Magnetotelluric measurements in the Monte Amiata region

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Abstract
A preliminary magnetotelluric (MT) survey was carried out in Southern Tuscany, Italy, to delineate the resistivity structure in an area which does not belong to classic geothermal zones but is still characterized by anomalously high heat flow. The one-dimensional (1-D) resistivity inversion shows a low resistivity zone characterized by high heat flow. Based on 1-D resistivity information, detailed two-dimensional (2-D) resistivity modelling was carried out. A reasonable 2-D resistivity model was proposed for shallow depths, and was found to be in good agreement with the available geological and geophysical information on the area. The present results show a low resistivity anomaly, characterized by high heat flow. The anomaly seems to extend beyond the classic Mt. Amiata geothermal region.

Key words *magnetotelluric – modelling*

1. Introduction

Tuscany, in Central Italy, is one of the better known geothermal regions 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 (fig. 1).

In the past, geophysical investigation was limited within these areas, therefore the regional assessment of the geothermal prospect was not fully exploited and the geological relation between Larderello and Mt. Amiata is still undefined although the two areas are 70 km apart from each other. 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 (Bellani *et al.*, 1993) 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 (fig. 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 in temperature approaching Mt. Amiata, but also define an anomalously high heat flow area which seems to have no close connection to the volcanic area (Bellani *et al.*, 1993). The same area, which was crossed by our profile, shows a very low resistivity anomaly at shallow depths.

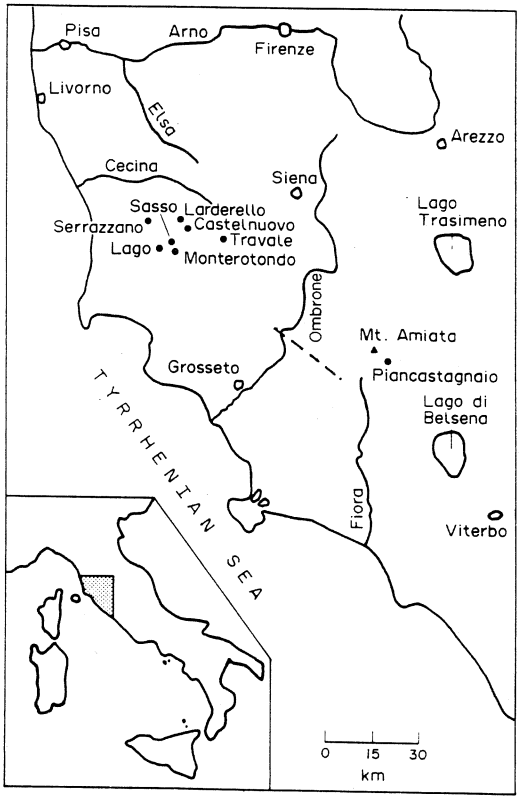

Fig. 1. Sketch of Southern Tuscany and profile location (dotted line).

2. Geological and structural setting

Surface geological data define in sufficient detail the stratigraphy and the tectonic setting of the cover complex, made by sedimentary neoautochthonous formations and by the underlying «Ligurian» and «Subligurian» allochthonous units.

The outcrops of these units cover almost entirely the whole area crossed by our profile and conceal the features of the underlying formations belonging to the «Tuscan Series» on which the Ligurian nappes are overthrusted.

Surface geology indeed provides scant information on the local setting of the «Tuscan Series», which occurs in small outcrops of its upper units only, «Macigno» (sandstones) and «Scaglia» (calcareous shales), and some patches of Jurassic limestones. These patches are strips of formations ripped from the substratum and resulting from the splitting up of the whole «Tuscan Series».

The series is overthrusted at the level of the «Burano Formation» (Upper Triassic) (Calamai *et al.*, 1970; Giannini *et al.*, 1971). Most of the units of the «Tuscan Series» have been sheared off and fractured due to the extensional tectonics in the region (Cameli *et al.*, 1993). Anidrites and dolomites of the «Burano Formation» are therefore the first horizon at depth with a certain degree of continuity, whose thickness ranges from one to several hundred meters. This horizon is sometimes affected by large shearing or piling up phenomena. Below the «Burano Formation» the metamorphic formations made by granites, phillites and metagreywackes (Triassic-Carboniferous) is inferred. This assumption comes either from the presence of outcrops in the nearby areas of Monticiano-Roccastrada or from the stratigraphy of the wells drilled in the Mt. Amiata area (Pandeli *et al.*, 1988).

Below the above mentioned formations, at depths not less then 4-5 km, micaschysts and gneisses belonging to the Tuscan crystalline basement are supposed to exist, as from the studies of the metasedimentary xenolites of the Mt. Amiata lavas (Van Bergen, 1983).

