ELECTRICAL RESISTIVITY STRUCTURES OF SOUTHERN TUSCANY GEOTHERMAL AREAS, ITALY

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SUMMARY – The magnetotelluric data acquired over the last ten years in southern Tuscany indicate that the metamorphic basement hosting the main geothermal reservoirs is characterised by a regional resistivity of a few thousand ohm-m, showing a sharp transition to lower values in the geothermal areas. This is evident in the Mt. Amiata geothermal area, a water-dominated system, and in Larderello, which is a vapour-dominated system. Since the alteration caused by thermal circulation is not extensive, a decrease in resistivity of one order of magnitude would be due almost entirely to fluid circulation, in both the vapour and liquid phase. The heat source of the geothermal systems, created by some shallow and still molten granite intrusions, has been identified beneath the Larderello area, but is much less clear below Mt. Amiata. A very narrow area with no surface manifestations, which does not belong to the known geothermal areas, shows deep features that are very similar to those of Larderello.

1. INTRODUCTION

Application of the magnetotelluric (MT) method in geothermal exploration in Tuscany was considered a challenge some ten years ago, The thousands of geoelectrical data acquired in the Larderello and Mt. Amiata areas never proved to be of real interest since they were able to define the resistivity distribution down to the resistive basement at most, whereas the main geothermal target for the past **30** years has been the deep reservoirs within the metamorphic basement. Due to the geological characteristics of the formations hosting the geothermal reservoirs in Tuscany, and their low permeability, geothermal fluid circulation does not produce a widespread alteration zone and the contribution to resistivity of very conductive clayey minerals can be neglected.

