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

# Integrated geoelectrical and magnetotelluric exploration at Gran Sasso d'Italia range (Central Apennines)

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**Abstract**
We carried out three electrical soundings, with continuous polar dipole-dipole array, and three magnetotelluric stations at Gran Sasso d'Italia, in the area of Campo Imperatore. Geoelectrical data show the existence of a resistive background with exceptionally high values of resistivity (greater than 25 000 $\Omega \cdot$ m) at a depth of about 250 m. The magnetotelluric data were used to constrain the thickness of this resistive layer, below which we find an intermediate conductive structure and a deeper resistive background. The geological interpretation of this result is still open to discussion, but we can exclude that the shallow resistive layer consists of Cretaceous limestones, since their resistivity has been estimated to be about 5000 $\Omega \cdot$ m.

**Key words** *magnetotelluric – dipole-dipole DC soundings – crustal exploration – Central Apennines*

## 1. Introduction

Within the framework of the LEMI project, devoted to the study of lithospheric structures in Italy with electric and electromagnetic methods, the Gran Sasso d'Italia massif was chosen as a test site. In this area some research teams have conducted measurements with different techniques and different apparatuses. The main goal of the project was the comparison among the responses of electrical and electromagnetic methods and of different apparatuses and data processing procedures. The secondary aim was not less important from the geological point of view: to collect new geophysical data in an area which has been scarcely investigated with geophysical methods before. The surface geophysical data collected so far at the Gran Sasso d'Italia range are palaeomagnetic measurements (Dela Pierre *et al.*, 1992) that have been used to reconstruct regional block tectonic models (Dela Pierre *et al.*, 1992; Salvini, 1993), and a test magnetotelluric survey (Zschau, 1995). Other geophysical data (strain measurements, electromagnetic wave recordings) have been collected at the INFN (Istituto Nazionale di Fisica Nucleare) laboratory within the motorway tunnel.

In this paper we present the results of the geoelectrical survey executed from the operating unit of Università degli Studi di Milano and of the magnetotelluric survey performed by the operating unit of Università degli Studi

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di Padova. A synthesis of the results and some preliminary considerations were presented in Alfano *et al.* (1997).

In Section 2 we describe the characteristics of the surveys; in Section 3 we discuss the field results; we discuss the geophysical interpretation of these results in Section 4 and some of the geological implications in Section 5.

## 2. Characteristics of the field surveys

The field survey was divided into two phases: in the first phase dipole-dipole electrical soundings were executed, whereas in the second one magnetotelluric data were recorded. The map of the area is represented in fig. 1, together with the location of the geoelectrical soundings and of the magnetotelluric stations.

The first phase was conducted by the operating unit of Milan (Participants: L. Alfano, M. Giudici, A. Cristina, J. Sommaruga, N. Turolla) in August 1994. Three soundings were executed with continuous polar dipole-dipole spread whose length was 8100, 9810 and 3500 m, respectively for sounding 1, 2 and 3. The acquisition equipment for the potentiometric dipole was of analog type for the shortest distances and of digital type for distances greater than a few kilometers.

The second phase was conducted by the operating unit of Padua (Participants: A. Zaja, M. Guzzon) in September 1994. Three magnetotelluric stations were recorded with standard measurement of the three components of the magnetic field and the two horizontal components of the electrical field. Data were acquired in the following frequency bands of 1/64-1 Hz, 1/8-8 Hz, and 1-100 Hz.

## 3. Results of the field surveys

Figure 2 shows the results of the geoelectrical soundings. Dashed lines are the curves of apparent resistivity for the dipole-dipole spread