As for the shallow tectonic features, the following elements are visible from NW to SE along the reference cross-section:

– a small irregular depression corresponding to the Paganico flat area crossed by the Ombrone river;

– a local N-S trending structural high at Poggi del Sasso;

– a shallow Mio-Pliocene basin in the Cinigiano area, corresponding to a graben type feature and trending N-S or NNE-SSW;

– a folded and thrusted structure made by sheared formations belonging to the Mesozoic carbonate parts of the Tuscan Series. This structure is pointed out by narrow outcrops of the topmost part of the fold with the axis elongated in a N-S direction, in the area Poggio Volturaie – Mt. Labbro.

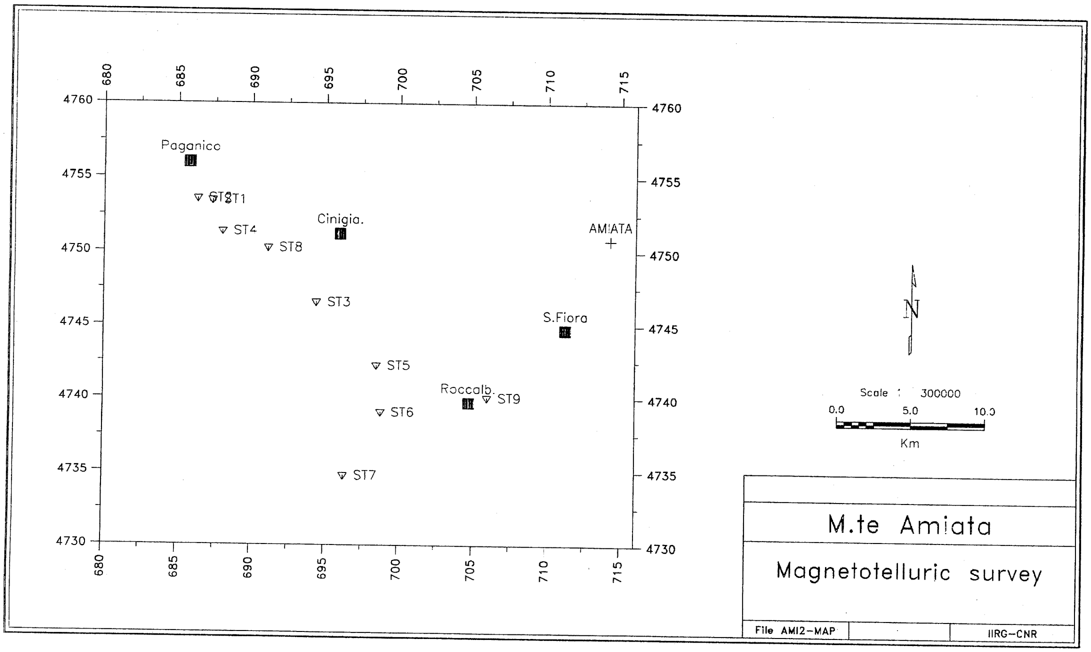

Fig. 2. Distribution of MT stations.

The above mentioned structures, which are sketched in the profile on fig. 3, are also underlined by weak residual gravity anomalies (a few mGal), consistent with the shallow depth of the source (Mouton, 1969 and ENEL unpublished data).

3. The magnetotelluric survey

Using two Phoenix Geophysics V5 systems, magnetotelluric data have been recorded at 9 locations along the profile shown in fig. 2. Two of these sites do not lie exactly on the profile, but at orthogonal directions to verify the dimensionality of the structure. Electric fields were recorded using unpolarizable Pb-PbCl2 electrodes. Using a cross-shaped layout with electrode separation of 120 m, the two components of the electric field were recorded in a north-south and east-west direction. On the same directions, the orthogonal components of horizontal magnetic fields were measured using induction coils whereas the vertical magnetic field was recorded using an air-loop (fig. 4).

The MT data were acquired at 40 discrete frequencies logarithmically spaced from 320 to 0.0005 Hz at 7 data points per decade. The data, transformed by DFT coefficients, were cross-multiplied with their complex conjugates to produce auto and crosspowers. These latter were further used to compute the impedence tensor, from which apparent resistivity and phase values were derived as a function of frequency. The processed data were further carefully edited to subtract the effect of incoherent noise.

