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GDS (Geomagnetic Depth Sounding) in Italy: applications and perspectives

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Abstract
The analysis of geomagnetic field variations is a useful tool to detect electrical conductivity contrasts within the Earth. Lateral resolution of outlined patterns depends on the array dimensions and density of measurement sites over the investigated area. The inspection depth is constrained by the period of geomagnetic variations considered in data processing. Regions with significant geological features such as boundaries of continental plates, marginal areas of contact between tectonic units or other geodynamical processes, are of primary interest for the application of the MagnetoVariational (MV) method. In the last ten years, in the frame of the ElectroMagnetic (EM) sounding techniques in applied geophysics, this method has been applied in Italy by researchers of the Istituto Nazionale di Geofisica, Rome, the Dipartimento di Scienze della Terra, Università di Genova and the Czech Science Academy of Prague. The Ivrea body in the Northwestern Alps and their junction with the Apennine chain, the micro-plate of the Sardinian-Corsican system and, recently, the central part of the peninsula along Tyrrhenian-Adriatic lithospheric transects were investigated. Studies in time and frequency-domain used in the first investigations, have been followed by more refined analysis involving tests on the induced EM field dimension, computations of single site Transfer Functions (TFs) through Parkinson arrows' and Fourier maps in the Hypothetical Event technique (HE). It was possible to describe the electrical conductivity distribution in the inner part of the SW Alpine arc and to confirm the presence of lithospheric and asthenospheric anomalies obtained by other geophysical methods. For the Sardinia-Corsica system, 2D and 3D inversion models highlighted the existence of two major conducting bodies, one north of Corsica, and the other south of Sardinia. In Central Italy, the regional electrical conductivity distribution pointed out a deep conductive structure beneath the Apennines and a very resistive root for this part of the mountain chain.

Key words *EM induction – magnetovariational method – 2D and 3D electrical conductivity modelling*

1. Introduction

Lateral and vertical soundings are the final step of a numerical processing applied on the magnetic transients generated by natural sources located in the magnetosphere and ionosphere (Schmucker, 1970). Based on the classical theory of low frequency electromagnetism, the MV method is related to an important electrical parameter, the skin depth $\delta = 30.2\,(T/\sigma)^{1/2}$, which gives, for a flat-earth model, the depth (in km) of penetration (*i.e.* the distance in which the signal is reduced by 1/e) of an EM inductive variable signal of period T (given in hours) in a subsoil of conductivity δ (given in S/m).

Application to regional studies depends on the choice of the MV frequency considered and on the size of the survey. The short-period (few minutes) variations provide indirect infor-

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mation about physical features and the nature of the shallow layers of the upper crust while longer periods (up to few hours) are related to the lower crust and the lithosphere. The most significant result from studies on planetary length scale, for which *Sq* and *Dst* signals are generally considered, refers about the relation between the sharp increase of the electric conductivity in upper mantle between depths of 400 and 800 km and the corresponding change of phase in the olivine structure (Hermance, 1995 and reference therein).

In recent years, some authors have mainly focussed on the regional effects of EM induction, bounding their investigation to areas of $10^3 \div 10^4$ km^2. In doing so, the regional electrical conductivity configurations are settled by mainly two EM methods: the MagnetoTelluric (MT) technique, which involves measurements of magnetic and orthogonal electric field variations and the magnetic gradiometric method, which estimates electrical conductivity contrasts from the vertical magnetic field and the horizontal divergence of the horizontal magnetic field. In this case, simple geometric representation in Cartesian coordinates instead of spherical ones are considered and typical time-variations (*event*), that last from a few minutes to 1-2 h with magnitude of several tens of nT, are taken into account (Banks, 1973; Gough and Ingham, 1983).

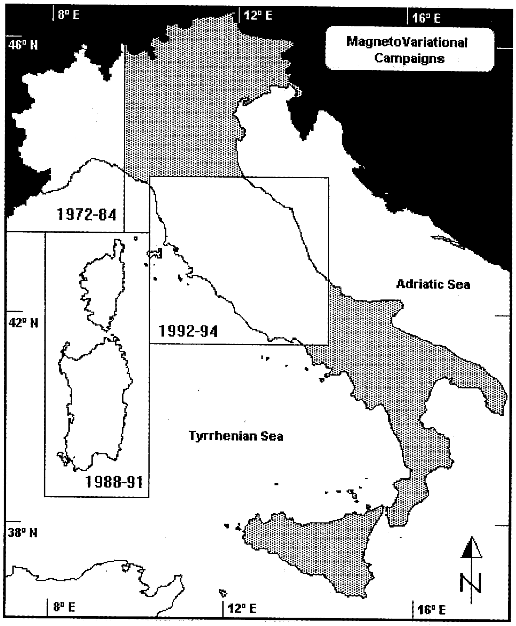

Fig. 1. 1972-1984 Campaign (see Bozzo and Meloni, 1989); 1988-1991 Campaign (see Červ *et al.*, 1993); 1992-1994 Campaign (see Di Mauro *et al.*, 1996).

