

New magnetotelluric soundings in the Mt. Somma-Vesuvius volcanic complex: preliminary results

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Abstract

During 1997 ten magnetotelluric (MT) soundings were recorded in *single-site* mode above the Mt. Somma-Vesuvius volcanic area. A first campaign of MT measurements was carried out, during spring, by the researchers of the University of Padua with their MSPM acquisition system. During autumn, the researchers of the International Institute of Geothermal Research (CNR Pisa) with their Phoenix equipment performed a second campaign. At each site, the horizontal components of the electrical and magnetic fields were recorded in the frequency band between 300-0.003 Hz. The MSPM system could record signals up to the frequency of 800 Hz. Data were recorded at one common site with both the different equipments to verify the compatibility of the two different acquisition systems. The soundings over the area of the volcano's caldera show a continuous morphology of the apparent resistivity and phase curves with small error bars: it means a good correlation between the orthogonal electrical and magnetic fields. The quality of data decreases going further from the caldera and approaching the sources of electromagnetic incoherent noise such as villages, antennas and repeaters. After a very accurate data analysis, the apparent resistivity and phase curves were interpreted with a 1D modelling instead a 2D one as it seems a more appropriate interpretative approach looking at the morphology of the curves and taking into account the 3D geological conditions of the area. The results show an extended conductive structure at a depth of 0.3-1.2 km. It could be connected with a change in the physico-chemical characteristics of the volcano-sedimentary cover (alteration paragenesis and possible hydrothermalism). A 3D MT forward modelling was then used to define the response MT curves for sites above this particular volcanic structure. This approach seems to be very interesting in view of specific interpretative targets, such as dimension and position of the magma chamber, when planning future MT surveys.

Key words *magnetotellurics - volcanology - crustal exploration - Mt. Somma-Vesuvius*

1. Introduction

The deep structure of Mt. Somma-Vesuvius volcanic complex has been widely studied by means of volcanology, petrology and seismic

methods. Electric and electromagnetic information should be used to complement the previous data. Natural-source electromagnetic studies are used to determine the interior structure and to make out processes inside volcanoes, to infer magma feeding system and to understand volcanoes in their non-active phase. The integration of electric and electromagnetic studies with other geophysical methodologies could yield information on the physical mechanism of eruption and long-term hazard evaluation.

Mt. Somma-Vesuvius is a high risk active volcanic system because of its dangerous past activity (Scandone *et al.*, 1993; Santacroce *et al.*,

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1996). During the last few years many geophysical surveys have been promoted by the National Group of Volcanology of the National Research Council (CNR) to study the behaviour and the geological structure of this volcanic complex. Many researchers have worked in this area applying different geophysical methods (see Di Maio *et al.*, 1998; Zollo *et al.*, 1998; Fedi *et al.*, 1998; De Natale *et al.*, 1998).

From the results of the high-resolution seismic tomography carried out in 1994 (Zollo *et al.*, 1998) four main features emerge:

1) A sub-aerial 0.5 thick layer with low seismic waves velocity values.

2) A strong reflector at a mean depth of 2-3 km that is well-correlated with the buried top of the Mesozoic limestone.

3) A high-velocity body ($V_p = 3.5-4$ km/s and depth of 1-3 km), located under the Mt. Somma caldera rim, likely representing a sub-volcanic structure constituted by a dense network of solidified dykes.

4) A sharp transition to a very low-velocity zone at a depth of about 10 km.

The authors believe that it may represent the top of an extended magmatic reservoir whose lateral and vertical extension cannot, however, be constrained.

An integrated electrical and electromagnetic survey (Di Maio *et al.*, 1998) showed the existence of a shallow largely conductive zone closely in correspondence with the Somma caldera, due to an intensively altered and mineralized block of cemented volcanic breccia and a deep (10-15 km) conductive intracrustal layer with a resistivity of some hundreds of $\Omega \cdot m$. A more conductive zone (30-50 $\Omega \cdot m$), inside this layer, beneath the central Vesuvius apparatus was also detected.

The aim for the new MT survey was to increase the number of MT soundings to better define the geological structure of the volcano and its feeding system which can provide a mean to understand the mid-term maximum expected event.

2. Geological setting

The Somma-Vesuvius volcanic complex is a potash-rich eruptive center located in the Campanian plane and belonging to the Roman

Comagmatic province. The Campanian plane can be considered as a structural low filled with recent and present alluvium, marine, volcano-sedimentary and volcanic deposits. The area is bordered by Tertiary and Mesozoic limestone forming the sedimentary basement of the volcano and lowered during the Pliocene and perhaps Pleistocene by a system of listric faults (Principe *et al.*, 1987). The main geo-structural features and the setting of volcanism are likely connected with the thinning of the continental sedimentary and metamorphic basement related to the opening of the Tyrrhenian basin.

