ANNALI DI GEOFISICA, VOL. 41, N. 3, August 1998

Electrical features of deep structures of Southern Tuscany (Italy)

Adolfo Fiordelisi (1), **Randall Mackie** (2), **Adele Manzella** (3), **Don Watts** (4) **and Annalisa Zaja** (5)
(1) *ENEL - VDTG, Pisa, Italy*
(2) *Geosystem s.r.l., San Francisco, U.S.A.*
(3) *CNR, Istituto Internazionale per le Ricerche Geotermiche, Pisa, Italy*
(4) *Geosystem s.r.l., Milano, Italy*
(5) *Dipartimento di Geologia, Paleontologia e Geofisica, Università di Padova, Italy*

Abstract

Over the last six years, magnetotelluric data were acquired at 86 sites covering much of Southern Tuscany. Twenty-four of these sites were acquired in single-site or local-reference mode, whereas 62 were aquired in very-remote-reference mode, with a remote site located on Capraia Island – 40 km from the cost – where the cultural noise is very low. The data modelling showed that Southern Tuscany is characterized by a fairly uniform middle-lower crust that has a resistivity of a few thousand $\Omega \cdot$ m below 10 km. At shallower depths in the crust, the resistivity is closer to values around 500 $\Omega \cdot$ m. This uniformity is interrupted only below the Larderello and Mt. Amiata geothermal fields where deep conductive bodies are believed to exist. A general anomalous condition can hence be depicted for this region, with low resistivity values typical of those in tectonically active areas as opposed to more resistive values typical in continental areas. These data and those from other geophysical techniques suggest that these conductive zones may be associated with hot material coming from deeper sources below the geothermal areas.

Key words *magnetotelluric – geothermics – crustal exploration*

1. Introduction

In the last six years a strong effort was made to define the electrical structure of Southern Tuscany, where the main Italian geothermal fields are located. Magnetotelluric (MT) surveys were undertaken primarily by ENEL (Italian Electricity Board which oversees all the geothermal fields) and then by CROP (Deep Crust Exploration). The area of concern for this paper is crossed by the CROP 03 and CROP 18 profiles (fig. 1).

Southern Tuscany has been extensively explored with MT soundings since 1973, when Musé performed a detailed MT survey in the Travale area, one of the most exploited in the Larderello geothermal field (Celati *et al.*, 1973). Of particular interest was the definition of the fluid properties in a place were the trapping structure was very well known. However, the MT measurements in this area were so noisy that they could not give a clear picture of the subsurface structure. The MT data processing at the time was not able to effectively remove the noise.

Between 1979 and 1983 the European Community funded a «Research and Development Program in Geothermal Energy». Among the geophysical techniques used to explore the chosen test site (again Travale site) were electromagnetic methods. Four European univer-

---

Mailing address: Dr. Adele Manzella, CNR-IIRG, Piazza Solferino 2, 56126 Pisa, Italy; e-mail: Adele.Manzella@iirg.pi.cnr.it

