RESISTIVITY STRUCTURE ON THE WESTERN SIDE OF Mt. AMIATA REGION

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ABSTRACT

A magnetotelluric survey was carried out in southern Tuscany, Italy, on the western side of the Mt. Amiata geothermal region The main purpose of this survey was to map the resistivity structure of an area which does not belong to the classical geothermal zones but is still characterized by anomalously high heat flow Furthermore a recent updating of the Southern Tuscany geothermal anomalies would refer this area as a western extension of the Mt Amiata geothermal anomaly Five components of the electric and magnetic fields have been recorded at the various locations in the area, which were few kilometers apart The one-dimensional resistivity inversion of the data shows a low resistivity zone characterized by high heat flow Based on one-dimensional resistivity information, detailed two-dimensional resistivity modelling has been carried out. A reasonable two-dimensional resistivity model is proposed for shallow to middle depths, and it is found to be in good agreement with the available geological and geophysical informations on the area

1. INTRODUCTION

Tuscany, in central Italy, is one of the better known geothermal region in the world. Geothermal exploration and exploitation have been carried out in the Larderello area for about a century. More recently another geothermal area was found, which takes the name from the extinct volcano Mt Amiata where it is centered (Figure 1)
Mt Amiata is a rhyolite-to-latite volcano not older than 441000 years From a geologic-structural and thermal point of view Mt Amiata and Larderello geothermal fields, which lie 70 km apart from each other, show considerable similarities. As well as Larderello, Mt. Amiata field is located on a structural high, which corresponds to a large relative gravimetric minimum.
The apparent contraddiction can be correlated to a light magmatic body which resides below the area, giving rise to the heat flow data maximum on the same area. Here the cap rock, mainly represented by flysch facies formations ("Ligurids") and clayly Neogene formations, is contineous and effective. The reservoir is constituted - like in Larderello - by the chiefly carbonate and anhydritic formations of the Tuscan Nappe and the underlying metamorphic units Productive fractures are located immediatly below the cap rock (500-1000 meters b g l), inside a belt with relatively reduced thickness - in the order of 150 meters. Permeability decreases below this belt, and increases again generally below roughly 1500-2000 meters This deep fracturing of metamorphic rocks does not show a link to any precise geologic-structural feature It could be explained by a juvenility of magmatic processes (Baldi *et al.*, 1993b). On the other hand, the shallower fractures are probably due to the overlapping of Ligurids on the Tuscan Nappe
The fluid circulating in all these fracture systems is water at hydrostatic pressure. This represents the main difference with Larderello field, which is characterized by saturated or superheated steam. The difference is likely due to the much higher natural drainage in the Larderello field because its huge natural manifestations at surface and the older exploitation of the field (Baldi *et al.*, 1993b)

Even though the link between Mt Amiata and Larderello geothermal field is evident, the regional assesment of the geothermal prospect was not fully exploited The main purpose of this survey was to map the resistivity pattern outside the classical geothermal areas, in order to clarify the general geological conditions of the region and to delineate new possible interesting areas for geothermal exploitation The survey was stimulated by recent heat flow measurements (Baldi *et al.*, 1993a) which showed anomalously high values also outside the classic areas
A magnetotelluric (MT) survey was carried out on the western side of Mt Amiata, covering about one half of the distance to the Larderello area The 9 sites of the sounding, at an average distance of 3 km from each other, lay along a NW-SE profile (Figure 2)
Geologic informations refers only to the shallower structures and are summarized in the geologic cross-section in Figure 2
Very limited geophysical information about the region is known The available heat flow data are mainly from the southern part, they point out not only a progressive increase of temperature approaching the Mt Amiata, but also define an anomalously high heat flow area on the western side of the volcanic area (Baldi *et al.*, 1993a) (Figure 3)
This same area, which was crossed by our profile, shows a very low resistivity anomaly at shallow depths