Several authors (*e.g.*, Barberi *et al.*, 1978; Santacroce, 1987 and Scandone *et al.*, 1991) suggested that the main feature of the Campanian plane is a structural depression, known as the «Acerra depression». The Somma-Vesuvius complex is located on a NE-SW trending faults system that borders the south-eastern edge of this depression. Information on the basement under the Vesuvian area is provided by the deep geothermal Trecase well intercepting the limestone series at about 1700 m below sea level (Balducci *et al.*, 1985).

The volcanic history of Mt. Somma is generally divided into four main periods (Santacroce, 1987). The first period (35 000-25 000 years bp) is characterised by lava flows with small-scale explosive activity. The second and third periods (25 000-3800 years bp) are instead characterised by explosive activity with plinian and subplinian events with maximum repose period of more than 4000 years, testifying that the volcano can be inactive for very long periods during its explosive phases. The fourth period can be divided into four cycles with explosive and effusive alternated activity. The Vesuvius cone started its growth during the third cycle (A.D. 472-1139). The last cycle starts with the A.D.1631 explosive eruption and ends in 1944 with the last effusive event. It has been characterised by Strombolian semi-persistent activity and lava emission. Since 1944 Vesuvius has remained inactive.

The location of the magma chamber and the characteristics of the feeding system of the volcano are still unclear. Rosi *et al.* (1987), on the basis of petrologic and isotopic studies, suggested the existence of a shallow reservoir hosted in the limestone layers at a depth of 3-4 km.

Cortini and Scandone (1982) hypothesised the presence of two magma chambers at 4-5 km depth. Belkin and De Vivo (1993) suggested a 4-10 km deep reservoir by fluid inclusion studies.

Santacroce *et al.* (1996) hypothesise a variable feeding system, with open or closed conduit, related to two different models of pre-eruption history. These authors suggest that the last cycle of Vesuvius activity (1631-1944) can be explained by the open conduit model with a shallow (1-2 km), continuously refilled, feeding system. The actual long period inactivity seems, instead, to indicate an evolution under a closed conduit condition with a deeper (5-7 km depth) and larger (1-2 km³) magma chamber.

3. Acquisition and data analysis

Ten MT soundings were carried out above the Somma-Vesuvius structure; the site position is shown in fig. 1.

MT data were recorded with two different equipments: one *MSPM* system and two *Phoenix V5*, real-time acquisition systems. The first system has recorded data at sites 1, 2, 3, 4 in three different frequency bandwidth: 800-1 Hz, 8-1/8 Hz, and 1-1/64 Hz. The second ones have recorded data at the remaining sites in the bandwidth: 320-60 Hz, 40-7.5 Hz and 6-0.03 Hz.

The four horizontal components of the electromagnetic wave were simultaneously record-

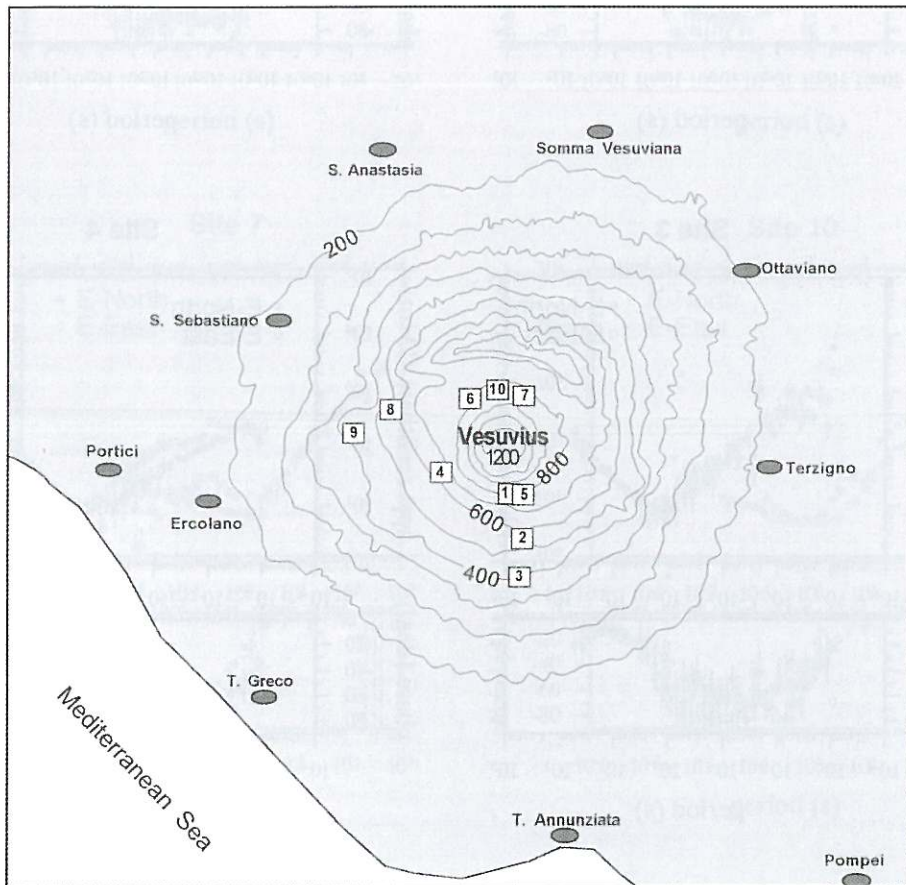


Fig. 1. MT soundings location of the study area.