Apparent resistivity and phase in two-polarization were plotted together with the strike at each station, and are shown in figs. 5 to 7. The quality of data was found to be good at most of the sites and the behaviour of apparent resistivity and phase variations were found to vary drastically from site to site. At lower periods, apparent resistivity shows almost the same values in both the polarizations, whereas at higher

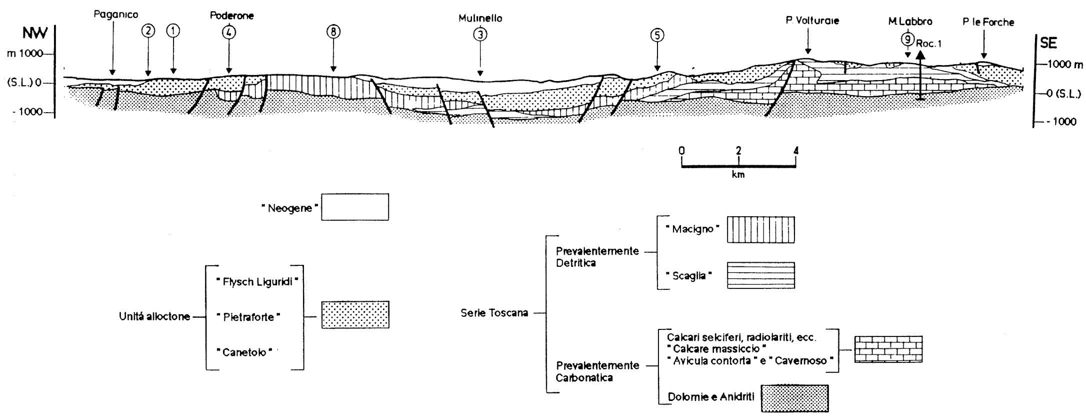

Fig. 3. Inferred geological profile.

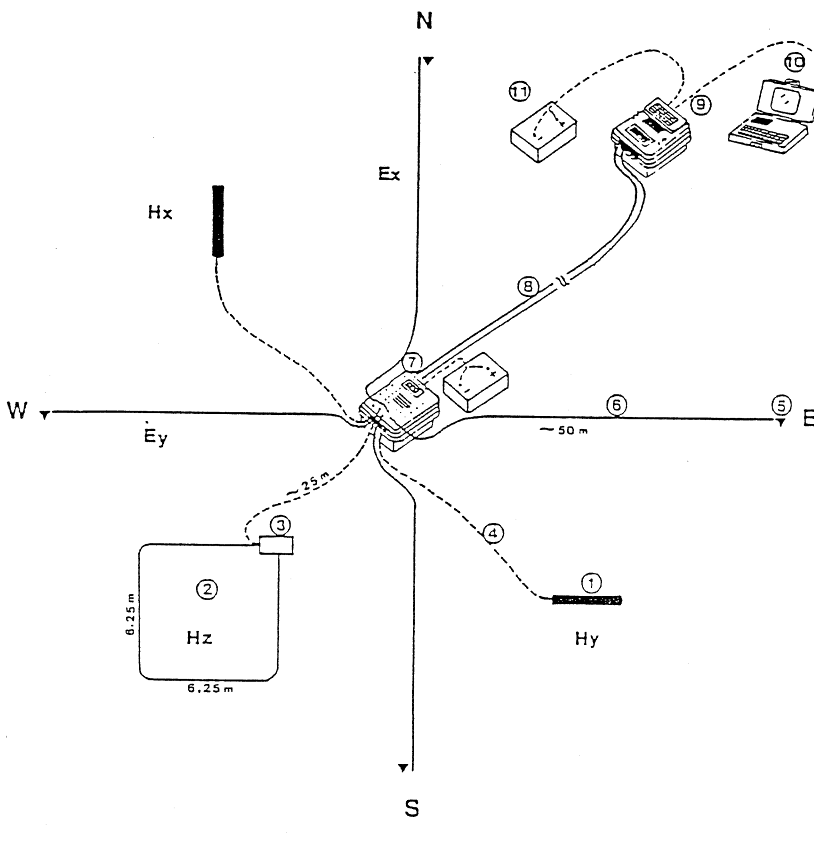

Fig. 4. Layout scheme: 1 = magnetic sensor, 2 = air loop, 3 = air loop preamplifier, 4 = coil cable, 5 = electrode, 6 = telluric cable, 7 = sensor processor, 8 = comunication cable, 9 = V5 acquisition system, 10 = personal computer, 11 = 12V battery.