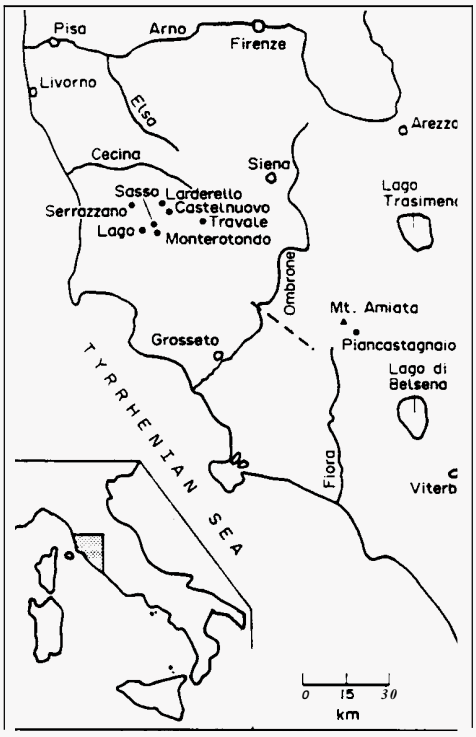

Figure 1. Sketch of southern Tuscany and profile location (dashed line)

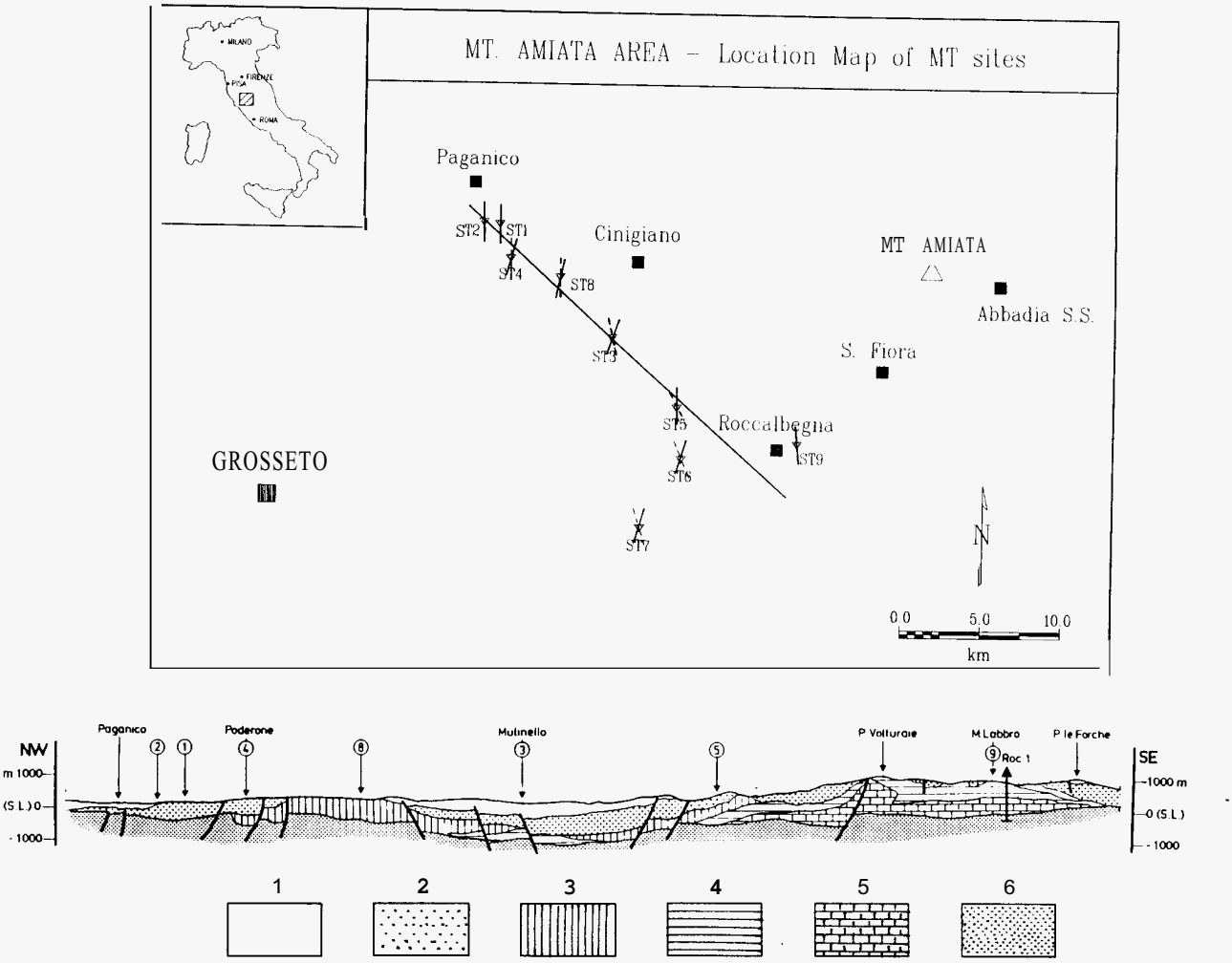

Figure 2. Location map of MT sites (triangles) and cross-section. The strike directions for low frequency range (dashed line) and high frequency range (solid line) are shown at each site. Below, inferred geological cross-section Legend 1) Neogenic formations, 2) Flysch facies complex "Ligurids", *3)* Macigno formation (Tuscan Nappe), 4) Scaglia formation (Tuscan Nappe). 5) Carbonatic formations (Tuscan Nappe), 6) Anhydritic formations (Tuscan Nappe)

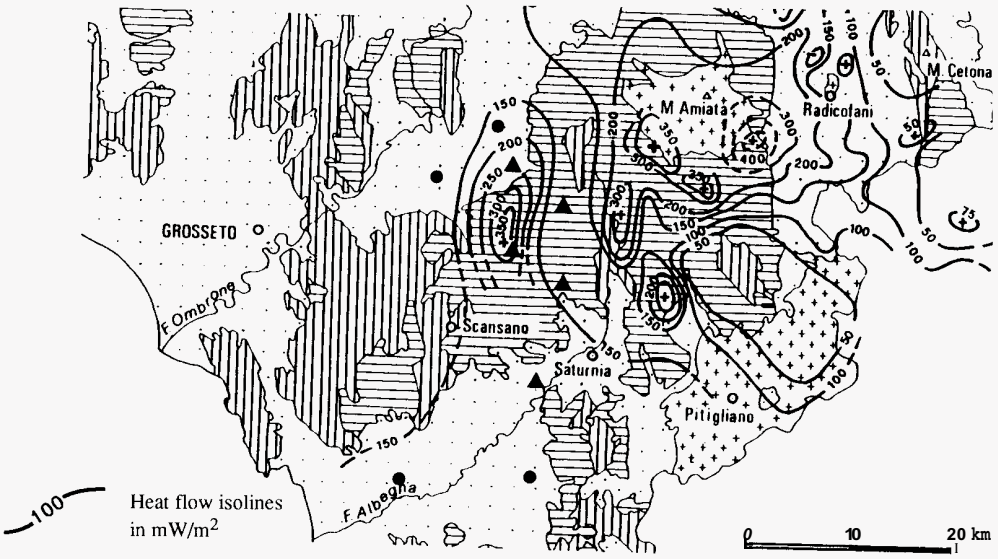

Figure 3. Heat flow data map of the Amiata region After Baldi *et al* , 1993a

2. THE MAGNETOTELLURIC SURVEY

Using two Phoenix **V5** systems, magnetotelluric data have been recorded at 9 locations along the profile shown in Figure 2. Two of these sites do not lay exactly on the profile, but at orthogonal direction to verify the dimensionality of the structure. Simultaneous telluric and magnetic field components were measured in two orthogonal directions (measurements axes): E_x, E_y, H_x, H_y, H_z (x northwards, y eastward and z downward) Electric fields have been

recorded using unpolarizable Pb-$PbCl_2$ electrodes, using a cross-shaped layout with electrode separation of 120 m The horizontal components of magnetic field were measured using two induction coil magnetometers whereas the vertical magnetic field was recorded using an air-loop