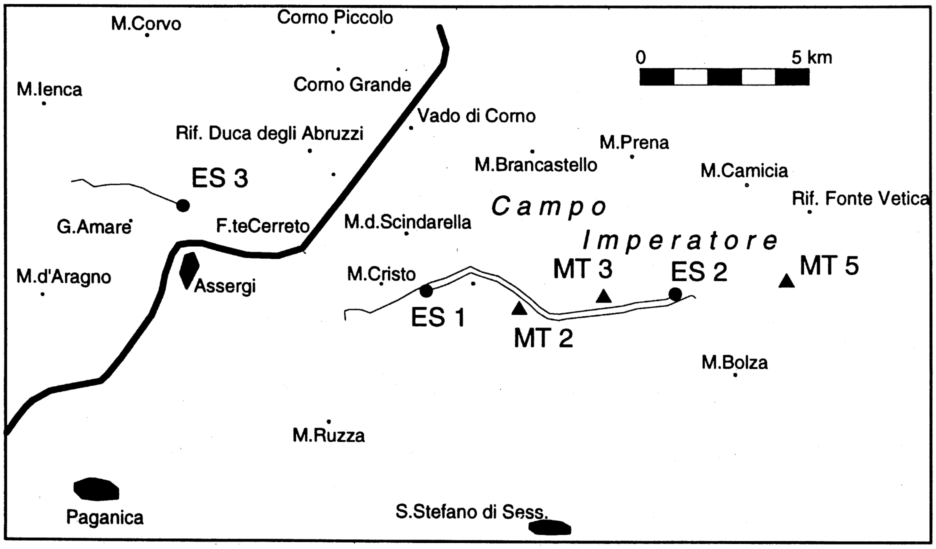

**Fig. 1.** Map of the investigated area and location of the geoelectrical soundings (ES) and the magnetotelluric stations (MT). Bullets and solid lines denote the centre of the potentiometric dipoles and the spread extension of the electrical soundings. Triangles denote the position of the magnetotelluric stations. Thick line is the highway.

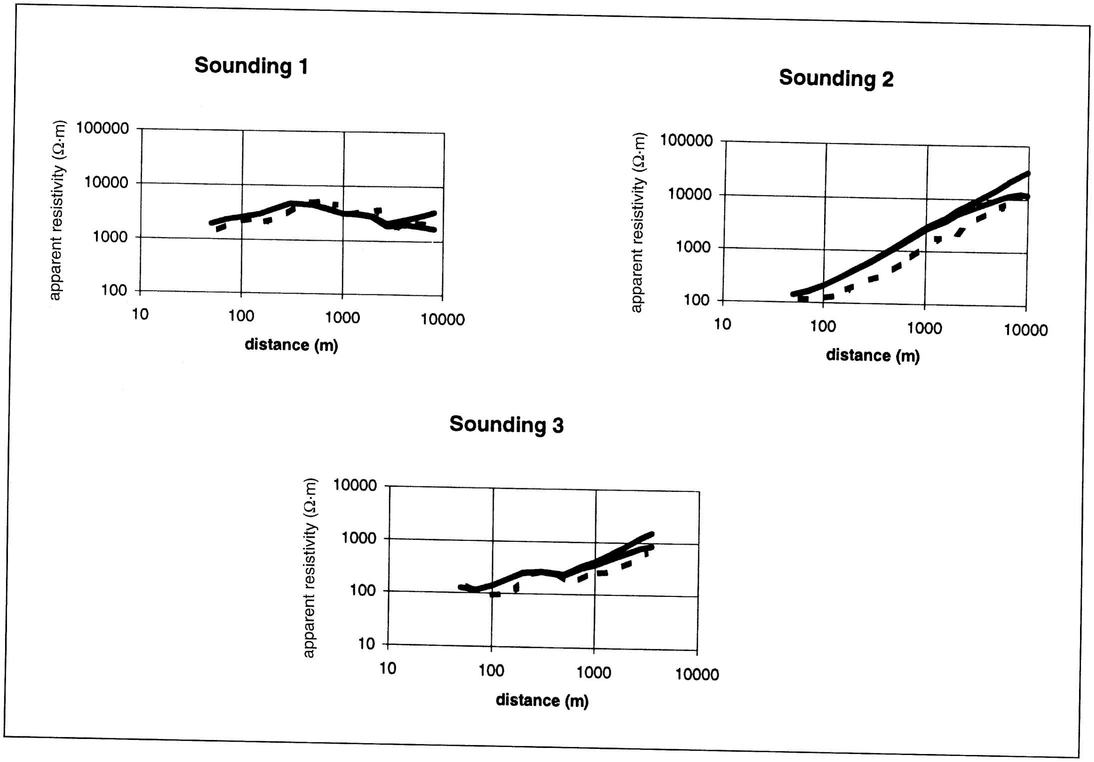

**Fig. 2.** Diagrams of apparent resistivity for the three electrical soundings. Dashed line = dipole-dipole curve. Continuous lines = transformed half-Schlumberger curves.

used in the field. The continuous lines are the curves of apparent resistivities for the corresponding half-Schlumberger arrays, computed following the technique described by Alfano (1974).

