The Siena Graben: combined interpretation of DES and MT soundings

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Abstract
The Siena Graben study area is located in Tuscany, Central Italy. The local geological structures were extensively studied in the frame of the Italian National Research Council (CNR) and the Commission of the European Communities (CEC) geothermal projects. Axial dipole-dipole geoelectrical soundings (DES) were also performed. Recently we carried out 13 broadband magnetotelluric (MT) soundings, most of which were located very close to the station sites of the mentioned DES. For six of them we made a DES-MT combined interpretation in order to put in evidence resistivity frequency dispersion effects. Indeed, four sites showed DES-MT anomalous responses, in the frequency range $1 \div 10^2$ Hz, which can be properly explained as due to dispersion effects in shallow layers. Three of these anomalous sounding sites are located on the neoautochthonous clayey formation, while the fourth is located on the eastern boundary of the graben over an extensive outcrop of the «Macigno» complex. The dispersion-affected soundings are all located in the northern part of the graben, while there is no evidence of such effects in the southern part. This circumstance, together with the estimate of very low time constants of the fitting Cole-Cole dispersion model, can be tentatively explained as due to local and shallow lithological effects (clay-like membrane polarization) rather than to deep geothermal effects (sulphide-like electrode polarization). Moreover, the MT soundings delineated a conductive zone in the upper crust below the resistive geoelectrical basement, located in the northern part of the graben, which appears at present difficult to interpret. Furthermore, the combined analysis of the DES and MT soundings in the same sites has allowed us to resolve one of the most intriguing ambiguities concerning the determination of the depth to the graben basement. The result is a remarkable reduction of the depth to the basement top, especially in the northern part of the graben. Finally, the easternmost MT soundings, located on the resistive outcrops of the massive calcareous formations of the basement and of the «Macigno» complex, permitted us to investigate almost all the lithospheric slab, thanks to the locally greater skin depth penetration. The lithosphere-asthenosphere transition is very well delineated, whereas the crust-mantle transition seems not to have an evident electrical signature.

Key words *dipolar geoelectrics – magnetotellurics – geothermal, lithospheric prospecting*

1. Introduction

The Siena Graben was the topic of numerous detailed investigations for geothermal purposes at the beginning of the eighties, both in the frame of the Italian National Research Council (CNR) and the Commission of the European Communities (CEC) target projects. In this context, 20 axial dipole-dipole geoelectrical soundings (DES) were performed in the Siena Graben, distributed along 5 profiles both parallel and perpendicular to the graben axis (fig. 1) (Patella and Tramacere, 1982). Notwithstanding the very high dipole-to-dipole spacings used, of the order of 10 km, the investigation depth of the DES was strongly lim-