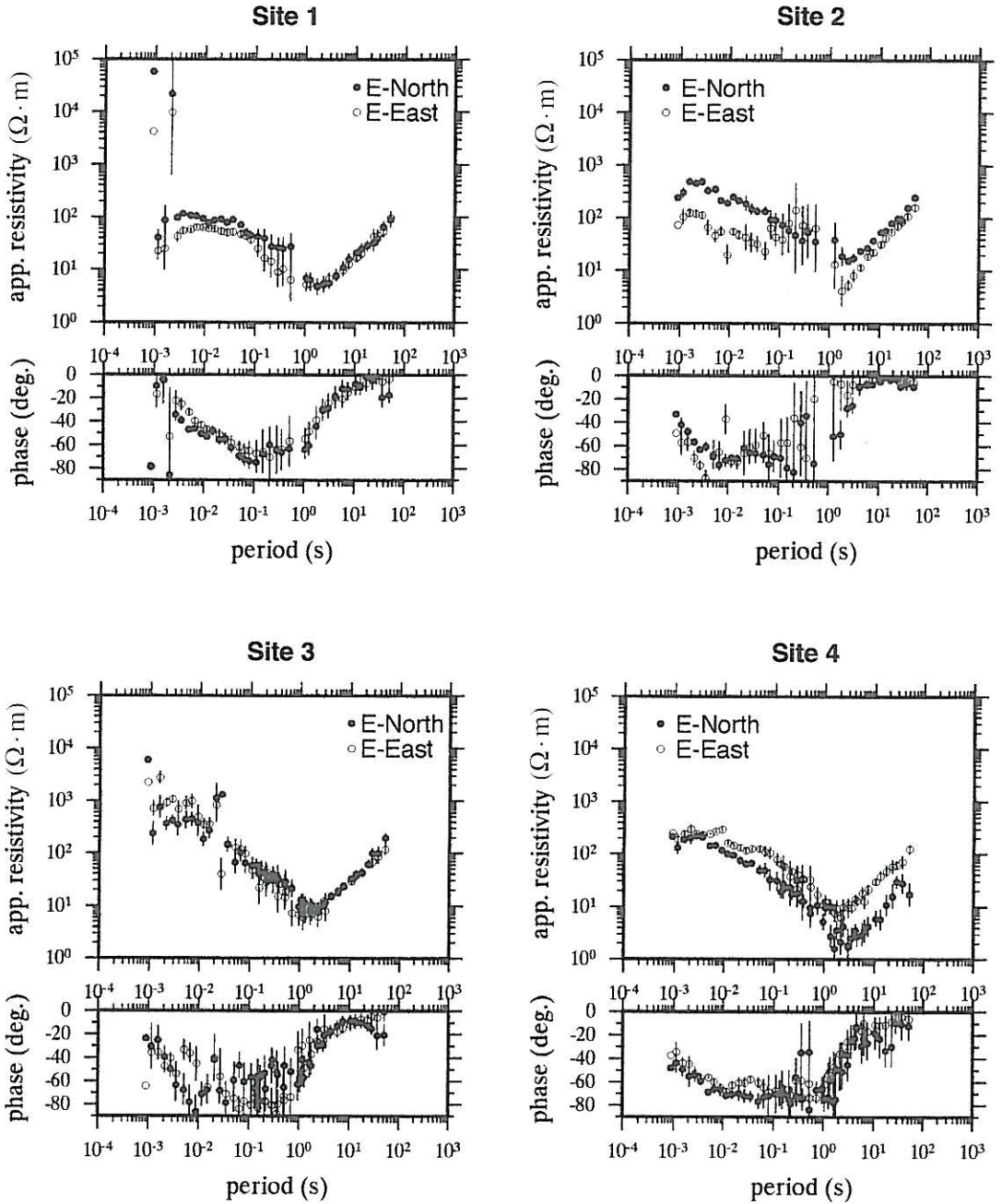


Fig. 2. Apparent resistivity and phase curves along N-S and E-W directions (MT sites: 1, 2, 3, 4).