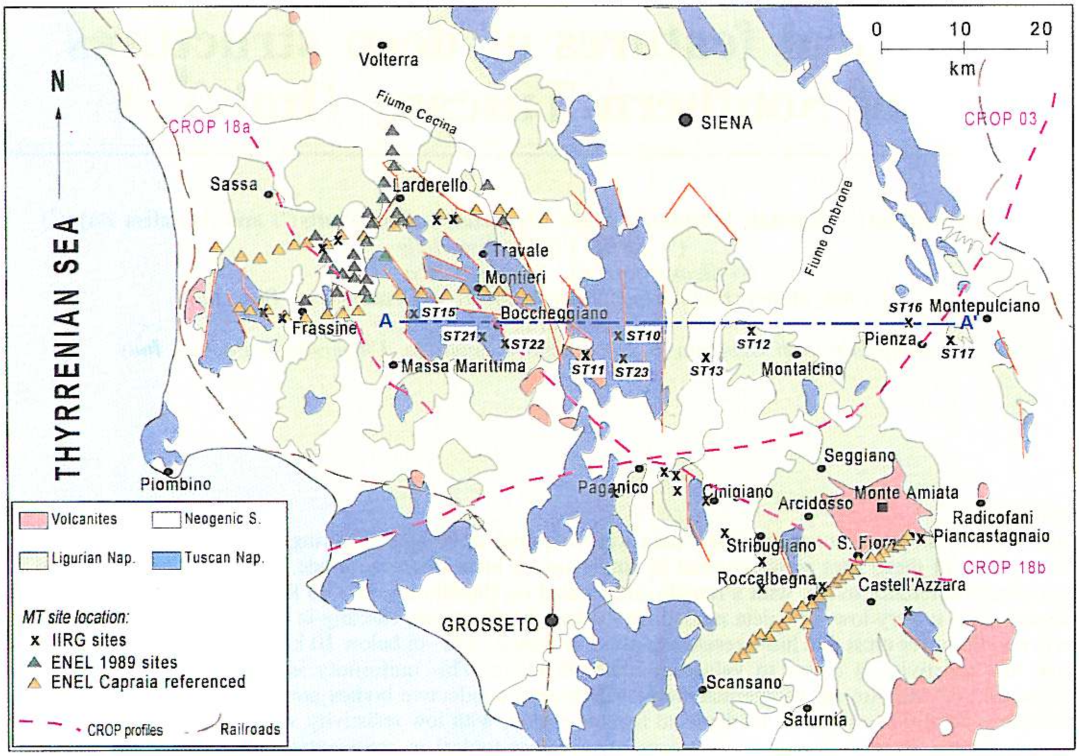

Fig. 1. Location map of the magnetotelluric sites over a schematic geological map. The CROP profiles and the main electrified railroad positions are also shown. Profile A-A′ is mentioned in the text.

sity groups from Edinburgh, Berlin, Munich and Padua undertook MT measurements (Hutton, 1985; Hutton *et al.*, 1985; Schwarz *et al.*, 1985; Berktold *et al.*, 1985). Noise was again a problem with these measurements, considering also that the measurements were acquired in single-site mode, *i.e.* without a reference site. Remote referencing (Gamble *et al.*, 1979) has become a standard in MT measurements and it is useful for reducing the effects of uncorrelated noise in MT processing. For these measurements, the noise was mainly a problem at lower frequencies, whereas the data quality for the high frequency bands (*i.e.* higher than 10 Hz) was good enough to enable modelling of the shallowest part of the site – which was the target of the project. At lower frequencies, the MT responses seemed anomalous with strongly rising apparent resistivities and near-0 degree phases (fig. 2), but at the time this was attributed to the anisotropy of the structure, which was strongly polarized because residing in a graben structure. Moreover the signal for the 'noise' was found to be quite coherent. More or less the same conclusions were arrived at in the same years by Duprat and Gole (1985), who extended the study performed by Musé in 1973.

In 1989 ENEL undertook a survey in the Larderello geothermal field (Geosystem, 1990). MT data were acquired at 26 sites in local-remote mode. This means that the sites used remote data from only a few kilometers away. A larger area than before was covered, with an average distance of the sites of about 3 km. This survey began to define deep conduc-