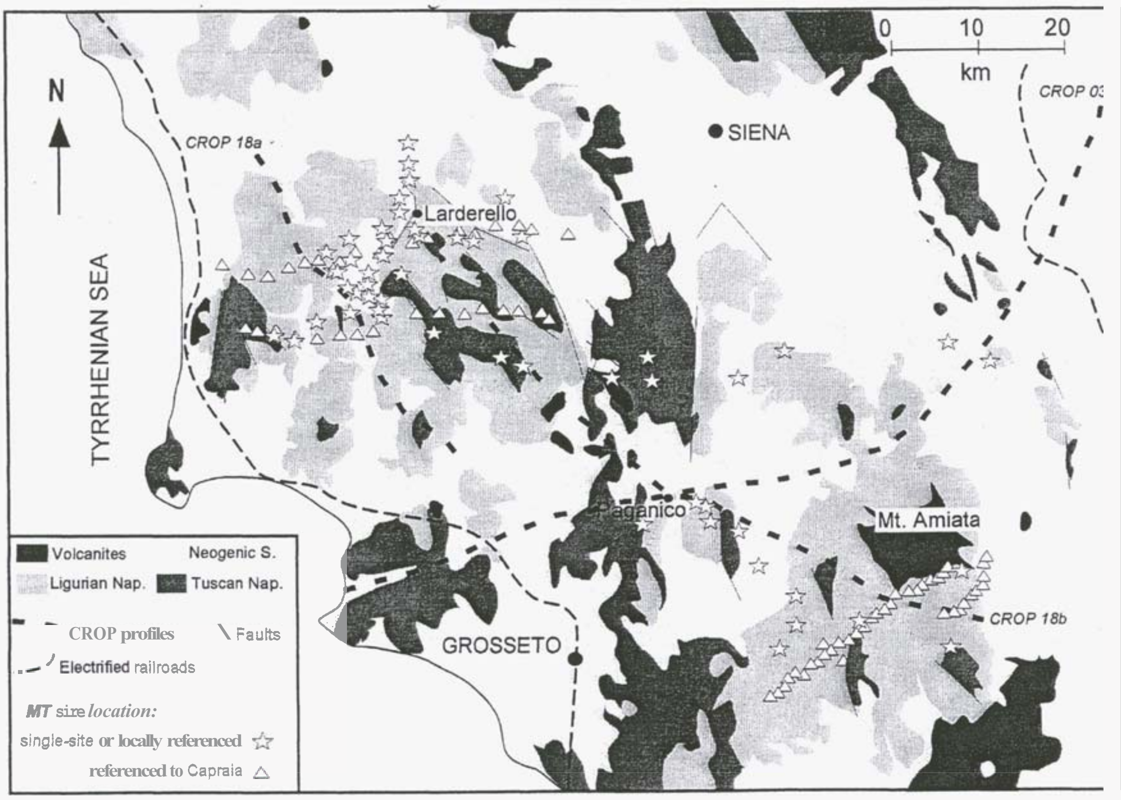

Figure 1 - Location of the magnetotelluric sites in a schematic geological map. The **CROP** profiles and the main electrified rail **tracks** are also shown.

Hence, the decrease in resistivity caused by thermal fluid circulation was not expected to be high, especially at Larderello, where the dominant fluid phase is steam. Larderello has been extensively explored with MT soundings since 1973 (Fiordelisi et al., 1998 and ref. therein).

Noise was pervasive in the period range of 1-1000 s. This highly coherent EM noise, produced by the currents discharged by the direct-current electrified railways at the passage of trains, required considerable study and data processing (Fiordelisi et al., 1995; Larsen et al., 1996). The most recent MT surveys, however, have showed that in most areas the noise can be effectively removed and the data interpreted without distortion, using appropriate data acquisition and processing techniques. The continuous profiling technique **was** used in the most recent surveys in order to increase the resolution of the shallower structures (Manzella et al., 1999; Volpi and Manzella, **2002).**

The MT surveys were undertaken primarily for geothermal and deep crustal exploration (CROP, Deep Crust Exploration Projects) (Fiordelisi et al., 1998; De Angelis et al., 1998; Manzella et al., 1999). The study area described in this paper is crossed by the CROP **03** and CROP 18 profiles (Figure 1). A total of **232** sites were acquired over the last 10 years, 108 of which, acquired for geothermal purposes, were referenced to a remote site on the island of Capraia to remove the highly coherent electromagnetic noise. The remainder were single-site or locally referenced and, in fact, many are affected by noise.

This paper describes the results obtained by modelling the entire set of data recorded after 1992. This gives a broad view of the deep electrical structure of the region.

2. GEOLOGICAL BACKGROUND AND GEOPHYSICAL OUTLINE

southern Tuscany belongs to the inner part of the Northern Apennines, originating from the collision between the Corsica-Sardinia and Apulia microplates (Gianelli et al., 1997 and ref. therein). The region is characterised by NNW-SSE faults linked to the Alpine orogeny (Figure 2). After the post-Tortonian prevalently extensional tectonics, the region underwent a general uplift, so that older units crop out in some places. Its extension was accompanied by anatectic magmatism whose ages decrease in an eastward direction. Shallow intrusive bodies are the heat sources of the two most important geothermal areas, Larderello and Mt. Amiata, which have undergone intensive exploratory and production drilling for almost half a century.

Direct exploration by means of hundreds of shallow and deep wells has permitted us to achieve a detailed reconnaissance of the first **4.5** km of the crustal structure. At Larderello, drill-holes within the first **4.5** km of depth encountered sequences of sedimentary, metamorphic and igneous rocks. Below the

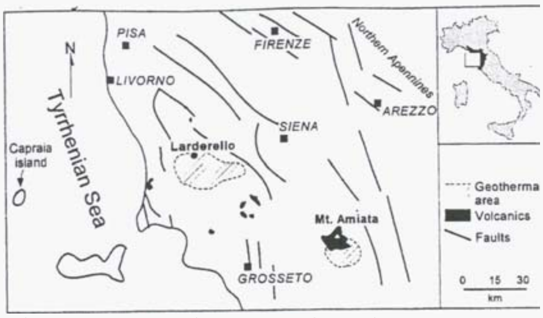

Figure **2 -** Location map of southern Tuscany, showing the geothermal areas and the main **faults.**

Jurassic-to-Cenozoic ophiolite and flysch units (Ligurids) and a Triassic-to-Tertiary allochthonous unit (Tuscan Nappe), there is a zone of tectonic slices, involving Mesozoic rocks and Paleozoic formations. The deepest metamorphic units are micaschist and gneiss. Buried dykes, subvolcanic bodies of granite and thermo-metamorphic minerals were frequently penetrated by deep drillings. The Mt. Amiata, with respect to Larderello area, is characterised by the presence of lava flows covering the sedimentary sequence and by the particular nature of the basement, which is made up mostly of graphite-bearing metasedimentary rocks.