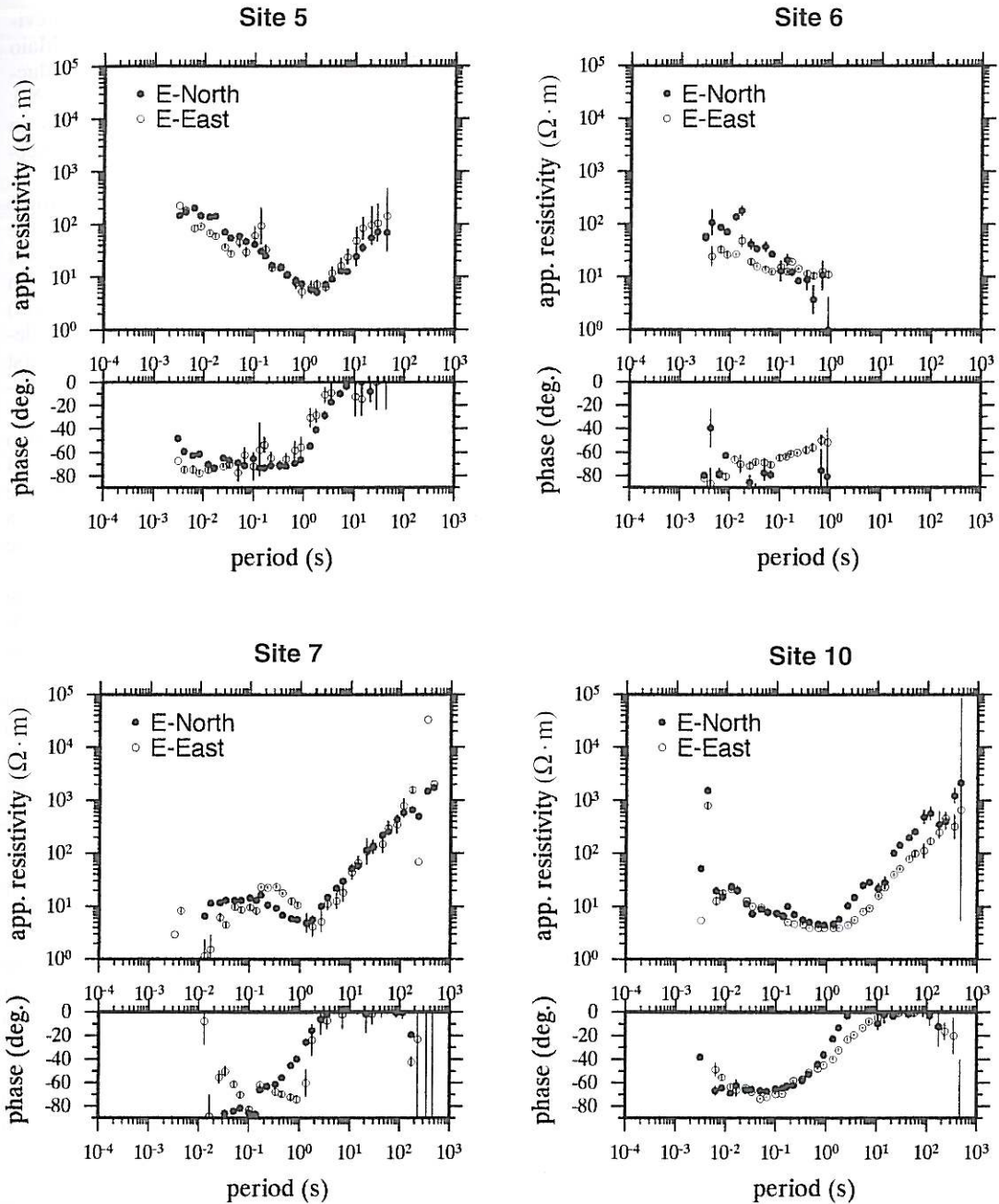


Fig. 3. Apparent resistivity and phase curves along N-S and E-W directions (MT sites: 5, 6, 7, 10).

ed in time domain and transformed by DFT in the frequency domain to obtain the least-squares impedance estimate including autopowers of the magnetic field components. Apparent resistivity and phase values along the measurement directions were also computed (Swift, 1967).

Soundings 1 and 5 were carried out in the same geographical position, by the two acquisition systems, in two different periods of the year. The obtained results are similar and confirm the good compatibility of the two acquisition systems and of the data processing techniques (see fig. 2).

The data quality is good for sites above the caldera but it becomes worse going towards west, approaching the urban centre of Ercolano. For this reason, soundings 8 and 9, showing large error bars and dispersion of data, have not been used for the interpretation of the area.

The apparent resistivity and phase curves for all sites used in the modelling and interpretation are shown in figs. 2 and 3. They display a similar pattern, attesting the presence of a three layer electrostratigraphic sequence (high-low-high resistivities). The curves show, at periods higher than 1 s, similar behaviour with high apparent resistivity values. At lower periods the apparent resistivity, ranging between 10 and 500 $\Omega \cdot m$, shows lower values at sites inside the caldera area (sites 6, 7, 10).

Curves at all sites in figs. 2 and 3 show a coincidence of the two polarization modes. The geological structure in a volcanic area such as this one is known to be complex and have 3D features. Hence, a 2D inversion modelling seems not to be appropriate since it could introduce spurious effects.

A 1D inversion modeling of the data was carried out to define two electrostratigraphic sequences along two profiles at N-S and WSW-ENE directions. The results of these 1D inversions are shown in fig. 4.

The obtained electrostratigraphic sequences for both profiles show a three layer structure «resistive-conductive-resistive».

The intermediate conductive layer (2.5-5 $\Omega \cdot m$) has a constant thickness along the N-S profile and it deepens towards the south. Along the WSW-ENE profile it does not deepen so much but it increases its thickness towards the

west (site 4). These features agree with a previous model inferred from direct current (Di Maio *et al.*, 1998) showing a shallow largely conductive zone closely in correspondence to the Mt. Somma caldera. It has been described as an intensively altered and mineralized block of cemented volcanic breccia.