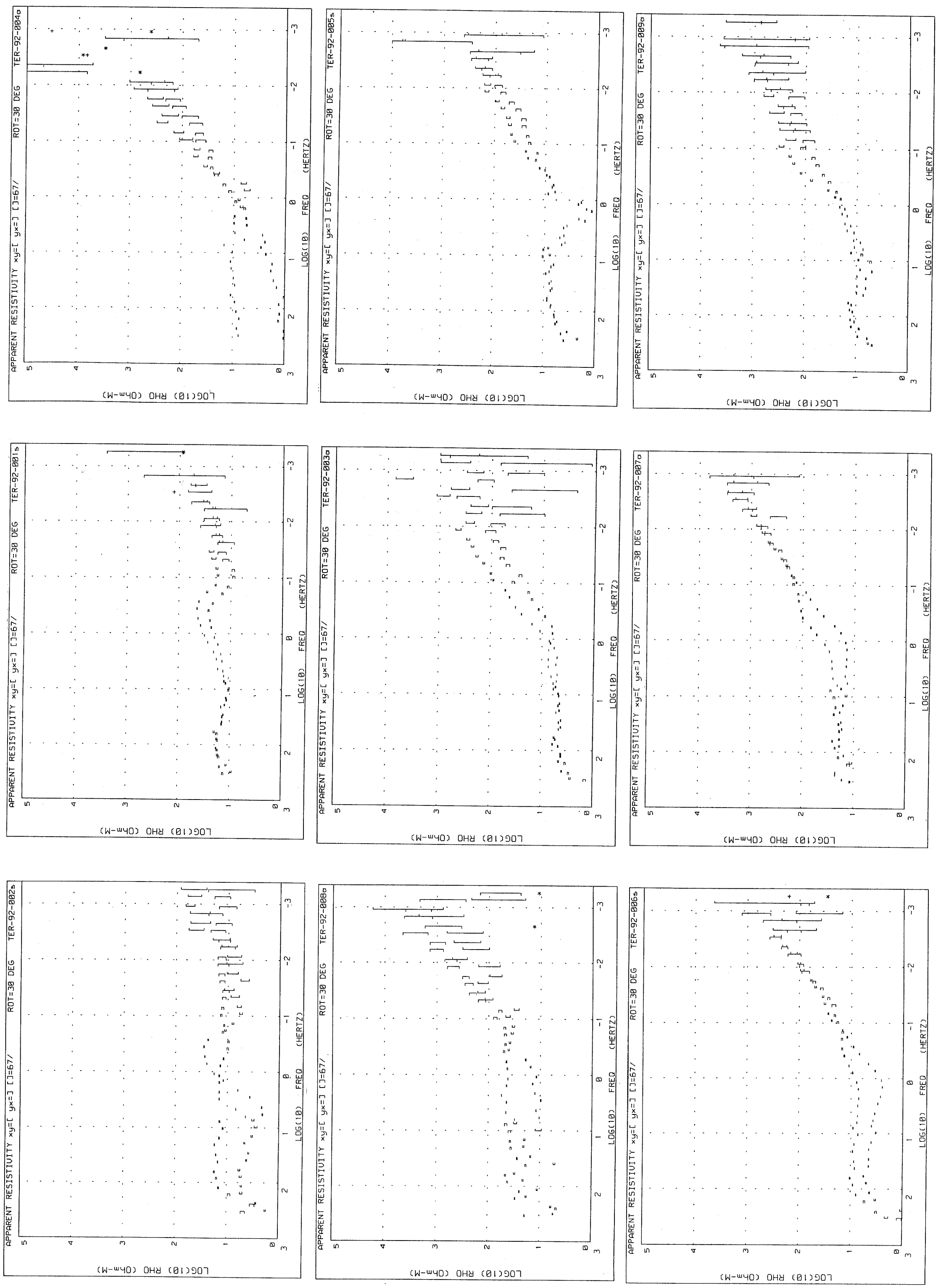

Fig. 5. Apparent resistivity curves.