The diagrams of apparent resistivity for sounding 1 show positive slope, that indicates the presence of a resistive body (5000 Ω · m) at a depth of 20 m; the diagrams show a decrease of apparent resistivity starting from a distance of about 300 m.

The centre of sounding 2 was on the quaternary cover of Campo Imperatore and shows a value of resistivity for the shallow materials of about 100 Ω · m. Then the curves of apparent resistivity have a strong positive slope, which can be interpreted assuming the existence of two resistive layers: the shallow one with a resistivity of about 4000 Ω · m and a deeper one with resistivity higher than 25 000 Ω · m.

We measured a maximum apparent resistivity higher than 10 000 Ω · m, with a favourable signal-to-noise ratio. Such high values of resistivity are quite exceptional for geoelectrical prospecting. In fact, we measured these values only on igneous rocks, for instance at the Val Masino-Bregaglia pluton in Central Alps. We stress that if we had obtained the same result with a Schlumberger array, we would doubt about its correctness; in fact for Schlumberger spread small leakage from the electrical cable connecting the current dipole could influence the measured voltage difference if the leakage occurs close to the potentiometric dipole. This problem is practically absent for dipole-dipole arrays.

Sounding 3 was performed with the goal of evaluating more precisely the resistivity of outcropping limestones. Unfortunately, we observed the effect of a lateral variation at a distance of about 400 m from the potentiometric dipole; this caused a clear effect on the whole diagram and as a consequence we could not evaluate with precision the resistivity of the outcropping limestones.

Figures 3a-d, 4a-d and 5a-d show the results of the magnetotelluric stations. In particular, for each station we present the apparent resistivity and the phase for the two orthogonal measurement directions. The symbols $\rho_{xy}$ and $\phi_{xy}$ denote the apparent resistivity and phase obtained for the orientation of the electric dipole along the NE-SW direction for the station 2 and along the N-S direction for soundings 3 and 5. The symbols $\rho_{yx}$ and $\phi_{yx}$ denote the apparent resistivity and phase for the orthogonal direction.

Station 2 is the one characterised by high quality data for frequencies higher than 1 Hz. The diagram of apparent resistivity is approximately constant at 1000 $\Omega \cdot$ m for both measurement directions when frequency is greater than 50 Hz. We observe an increase of apparent resistivity for frequency of about 7 Hz.

Station 3 was very disturbed: as it is apparent from fig. 4a-d, it was not possible to obtain confident data at the intermediate band (1-10 Hz). At the highest frequencies the apparent resistivity is about 10 $\Omega \cdot$ m, whereas it increases to 100 $\Omega \cdot$ m at frequencies smaller than 1 Hz.

Station 5 shows an evident effect of static shift. However, we can observe that the trend is very similar to the one observed for station 2 (compare figs. 5a and 3a), although along one of the two measurement directions we obtain lower values of apparent resistivity.

The general behaviour of the magnetotelluric data for these three stations is in good agreement with the measurements performed at short distance by Zschau (1995). In particular,

