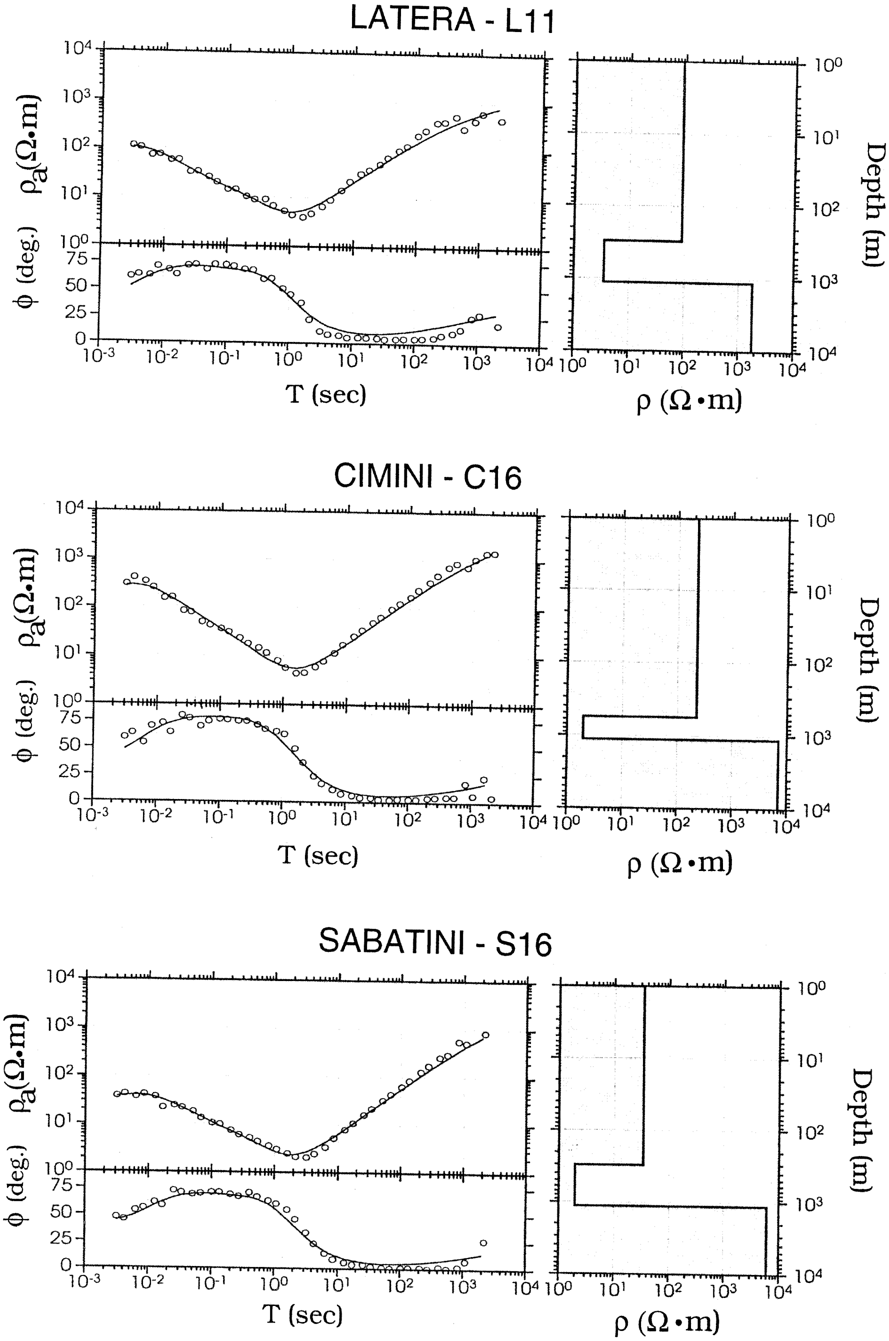


Fig. 2. Examples of apparent resistivity and phase curves of MT sounding (TE and TM mode) located in the northern (Latera), central (Cimini) and southern (Sabatini) parts of the investigated area.

The application of 1D inversion using invariant impedance to the soundings of fig. 2 is reported in fig. 3. The inversion was carried out imposing that the number of layers must be as small as possible. The estimate of the model parameters was based on the damped least-squared criterion (Marquardt, 1963).


LATERA - L11

CIMINI - C16

SABATINI - S16

Fig. 3. Examples of MT 1D inversion model. The soundings are the same as fig. 2. Circles represent the observed data and continuous line represents the model data.

2.2. *Gravity data*

The gravity data were collected in different surveys carried out in the area for geothermal exploration purposes. The gravity stations were located with an average density of 1 per km^2, over a total area of approximately 7000 km^2. The collected data include the surveys carried out on the Bolsena lake by ENEL and on the Bracciano lake by Di Filippo *et al.* (1982).