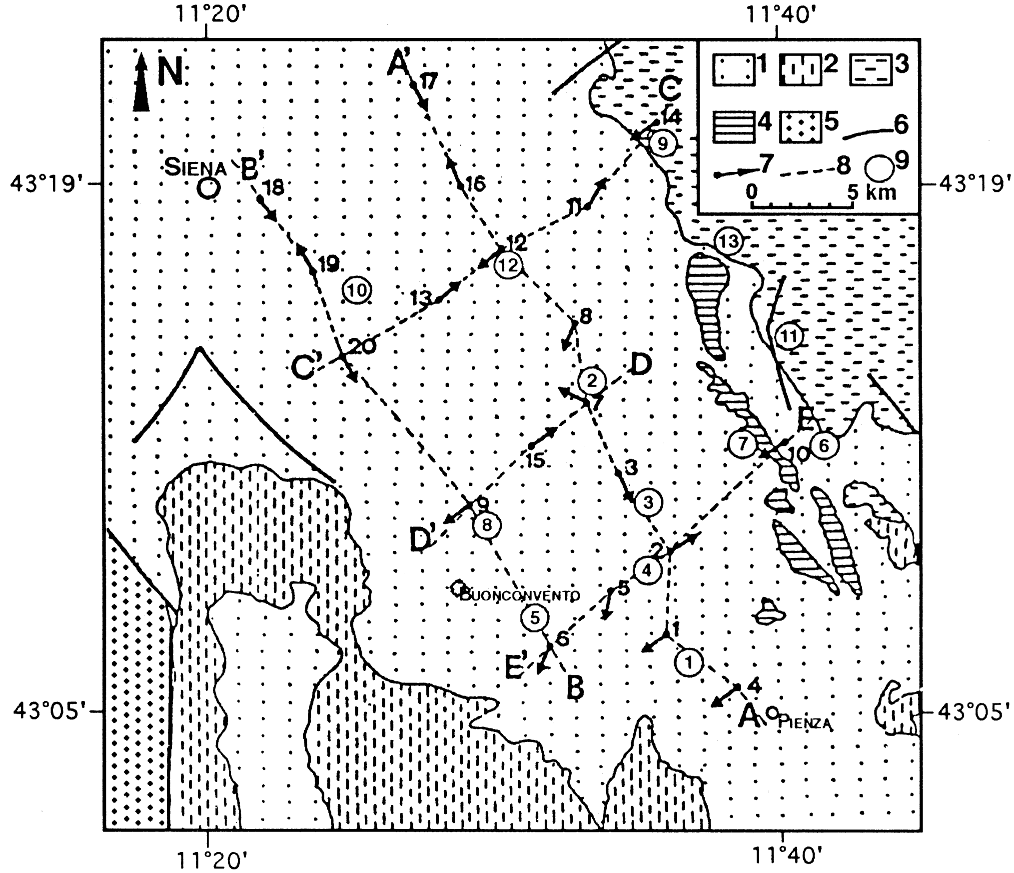

Fig. 1. Schematic geological map of the survey area with the location of the electrical (DES) and magnetotelluric (MT) soundings. 1 = Neoautochthonous complex; 2 = Flysch-facies complex; 3 = «Macigno» complex; 4 = Carbonatic complex; 5 = Metamorphic complex; 6 = main faults; 7 = centres of the DES and directions of the expansion axes; 8 = surface traces of the geoelectrical cross-sections; 9 = MT soundings (redrawn after Patella and Tramacere, 1982).

ited by the presence of a relatively shallow resistive basement. For this reason we decided to promote an extensive broadband magnetotelluric (MT) survey (about 0.01-1000 s) in order to investigate the whole upper crust and possibly down to the lithosphere-asthenosphere boundary. Moreover, accounting for the peculiar geothermal interest of the Siena Graben area, the MT sounding sites were located as close as possible to the DES stations, in order to highlight the eventual presence of resistivity frequency dispersion effects, which, as recently outlined, are good indicators of some geothermal activity underground. The comparison between DES and MT soundings can also provide a set of useful information for solving ambiguities typical of DES and MT soundings, when considered separately (DES depth to resistive basement determination, MT static shift and impedance estimates).

In this paper, we first give a geological outline of the investigation area and a description of the adopted techniques for MT data acquisition and processing. Then, we describe in detail the combined interpretation of the DES and MT soundings, by focusing on the above mentioned problems, namely the resistivity dispersion effects and the electrical structure of the upper crust.

2. Geological outline

The Siena Graben geothermal area lies in the eastern part of Southern Tuscany (fig. 1). Its stratigraphic sequence can be schematically described as follows, from top to bottom (Patella *et al.*, 1979):

1) *Post-orogenic complex*, made up of formations that deposited after the cover of allochthonous units of the Tuscan series. It consists of neogenic deposits (Pliocene-Upper Miocene), characterized by clay, conglomerates, sand and organogenous limestone. These deposits filled the sedimentary basins (graben), initially lacustrine, then lagoonal and finally marine, that formed from the Late Miocene to the Pliocene.

2) *Flysch-facies allochthonous complex* («Argille scagliose» or «Ligurids» of the authors) of Upper Jurassic-Eocene. It is mainly made up of shale, silt, marl, limestone and sandstone. This complex lies in tectonic contact above any one of the stratigraphic terms described below.

3) *Upper part of the Tuscan Series* characterized, from top to bottom, by the «Macigno» and «Scaglia». The «Macigno» is a formation of quartzose-feldspathic-micaceous sandstone alternating with silt and clay (Oligocene). The «Scaglia» consists of varicoloured shale alternating with calcilutite and calcarenite (Eocene-Cretaceous).

4) *Middle and lower parts of the Tuscan Series* (carbonate complex) of the Malm-Norian. Many formations belong to this complex, including, from top to bottom: radiolarite, marl and «Posidonia» marly limestone, stratified cherty limestone, Ammonitic red limestone, massive limestone, stratified black limestone and dolomite, cavernous limestone and breccia, anhydrite and dolomite (anhydritic formation). This complex outcrops along the Trequanda-Rapolano ridge on the eastern boundary of the graben.

5) *Metamorphic complex.* By this term we indicate all the metamorphic formations mainly consisting of phyllite, quartzite and quartzose conglomerates (anagenite) of age varying between the Middle-Upper Trias and Carboniferous, and older.

A simplified scheme of the structures present in the Siena Graben can be related to (Costantini *et al.*, 1982):

– fold dislocations, characterizing the Middle Tuscan and the Trequanda-Rapolano ridges, in correspondence of which the carbonatic complex outcrops to a large extent;

– strike dislocations along sub-vertical planes, distributed transversally to the graben axis (Arbia and Grosseto-Pienza lineaments), which divide the graben into three different sectors. We have concentrated our research program inside the central sector, which corresponds to the Siena Graben *strictu sensu.*

3. MT data acquisition and processing

Thirteen MT soundings were performed in the Siena Graben, whose locations are depicted in fig. 1. The MT soundings were programmed within a large frequency range (0.001-100 Hz in the average) in order to have the greatest possible information on both the shallow and the very deep structures.