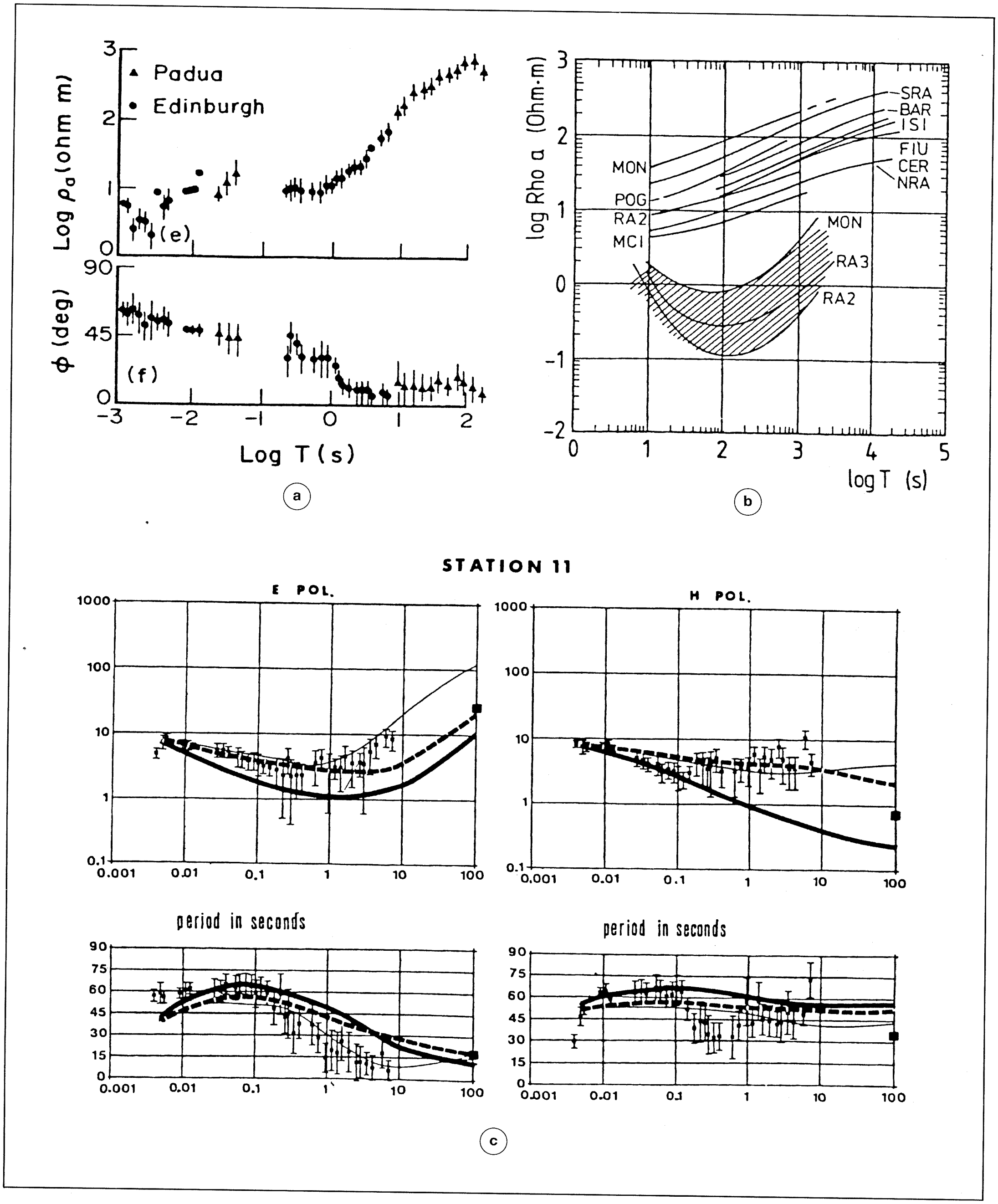

Fig. 2a-c. Examples of results from Hutton (1985) (a), Berktold *et al.* (1985) (b) and Hutton *et al.* (1985) (c). An increase in apparent resistivity and decrease of phase values is evident for all the curves at frequencies lower than 10 Hz.

tive anomalies inside a resistive basement. The EM signals produced by power plants, power lines and other sources (noise for MT methods) were reduced by means of data processing. These noise sources affect the higher frequency bands and were effectively eliminated. Another noise source was then recognized, affecting the low frequency band (lower than 10 Hz): the leakage currents produced by the electrified railroads. At the time the problem was not well known but had been observed in other places (Fontes *et al.*, 1989; Quian and Pedersen, 1991). Over the course of a few years it became clear that this kind of signal is very coherent and is often of larger amplitude than the natural MT signals. This response produces a slope of 45° in the bilogarithmic plot of apparent resistivity *versus* period, and a decrease of phase to near zero, exactly the same features observed above.

Starting from 1991 the main effort was devoted to improving current data processing techniques to separate the train induced electromagnetic signals from those due to the MT source fields. The standard remote-reference analysis was hardly applicable here since it is based on the recognition of bad data sets and their removal. In this case the whole data set is affected by noise due to the almost continuous passage of trains over the railroads. MIT and IIRG were involved in the project and in 1992 a first survey was performed in the Larderello geothermal area following the suggestions given by MIT (Geosystem, 1993; Mackie *et al.*, 1993; Manzella, 1993). Thirty-four MT sites located along two east-west profiles were recorded (fig. 1). The data were acquired with both a local reference at the closest site (2 km apart) and a remote reference on Capraia Island, 40 km off the coast. The appropriateness of the remote site and the details of the processing are discussed in Rieven *et al.* (1998). The study allowed the separation of the various electromagnetic fields and the modelling of data not too biased by the noise (Fiordelisi *et al.*, 1995; Larsen *et al.*, 1996). The same methodology tested in Larderello was then applied in a new MT survey performed in the Mt. Amiata geothermal area in 1994 (Manzella, 1995).

In the same years IIRG performed various MT surveys with a total of 30 sites recorded in single-site or local-reference modes (Manzella *et al.*, 1994; De Angelis *et al.*, 1996). Most of these data were acquired for CROP projects; hence the distribution is more homogeneous over the whole region than those described before.