The Bouguer anomaly map computed for a density of 2400 kg·m^{-3} is shown in fig. 4.

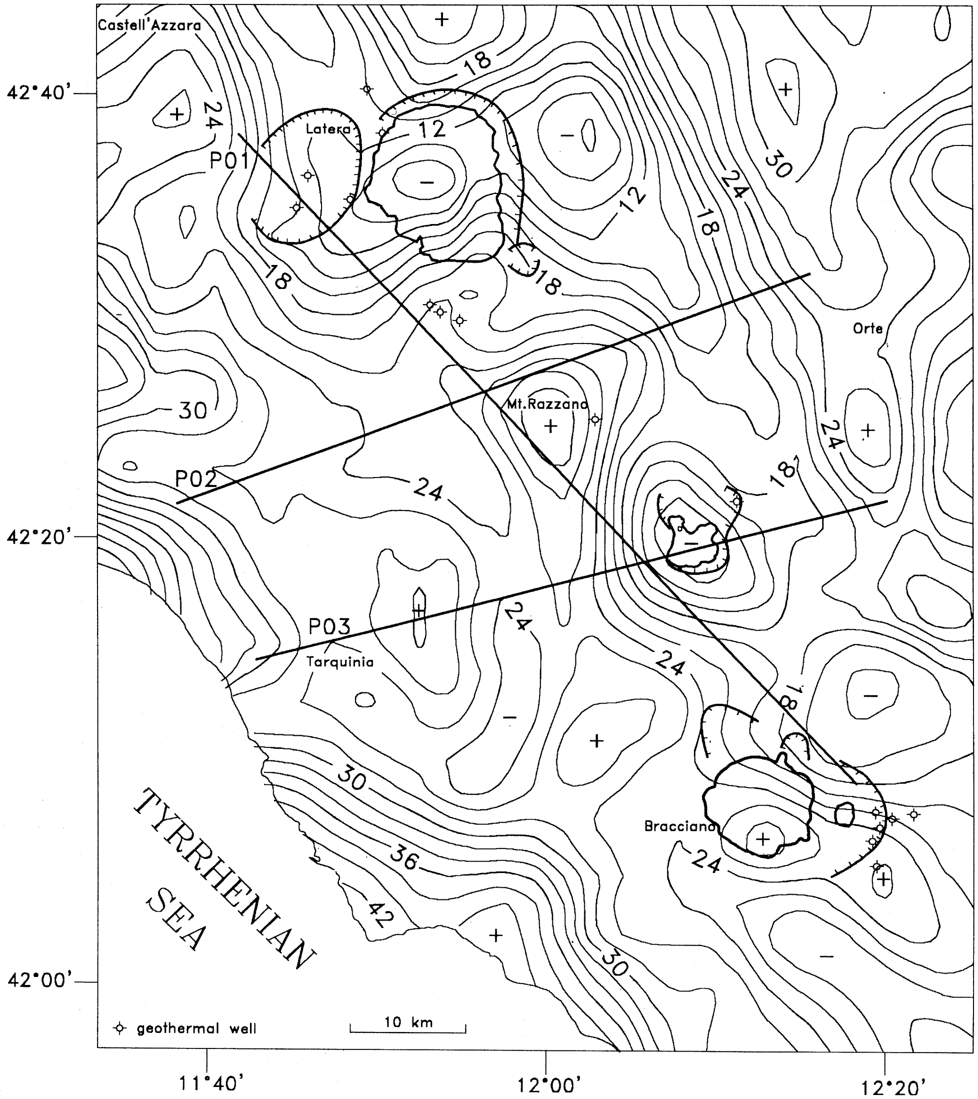


Fig. 4. Bouguer anomaly map contoured at 2 mGal intervals. The reduction density is 2400 kg·m^{-3}. The trace of the interpreted profiles is shown. + and − indicate relative maximum and minimum.

This density was chosen because it is an approximate average between the 2200-2300 $kg \cdot m^{-3}$ of the Neogenic volcanic rocks and the 2500-2600 $kg \cdot m^{-3}$ of the flysch formation, which cover the largest part of the area.

Bouguer anomalies are in the range 5-44 mGal. The most prominent features are:

– The presence of a broad, NW-trending, gravity low, which is bounded at SW by a high corresponding to the Thyrrenian margin, and at NE by a high located along the carbonatic mountains of the Apenninic chain.

– Marked lows are located in the Vulsini sector and in the Vico area. They correspond to caldera structures and conform to the observation that collapse calderas are usually accompanied by a well-pronounced gravity low (Scandone, 1990).