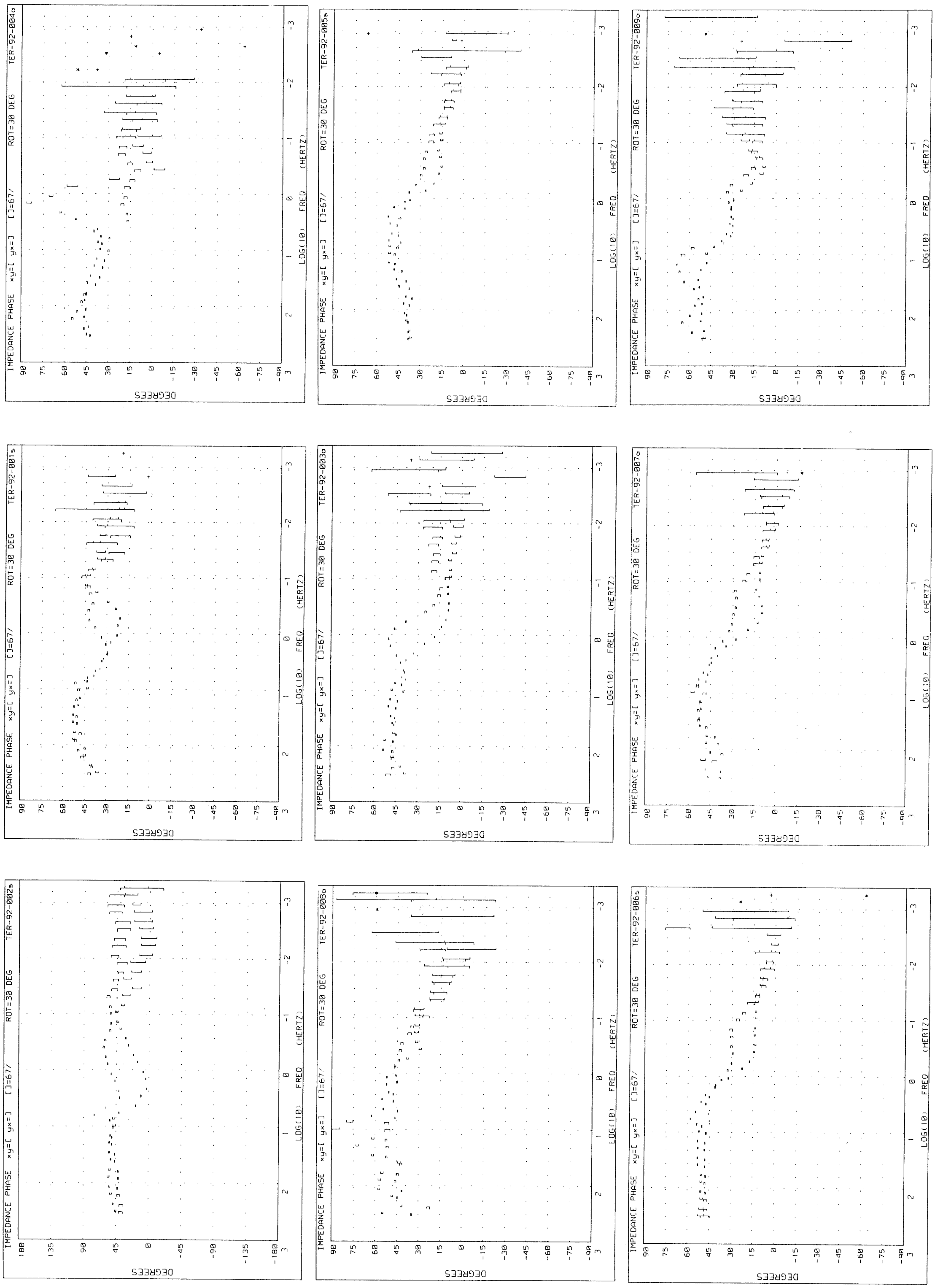

Fig. 6. Phase curves.