The vapor-dominated geothermal system of Larderello and the water-dominated geothermal system of Mt. Amiata both comprise two reservoirs: the shallow reservoir within the carbonate units at 0.5-1 km depth, and the deeper, more extensive reservoir within the metamorphic basement at depths of more than 2 **km** beneath the **known** geothermal fields, at pressures of up to 70 bar and temperatures between **300** and **350** °C (Barelli et al., 2000; Fiordelisi et al., 2000). The geothermal fluids circulate through the larger fractures and faults, whose main orientation is the regional Apenninic one. Permeability is usually low and heterogeneously distributed. The results of many studies on contact metamorphic and hydrothermal minerals suggest that there were two main stages of hydrothermal activity: an early high-temperature stage related to the intrusion of the granites, which produced contact metamorphic and metasomatic processes in the basement rocks, and a second **stage** characterised by precipitation of lower-temperature mineral assemblages filling veins at shallow-intermediate depths or, in certain places, replacing early-stage contact metamorphic or igneous minerals (Magro et al., 2002 and ref. therein). Since the structure is not widely fractured and the alteration minerals are localized around the faults and fractures, the alteration is not widespread.

Seismological studies have shown that the area extending fkom NE of Corsica to the inner part of the Northern Apennines is characterised by a thinned continental lithosphere and a large anomalous structure within the upper mantle (Gianelli et al., *1997* and ref. therein). The thin, elongated Tuscan Moho (depth ~ 25 km) lies directly over a soft asthenosphere that has risen 40-50 km. The effects of this thinning and subsequent magma intrusions at shallow depth are evident in the present heat flow regime, which shows a regional value of 120 mW/m^2 and higher values in the geothermal areas (Figure 3a). The thermal regime leads to a lower seismic velocity and density in the crust and in the upper mantle, as revealed by seismic tomography and gravity data (Batini et al., *1995;* Bernabini et al., 1995). Minimum Bouguer values in correspondence to the geothermal areas (Figure 3b), filtered for shallow structures and mantle effects, have been modelled as a roughly drop-shaped low-density body between 7-8 and 20 km depth, and interpreted as shallow intrusive and still molten bodies (Bernabini et al., *1995;* Fiordelisi et al., *1995).* Seismic data have provided valuable indications as to the shape and depth of the anomalous body in the Larderello region. Inversion of local earthquake arrival times and teleseismic travel time residuals have revealed the presence of a low velocity anomaly, 20 km wide at its top and possibly wider as it approaches the Moho, at depths of more than 8 km below ground level (see Figure 5) (Batini et al., *1995).* A low velocity body was also identified below the Amiata area, but resolution here is much lower than at Larderello (Chiarabba et al., *1995).* Another clue is provided by a seismic horizon, K, identified in the Amiata area and given the same name as the seismic horizon first observed at Larderello. Seismic reflectors having the same seismic signature as the K-horizon were recognised not only in the geothermal fields of Larderello and Mt. Amiata, but also along the deep seismic reflection profiles CROP-03 and CROP-18 (e.g., Cameli et al., *1998).* These horizons are often referred to as a single horizon, but this is not strictly true. The K- horizon locally shows "bright spot" features and is located at 3-4 km depth below the central parts of the geothermal fields of Larderello and Mt. Amiata, at 5-6 km depth along the margins of these same fields, and at 10-12 km depth outside the geothermal areas, where it becomes relatively flat. The form of the K horizon shows many similarities with the heat flow and gravity maps (Figure 3c), rising sharply above the deep anomalous bodies defined by seismic tomography. The most common interpretation of this horizon is that it represents the brittle-ductile transition of the Tuscan crust, where fluid-filled fractures determine the bright-spot appearance in geothermal areas (Cameli et al., *1998* and ref. therein).