– A gravity high is on the Bracciano complex. This reinforces the idea that the Bracciano lake structure is located at a structural high of the carbonate substratum (Funiciello *et al.*, 1976) and it is not a classical caldera (Di Filippo *et al.*, 1982).

– A gravity high is located on Mt. Razzano. It corresponds to the S sector of the Castel-l'Azzara-Mt. Razzano ridge. According to Baldi *et al.* (1974), it represents the remnants of a Pliocene median ridge. Gravity anomalies are not consistent with the continuity of such a structure.

2.3. *Aeromagnetic data*

From 1971 to 1980, AGIP carried out an aeromagnetic survey of Italy, with a total of 265 305 km of survey lines and an average grid size of 5×10 km (AGIP, 1981). AGIP computed the proper corrections and subtracted the regional field from the measured total field (AGIP Reference Geomagnetic Field, which is about 3.232 nT/km in the S-N direction and 0.726 nT/km from W to E). After this operation, the magnetic anomalies can be considered as originating from sources present in the Earth's crust.

As for gravity data, the aeromagnetic data used were extracted from a window centered in the area of Vico lake. The magnetic field in this area was measured at an elevation of 1460 m. The data set consists of total intensities on a 6 km grid.

The aeromagnetic map (fig. 5) is characterized by three intense anomalies over the volcanic areas of Bolsena, Vico and Bracciano. These dipole anomalies have a wavelength of about 20-25 km. Outside the volcanic area the field is fairly quiet. Dipole anomalies are probably due to the strong susceptibility contrast between volcanic cover and the underlying sedimentary formations (flysch and carbonates).

3. Discussion

Apparent resistivity and phase curves of the MT soundings, obtained from Z_{inv} were inverted using a three-layer model (resistive-conductive-resistive). The comparison with the boreholes information indicates that the shallow resistive layer is formed by the upper part of the volcanic cover, the intermediate conductive layer is formed by hydrothermally altered volcanic products, and the resistive basement is the flysch formations and/or the carbonate formations. The high resistivity of flysch can be ascribed to its lithology, with prevalent marls and limestones. No evidence of a deeper conductive layer is found.

Computed depths to the top of the resistive basement are represented in fig. 6. The thickness of the volcanic cover is highest around the Latera and Vico calderas and NE of Bracciano lake.

MT, gravity and aeromagnetic data were inverted along three profiles (for location see fig. 1) using the interpretation scheme indicated in the Introduction. Gravity and aeromagnetic anomalies were inverted using 2.5D models. Profile P01 runs all over the area from NW to SE, while P02 and P03 are trending WSW-ENE (fig. 7, 8 and 9). Because of the orientation of selected profiles, aeromagnetic data were interpreted along P01 only.

Aeromagnetic anomalies are successfully modeled in terms of varying thickness of the volcanic cover, using a magnetic susceptibility of $6.9 \cdot 10^{-2}$ SI ($7 \cdot 10^{-3}$ e.m.u.) based upon