The present paper describes the results obtained by the modelling of the whole set of data recorded after 1990. This gives a broad view of the deep electrical structure of the region. Some hypotheses are then proposed on the nature of the mid to lower crust.

2. Data description

The data were acquired with Phoenix V-5 systems, except for those of the SW-NE profile made for ENEL in the Mt. Amiata area, which were acquired with EMI systems. Most of the data were cascade-decimated to reduce the incoherent (statistical) error (Wight and Bostick, 1980). The single-site data were processed with standard analyses and provided apparent resistivity and phase values, together with all the parameters routinely used for the standard analysis (Vozoff, 1972). The remote-referenced data were processed with robust-analysis codes. Since the data were both local-referenced and remote-referenced, data quality in both high and low frequency bands could be enhanced and the composite analysis results were usually very good (Fiordelisi *et al.*, 1995; Manzella, 1995; De Angelis *et al.*, 1996).

Most of the sites showed the effect of leakage currents induced by the electrified railroads. This is evident in the whole region both approaching the Thyrrenian Sea coast on the west (Rome-Turin railroad) and the eastern border of the region (Rome-Milan railroad) (see fig. 1). However there are sites showing almost clean data, as can be seen in fig. 3.

A good picture of the MT data modelling results is the collection of data along the profile defined as AA′ in fig. 1. This profile comprises those data acquired by IIRG for the CROP 03 project and the southern profile