3. RESISTIVITY DATA

The geoelectrical data acquired in the Larderello and Mt. Amiata areas, together with the results of a few resistivity logs in the Larderello area, and laboratory data (Losito, 1991) have been used to determine the resistivity values of the shallow geological units and to formulate hypotheses with regard to the deepest units. The shallow Neogenic deposits and Flysch units are electrically conductive (10 to 20 ohm-m). The carbonate formations are only moderately resistive (usually around *100* ohm-m), whereas the anhydritic formations, interbedded with the carbonates, are occasionally very resistive, reaching values of 1000 to *1500* ohm-m.

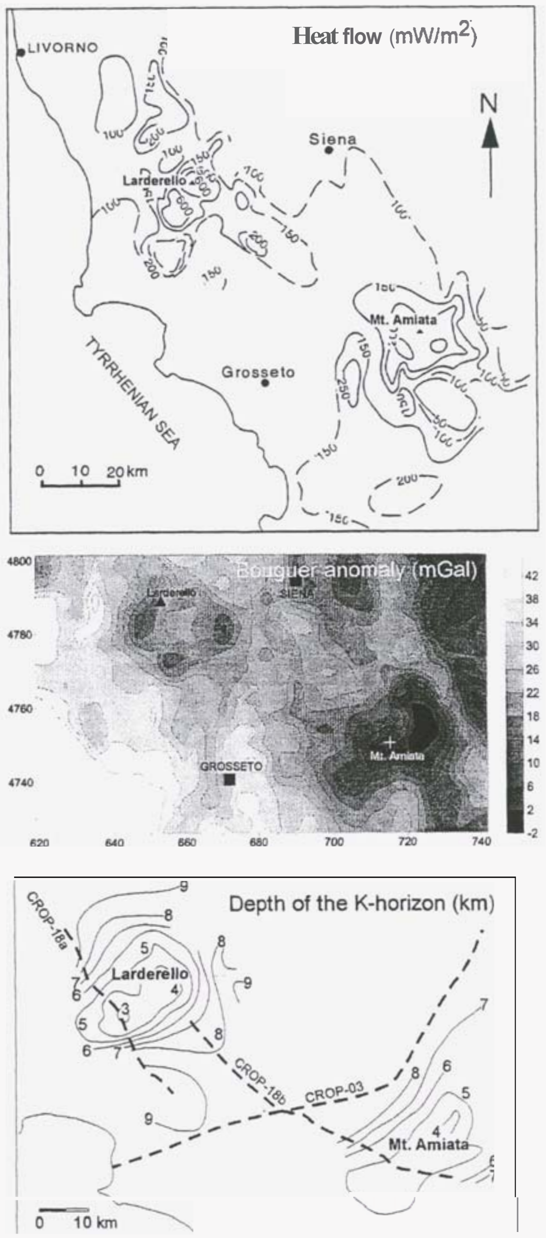

Figure 3 - Maps showing (a) heat flow regime (top), (b) Bouguer anomaly (center) and (c) K-horizon depth (bottom).

The resistivities of the metamorphic units measured in a few deep wells in the Larderello area are quite low (about 100 ohm-m) compared to those of the anhydrites and to the values measured on laboratory samples. These resistivities are probably representative of the upper, most fractured part of the metamorphic basement only and a bulk value of many thousands of ohm-m is expected on the basis of the laboratory data, even accounting for the very high temperature and pressure conditions.

MT penetration depths of more than **2** km were achieved only where electromagnetic noise **was** absent, or could be eliminated. The data show that below this depth the resistivity reaches values of only a few thousands of ohm-m, which is far lower than in metamorphic formations in other parts of the world. It is not unusual, however, for a tectonically active area such as southern Tuscany, where the high reflectivity and the high heat flow could indicate the presence of fluids and/or melts on a fairly wide scale. The data also indicate that there is a strong anisotropy in the Tuscan crust. The first, most obvious observation, is that there is an abrupt transition to lower resistivity values in the resistive substratum below the geothermal areas. The distance between MT sites was found to be of critical importance for defining the extension of these low resistivity areas.