According to volcanologic and petrologic studies (Santacroce *et al.*, 1996. See also the *geological setting*) the last cycle of Vesuvius activity (1631-1944) can be explained by an open conduit model with a shallow (1-2 km) feeding system continuously refilled. The development of a hydrothermal system in the first two kilometres of the volcano-sedimentary cover is suggested.

Recent results of seismic tomography point to the existence of a high-velocity body ($V_p = 3.5-4$ km/s, depth of 1-3 km), located under the Mt. Somma caldera rim, likely representing a sub-volcanic structure, constituted by a dense network of solidified dikes.

We suppose that the subvolcanic structure inferred by the seismic data might be genetically connected with the «shallow plumbing system» suggested by Santacroce *et al.* (1996).

On the other hand, the sequence overlying this sub-volcanic structure (hydrothermalized volcanic rocks) has likely lower resistivity values than the subaerial layers, made by fractured lava and volcanic scoriae. Residues of hydrothermalism cannot be excluded. The sub-volcanic structure itself can instead explain the sharp transition to high resistivity values for depths greater than 1.5 km. For this reason, we suggest that the strongest changes in resistivity of the first two kilometres are connected either with the physical and chemical setting of a common matrix of volcanic rocks or with a change from volcanic to sub-volcanic structures.

Any consideration on the deep (> 2 km depth) electrostratigraphy of the area deriving from *inversion* of data seems to be unsure. The part of the resistivity curves having periods higher than 1 second seems in fact to be contaminated by coherent-correlated electromagnetic noise.

However, starting from the shallower electric evidence some suggestions can be drawn on the basis of 3D *forward* modelling.

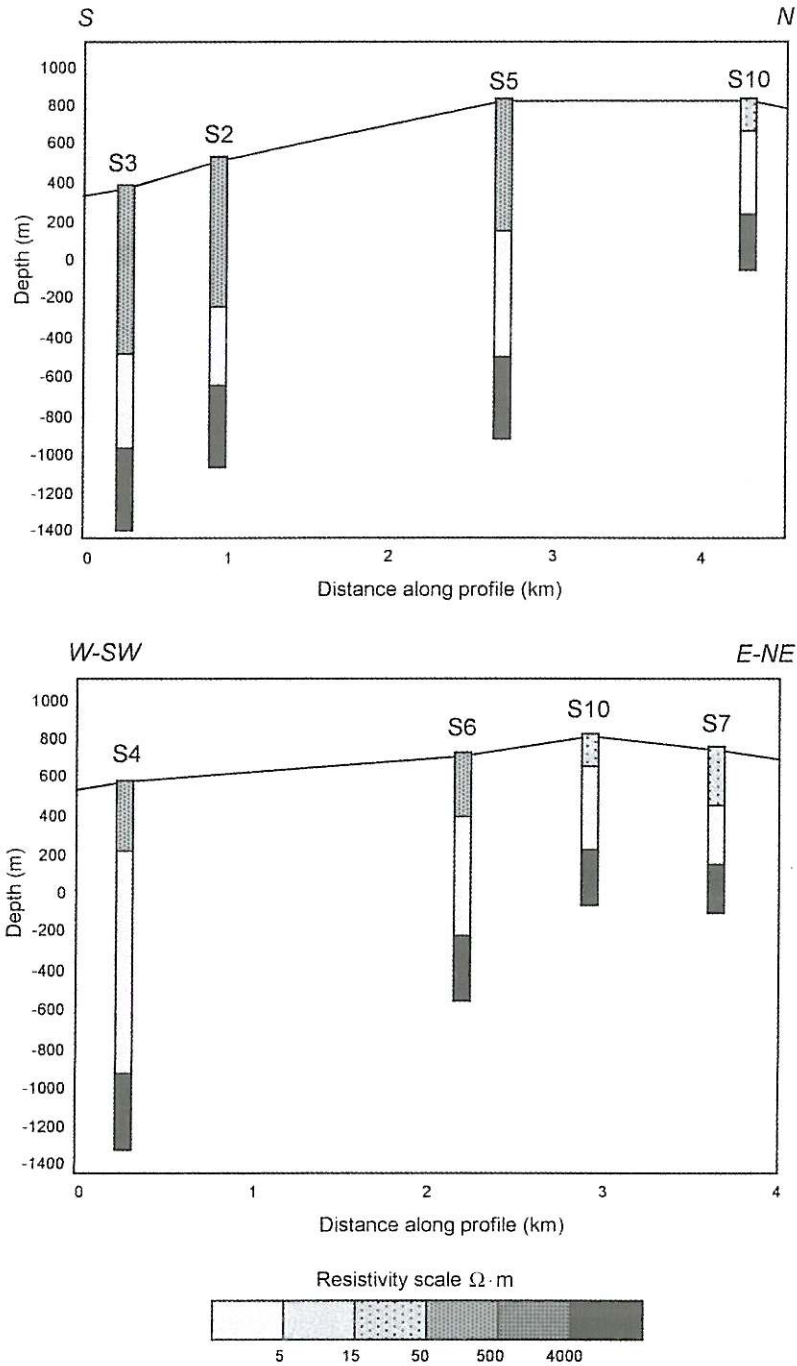


Fig. 4. Electrical 1D interpretation along a N-S and a WSW-ENE profile.