The MT data were acquired at 40 discrete frequencies logarithmically spaced from 320 to 0 0005 **Hz** at 7 data points per decade The signal was recorded with a sampling frequency ranging between 2560 **Hz** to **24** Hz, depending on the frequency band A cascade decimation (Wight & Bostick, 1980) was then applied to filter out the random noise The data, transformed to frequency domain by Discrete Fourier Transform coefficients, were cross-multiplied with their complex conjugates to produce auto and crosspowers (Vozoff, **1972).** The latter were further used to compute the impedence tensor, from which apparent resistivity and phase values were derived as a hnction of frequency. Then the processed data were carefully edited to subtract the effect of incoherent noise

Apparent resistivity and phase in two-polarization have been plotted at each station, and are shown in Figure **4.**

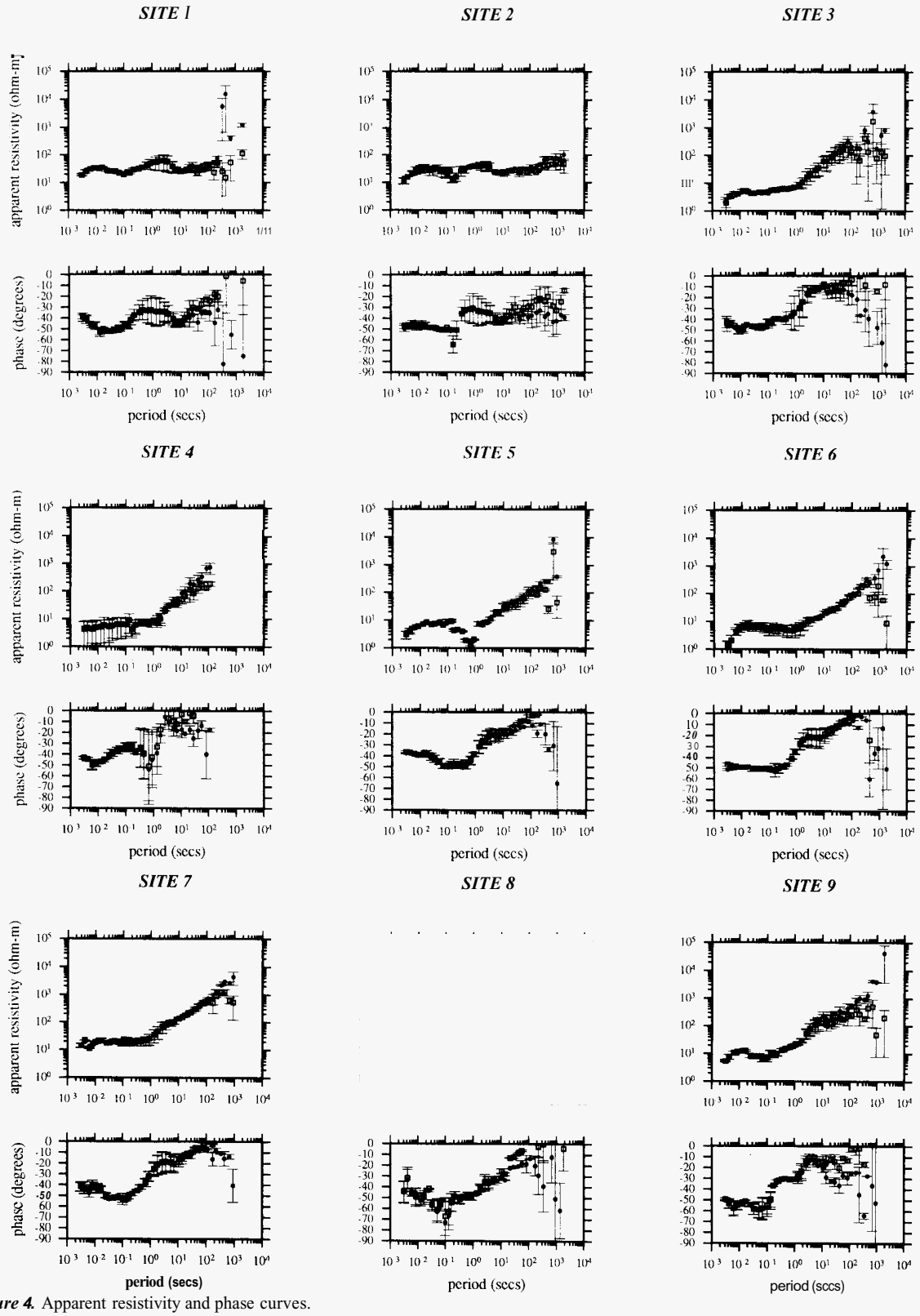

Figure 4. Apparent resistivity and phase curves.