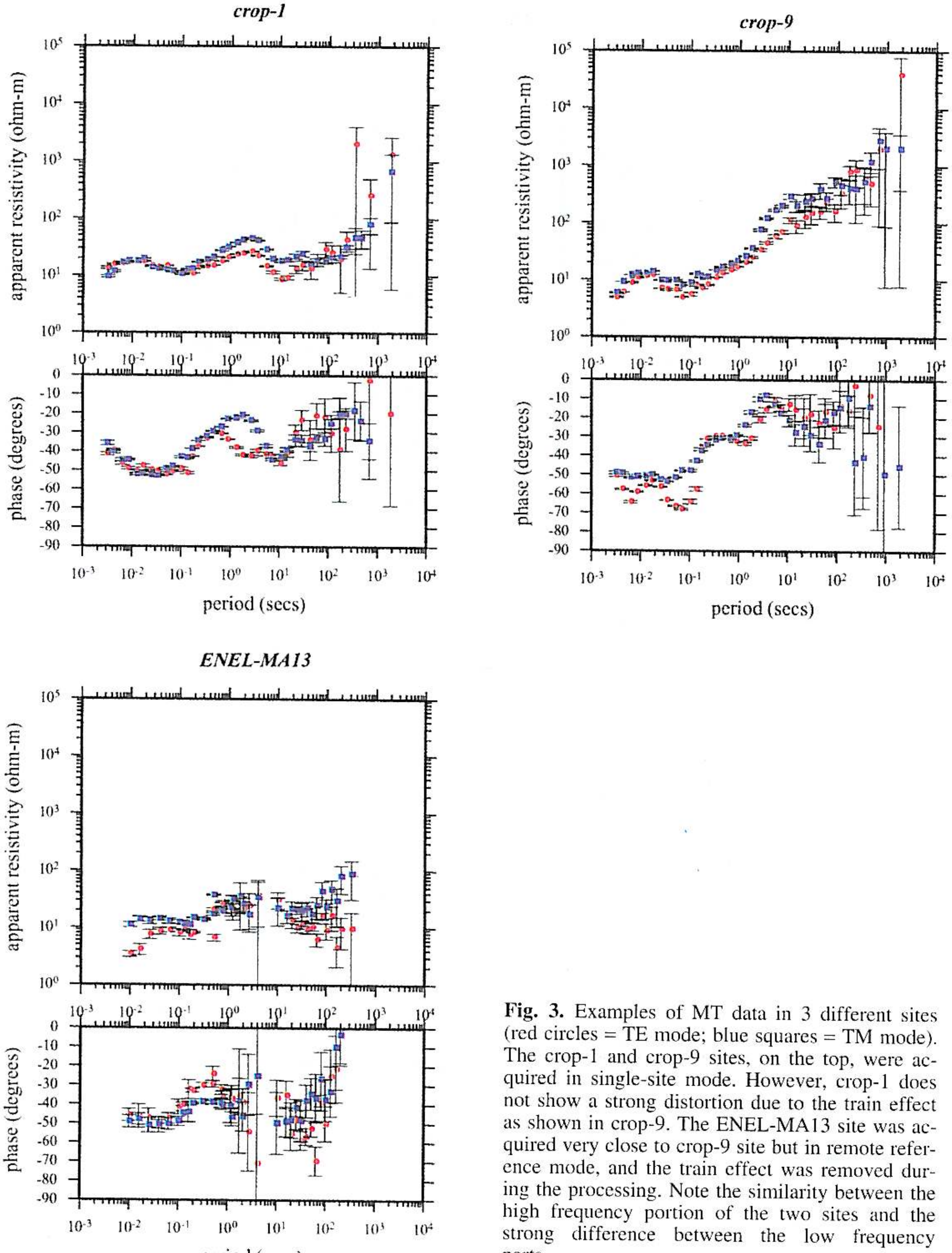

Fig. 3. Examples of MT data in 3 different sites (red circles = TE mode; blue squares = TM mode). The crop-1 and crop-9 sites, on the top, were acquired in single-site mode. However, crop-1 does not show a strong distortion due to the train effect as shown in crop-9. The ENEL-MA13 site was acquired very close to crop-9 site but in remote reference mode, and the train effect was removed during the processing. Note the similarity between the high frequency portion of the two sites and the strong difference between the low frequency parts.