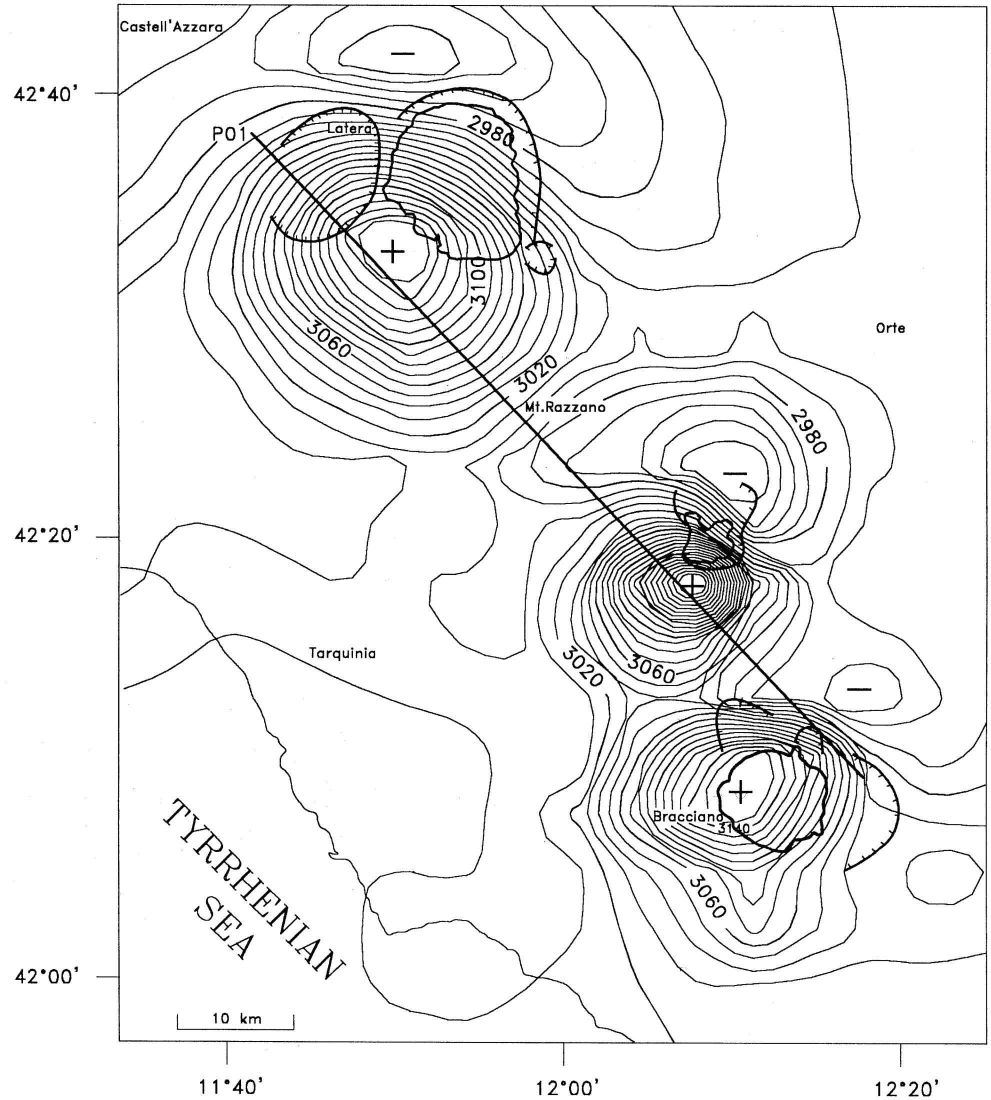


Fig. 5. Aeromagnetic anomaly map contoured at 10 nT intervals. The elevation flight is 1460 m. The trace of the interpreted profile is shown. + and – indicate relative maximum and minimum.

measurements carried out on several outcropping rock types in the Vico area (Gandino *et al.*, 1989). The morphology of the bottom of this layer was detailed using the information from MT soundings and from stratigraphy of geothermal wells.

Gravity anomalies were interpreted using a 3-layer model, except where evidence of the presence of the neogenic layer exists. The assumed densities are:

- carbonatic basement: 2700 kg · m^{-3};
- flyschiod complex: 2600 kg · m^{-3};