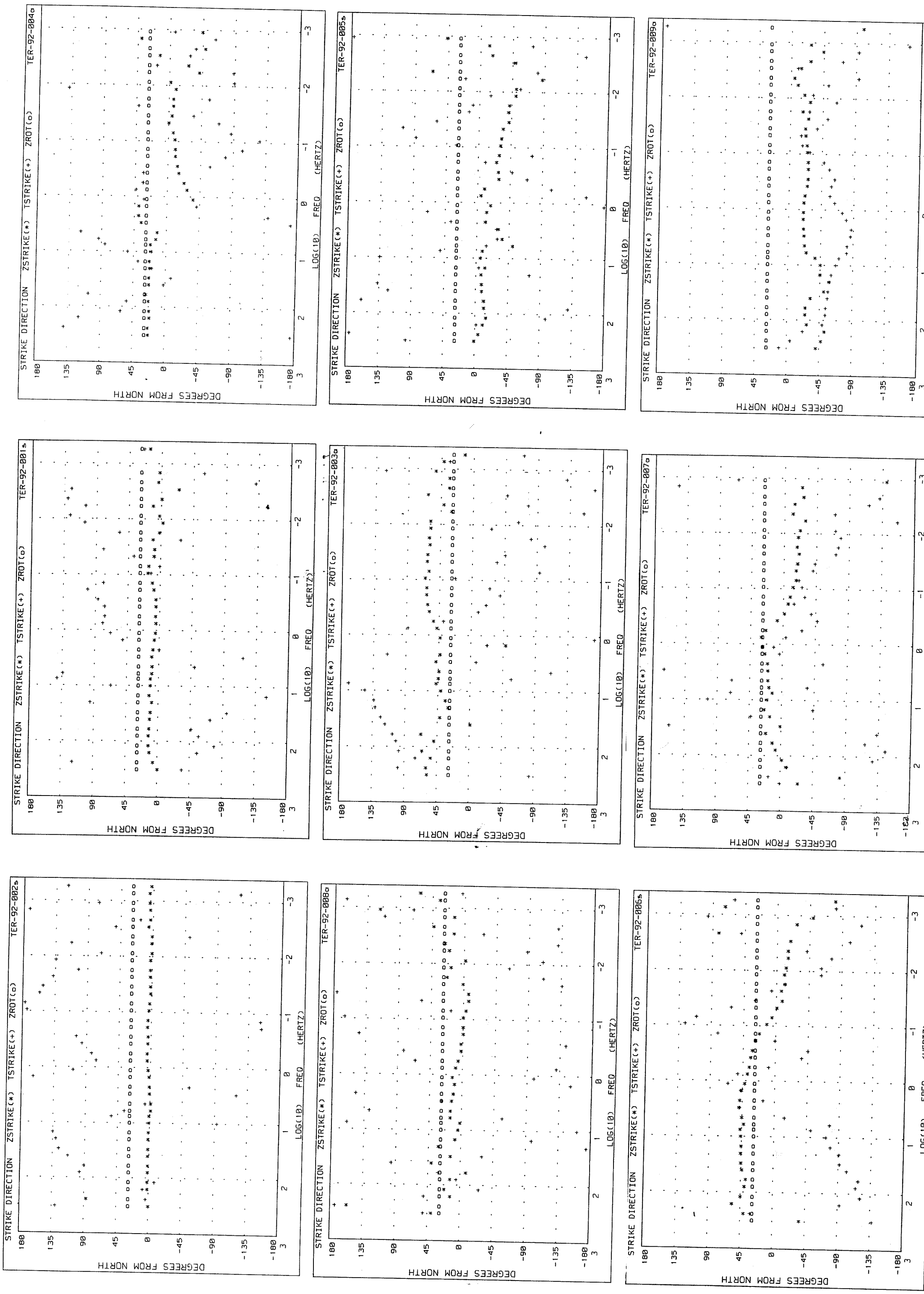

Fig. 7. Strike curves.

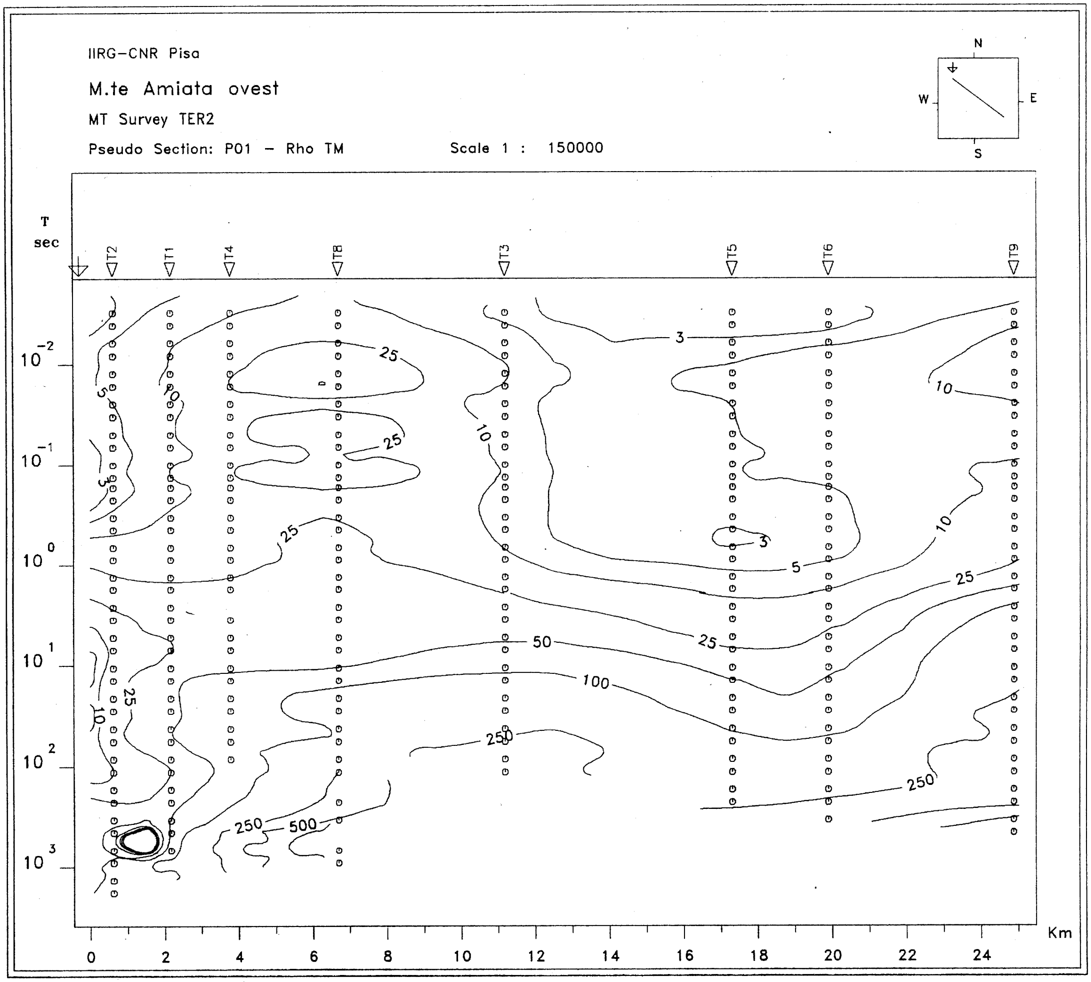

Fig. 8. Apparent resistivity pseudosection for TM polarization.

periods the values show a significant difference in the two modes. This fact can be attributed either to the effect of a two-dimensional structure at deeper level or due to the presence of a resistivity anisotropy at great depth. The behaviour of apparent resistivity and phase curves shows a higher resistivity at a great depth.