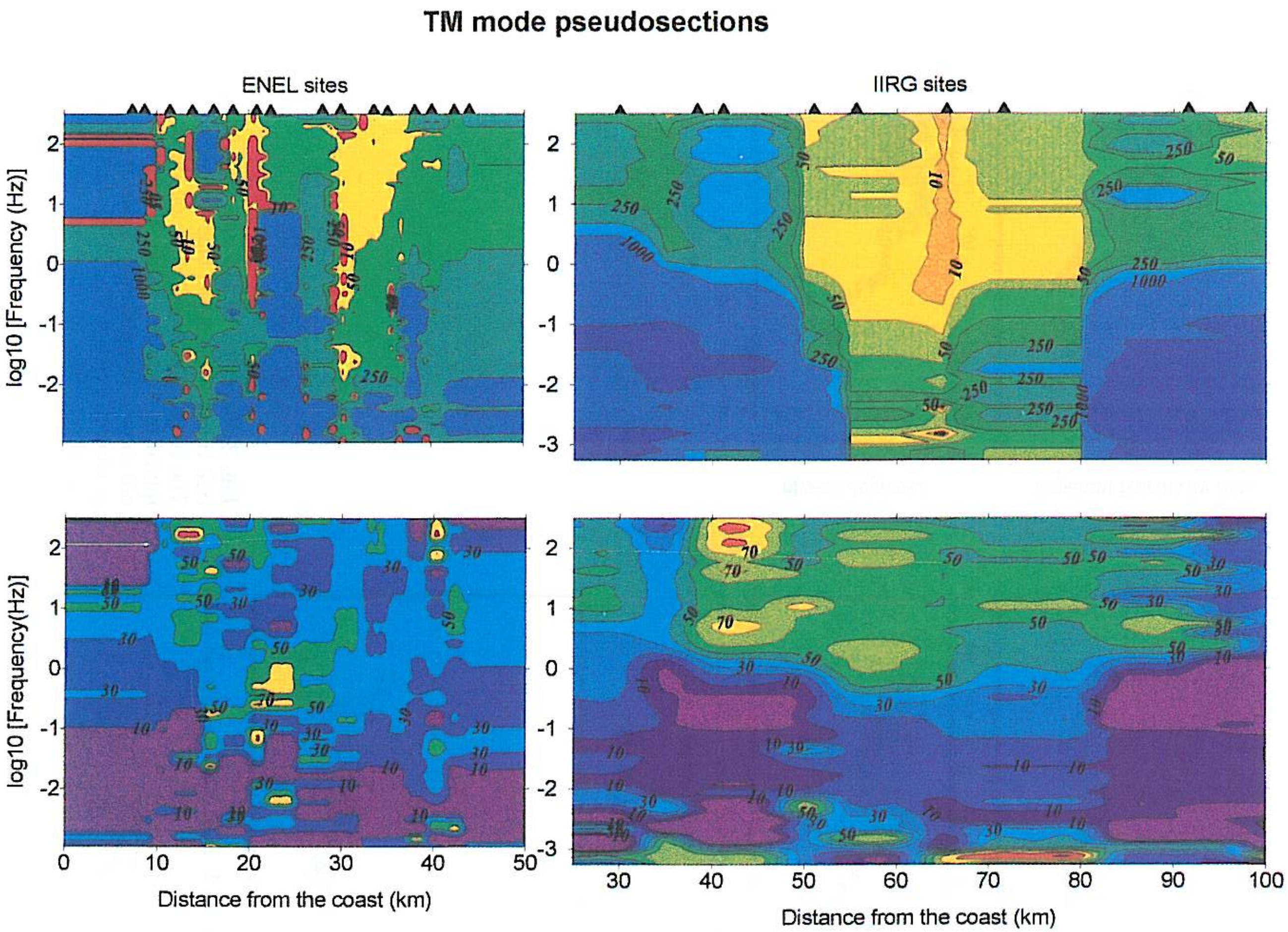

Fig. 4. Pseudosections of TM mode data for the Larderello profile committed by ENEL on the left, and the A-A′ made for the CROP project on the right. The data are plotted as logarithms of apparent resistivity (above) or phase values (below) *versus* distance from the Thyrrenian coast. Most evident is the increase in apparent resisitivity and decrease of phase in the low frequency portion of the lateral sites in the CROP profile. This effect disappears in the ENEL profile for almost the same location of the western portion of the CROP profile, proving it is just the result of the electromagnetic noise induced by the passage of trains along the nearby railroad.

made for ENEL in the Larderello area. The two profiles almost overlap for about 15 km and this also gives a good idea of what kind of information can be lost or gained performing surveys in different ways.

Sixteen sites at an average distance of 2 km define the Larderello profile; they were both local-referenced to nearby sites and remote-referenced to the Capraia Island site. The CROP profile comprises 10 sites located where the shallow geological structure undergoes major exchanges. The acquisition time was quite long for the latter, hence allowing a better definition of data in the low frequency band.

The geoelectrical strike direction, *i.e.* the direction at which the geoelectrical structure shows the highest homogeneity, is along the regional geological strike for most of the sites. It is slightly NE-SW or NW-SE for the various sites at the highest frequencies – related to the shallower structure – and then usually goes to a N-S direction.

Figure 4 shows the apparent resistivity and phase pseudosections of the two profiles for the Transverse Magnetic (TM) mode. This mode, where the electric field is orthogonal to the strike direction and the current flows across the structure, is less affected by the three-dimensionality of the structure (Wannamaker *et al.*, 1984), and hence these pseudosections should give the best picture of the distribution of electrical features.

The 8 easternmost sites of ENEL profile almost correspond in location to the 3 westernmost sites of IIRG profile. However, the two pseudosections look different. For the high frequency part this is due to the not perfect correspondence in location between the two profiles. The 3 IIRG sites are located over resistive allochthonous units (Tuscan nappe outcrops in fig. 1). A complex system of faults cuts this unit further on north, where the ENEL sites are located, allowing the interposition of much more conductive units, which attract most of the current. Indeed, resistivity values of a few hundreds of Ω · m can be recognized below all the sites residing over Tuscan nappe outcrops. At lower frequencies the train effect arises. The effect of the train induced noise is evident in the CROP profile, with its strong increase in resistivity and decrease of phase on the two sides. If we use these data as they are, we would need to insert deep resistive bodies on the two sides of the model. The ENEL data, from which this noise was removed, suggest the real distribution of electrical properties at low frequencies and neglect the deep resistive body required by the CROP data on its western side. For this reason in the modelling we did not consider the strong increase in resistivity of the CROP low frequency data for the most extreme positions.

3. Modelling results

Due to the strong heterogeneity of the area and the distribution of sites only along profiles, the data were modelled with two dimensional (2D) modelling codes. The TM mode data of the Larderello profile were inverted using the 2D inversion code of Mackie (Fiordelisi *et al.*, 1995). TM and TE modes of CROP data were modelled both by the same inversion code and by the Wannamaker 2D forward code (De Angelis *et al.*, 1996). In all modelling inversions the effect of sea water was taken into account, and a uniform *a priori* model was used for land. The result of the composite modelling is given in fig. 5, showing the geoelectrical section obtained by modelling.

The general structure of the area is mostly homogeneous. The shallowest resistivity values, ranging between 5 and 30 Ω · m are likely to be Neogenic sediments and flysch facies formations. This connection is easily defined by the geological distribution of the formations at the surface and by the electrical logging data in Larderello drillings. This same data set also gives a definition of resistivity values for the deeper Tuscan nappe formations, to which we attribute an average value of 200 Ω · m. The 50 Ω · m layers that appear at the surface we consider to be outcropping Tuscan nappe formations.