The magnetic sensors are induction coils, designed to give an amplitude-versus-frequency response curve closely conforming to the natural magnetic spectrum. Low noise Pb-PbCl impolarizable porous pot electrodes were used for the detection of the electric field components across dipoles generally not less than 100 m long. In correspondence with resistive outcrops dipole lengths as great as 270 m at most were used, in order to account for the expected greater depths of penetrations.

In each site, data were sampled (and stored on floppy disks) over 3, sometimes 4, overlapping frequency bands. The aim of this choice is twofold: first, to optimize analog/digital converter resolution; second, to control the noise level in the overlapping zones and hence generate almost noise free data sequences for the whole sounding. Each frequency band was divided into blocks of 512 points.

After removal of spikes, application of the FFT algorithm and correction for instrument transfer function, the auto and cross-power average spectra were calculated, which are necessary to apply the least-squares estimate procedures (Sims *et al.*, 1971). To this purpose, in order to have a control over the influence of the various noise sources, three different procedures were applied: 1) the procedure commonly referred as to the standard analysis, since it is the method that is most commonly used (Vozoff, 1972), by which the calculated impedances depend on autopowers of the magnetic field components and as a result they are downward biased; 2) the admittance analysis, by which the calculated impedances depend on autopowers of the electric field components and as a result they are upward biased (Sims *et al.*, 1971); 3) the method consisting in making the average of the four possible impedance stable estimates (Sims *et al.*, 1971).

Finally, the MT apparent resistivity and phase diagrams for the two polarization modes TE and TM were plotted against the period (fig. 2). Most of the MT soundings, even though more or less affected by high wavenumber noise, show a prominent 1D effect. Only three MT soundings, all located close to the strike dislocations bordering to the north and south of the central sector of the graben, present a very pronounced splitting of the two apparent resistivity diagrams, which indicate the presence of sharp and extended lateral contrasts. In order to have a means for rapid and effective 1D interpretation of all the MT soundings, not affected by a subjective determination of the electrical strike, we calculated and interpreted the apparent resistivity related to the determinant of the impedance tensor, which, as is well known (see *e.g.* Ranganayaki, 1984), is rotationally invariant (fig. 3). This configuration was also used for the comparison with the DES apparent resistivity diagrams (fig. 4). Note that soundings MT-12 and DES-12, MT-10 and DES-19, MT-9 and DES-14, MT-3 and DES-3, MT-2

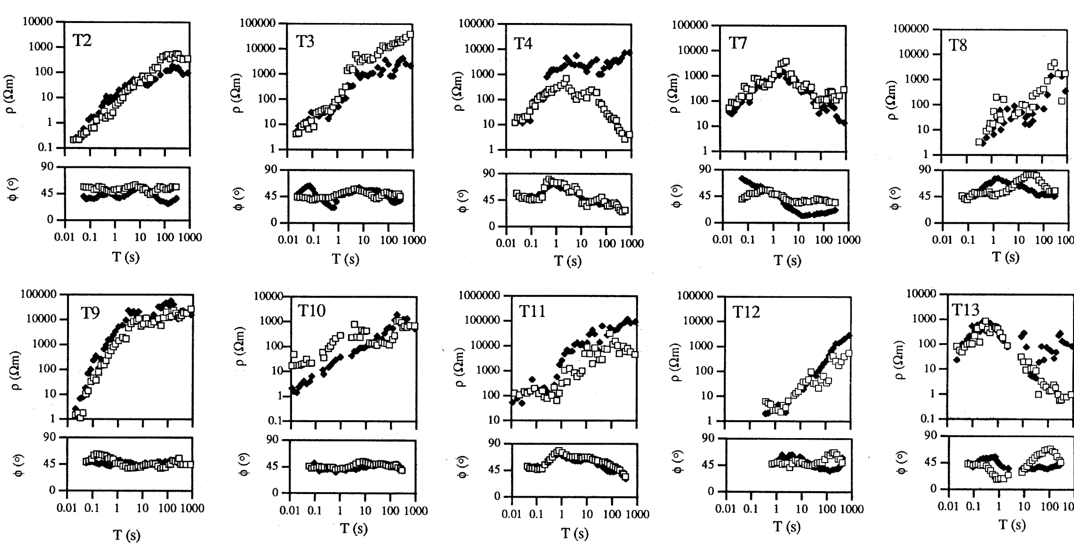

Fig. 2. Rotated MT apparent resistivity and phase diagrams for the two local polarization modes TE (□) and TM (♦) plotted against the period. The MT soundings T1, T5 and T6 are not reported because affected by very low signal-to-noise ratio.