Most of the sites in fig. 7 display a strike direction NNE-SSW, *i.e.*, orthogonal to that of the profile, at periods shorter than some seconds. This can be related to the graben structure already shown in the geological section and evidenced by geological maps. Below a certain depth all the sites display a NNW-SSE strike direction, which is more compatible with the regional one.

A pseudosection based on invariant curve inversion is shown in fig. 8. It begins to give an idea of the resistivity pattern in the area: a very strong conductive feature is evident below sites 5 and 6.

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 1-D 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 was mainly based on the phase values.

The 1-D inversion of apparent resistivity and phase was performed using a conventional parametric inversion technique (Whittal *et al.*, 1986). Results are shown in fig. 9. The apparent resistivities and phases are found to fit well with the three to five layered model. A zone of extremely low resistivity (< 5 ohm.m) and sensible thickness exists below sites 5-6, at a shallow depth.

4. Modelling the shallow electrical response

On the basis of the geological section (fig. 3) and on the results of a preliminary 1-D inversion of data, based upon resistivity and phase values, we took the starting model for a 2-D forward modelling.

The 1-D results could give just a rough idea of the structure since the latter shows an appreciable anisotropy. The 1-D modelling usually provides quite correct layer resistivities but underestimates interface depths.

The 2-D model presented in fig. 10 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 (fig. 11) data, and also fulfils the geological constraints.

The northern stations, 1 and 2, are not yet

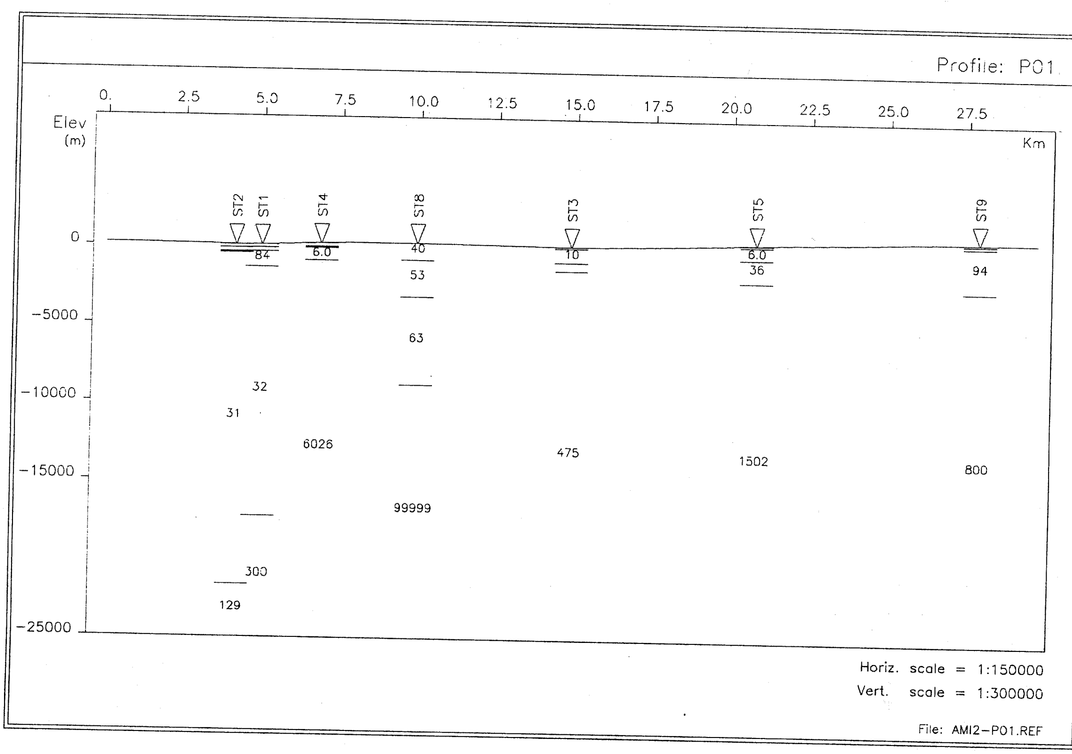

Fig. 9. 1-D inverse modelling result.