The quality of data was found to be good at most of the sites. Most of the sites display a NNE-SSW strike direction, i.e., orthogonal to the profile's one, at periods shorter than some seconds (see Figure 2) Below a certain depth all the sites display a N-S or slight NNW-SSE strike direction, whch is more compatible with the regional trend. The shallow strike direction can be related to a graben structure evidenced by geological maps and shown in the geological cross-section. This graben, filled at surface of Neogene sediments, is limited on the **SE** by a main fault with N-S direction, which borders an uplift of the Tuscan Nappe formations where site 9 resides, as shown in Figure 2 In the following discussion the data sites were rotated to N30°E, i.e., orthogonal to the profile direction, which corresponds to the shallow strike direction for most of the sites. In this direction the apparent resistivity and phase curves show almost the same value in both polarizations. Rotating the data in the direction of regional tectonic trend we obtained a significant difference in the two modes at some site, for period larger than few seconds This fact can be attributed to the presence of a resistivity anisotropy at great depth with three dimensional features. For the moment only a shallow interpretation has been attempted, reaching only those depths where a two dimensional interpretation can be considered good enough. The behaviour of apparent resistivity and phase curves show a higher resistivity at a great depth. However. the most peculiar feature is the increase in conductivity located below sites 5 and 6 **A** clear picture can be found in Figure *5,* where the apparent resistivity pseudosections of Transverse Magnetic (TM) and Transverse Electric (TE) modes are shown

The first stage of interpretation was to model the apparent resistivity curves in terms of layered structure. Since most of the curves show different apparent resistivity values in the two (TM and TE) modes, we had to choose the curve to model Since the geologic and tectonic structure of the area is quite complex, we chose to use the invariant apparent resistivity (Ranganayaki, 1984) for our ID modelling, which should give more accurate estimates

Site **4** shows a strong static **shift** at higher frequencies, and site 8 is quite noisy at the same frequency range. Modelling of the shallowest part of those sites were mainly based on the phase values.

The one-dimensional (1-D) inversion of apparent resistivity and phase was performed using a conventional parametric inversion technique (Whittal & Oldenburg, 1986). The apparent resistivities and phases fit well with the three to five layered model. **A** cross-section based on invariant curves inversion is shown in Figure ***6***. It begins to give an idea of the resistivity pattern in the area. a zone of extremely low resistivity (< 5 ohm m) and sensible thickness exists below sites 5-6, at a shallow depth.

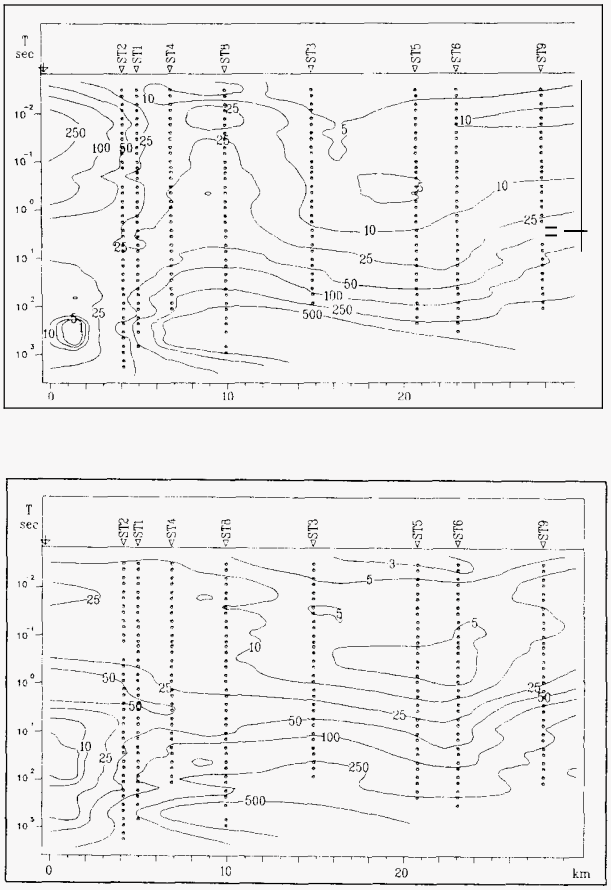

Figure 5. Apparent resistivity pseudosections for TM (above) and TE (below) modes