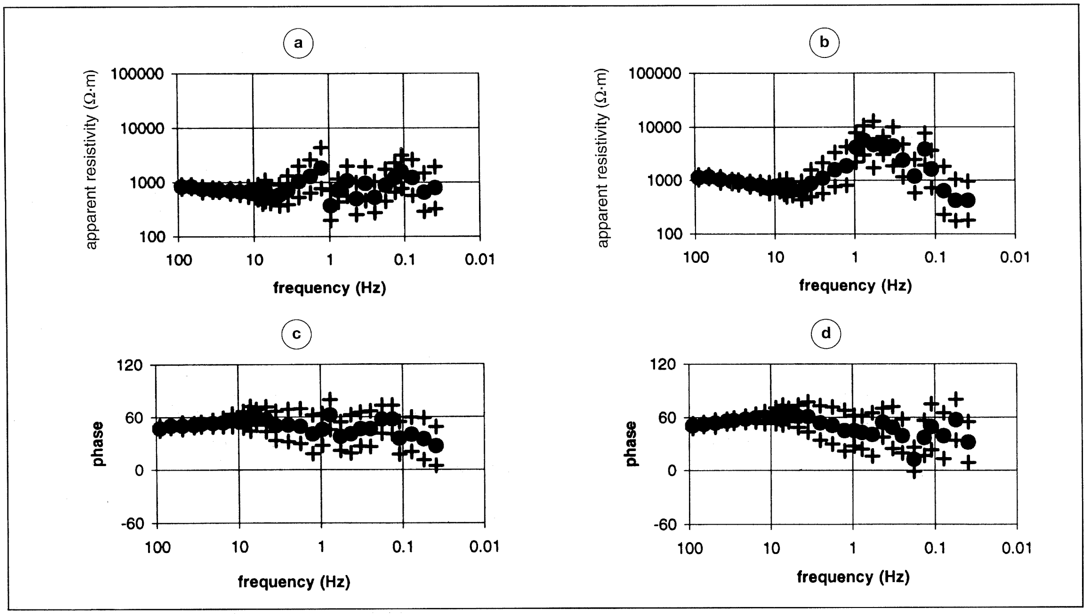

**Fig. 3a-d.** Results of the magnetotelluric station 2: apparent resistivity (a) $\rho_{xy}$ and (b) $\rho_{yx}$; phase (c) $\phi_{xy}$ and (d) $\phi_{yx}$. Dots denote the estimated value; crosses denote the error bounds.

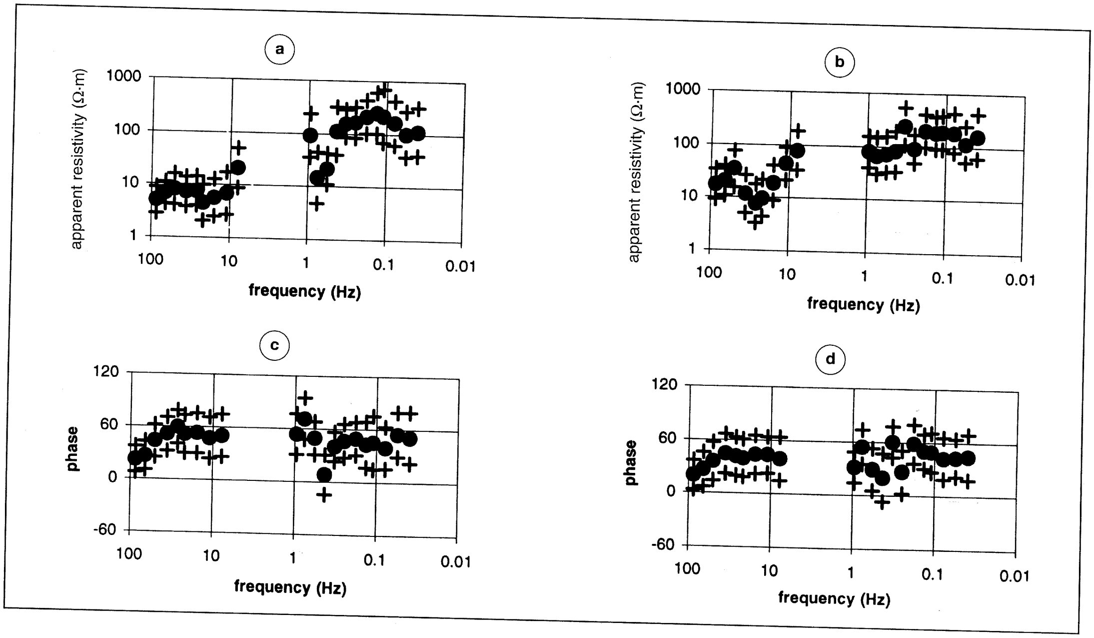

**Fig. 4a-d.** Results of the magnetotelluric station 3: apparent resistivity (a) $\rho_{xy}$ and (b) $\rho_{yx}$; phase (c) $\phi_{xy}$ and (d) $\phi_{yx}$. Dots and crosses as in fig. 3a-d.