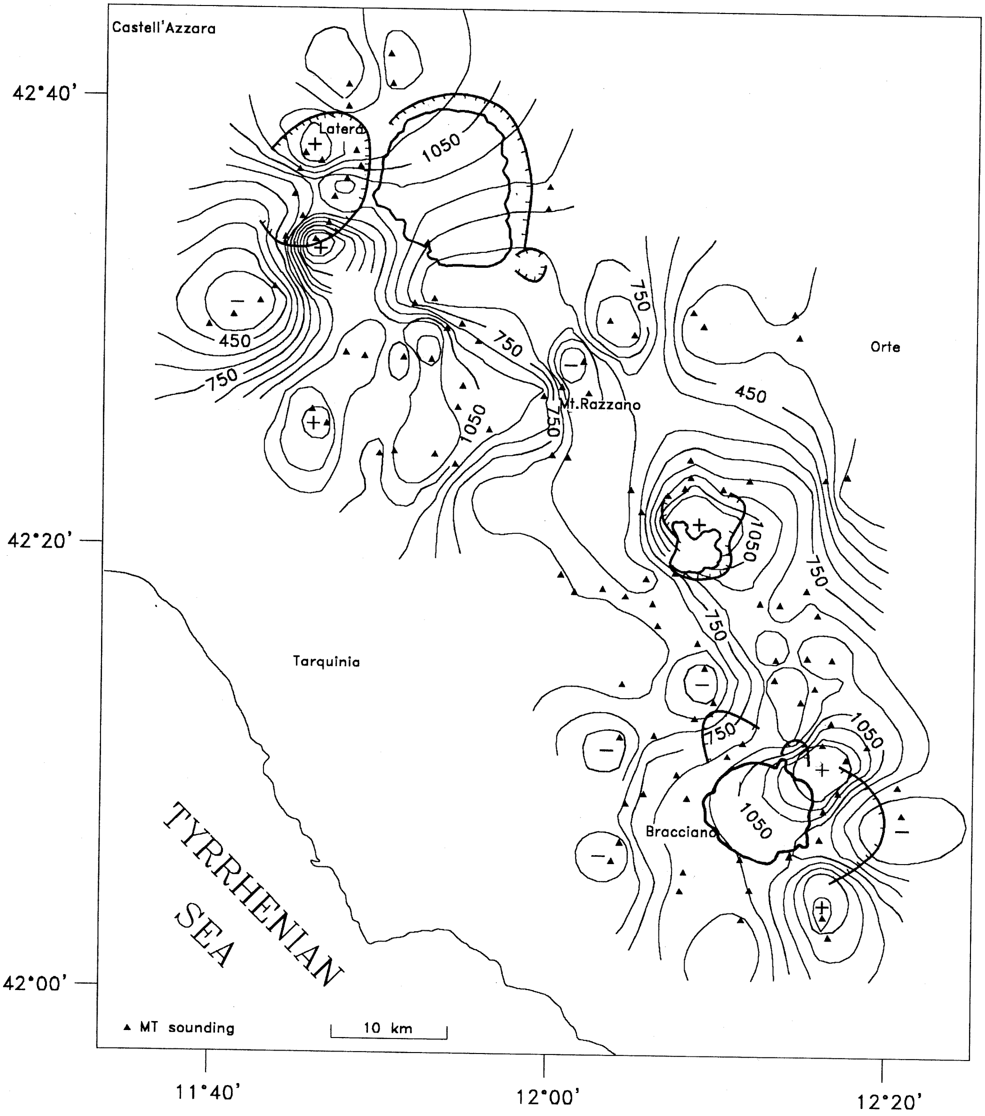


Fig. 6. Depth to the top of the resistive layer as inferred from MT data, contoured at 100 m intervals. The locations of MT soundings (filled triangles) is shown. + and – indicate relative maximum and minimum.

- neogenic complex: 2200 kg · m^{-3};
- volcanites: 2300 kg · m^{-3}

They are in agreement with those used in previous works (Barberi *et al.*, 1993; De Rita *et al.*, 1997). 2.5D modelling has shown that most of the gravity anomaly pattern can be ascribed to variations of the depth to the top of the carbonate basement underlying the flysch formations.

Although some volcanological considerations and some drillings data in the Latera caldera indicate the presence of syenitic bodies

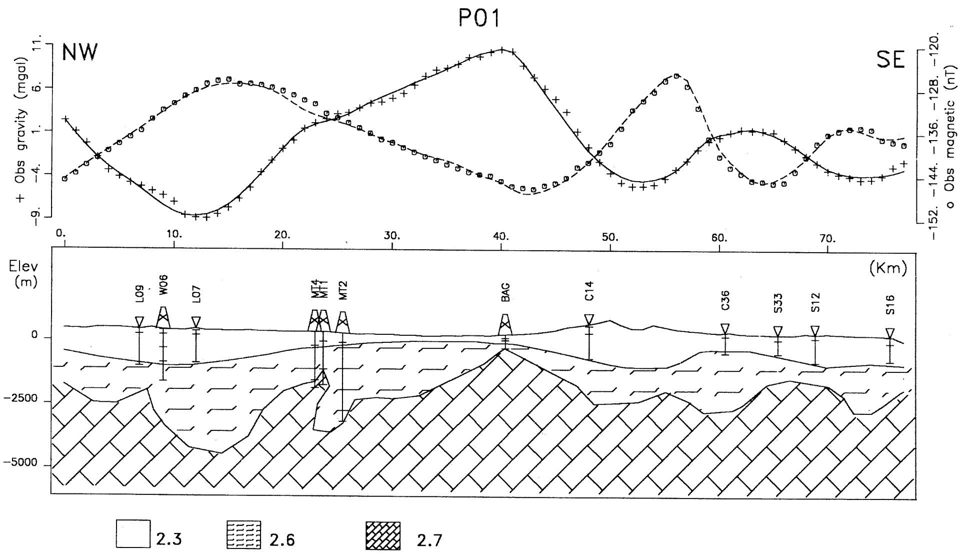


Fig. 7. Gravity and magnetic modelling across the profile P01 shown in fig. 4. Circles are the observed magnetic anomalies, crosses are the observed gravity anomalies. The model shows the boreholes and MT soundings that constrain the shallower part of the model. Densities are in g · cm^{-3} (2.7 = carbonatic basement; 2.6 = flyschiod complex; 2.3 = volcanites). The volcanites magnetic susceptibility is $6.9 \cdot 10^{-2}$ SI ($7 \cdot 10^{-3}$ e.m.u.).