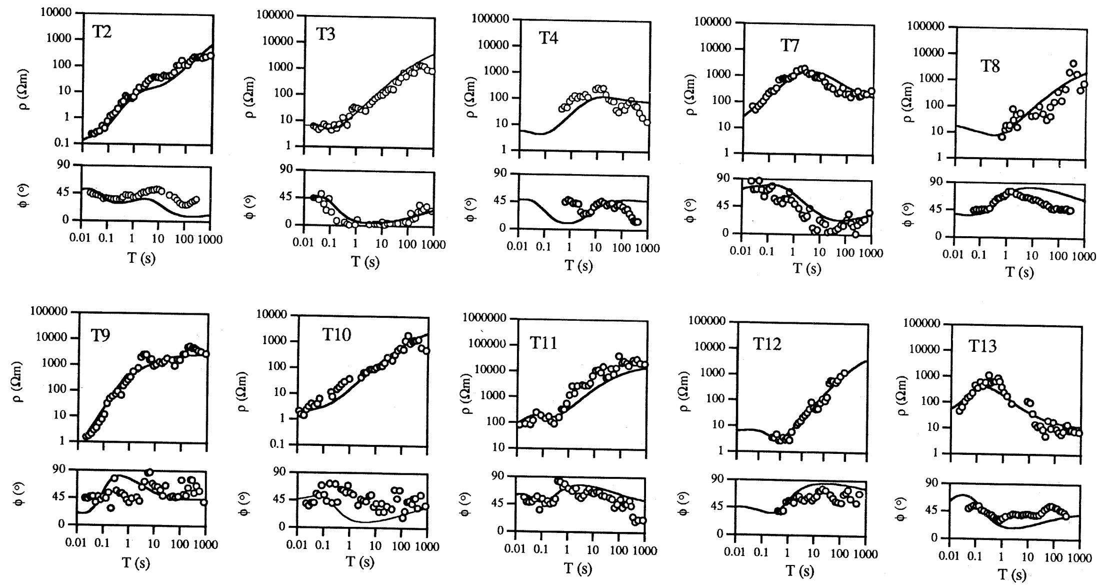

Fig. 3. Experimental MT apparent resistivity and phase diagrams for the determinant of the impedance tensor (○). The continuous lines are the fitting model curves.

and DES-7, MT-4 and DES-2, MT-8 and DES-9 and MT-5 and DES-6 constitute almost perfect single site sounding couples, very useful for cross-check analysis in view of the identification of dispersion effects and reduction of geometric interpretation ambiguities. However, the last mentioned couple was not subjected to further analysis as the MT data still present high level residual noise, which makes any interpretational effort difficult. The same problem afflicted soundings MT-1 and MT-6. In conclusion, 10 MT soundings underwent further analysis as follows.

4. Combined interpretation of MT and DES data

4.1. *Basement depth*

As previously outlined, the combined analysis of MT and DES soundings resolves interpretation ambiguities related to each single method data set.

The starting point for this new interpretation was the electrostratigraphic model previously suggested by the analysis of the DES (Patella and Tramacere, 1982). In particular, the DES information about the shallowest layers was taken for granted, as in MT they would correspond to the audio frequency band, not completely and accurately detectable by our instrumentation. The combined interpretation permitted us to draw a new electrostratigraphic model, in which the most relevant effect is a marked reduction of the depth to the basement in some places, with respect to the previous DES model. The conceptual approach to the new combined interpretation was not to give any particular emphasis to the role of one method over the other, in the sense that we tried to extract most common information from the analysis of the DES and MT curves. In particular, we assumed the guideline of searching a common datum for the depth to the top of the resistive basement, as we do not know any physical mechanism which could justify at those depths a discrepancy between DES and MT information. This assumption led us to uti-