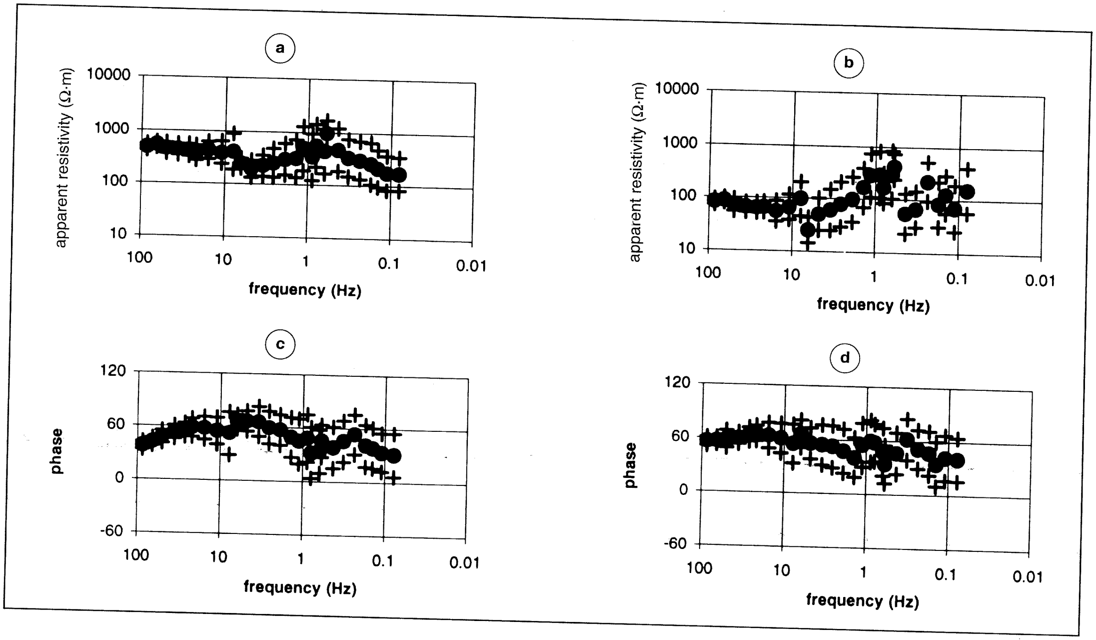

**Fig. 5a-d.** Results of the magnetotelluric station 5: apparent resistivity (a) $\rho_{xy}$ and (b) $\rho_{yx}$; phase (c) $\phi_{xy}$ and (d) $\phi_{yx}$. Dots and crosses as in fig. 3a-d.

the values of apparent resistivity are comparable, the trend of the diagrams is similar and the effect of static shift is common to our and their results.

## 4. Geophysical interpretation

One of the main results obtained from the dipole-dipole soundings is the proof of the existence of a resistive layer, which is located below the outcropping limestones. In fact, we can assign to these limestones a resistivity of about 5000 Ω · m, whereas the background shown by sounding 2 has resistivities greater than 25 000 Ω · m. The results of mathematical models (Giudici and Alfano, 1996) show that this resistive background should have a wide extension, both along the direction of the spread and along the transverse direction.

We modelled the results of sounding 2 by means of a layered structure. We obtained a thickness of 40 m for the shallow 100 Ω · m layer, underlain by a 200 m-thick layer with 5000 Ω · m and finally the resistive background, whose resistivity could be greater than 25 000 m. We estimated the minimum thickness of this resistive background to be greater than 3000 m. It is not possible to fit precisely the field results with 1D models. In fact, the diagram of apparent resistivity is too steep, so that we can make the hypothesis that the resistive background is dipping and in particular it immerses toward east.

Sounding 1 does not show the resistive background. This can be explained because conjugated soundings can give different results if discontinuities are dipping, as shown with a simple example by Alfano *et al.* (1994). In this case the fact that the discontinuity between the 5000 Ω · m-structure and the resistive background could be dipping is confirmed also from the results of sounding 2, as just mentioned. In addition, we remark that at distances from the potentiometric dipole greater than 1 km, the current dipoles of sounding 1 are located within a wide region («Gobbe di Santo Stefano») characterised by low resistivity quaternary cover, corresponding to the shallowest layer found with sounding 2. Therefore this structure could act as a conductor that induces the electric current injected with the energising electrodes to circulate within it; as a consequence the current flow density is mainly confined inside this conductive structure and below the potentiometric dipole current flow density is reduced as well as the electric field and the measured potential difference.