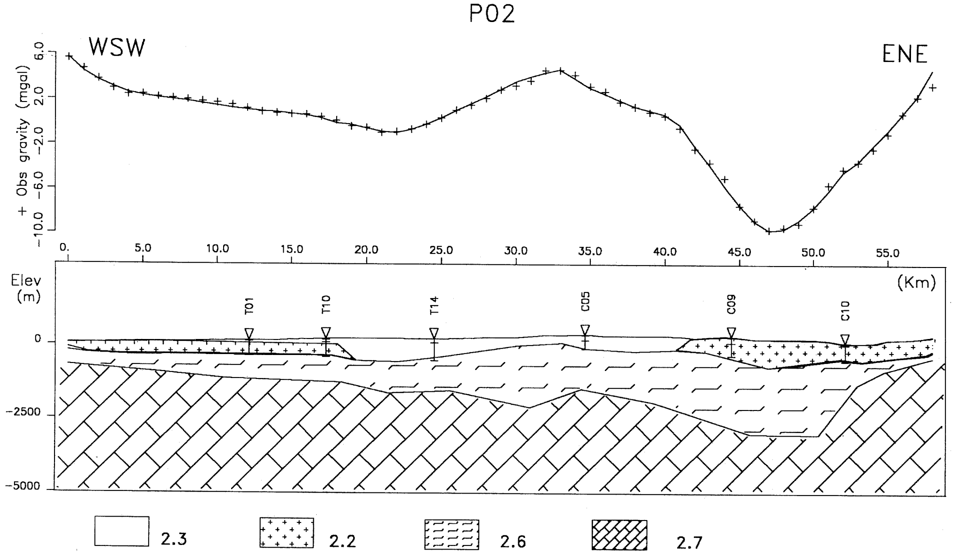


Fig. 8. Gravity modelling across the profile P02 shown in fig. 4. Circles are the observed magnetic anomalies, crosses are the observed gravity anomalies. The model shows the MT soundings that constrain the shallower part of the model. Densities are in g · cm^{-3} (2.7 = carbonatic basement; 2.6 = flyschiod complex; 2.3 = volcanites, 2.2 = neogenic complex).

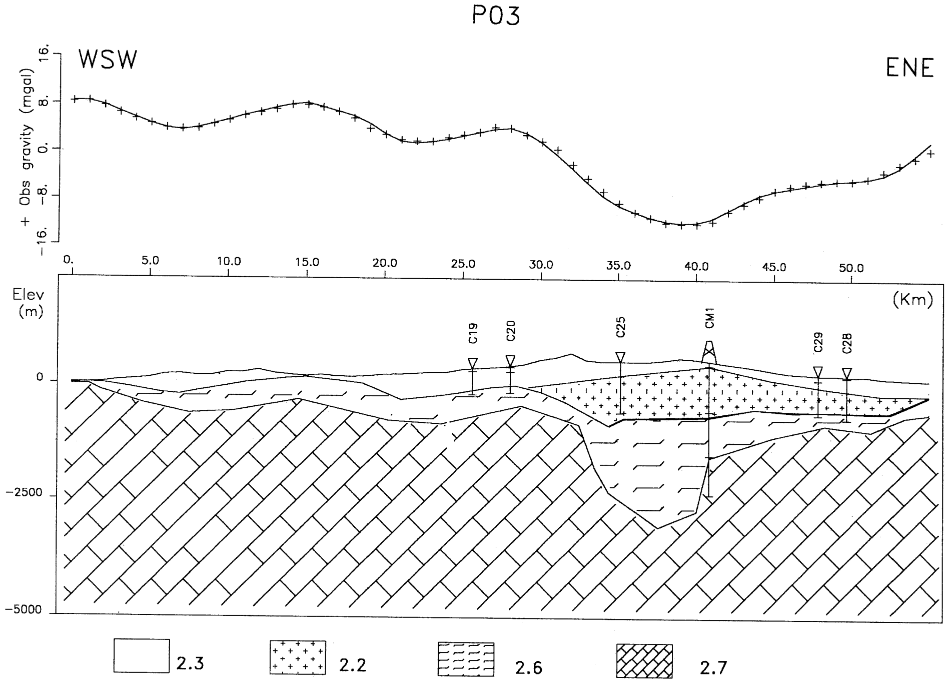


Fig. 9. Gravity modelling across the profile P03 shown in fig. 4. Circles are the observed magnetic anomalies, crosses are the observed gravity anomalies. The model shows the boreholes and MT soundings that constrain the shallower part of the model. Densities are in g · cm^{-3} (2.7 = carbonatic basement; 2.6 = flyschiod complex; 2.3 = volcanites, 2.2 = neogenic complex).

at depth in the study area (Barberi *et al.*, 1984), we did not consider such intrusive rocks in our modelling. In fact its density should be very similar to that of the rocks in which they should be included (limestones), *i.e.* 2700 kg m^{-3} (Carmichael, 1982) resulting in a lack of any gravity signature. It may be argued that syenitic bodies at depth constitute a source of magnetic anomalies (their average susceptibility is about $6.5 \cdot 10^{-3}$ e.m.u.; Carmichael, 1982). However, the observed magnetic anomalies are fully justified by thickness variations of the volcanic cover ($\chi = 7 \cdot 10^{-3}$ e.m.u.) so that there is no room for a further deeper source of anomaly. Thus unlike other authors, (Barberi *et al.*, 1993) we chose not to include these intrusive syenitic rocks in our models.