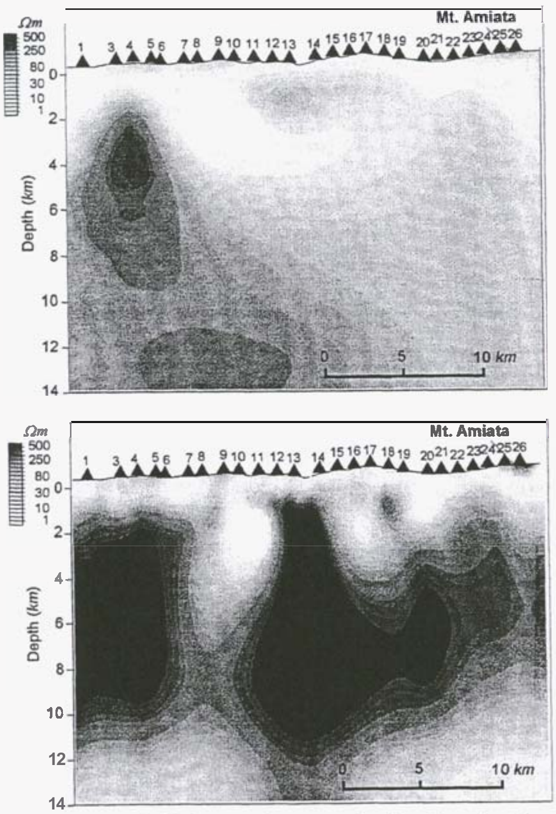

Figure **4** - **2-D** inversion results in the Amiata area: TM mode inversion **of** *26* MT sites along a profile (top); TM mode inversion **of** 126 sites along **the** same profile **(bottom).**

An example is given in Figure **4,** which shows two models obtained by inverting the TM-mode MT data fiom just **26** sites at an average distance of 1 km (on the left), and by inverting the TM-mode MT data from 126 sites at an average distance of 200 m on the same profile (on the right). The figure shows that, with continuous profiling data acquisition, we can define the exact location, dimensions and eventual interaction between the deep reservoirs, as well as details on the shallowest structure (< **2** km). **A** spacing of just 1 km between MT sites is unable to resolve the lateral changes in resistivity occurring in an area with a sharp transition to lower resistivity, since this is caused by an abrupt increase in permeability through fractures and faults. The data, for the moment, are unable to predict the exact location and direction of the fractures at such great depths, which would be of considerable interest in geothermal exploration, but they do identify very clearly the areas that are affected **by** deep circulation of geothermal fluids. The correspondence between areas of low resistivity inside the resistive basement and geothermal reservoirs was very evident in the Mt. Amiata water-dominated system, which is the system referred to in Figure **4** and monitored by two continuous profiling surveys (Manzella et al., **1999;** Volpi and Manzella, **2002).** However, a clear definition of the geothermal reservoirs was also obtained for the vapor-dominated system at Larderello (Manzella et al., **2002),** showing that the circulation of mainly steam in fractures and faults is causing the decrease in resistivity (Figure 5).

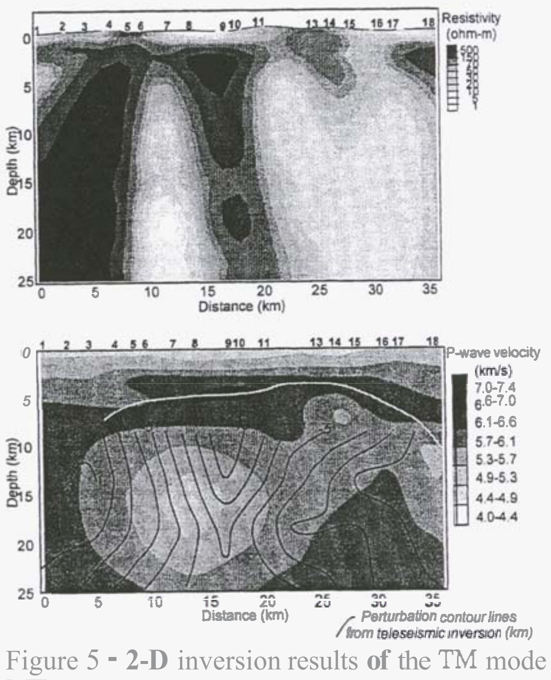

Figure 5 - **2-D** inversion results **of** the TM mode MT data along a profile in the Larderello area **(top);** local earthquake and teleseismic inversion results along the same profile (from Batini et **al.,** 1995, modified) **(bottom).**