Below these formations an increase in resistivity is evident, and the geological information indicates the presence of metamorphic rocks (Phillite, quarzites and then gneiss formations). These are probably the same as the 500 Ω · m

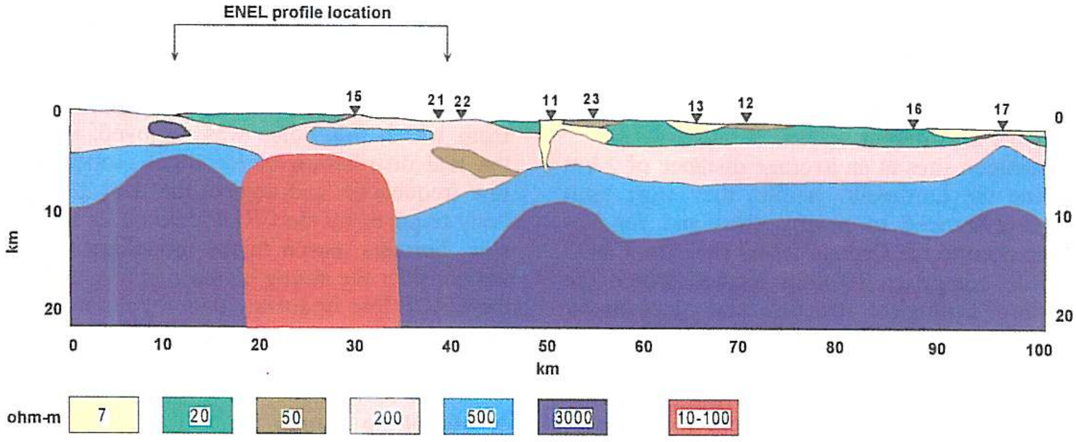

Fig. 5. General picture of the electrostratigraphic situation resulting from 2D finite element modelling of MT stations along an EW profile (profile A-A′ and western portion of ENEL profile). Principal structures include a conductive body (10-100 Ω · m) in the western portion, where the Larderello geothermal field has its southern margin; the generally anomalous (conductive) condition around this body (below ST15-ST22 sites); the uplift of resistive basement below ST11-ST23, *i.e.* the Monticiano-Roccastrada unit; the uplift of Tuscan nappe and possibly of deeper formations at ST17 site.

electrical layer of the CROP section. At an average depth of 12 km the resistivity reaches the value of thousands of Ω · m, hence defining a lower crustal condition. This sequence can be easily followed in the CROP profile, but is quite disturbed in the Larderello area, where it is interrupted by resistive bodies and a large conductive anomaly at a depth of a few kilometers. This anomaly is very well correlated to the one defined by seismic tomography as a decrease of *P* wave velocity and is also characterized by a decrease of gravimetric Bouguer values (see Fiordelisi *et al.*, 1995 and Batini *et al.*, 1995 for details). The whole set of geophysical data in the Larderello area lead one to the conclusion that a magmatic and still hot body may be present below the geothermal area. A similar situation is found in the Mt. Amiata geothermal region, but here the conductive anomaly is much shallower. The conductive body in the Larderello area represents the center of a disturbed area, between 15 and 45 km from the coast in fig. 5, where the electrical sequence found in the rest of the region is not seen. On the eastern part of this body there is a general decrease of resistivity; here the resolution is not very high since the sites are less dense (those for the CROP profile). On the western side we see highly resistive bodies. These bodies are likely to be cold granitic intrusions in the crust since they appear close to granitic outcropping or where granites were found in the deep geothermal drilling. A similar increase in resistivity at depth can be noticed below site 11 in the CROP profile, which is characterized at its surface by the Roccastrada volcanites – here defined as conductive formations. It seems that where volcanites are present at the surface or granite is present at shallow levels, there is usually an increase in resistivity at depth.

4. Conclusions

Magnetotelluric soundings are a good source of information in geothermal regions like Southern Tuscany and have been successful in defining the deep structure of geothermal areas in conjuction with other geophysical methods.

In Southern Tuscany, the applicability of the method was biased by the strong electromagnetic noise present over most of the area. In recent years the development of new techniques of data processing allowed us to achieve very good results and a good structural definition in this difficult area.

It was possible to define a general model typical of tectonically active areas, where the resistivity of the crust does not reach the high values usually found in continental areas. This homogeneity is interrupted wherever magmatic activity is evidenced, as in Larderello and Mt. Amiata geothermal areas and below Roccastrada volcanites.