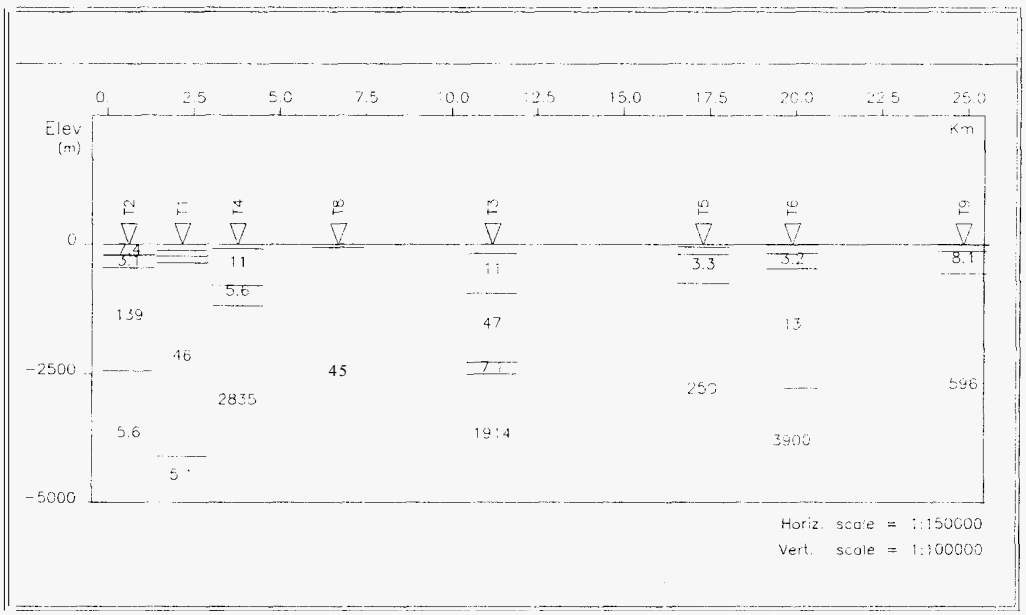

Figure 6. Resistivity cross-section along profile. Models were obtained with the 1-D inversions of invariant values for each site

3. MODELLING THE SHALLOW ELECTRICAL RESPONSE

On the base of the geological section (Figure 2) and of the results of a preliminary 1-D inversion of data. based upon resistivity and phase values (Figure 6), we defined the starting model for a two-dimensional (2-D) forward modelling.

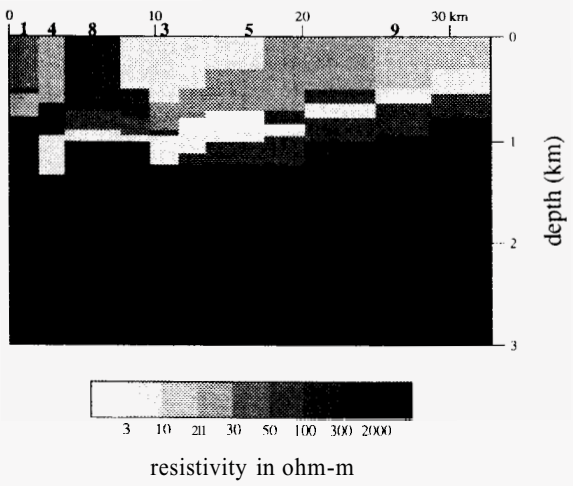

Figure 7. 2-D forward model

The 1-D results could give just a rough idea of the structure since the latter shows an appreciable anisotropy The 2-D model presented in Figure 7 **is** the result of an extensive trial-and-error forward model testing with the Wannamaker (Wannamaker *et al.*, 1986) algorithm, and is only a schematic response along the profile.