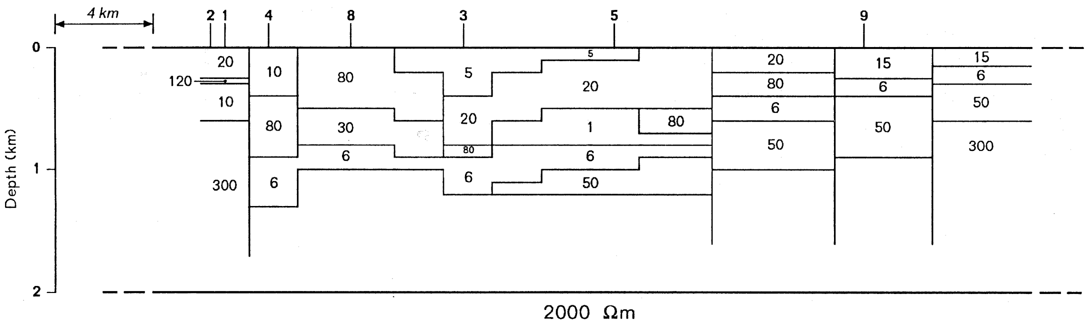

Fig. 10. 2-D forward modelling result.

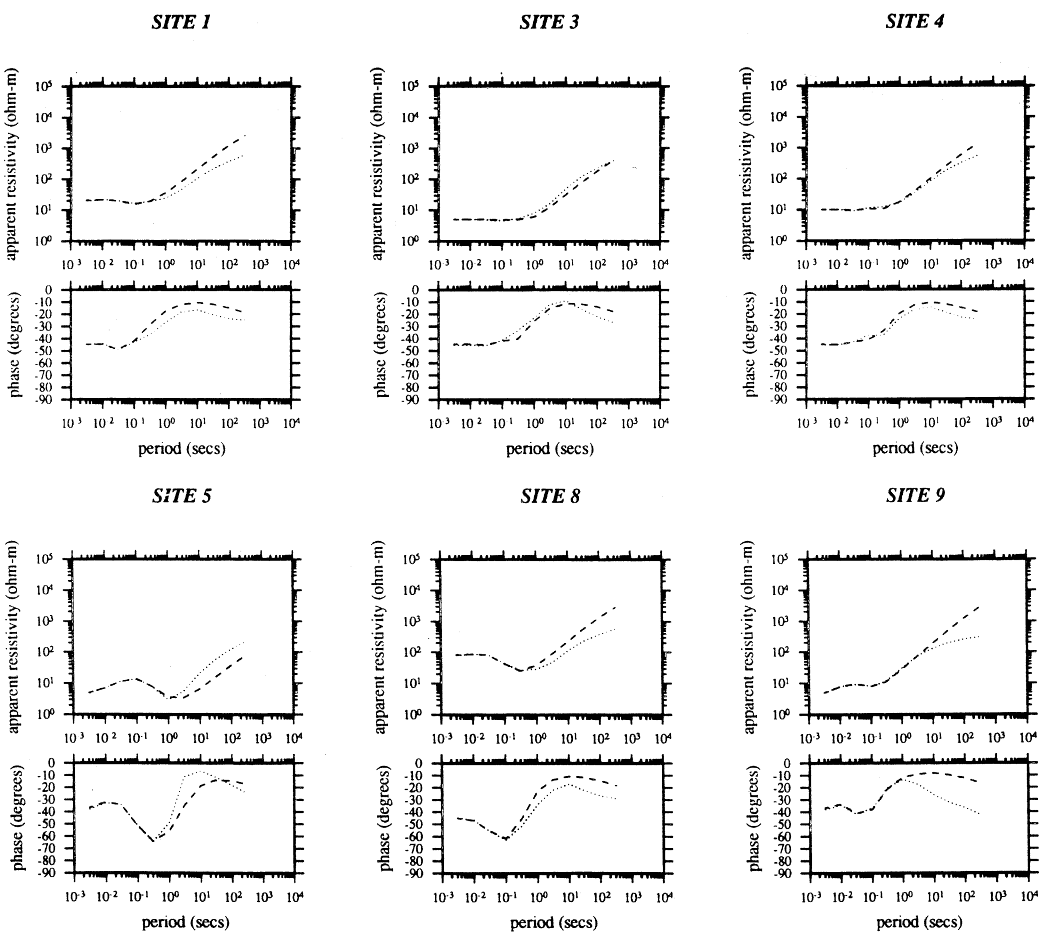

Fig. 11. Computed apparent resistivity and phase curves.

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 conductor nearby which drives all the deep currents. This conductor could be related to shallow warm and salty water like that 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 the subject for further investigations.

The resistivity values used in the modelling are those obtained by electric sounding data (Albo *et al.* 1974, ENEL unpublished data) in other parts of Tuscan region for the same kind of rocks. In fig. 10 it is possible to follow the setting of the horizons masked at the surface by the flysch cover. A very thick conductive layer must be modelled below sites 5 and 6 to explain the shape of the relative curves. This site corresponds to the area where the highest heat flow was observed (Bellani *et al.*, 1993).

For modelling of the data obtained from stations 4 and 8, we used the same criteria as the 1-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.

5. 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 lies 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.

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