Along profile P01, «neoautochtonous» rocks of the neogenic cycle never outcrop and the stratigraphies of many geothermal wells and test holes (Barberi *et al.*, 1993) demonstrate that this area was always above the sea level from Messinian ages. So the interpretation of P01 profile does not include rocks of the neogenic complex. This profile is constrained by 5 geothermal wells and 7 MT soundings that are present along or near its line. In particular, wells MT1, 2 and 4 single out an interesting buried structure of the carbonatic basement that may be related to a thrust of carbonatic units above flyschoid ones or to a big fault scarp. In correspondence to the Bagnaia well (BAG) there is a high in the carbonatic basement (near the Mt. Razzano) with associated gravity high. In general, the morphology of the top of the carbonate basement appears to be uneven and complex, strongly affected by faults and thrusts, while the bottom of the volcanic sequence appears to have a smooth surface. In correspondence of the Latera caldera the carbonatic basement deepens to almost 5 km below sea level.

In the area of Bracciano, a high of Bouguer anomalies indicates a structural high of the limestone basement. Interpretation of MT soundings and aeromagnetic anomalies indicate a thickening of the volcanic cover, with a consequent thinning of the flysch layer.

Profile P02 is constrained by 6 MT soundings that give information about the volcanic cover thickness. The interpretation of gravity data shows a regular deepening of the carbonate basement eastward, reaching its maximum depth (about 2500 m deep) in correspondence with the Chiani-Tiber neogenic basin. The basement appears bounded eastward by a system of direct faults. The occurrence of a neogenic basin at the western end of the profile fits well the observed gravity field.

Profile P03 is constrained by CM1 well and by 5 MT soundings. The most striking feature is a strong deepening of the carbonate basement in correspondence of the Cimini volcanic complex, where a thick (about 1 km) neogenic succession should be present below the volcanic layer.

4. Conclusions

New contributions to the knowledge of the shallow crustal structure in the Vulsini, Vico and Sabatini volcanic areas are given by the interpretation of 120 high-quality MT soundings carried out in the framework of a geothermal project. The apparent resistivity curves and other indicators (skew and tipper) show that in almost all cases the local structures can be considered one-dimensional. Apparent resistivity and phase curves of most of the soundings fit well a simple 1D three-layer model (resistive-conductive-resistive) where the top of the deeper resistive layer is the top of the sedimentary sequence, which is generally the flysch formation. This interpretation agrees with the lithology of this formation, which is very rich in marls and carbonate rocks. The morphology of this resistive layer seems to indicate a southward continuation of the horst structure of Mt. Razzano, which is not clearly evidenced by gravity anomalies.

MT results and the borehole information were used to constrain the gravity and magnetic modelling. The pattern of Bouguer and magnetic anomalies is justified by the morphology of the volcanic cover and the morphology of the carbonate basement, which is characterized by a sharp deepening in the caldera areas. In the Bracciano area gravity and MT data show that the carbonate basement is relatively shallow, but the flysch formation is thinner. There is no evidence for other important density and susceptibility heterogeneities and deeper sources of magnetic and/or gravity anomalies throughout the surveyed area.

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REFERENCES

AGIP (1981): *Carta Aeromagnetica d'Italia: foglio D, E*, Att. Min., Direz. Espl. Idrocarburi, S. Donato Milanese.

BALDI, P., F.A. DECANDIA, A. LAZZAROTTO and A. CALAMAI (1974): Studio geologico del substrato della copertura vulcanica laziale nella zona dei laghi di Bolsena, Vico e Bracciano, *Mem. Soc. Geol. It.*, **13**, 575-606.

BARBERI, F., F. INNOCENTI, P. LANDI, U. ROSSI, M. SAITTA, R. SANTACROCE and I.M. VILLA (1984): The evolution of Latera caldera (Central Italy) in the light of subsurface data, *Bull. Volcanol.*, **47**, 125-141.

BARBERI, F., G. BUONASORTE, R. CIONI, A. FIORDELISI, L. FORESI, S. IACCARINO, M.A. LAURENZI, A. SBRANA, L. VERNIA and I.M. VILLA (1993): Plio-Pleistocene geological evolution of the geothermal area of Tuscany and Latium, *Mem. Soc. Geol. Ital.*, **49**, 69-109.

BERDICHEVSKY, M.N. and V.I. DMITRIEV (1976): Basic principles of interpretation of magnetotelluric soundings curves, in *Geolelectric and Geothermal Studies*, edited by A. ADAM, KAPG, *Geophys. Monogr.*, Akademiai Kiado, Budapest, 165-221.