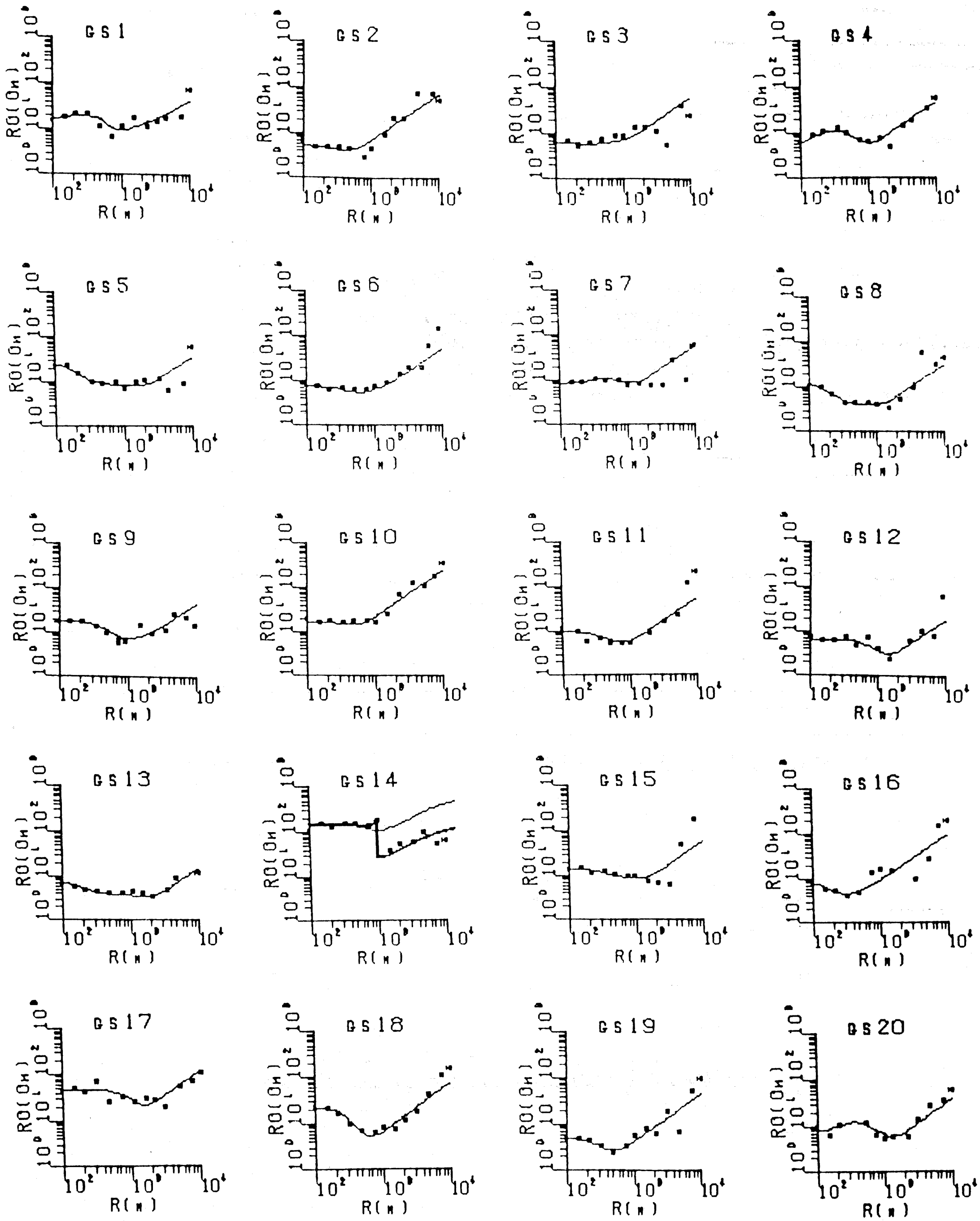

Fig. 4. Experimental DES apparent resistivity (■) diagrams. The continuous lines are the fitting model curves.

lize the least-squares minimum estimate of the MT impedance elements, *i.e.* the previously mentioned standard analysis. Such an approach had, as natural consequence, that in some places the DES and MT data showed marked discrepancies in the part of the curves corresponding to shallower layers. This occurrence, however, is fully justifiable by the resistivity frequency dispersion phenomenology. Had we utilized the approach of not enhancing the role of the resistivity frequency dispersion effects, by forcing DES and MT curves to match together in the typical dispersion frequency band, we would have obtained irremediable discrepancies in the portion of the curves belonging to the resistive basement. In both figs. 3 and 4 the continuous lines fitting the experimental data correspond to the common electrical model. The new DES fitting was directly made by curve-matching with computer simulated 1D and 2D dipolar diagrams (Patella and Tramacere, 1986), without passing through the half-Schlumberger transformation. In figs. 5a,b we show the common DES-MT electrostratigraphies along the five profiles of fig. 1, restricted to the first 2.5 km of depth from the ground level. In fig. 6, instead, we report the MT electrostratigraphy in correspondence with the profile along the eastern ridge of the graben, where notably higher investigation depths were reached.

These results shed new light on the interpretation of the basement geometry. Indeed, by surface geology (Costantini *et al.*, 1982), although with arduous extrapolations, as stated by the above authors, it was believed that the basement could be located at depths of the order of 1600-2000 m in the central part of the graben. This hypothesis strongly constrained the old DES interpretation. On the basis of the new combined DES-MT interpretation, the depth to the top of the basement seems not to exceed about 1400 m at most around the central-northern part of the investigated graben.