It shows a good agreement of real and synthetic apparent resistivities and phase (Figure 8) data, and fulfils also the geological constraints. The resistivity values used in the modelling are those obtained by electric sounding data (Albo *et al.* 1974) in other parts of Tuscan region for the same kind of rocks In Figure 7 it **is** possible to follow the location of the horizons masked at the surface by the flysch cover. The northern stations, 1 and 2, are not yet clarified and the fit was not good enough. It requires an extension of the model to further parts beyond those strictly investigated The almost constant resistivity with depth could be due to the presence of a strong nearby conductor which drives all the deep currents. This conductor could be related to shallow warm and salty waters like those found in zones not so far from those sites **A** different tectonic condition related to the Monticiano-Roccastrada structure, possibly allochthonous (Burgassi *et al.*, 1979) could also be recalled The situation will be subject for further investigations. For modelling of the data obtained from stations **4** and 8, we have used the same criteria of the I-D inversion, i.e., the high frequency part was modeled mainly on phase values Site 9 shows not very well explained features; probably they are related to nearby areas which were not crossed by our profile. **A** very thick conductive layer must be modelled below sites *5* and ***6*** to explain the shape **of** the relative curves These sites correspond to the area where the highest heat flow was observed (see Figure 3). Below this very conductive layer a little more resistive layer can be found. which seems to be spread over the whole profile