The interpretation of magnetotelluric data leads to a different model. In particular, we considered the results of station 2, since these are the best quality magnetotelluric data, and interpreted them with 1D modelling. The invariant mode (Ranganayaki, 1984) was considered in the modelling, since for this station the effects of static shift are very small and the invariant mode is therefore physically significant. We obtained a good fit with the hypothesis of a layer whose thickness is about 3000 m and resistivity is about 900 Ω · m, overlying a conductive layer (200 Ω · m). At greater depths (about 6000 m) another resistant layer is found with resistivity greater than 10 000 Ω · m and thickness greater than 17 000 m.

At first glance the results of geoelectric and magnetotelluric surveys do not appear to be coherent. Actually we have to recall that the two methods are complementary and the differences in the response of the methods can be due to a great number of factors, that we now summarise.

The magnetotelluric method can reach exploration depths greater than geoelectrical surveys, but the resolution of shallow structures with magnetotelluric methods is not very good, unless very high frequencies are considered.

Methods using stationary or time-varying fields show different responses to resistive and conductive layers, as shown with some simple examples in Giudici and Alfano (1997).

Possible variations of electrical resistivity with frequency could also affect the results and produce differences between magnetotelluric and geoelectric responses.

Despite this, we tried to find a 1D model whose results honor both geoelectrical and magnetotelluric data. In particular, we consider electrical sounding 2 – that shows the most interesting feature, namely the resistive background – and magnetotelluric station 2 – that is

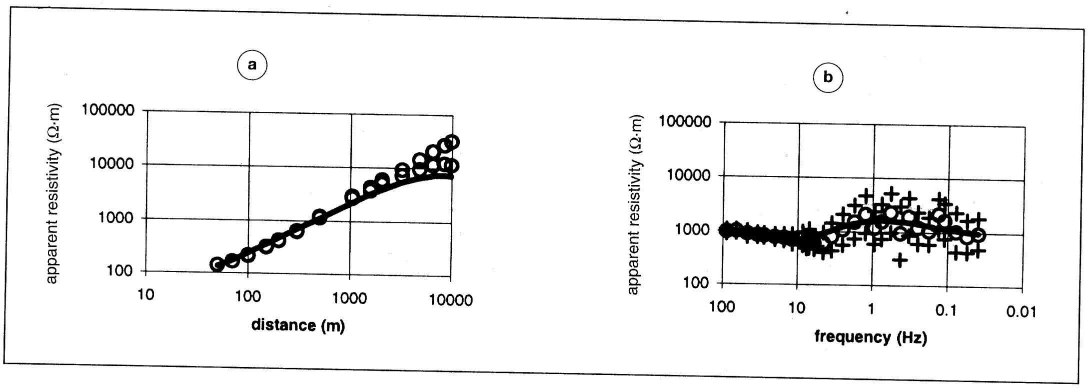

**Fig. 6a,b.** Comparison between theoretical results of the model presented in table I (continuous line) and field results (circles). a) Geoelectrical sounding 2; b) invariant apparent resistivity for station 2.

**Table I.** One-dimensional model.

| Resistivity (Ω · m) | Thickness (m) |
|---|---|
| 100 | 40 |
| 5000 | 200 |
| > 25 000 | 1000 |
| 200 | 1000 |
| > 10 000 | > 10 000 |
| 1000 | |

the magnetotelluric station with the best quality data and free from apparent 3D effects. The model is constrained by geoelectrical data for the shallowest levels and by magnetotelluric data for the deeper levels.

The final result of a standard manual trial-and-error procedure is represented in table I. The comparison between theoretical and field results is shown in fig. 6a,b: the fitting is satisfactory.

An important remark is that taking into account the magnetotelluric results we limited the thickness of the resistive background revealed by sounding 2. Its thickness was greater than 3 km when estimated only from geoelectrical data; however this value could have been biased because of the slope of the diagram of apparent resistivity.

## 5. Problems of the geological interpretation

The main result emerging from the geophysical interpretation is the existence of two resistive bodies, underlying the Cretaceous limestones and separated from a 1 km-thick conductive structure. The geological interpretation of this result is debatable.