Unfortunately, the MT data for Larderello were acquired during the first field test of **1992,** when the sites were at an average distance of **2** km. Hence, we can note a clear correlation between the main resistivity anomalies at a depth of a few km and the most exploited areas, but we are unable to define the extension of the reservoirs and any interconnection at depth, for the reasons discussed above.

Apart from the resistivity anomalies created by geothermal systems at depths of 2-5 km, the MT data also reveal that the resistivity distribution is no longer homogeneous below 7-8 km depth, and that low resistivity bodies do not always correspond to geothermal manifestations. In a schematic view, three main categories of sites can be defined: 1) ***normal sites,*** located outside the geothermal area, whose apparent resistivity is quite high at longer periods (i.e., at greater depths); 2) ***strictly geothermal sites,*** characterised by the lowest apparent resistivities at longer periods; and 3) ***geothermal sites,*** located in intensively exploited geothermal areas, whose apparent resistivities at longer periods are lower than in ***normal sites*** but higher than in ***strictly geothermal sites.*** Their distribution is shown in Figure *6*.

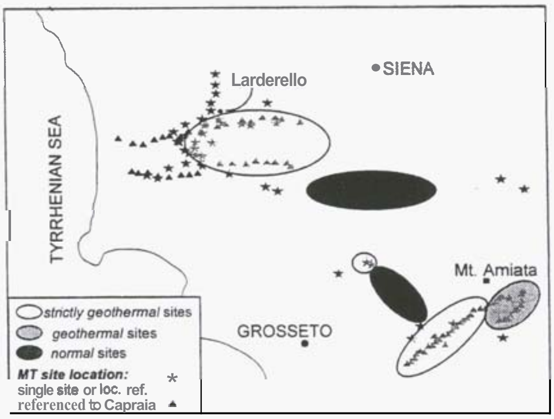

Figure 6 - Distribution of the three main categories of MT sites (see text): light grey indicates areas of very low deep resistivity (few ohm-m); medium grey corresponds to areas of average deep resistivity (100-200 ohm-m) and dark grey indicates areas of high deep resistivity (1000-2000 ohm-m).

Mapping of these sites shows that the deep structure can be identified in the Larderello area only. All the geophysical and geological data indicate that hot, molten granite intrusions are present beneath the Larderello geothermal area; the depth, dimensions and location of these intrusions can be derived from the seismic, gravity and MT data (Figure 5). In the Mt. Amiata area, the sites with the lowest deep resistivities do not belong to the exploited geothermal areas, but are located a few kilometres south-west of Mt. Amiata. The resistivity decrease in the sites within the Mt. Amiata geothermal areas is due to the presence of the reservoir, below which there is no indication of deep conductive conditions, hence the effect of a granitic intrusion must be deeper and was not reached by MT data. Outside the geothermal areas the deep resistivity shows to increase to values of few thousands of ohm-m.

4. CONCLUSIONS

The MT data show evidence of an extremely heterogeneous distribution of crustal resistivity in Southern Tuscany. The geothermal reservoirs at a depth of 2-5 km could be clearly defined by MT data, in both the Larderello and Mt. Amiata geothermal areas. The resistivity distribution at depths greater than 7-8 km is not homogeneous, but low resistivity bodies do not always correspond to geothermal manifestations. Outside the geothermal areas the MT data are difficult to interpret because of electromagnetic noise, since all the sites were acquired without a remote reference.

In a few sites in which noise is not a problem, it was possible *to* define a complex deep resistivity distribution. The MT data show that only the south-westem part of the Amiata area can be compared to deep conditions at Larderello, whereas deep resistivity in the central Amiata area has been observed to increase. The MT data indicate that the intrusions lie at greater depth in the Amiata area than in the Larderello area, and that intrusions comparable to those at Larderello may be present in areas that have still to be explored. The connection at depth between the latter and the intrusions in the Mt. Amiata area has still to be investigated.