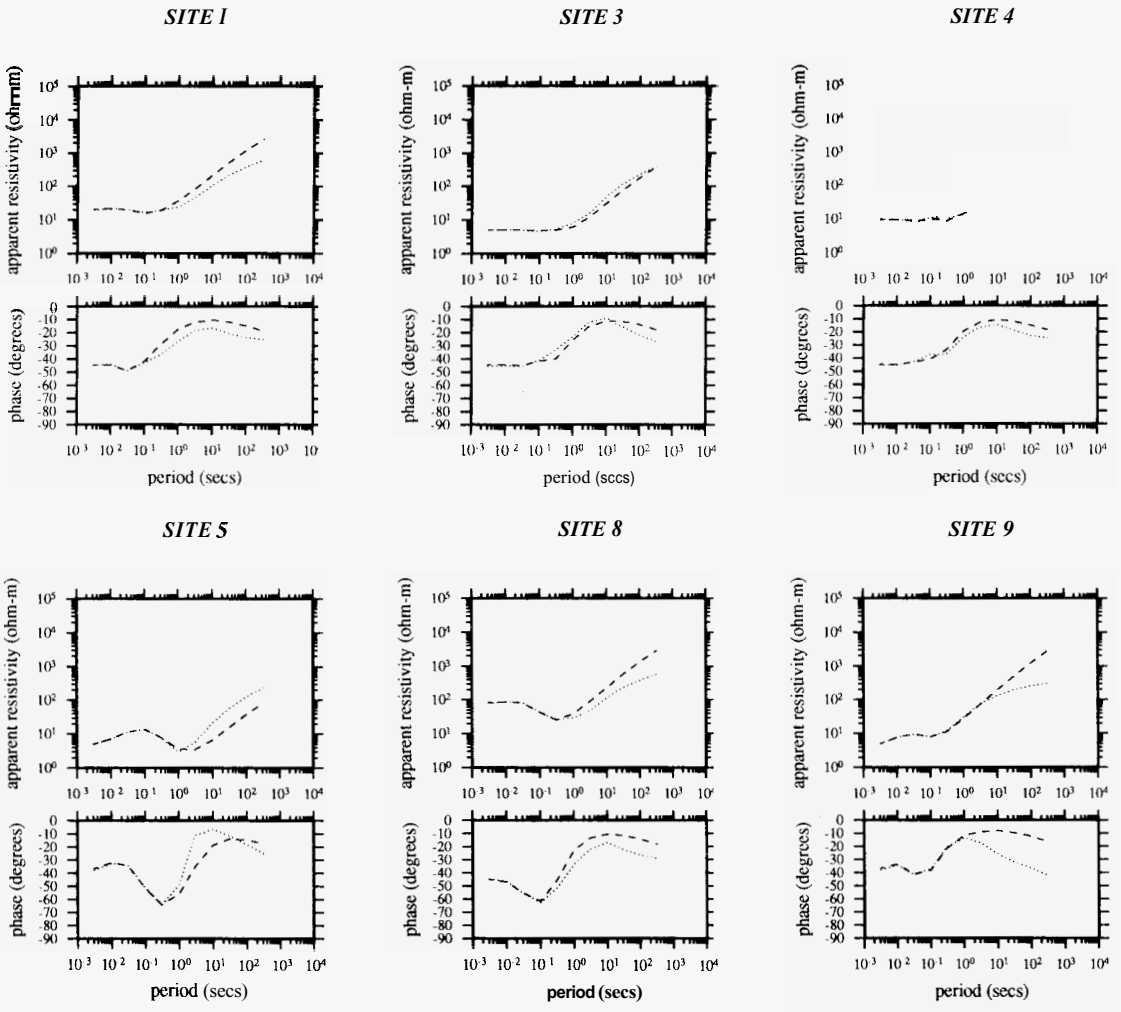

Figure 8. Computed curves for the model in Figure 7

This layer. with a resistivity of about 6-7 ohm-m, is located at the base of the Ligurids or at the top of Tuscan Nappe It could be related to a fracture system due to the overlapping of Ligurids over Tuscan Nappe formations, the same kind of mechanism which occurs in Mt Amiata area Below sites 5 and 6, this fracture system could be tilled with hot fluids, giving rise to the thermal anomaly recorded on the surface

4. CONCLUSIONS

The magnetotelluric responses recorded along one side of Mt Amiata geothermal region were in good agreement with the limited available information in the area The shallow structure has been reconstructed on the basis of electrostratigraphic features related to geologic formations. It shows a conductive anomalously thick horizon in the area where maximum heat flow was recorded The 2-D model based on the present result shows a quite undisturbed and flat area Our profile lays along the regional strike direction, therefore the apparently simple structure comes out with no surprise. The presence of very low resistivity zones near the surface shields the deeper structure, however a reasonable deeper model of the area can be achieved from the modelling of the long period magnetotelluric response in future The present results show an extension of low resistivity anomalous zone outside the classic Mt Amiata area which needs further investigation

REFERENCES

Albo M , Cameli G M and Cataldi R (1974) *Studio della conducibilita' elettrica delle rocce nell'area di Larderello* ENEL, Internal report

Baldi P , Bellani S , Ceccarelli A , Fiordelisi A , Squarci P and Taffi L (1993) *Correlazioni tra le anomalie termiche ed altri elementi geofisici e strutturali della Toscana meridionale* Studi Geologici Camerti, Vol 111993 (in press)

Baldi P , Bertini G and Ceccarelli 4 (1993) *Geothermal fields of Central Italy* Resources Geology Special Issue, Vol 16, pp 69-81

Burgassi F , Costantini A , Dell'Agnello L , Lazzarotto A and Sandrelli F (1979) *Esame dei rapporti tra le formazioni metamorfiche del basamento nella Torcana a sud dell'Arno* Mem Soc Geol It, Vol 20, pp 123-133

Ranganayaki R P (1984) *An interpretive analysis of magnetotelluric data* Geophysics, Vol 49, pp 1730-1748

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

Wannamaker P E., Stodt J A and Rijo L (1986) *Two dimensional topographic responses in magnetotellurics modeled using finite elements* Geophysics, Vol 51, pp 2131-2144

Wight D E and Bostick F X (1980). *Cascade decimation- a technique for real rime estimation of power spectra* '80 Proceedings IIEE International Conference on Acoustic Speech and Signal Processing, April 9-11, 1980, Denver, CO pp. 626-629

Whittall K P and Oldenburg D.W (1986) *Inversion of magnetotelluric data using a practical inverse scattering formulation* Geophysics, Vol 51, pp. 383-395