4. Forward 3D modelling

By means of our MT data it was possible to define a shallow resistivity pattern that was interpreted according to volcanological and geological indications. In particular, the three layer electrostratigraphic sequence was related to a change in the physico-chemical characteristics of a common matrix of volcanic rocks.

Our data do not show any drop in resistivity at periods higher than 10 s, so there is no indication of a deep (> 5 km) magmatic and conductive body. Assuming that a deep magmatic body produces a sharp drop in resistivity, it was interesting to understand why our data missed it. The detectability of the magma chamber was then tested computing the magnetotelluric responses of various feeding systems suggested for Vesuvius. Due to the three-dimensional nature of the study area, a 3D forward modelling code (Mackie *et al.*, 1993) was used.

According to volcanologic and petrologic suggestions (Santacroce *et al.*, 1996) the electrical features of the magma chamber were investigated modelling various 3D conductive bodies: the apparent resistivity and phase response curves were calculated at increasing distance from the vertical of the conductive body.

The bodies, with different lateral dimensions, were put at various depths inside a bedrock with $1000 \Omega \cdot \text{m}$ constant resistivity representing carbonate-metamorphic sequence underlying the Vesuvian volcanic area. The electrostratigraphic sequence, previously obtained by mean of the 1D inversion modelling, defines the shallower portion of the models. All the models take into account the presence of the Tyrrhenian Sea. For all the models, the first 3 km structure is a sequence of three layers having resistivity values of 150, 5 and $300 \Omega \cdot \text{m}$ (see figs. 5a,b and 6a,b). Due to the presence of the sea, all the models are characterised by a N-S very shallow strike direction.

According to Newman *et al.* (1985), the detectability of 3D conductive bodies embedded in resistive media is a difficult task. In our case, the closeness of the Vesuvian area to the coast line plays an important role on the detectability of the conductive bodies. Several different 3D models showed that the drop in resistivity curves

connected with the conductive body is strongly affected by the currents injected into the middle and lower crust by the presence of the Tyrrhenian Sea.

Two models are presented in figs. 5a,b and 6a,b (Model 1 - Model 2), along with the response apparent resistivity and phase curves.

The first one (fig. 5a,b) consists of a 3D prismatic conductive body ($10 \Omega \cdot \text{m}$) with base area of 1 km^2 . The top of the body has a depth of 5 km and its vertical extension is 4 km. The second one (fig. 6a,b) is a prismatic body ($10 \Omega \cdot \text{m}$) with a base area of 0.16 km^2 . Its vertical extension is again 4 km but the top of the body has a depth of 7 km.

For the two models, the shape of the resistivity and phase curves is almost the same. Calculated resistivity responses show the following features:

- A drop of values at higher frequencies due to the shallow conductive layer.
- A bipolarization, connected to the presence of the sea.

The effect of the 3D conductive body is clearly visible for periods higher than 1000 s for the polarization having the electric field parallel to the coast line. It consists in a drop in the apparent resistivity reaching its minimum between 8000 and 9000 s. The $5 \Omega \cdot \text{m}$ shallow conductive layer shifts toward lower periods the drop in resistivity of the 3D bodies.

Different symbols of the resistivity and phase curves displayed in figs. 5a,b and 6a,b refer to different sounding positions (see captions). The curves at various distances from the vertical to the conductive body are very similar, especially for the smaller and deeper body of Model 2. For periods higher than 10000 s, Model 1 displays instead different curves for different sounding positions. The general trend is a weaker rise in resistivity for soundings closer to the vertical of the body.

5. Conclusions

In soundings over a restricted area close to Vesuvius caldera, MT data are highly correlated and coherent: the apparent resistivity and phase curves show small error bars and low dispersion