5. REFERENCES

Barelli, A., Bertini, G., Buonasorte, G., Cappetti, G and Fiordelisi, **A.** (2000). Recent deep exploration results at the margins of the Larderello Travale geothermal system. In: ***Proc. World Geothermal Congress 2000. Kyushu-Tohoku, Japan,*** pp. 965-970.

Batini, F., Fiordelisi, **A.,** Graziano, F. and Toksoz, M.N. (1995). Earthquake tomography in the Larderello geothermal area. In: ***Proc. World Geothermal Congress 1995. Florence, Italy,*** pp. 817-820.

Bernabini, M., Bertini, G., Cameli, G.M, Dini, I. and Orlando, L. (1995). Gravity interpretation of Mt. Amiata geothermal area (Central Italy). In: ***Proc. World Geothermal Congress 1995. Florence, Italy,*** pp.859-862.

Cameli, **G.M.** ,Dini, I. and Liotta, D. (1998). Brittle/ductile boundary from seismic reflection lines of southern Tuscany (Northern Apennines, Italy). ***Mem. Soc. Geol.*** *It.,* Vol. ***52,*** 153-163.

Chiarabba, C, Amato, A. and Fiordelisi, **A.** (1995). Seismicity and velocity images of the Roman Magmatic Province. In: ***Proc. World Geothermal Congress 1995. Florence, Italy,*** pp.827-832.

De Angelis, M., Fiordelisi, A., Manzella, A., and Zaja, A.(1998). Two-dimensional analysis of a magnetotelluric profile in the CROP 03 area in southern Tuscany. *Mem. Soc. Geol. It.*, Vol. *52,* 295-304.

Fiordelisi, A., Mackie, R., Madden, T., Manzella, A., and Rieven, S., (1995). Application of the magnetotelluric method using a remote-remote reference system for characterizing deep geothermal system. In: ***Proc. World Geothermal Congress 1995. Florence, Italy,*** pp. 893-898.

Fiordelisi, A., Mackie, R., Manzella, A., and Zaja, A.(1998). Electrical features of deep structures in southern Tuscany (Italy). ***Annali di Geofisica,*** Vol. 41(3), 333-341.

Fiordelisi, A., Manzella, A., Buonasorte, G., Larsen, J., and Mackie, R. (2000). MT methodology in the detection of deep, water-dominated geothermal systems. In: ***Proc. World Geothermal Congress 2000. Kyushu-Tohoku, Japan,*** pp. 1121-1126.

Gianelli, G., Manzella, A. and Puxeddu, M.(1997). Crustal models of the geothermal areas of southern Tuscany (Italy). ***Tectonophysics,*** Vol. 281,221-239.

Larsen, J. C. , Mackie, R. L., Manzella, A., Fiordelisi, A. and Rieven, S. (1996). Robust smooth magnetotelluric transfer functions. ***Geophys. J. Int.,*** Vol. 124, 801-819.

Losito, G. (1991). Proprietà elettriche delle rocce lungo il profilo CROP 03. In: ***Studi Geologici Camerti,*** Vol. Spec. 1991/1, pp. 33-40.

Magro, G., Ruggieri, G., Gianelli, G and Bellani, S. Helium isotopes and present-day fluids of the Larderello geothermal field: constraints on the heat source. ***J. Geophys. Res.*** In press.

Manzella A., Mackie R. and Fiordelisi A. (1999). MT survey in the Amiata volcanic area: A combined methodology for defining shallow and deep structures. ***Physics and Chemistry of the Earth (A),*** Vol. 24(9), 837-840.

Manzella, A., Volpi, G., Corsi, F. and Fiordelisi, A. Distribution of resistivity in the upper crust of the Larderello geothermal area. ***Proc. COFIN2000 Project Meeting.*** In press.

Volpi, G. and Manzella, A. Investigation of geothermal structures by magnetotelluric (MT): an example from the Mt. Amiata area, Italy. Submitted to Geothermics.