Actually the geological situation of Gran Sasso d'Italia is quite complex and is schematically sketched in fig. 7, which is based on the geological map published by Servizio Geologico d'Italia (1963). The area is located within the Latium-Abruzzi carbonatic platform, which is divided into a number of «thin» crustal blocks reconstructed from palaeomagnetic and structural data (Dela Pierre *et al.*, 1992; Salvini, 1993). In the investigated area there is a major outcropping of Cretaceous limestones; Jurassic and Upper Triassic limestone outcrops in a more limited region. In several areas the limestones are covered by quaternary deposits, as is the case at Campo Imperatore.

The investigated area is also characterised by the presence of a thrust fault (thick line in fig. 7) that separates the northern and the southern blocks. This is more evident from the schematic geological section of fig. 8, that has been redrawn from Catalano (1984) and Catalano *et al.* (1986). This is based on the geological survey conducted both at the surface and

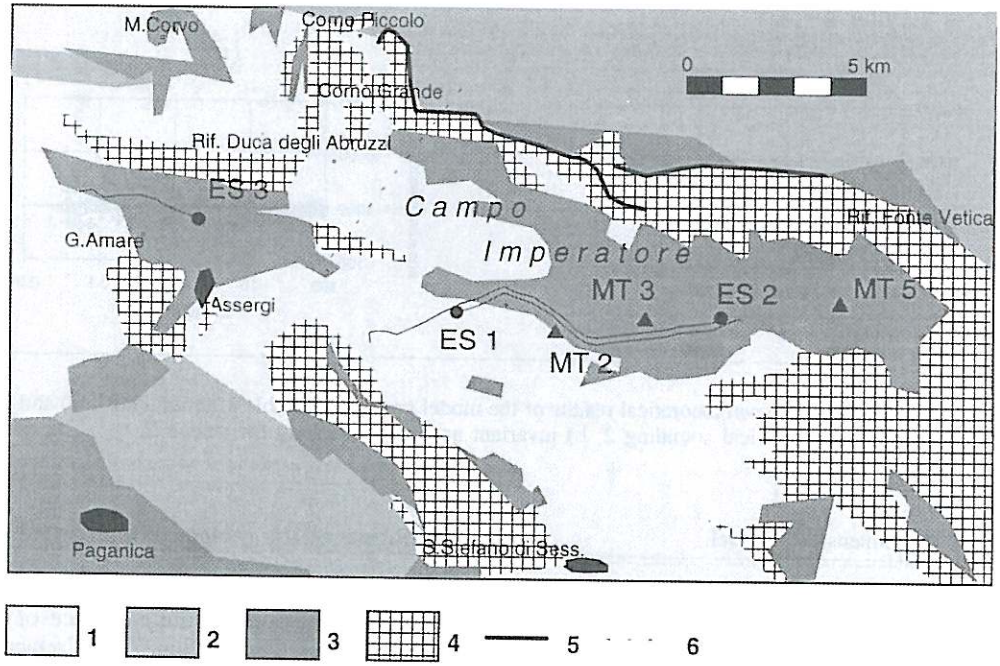

**Fig. 7.** Geological scheme of Gran Sasso d'Italia range. 1) Sedimentary cover; 2) Miocene marls, limestones and sandstones; 3) Cretaceous limestones; 4) Jurassic and upper Triassic limestones; 5) main overthrusting fault; 6) highway tunnel.