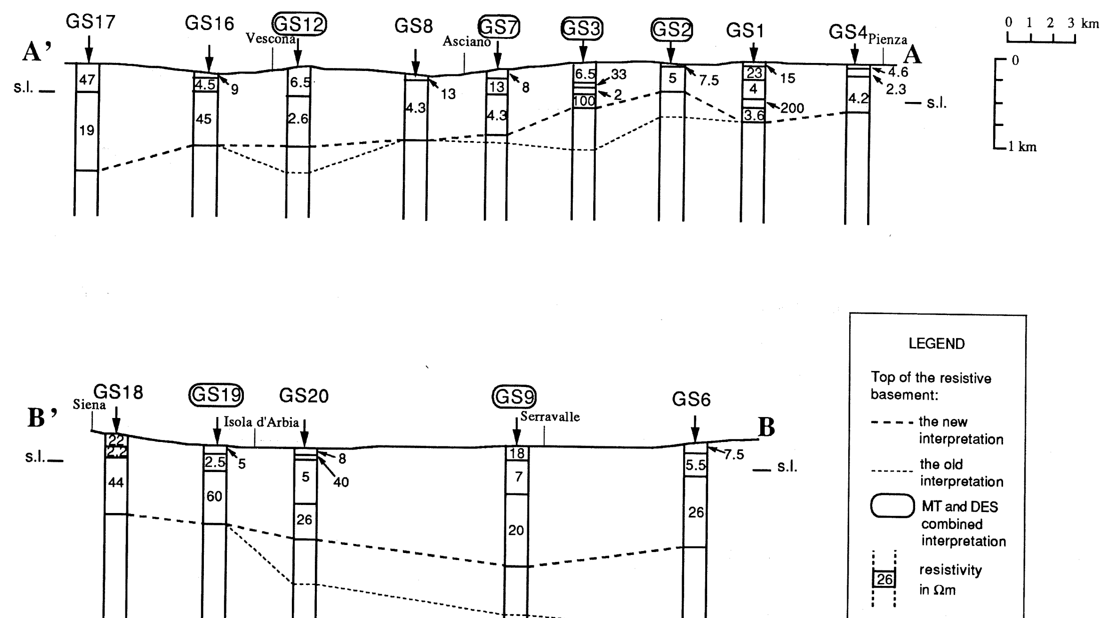

Fig. 5a. Common DES-MT electrostratigraphies along the five profiles reported in fig. 1: profiles AA′ and BB′.

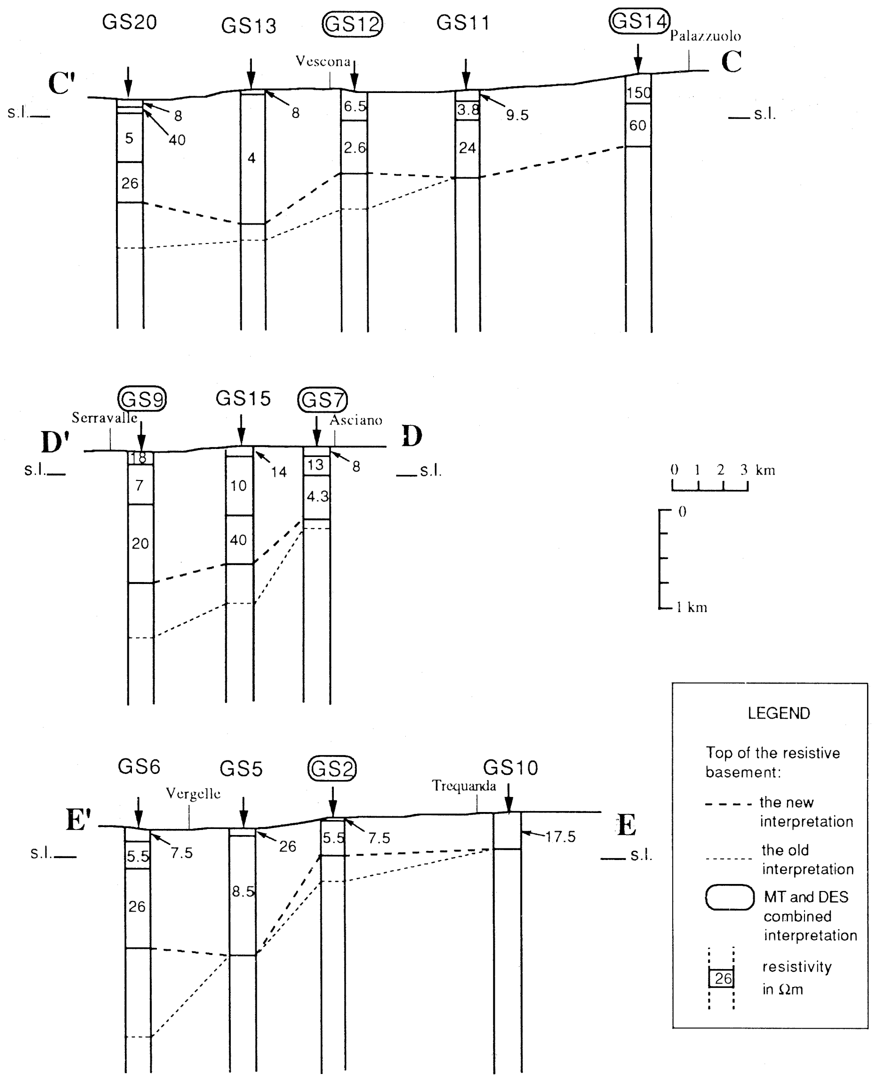

Fig. 5b. Common DES-MT electrostratigraphies along the five profiles reported in fig. 1: profiles CC′, DD′ and EE′.

4.2. *Resistivity dispersion analysis*

The occurrence of Induced Polarization (IP) in the rocks and its influence on the MT diffusion process has been widely studied from a theoretical point of view (Stoyer, 1976; Patella, 1987). It was demonstrated that MT can be seriously affected by the resistivity frequency dispersion phenomenology (IP) and that the corresponding sounding diagrams do not substantially differ from those relative to the classical dispersion-free MT curves. To solve this equivalence problem, Patella (1987) proposed to make independent DES and MT soundings in the same site and then to submit the collected data to a combined interpretation. He called this method «Dispersive Magnetotellurics» (DMT). In fact, an electrical sounding is by definition a dispersion-free method, as it operates in a nearly steady state regime. The MT sounding, however, operates in the frequency domain and, hence, can be affected by dispersion. By constructing synthetic MT non-dispersive diagrams from a preliminary DES interpretation, it is possible to evidence dispersion effects from the comparison between the true MT diagrams and the synthetic ones (for more details on the practical procedure, the reader is referred to Patella *et al.*, 1991).