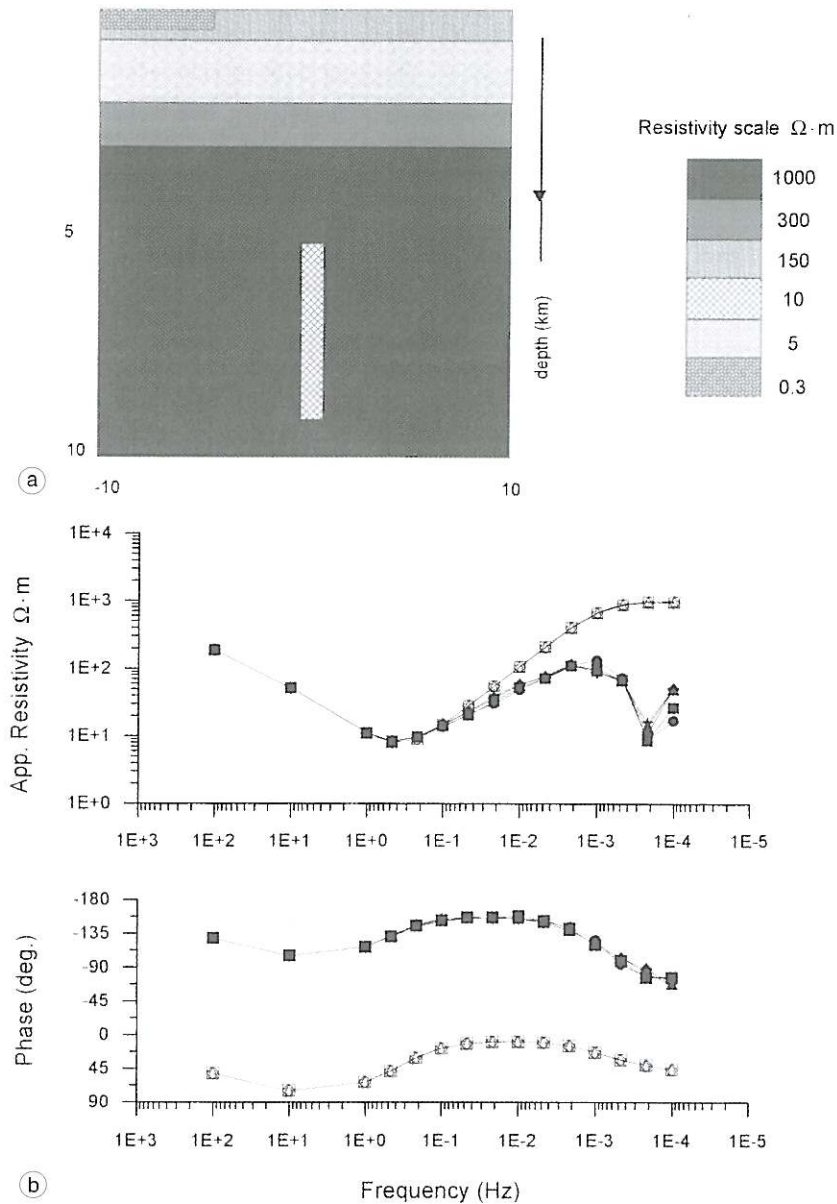


Fig. 5a,b. a) 3D electrical model for a 5 km deep magma chamber. It is modelled by a 3D prismatic conductive body ($10 \Omega \cdot m$) with base area of 1 km^2 . The top of the body has a depth of 5 km and its vertical extension is 4 km. The shallow dotted layer models the features of the Tyrrhenian Sea. The drop in resistivity due to the 3D body is clearly visible on the polarization having the E-field parallel to the coast line (E-North), here represented by filled symbols. b) Apparent resistivity and phase response curves. Different symbols refer to various sounding positions with respect to the vertical of the conductive body: circles = 0 km (vertical); squares = 0.35 km; diamonds = 0.65 km; triangles = 1.5 km; stars = 3 km.