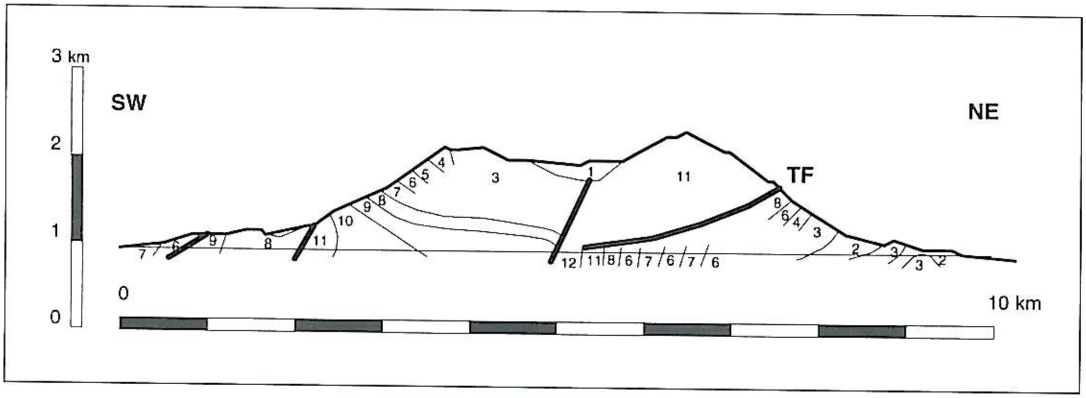

**Fig. 8.** Geological schematic section of the massif of Gran Sasso d'Italia, derived from surface geological survey and investigations performed during the drilling of the motorway tunnel (see the position in fig. 7), whose height over the surface is represented by the horizontal continuous line. TF = Major thrust fault (thick line in fig. 7). Quaternary: 1) Glaciofluvial detritus. Miocene: 2) Marls; 3) Marly limestone; 4) Glauconitic limestone. Oligocene: 5) Red marly limestone. Cretaceous: 6) Siliceous limestone «Scaglia»; 7) Bioclastic massive limestone; 8) Siliceous limestone «Maiolica». Jurassic: 9) Siliceous or detrital limestone: 10) Siliceous limestone «Corniola»; 11) Dolomitic limestone. Upper Trias: 12) Dolomite. Redrawn from Catalano (1984) and Catalano *et al.* (1986).

along the motorway tunnel, during the drilling operations and on the data of three stratigraphic wells drilled from Campo Imperatore down to the tunnel. The presence of a series of normal faults that introduce large displacements is clear within the southern block, whereas the northern block shows a reversed series.

The geological complexity suggests that the hypothesis of a one-dimensional model is poor from the geological point of view. However, the collected geoelectrical and magnetotelluric data do not allow any 3D reconstruction. Moreover, from the lithological point of view there are only minor variations, so that we cannot expect great contrasts of resistivity due to varying lithology, except for the contact between glaciofluvial deposits and limestones. On the other hand, the presence of fractures and fluids circulating within limestones can affect resistivity.

Although the 1D model is a crude approximation, the results of geoelectrical sounding 2 are very important. In the first place, we have already mentioned that we have never measured such high values of resistivity on sedimentary and metamorphic formations, but we measured comparable resistivities on igneous rocks. It is difficult to ascribe such high values of resistivity to limestones. In particular they should be very compact, not fractured and water free: the field conditions seem to be exactly the opposite of this. However, we stress that our soundings have been realised mainly within the outcropping of Cretaceous limestones, whose electrical resistivity is about 5000 $\Omega \cdot$ m, but we did not measure the electrical resistivity of Jurassic and Upper Triassic limestones. Furthermore, we did not measure the resistivity of anhydrite Triassic formations; their resistivity could be very high, so that they could possibly be one of the constituents of the resistive structure.

An important fact to be recalled for the geological interpretation is that from the geoelectrical data we can argue that the resistive background found with sounding 2 has a wide extension; roughly speaking we can estimate its minimum areal extension to be almost the same as the area of Campo Imperatore.

Since the geological interpretation of the first resistive body is so difficult, it is even more difficult to suggest geological hypotheses on the deeper structures.

## 6. Conclusions

We have presented the results of a geoelectric and magnetotelluric survey of Gran Sasso d'Italia.

From the methodological point of view, with a field example we have shown the importance of integrating different exploration techniques for better constraining the geophysical interpretation. This is fundamental when geophysical techniques either measure different physical parameters or measure the same physical parameter with different methods, *e.g.*, stationary *versus* time varying fields.

The geophysical interpretation has shown that below the outcropping Cretaceous limestones, whose resistivity is about 5000 $\Omega \cdot$ m, we find two resistive bodies, separated by a conductive layer. The geological interpretation of this result is troublesome and we have suggested some hypotheses, whose validity could be decided on the basis of new geophysical data.

## Acknowledgements

This work was funded from MURST (ex 40%) - LEMI project.

We thank the reviewers for some valuable suggestions.

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