As previously stated, six of the DES-MT common site sounding couples underwent combined interpretation. Three of them put in evidence a more or less large discrepancy in the MT frequency range 1 ÷ 10^2 Hz that can be well explained by the IP effects in shallower layers. Two of these sounding pairs are placed on the prevailingly clayey neoautochthonous formation, which is present all over the graben to a large extent; the third pair is located on the western edge of the extensive outcrop of the «Macigno» complex. All IP-affected sounding pairs are, however, located in the northern part of the graben, while there is no evidence of IP phenomena in the sounding pairs located in the southern part of the graben.

The Cole-Cole resistivity dispersion model (Pelton *et al.*, 1978) was assumed to interpret the IP-affected MT sounding diagrams. Table I

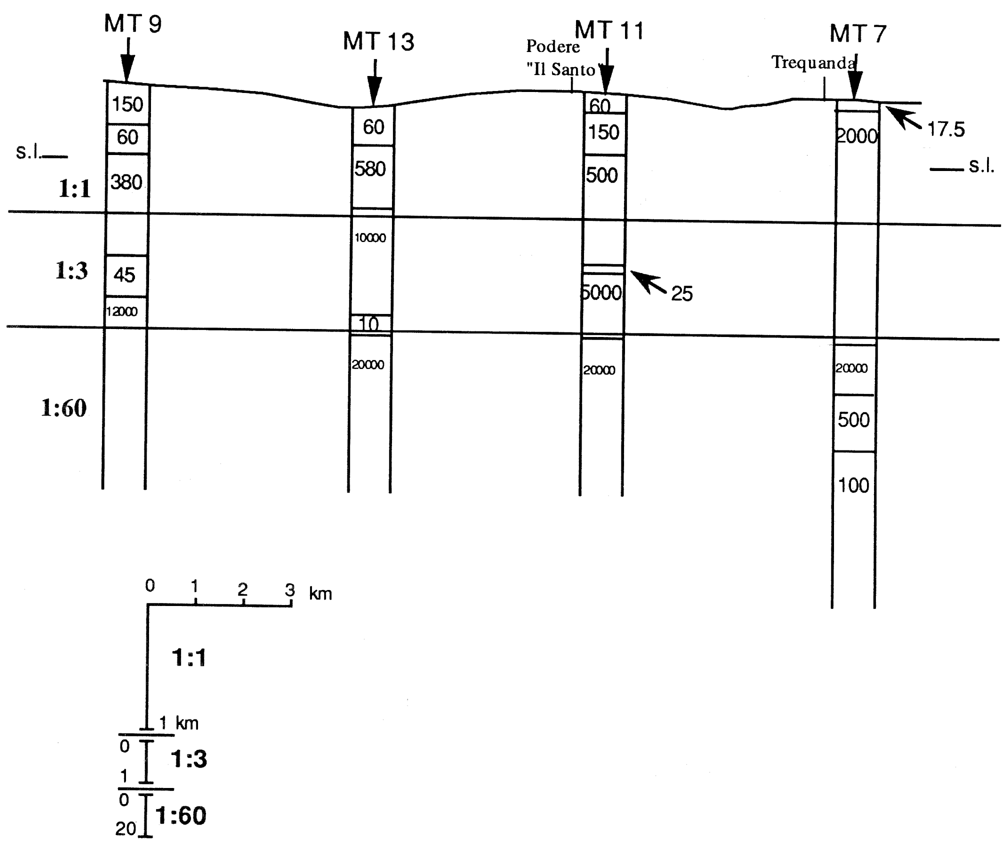

Fig. 6. MT very deep electrostratigraphy along the eastern ridge of the Siena Graben. Numbers along the electrostratigraphic columns are resistivities in Ωm.

Table I. Cole-Cole IP parameters of the disclosed dispersive layers.

MT soundings	Depth range (m)	$\tau(s)$	m	c
T2	0-100	0.2	0.9999	0.7
T2	100-300	1	0.9999	0.7
T9	0-300	0.12	0.9999	0.6
T9	300-500	1.9	0.9999	0.7
T10	0-100	0.1	0.96	0.6

shows the obtained Cole-Cole parameters associated to the evidenced dispersive layers, whose depths to the top and bottom are also indicated. As it can be observed, the dispersive layers are located within the first 300-500 m of depth, *i.e.* within the neoautochthonous formation (two soundings) and the «Macigno» complex (one sounding). Thus, the membrane IP mechanism, related to a more or less diffuse presence of clay particles, seems most likely to be responsible for the observed effects. In the area, as far as we know, there is no evidence of sulphide-type particle deposition at those depths, which may suggest an electrode IP mechanism.