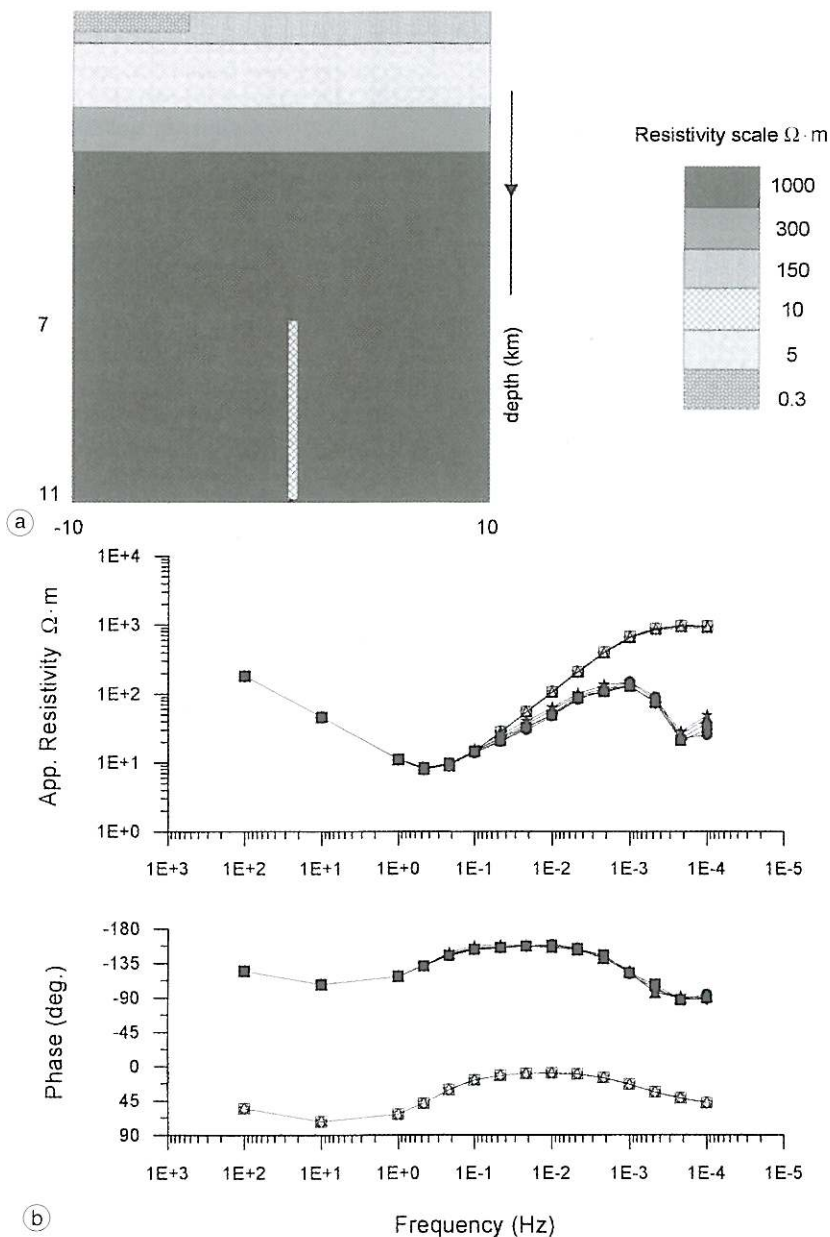


Fig. 6a,b. a) 3D electrical model for a 7 km deep magma chamber. It is modelled by a 3D prismatic conductive body ($10 \Omega \cdot m$) with base area of 0.16 km^2 . The top of the body has a depth of 7 km and its vertical extension is 4 km. The shallow dotted layer models the features of the Tyrrhenian Sea. See fig. 5a,b for comments. b) Apparent resistivity and phase response curves. Different symbols refer to various sounding positions with respect to the vertical of the conductive body: as in fig. 5a,b - circles = 0 km (vertical); squares = 1 km; diamonds = 2 km; triangles = 3 km; stars = 4.5 km.

of data. Going further from the caldera, MT data show the effect of the uncorrelated noise, mainly at higher frequencies, due to high level of urbanization which produces strong cultural noises. According to this consideration two MT soundings have not been used in interpretation; from the other sites it was possible to model the shallower part of the volcanic complex up to the depth of 2 km b.s.l..

The 1D inversion modelling has shown a three layer structure «resistive-conductive-resistive». The intermediate conductive layer has a resistivity of 2.5-5 $\Omega \cdot m$ and depth of 0.3- 2 km b.g.l. The shallow resistivity values are higher by one or two order of magnitude. This strong drop in resistivity is probably connected with the physico-chemical setting of a common matrix of volcanic rocks (compactness, cementation and mineral alteration). The subaerial layers are made of fractured lava and volcanic scoriae. Small residues of hydrothermalism, involving the deepest part of the first two kilometres of the volcano-sedimentary cover, cannot be excluded. These suggestions are in agreement with volcanological and seismic data (Zollo *et al.*, 1998; Santacroce *et al.*, 1996).

Comparing our data to those of previous MT surveys (Di Maio *et al.*, 1998) the apparent resistivity curves show the same shape but they are shifted to lower resistivity values. Our interpretation appears, hence, quite different from the one defined, in the same paper, by the MT data. The obtained 1D electrostratigraphic sequence agrees, instead, with the model inferred by Di Maio *et al.* (1998) from direct current methods.

The shift effect is very common in MT data and various attempts have been made in literature to face it (*e.g.*, Ranganayaki, 1984). *A priori* it is not possible to define which data are correct; all of them could suffer different shifts. It is, hence, important to collect data by a different methodology which is not affected by shift problems. At the moment a new electromagnetic TDEM survey is planned in the area; their results should solve the doubts about MT interpretation and make all the data, old and new, compatible.

The lowest frequency data seem to be affected by some coherent and correlated noise which

can mask information at depth. It behaves as a sort of controlled source MT signal and should be removed from the natural field by remote-referenced acquisition. In the near future new MT remote-referenced survey is planned to try to overcome this problem.

However, in order to quantify the influence on the apparent resistivity and phase curve of a conductive 3D body representing the possible magma chamber, various 3D buried bodies have been forward modelled. The volumes of the modelled bodies did not exceed 4 km³.

The effect of these 3D conductive bodies is clearly visible for periods higher than 1000 s for the polarization having the electric field parallel to the coast line. In the resistivity curves it produces a strong drop reaching its minimum between 8000 and 9000 s.

Some considerations emerge from the 3D modelling:

- The detection of a magma chamber seems to be possible even if it is relatively small.
- The presence of the shallow conductor in the volcano-sedimentary cover contributes to increase the period showing the drop in resistivity related to the deeper magma chamber.
- The presence of the Tyrrhenian Sea plays an important role in the detection of the buried bodies.

It seems that if we want to define the deep geological structure for the Mt. Somma-Vesuvius we have to record MT data at least up to 10000 s.

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