REFERENCES

BATINI, F., A. FIORDELISI, F. GRAZIANO and N. TOKSOZ (1995): Earthquake tomography in the Larderello geothermal area, in *Proceedings of World Geothermal Congress*, **2**, 817-820.

BERKTOLD, A.J., H.J. DITTUS, K.-H. EIGNER and U. TEUFEL (1985): Investigation of geothermal anomaly of Travale (Tuscany) by telluric, magnetotelluric and geomagnetic deep sounding measurements, *Geothermics*, **14**, 663-672.

CELATI, R., L. MUSE, A. ROSSI, P. SQUARCI, L. TAFFI and B. TORO (1973): Geothermal prospecting with magnetotelluric method (MT-5 E. X.) in the Travale area (Tuscany, Italy), *Geothermics*, **2**, 186-190.

DE ANGELIS, M., A. FIORDELISI, A. MANZELLA and A. ZAJA (1996): Two-dimensional analysis of a magnetotelluric profile in the CROP 03 area, Southern Tuscany, *Mem. Soc. Geol. Ital.*, special issue for CROP 03 profile geophysical results (in press), **52**, 295-304.

DUPRAT, A. and F. GOLE (1985): Magnetotelluric soundings in the Travale area, Tuscany, *Geothermics*, **14**, 689-774.

FIORDELISI, A., R. MAKIE, T. MADDEN, A. MANZELLA and S. RIEVEN (1995): Application of magnetotelluric method using a remote-remote-reference system for characterizing deep geothermal system, in *Proceedings of World Geothermal Congress*, **2**, 893-898.

FONTES, S.L., T. HARINARAYANA, G.J.K. DAWES and V.R.S. HUTTON (1988): Processing of noisy magnetotelluric data using digital filters and additional data selection criteria, *Phys. Earth Planet. Int.*, **52**, 30-40.

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

GEOSYSTEM s.r.l. (1990): Elaborazione ed interpretazione dati geofisici dell'area geotermica di Larderello-Monterotondo, *ENEL Internal Report.*

GEOSYSTEM s.r.l. (1993): Magnetotelluric survey in the Castelnuovo-Val di Cecina area, Tuscany, *ENEL Internal Report.*

HUTTON, V.R.S. (1985): Magnetic, telluric and magnetotelluric measurements at the Travale test site, Tuscany, 1980-1983: an overview, *Geothermics*, **14**, 637-644.

HUTTON, V.R.S., G.J.K. DAWES, T. DEVLIN and R. ROBERTS (1985): A broadband tensorial magnetotelluric study in the Travale geothermal field, *Geothermics*, **14**, 645-654.

LARSEN, J., R. MACKIE, A. MANZELLA, A. FIORDELISI and S. RIEVEN (1996): Robust smooth magnetotelluric transfer functions, *Geophys. J. Int.*, **124**, 801-819.

MACKIE, R., T. MADDEN, A. MANZELLA and S. RIEVEN (1993): Two-dimensional modelling of magnetotelluric data from Larderello geothermal area, Italy, *ENEL Internal Report.*

MANZELLA, A. (1993): Analisi delle serie temporali e modellazione di dati magnetotellurici acquisiti nell'area di Larderello-Travale, *ENEL Internal Report.*

MANZELLA, A. (1995): Analisi delle serie temporali e modellazione bidimensionale di dati magnetotellurici acquisiti nell'area del Monte Amiata, *ENEL Internal Report.*

MANZELLA, A., S. BELLANI, L. BROGI, QI JONG, E. PINNA and A. ROSSI (1994): Magnetotelluric measurements in the Monte Amiata region, *Ann. Geofis.*, **37** (suppl. n. 5), 1229-1239.

QUIAN, WEI and L.B. PEDERSEN (1991): Industrial interference magnetotellurics: an example from the Tangshan area, China, *Geophysics*, **56**, 265-273.

RIEVEN, S., R. MACKIE, T. MADDEN, J. LARSEN, A. MANZELLA and A. FIORDELISI (1998): A magnetotelluric survey of the Larderello geothermal field (in preparation).

SCHWARZ, G., V. HAAK and V. RATH (1985): Electrical conductivity studies in the Travale geothermal field, Italy, *Geothermics*, **14**, 654-662.

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

WANNAMAKER, P.E., G.W. HOHMANN and S.H. WARD (1984): Magnetotelluric responses of three-dimensional bodies in layered earths, *Geophysics*, **49**, 1517-1533.

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