Let us proceed now to delineate a general scheme, which gives a geophysical meaning to the Cole-Cole parameters; in particular with respect to the geothermal condition of the graben. To this purpose, the chargeability m and the time constant τ are the most significant parameters.

As is known, the chargeability gives a measure of the amount of polarization in the dispersive medium. According to the results of many IP experiments carried out in hydrogeological exploration, over bodies with a diffuse presence of clay particles, chargeability seems closely related to the volume percentage and size of clay particle aggregates. Against these two quantities chargeability generally manifests a bell-shaped relationship, the maximum of which may be thought to set the transition from a prevailing electrolytic conduction style to a prevailing electronic conduction mode. In our case, the highest chargeability values obtained ($m \geq 0.96$) would indicate that in the layers which manifest dispersion effects the volume percentage of clay should be around 20% (Ogilvy and Kuzmina, 1972).

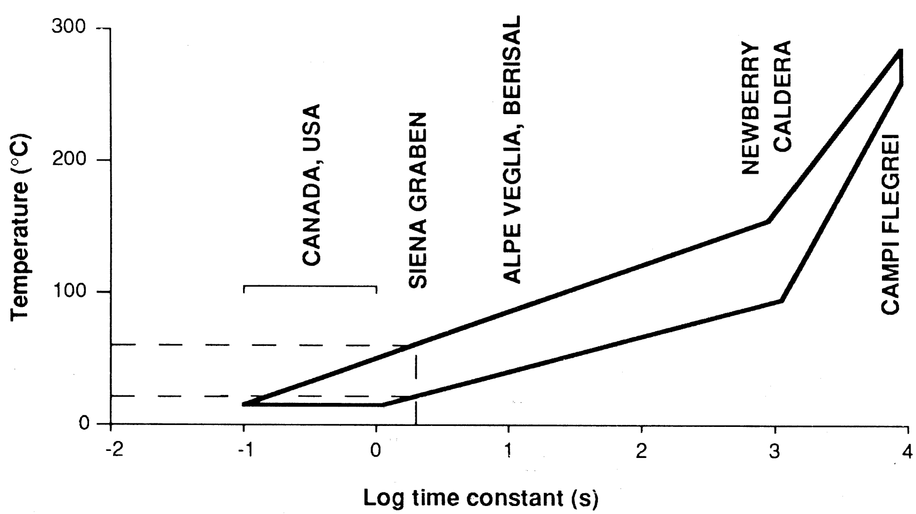

Fig. 7. Temperature-versus-IP time constant empirical diagram.

The time constant, in its turn, gives a measure of the time required by the main electric charge carriers to polarize or depolarize and seems strongly dependent on the thermal status of the dispersive body (Coppola *et al.*, 1993). Very small time constants, not exceeding 2 s at most, are the rule at room temperature, while values as great as 10^4 s has been associated to rocks with temperatures as high as 300°C. Intuitively, thermal agitation would contrast any regular polarization or depolarization ionic movement, and this explains why much longer times would be required to reach steady-state conduction regimes in rocks. Figure 7 shows an empirical time constant-versus-temperature diagram, which was drawn on the basis of previous interpretations related to controlled temperature conditions in various volcanic and/or geothermal areas. Looking at this diagram, we notice that the time constants obtained by the present analysis would indicate temperatures not exceeding 45°C in the depth range of the dispersive layers, where such values are consistent with the normal geothermal gradient. This interpretation also fully conforms to the heat flow data in the investigated area (Mongelli *et al.*, 1989).

5. Further lithospheric information

Four MT soundings located in the northern part of the graben (MT-2, MT-9, MT-11 and MT-13) disclosed the presence of a conductive layer in the lower part of the upper crust, at a depth of the order of 3 km, not exploited by the DES method. At present, it is difficult to give an explanation justifying the presence of this conductive zone. Tentatively, this zone might be associated to a highly fractured carbonatic formation filled with saline and hot waters. Indeed, all Tuscany is more or less affected by geothermal surface evidence, which could be related to a common deep source system. At the depths of the order of the above conductive crustal layer, the geothermal anomaly may have a wavelength of regional extent. In addition, the local tectonics may produce favourable conditions for fluid invasion in largely opened fractures. Altogether, these conditions are consistent with a notable decrease in resistivity.

A second implication, related, however, to the very deep portion of the investigated sections, concerns the presence of a conductive layer in the depth range 50-60 km. This effect was clearly put in evidence by the soundings located on the resistive outcropping formations on the east of the investigated area, which permit a deeper probing with the same operating frequency range. This evidence would very probably indicate the lithosphere – asthenosphere transition, as supported by many field and laboratory experiments all over the world (Constable, 1990; Duba and Shankland, 1987; Schwarz, 1990) and seems to be consistent with the seismological (Calcagnile and Panza, 1980) and heat flow (Mongelli *et al.*, 1989) interpretations.

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