BUONASORTE, G., A. FIORDELISI, E. PANDELI, U. ROSSI and F. SOLLEVANTI (1987): Stratigraphic correlations and structural setting of the pre-neoautochtonous sedimentary sequences of Northern Latium, *Period. Mineral*, **56**, 111-122.

CAPUANO, P., P. GASPARINI and A. ZERILLI (1988): Improvement of the MT soundings through combination with TDEM soundings, *Jeofizik*, **2**, 143-150.

CARMICHAEL, R.S. (1982): *Handbook of Physical Properties of Rocks* (CRC Press Inc., Boca Raton, Florida), vol. II, pp. 228.

CAVINATO, G.P., D. COSENTINO, D. DE RITA, R. FUNICIELLO and M. PAROTTO (1994): Tectonic-sedimentary evolution of intrapenninic basins and correlation with the volcano-tectonic activity in Central Italy, *Mem. Descr. Carta Geol. d'Italia*, **49**, 63-76.

CIVETTA, L., G. ORSI, P. SCANDONE and R. PECE (1978): Eastward migration of the Tuscan anatectic magmatism due to anticlockwise rotation of the Apennine, *Nature*, **276**, 604-605.

DE RITA, D., A. BERTAGNINI, C. FACCENNA, P. LANDI, C. ROSA, F. ZARLENGA, M. DI FILIPPO and M.G. CARBONI (1997): Evoluzione geopetrografica-strutturale dell'area tolfetana, *Boll. Soc. Geol. It.*, **116**, 143-175.

DI FILIPPO, M., A. MAINO and B. TORO (1982): La prospezione gravimetrica del lago di Bracciano (Italia Centrale) effettuata con l'ausilio del sottomarino «F.A. Forel», *Boll. Serv. Geol. It.*, **C3** (6), 277-284.

FACCENNA, C., R. FUNICIELLO and M. MATTEI (1994): Late Pleistocene N-S shear zones along the Latium Tyrrhenian margin: structural characters and volcanological implications, *Boll. Geofis Teor. Appl.*, **36**, 507-522.

FUNICIELLO, R., E. LOCARDI and M. PAROTTO (1976): Lineamenti geologici dell'area Sabatina Orientale, *Boll. Soc. Geol. It.*, **95**, 831-849.

FUNICIELLO, R., G. MARIOTTI, M. PAROTTO, M. PREITE-MARTINEZ, F. TECCE, R. TONEATTI and B. TURI (1979): Geology, mineralogy and stable isotope geochemistry of the Cesano geothermal field (Sabatini Mts. volcanic system, Northern Latium, Italy), *Geothermics*, **8**, 55-73.

GAMBLE, T.D., W.M. GOUBAU and J. CLARK (1979): Magnetotellurics with a remote magnetic reference, *Geophysics*, **44**, 53-68.

GANDINO, A., R. LANZA, P. LA TORRE and M. MANZONI (1989): The role of remanent magnetization in magnetic interpretation of the Cimini-Vico area, *Boll. Geofis. Teor. Appl.*, **31**, 233-244.

INGHAM, M.R. (1988): The use of invariant impedance in magnetotelluric interpretation, *Geophys. J. R. Astron. Soc.*, **92**, 165-169.

MARQUARDT, D.W. (1963): An algorithm for least squares estimation of non-linear parameters, *SIAM J.*, **11**, 431-441.

MONGELLI, F., G. ZITO, N. CIARANFI and P. PIERI (1989): Interpretation of heat flow density of the Apennine chain, *Tectonophysics*, **164**, 267-280.

NICOLICH, R. (1989): Crustal structures from seismic study in the frame of European Geotraverse (Southern sector) and CROP project, in *The Lithosphere in Italy: Advances in Earth Science Research*, edited by A. BORIANI, M. BONAFEDE, G.B. PICCARDO and G.B. VAI, *Atti Accad. Naz. Lincei*, 41-61.

SCANDONE, R. (1990): Chaotic collapse of calderas, *J. Volcanol. Geother. Res.*, **42**, 285-302.

STERNBERG, B.K., J.C. WASHBURN and L. PELLERIN (1988): Correction for the static shift effect in magnetotellurics using transient electromagnetic soundings, *Geophysics*, **53**, 1459-1468.

VOZOFF, K. (1972): The magnetotelluric method in the exploration of sedimentary basins, *Geophysics*, **37**, 98-141.

WIGHT D.E. and F.X. BOSTICK (1980): Cascade decimation a technique for a real-time estimation of power spectra, in *Proceedings IEEE Int. Conf. on Acoustic Speech and Signal Processing*, 626-629.