The present paper deals with the MV studies from data collected during three different measurement campaigns held in Italy in the last decade (see fig. 1) by means of quasi-simultaneous arrays of magnetometers covering relevant tectonic structures in order to extend the knowledge of the local geological settings, adding new elements to their geophysical interpretation.

2. The magnetovariational method

The standard self-powered measurement system adopted in MV investigations consists essentially of a three-component fluxgate magnetometer and a data logger. Time-variation recordings for the X, Y and Z components, displayed by magnetograms, allow to select an appropriate number of events that last $1 \div 2$ h. If the inducing magnetic field is considered (at mid-latitude) as a downwards propagating plane wave, then the three components, fast Fourier transformed into the frequency domain, are combined by the well known linear relation

$$Z(f) = A(f)X(f) + B(f)Y(f) + \varepsilon$$

in which, for each site, the observed vertical component Z is associated to the external horizontal ones through the Transfer Functions (TFs) $A(f)$ and $B(f)$ (Everett and Hyndman, 1967; Gough and Ingham, 1983; Parkinson, 1989). The latter can be estimated minimizing the residual ε employing a standard spectral analysis (Schmucker, 1970) or a standard least-squares method (Everett and Hyndman, 1967). More refined methods on robust estimation of TFs have been proposed by Egbert and Booker (1986, 1989) by means of a statistical approach in which the residual ε is considered as a function of the frequency, *i.e.* $\varepsilon = \varepsilon(f)$.

The real parts of $A(f)$ and $B(f)$ can be regarded as directive cosines of the corresponding plane from which an orthogonal unitary 'vector' points towards high electrical conductive bodies or current concentrations interpreted as zones of high internal conductivity (Parkinson, 1959, 1962, 1989; Parkinson and Jones, 1979). The projections of a such 'vector' in the tangent plane to the site, that is, the quantities $A(f)$ and $B(f)$, define the induction arrows, also known as «Parkinson vectors», with magnitude and direction from the north given by

$$V_r = [A_r(f)^2 + B_r(f)^2]^{1/2}$$

$$\theta_r = \arctan[B_r(f)/A_r(f)] + \pi$$

and similar expressions for the imaginary parts. The directions of induction arrows are reversed such that they both actually point towards the current concentrations or, in general, towards higher values of the electrical conductivity (Bailey *et al.*, 1974; Lilley and Arora, 1982; Jones, 1986; Weaver and Agarwal, 1987).

This single-site approach can reveal an intrinsic limitation in the case of non-simultaneous events when an array response has to be determined: it is quite difficult to distinguish local deviations from a presumed uniformity of the geomagnetic horizontal field (especially for large arrays or arrays arranged at high latitudes), from an effective underground response (obviously different) in each point of the array. Beamish and Banks (1983) have computed TFs in relation to a reference station while Egbert (1991) has developed a technique that combines the measurement of different parts of the same array to determine the overall response (overlapping arrays).

Hence, a map that could connect different results from amplitude and phase isolines of TFs (Fourier map) in different sites needs a simultaneous array of recording stations (Reitzel *et al.*, 1970). In order to avoid the practical difficulties of keeping a large number of simultaneous recording stations, it is possible to adopt the Hypothetical Event Technique (HET, Bailey *et al.*, 1974). In fact, from the estimation of the double couple of TFs (both real and imaginary) that contain the physical information of the underground electrical conductivity of the corresponding site, it is possible to re-compute the Z values, imposing the same hypothetical horizontal magnetic field, linearly polarized

$$Z^{\mathrm{hyp}}(f) = A(f)X^{\mathrm{hyp}}(f) + B(f)Y^{\mathrm{hyp}}(f)$$

in appropriate directions for each site over the entire array. These directions are generally suggested by the geological features of the investigated area to better highlight tectonic boundaries and possible conductivity contrasts.

The difficult reconstruction of the electrical conductivity model in a 2D medium (exactly obtainable only in 1D case from the analytical expression of the EM field) or even worse in a 3D case, has been attempted by several numerical techniques of inversion. The forward modelling is carried out by solving the differential or integral equations of time-varying low frequency electromagnetic field (E polarization in the case of 2D conductivity distribution). Basically, the most widely used techniques are: 1) the finite element method; 2) the transmission surface; 3) the finite difference method; 4) the integral equation method (Gough and Ingham 1983 and references therein). Inversion can be achieved by linearized (generalized inversion, Backus-Gilbert approach, stochastic inversion) or non-linear methods (*e.g.*, Dimri, 1992).

3. Data analysis on Italian areas and interpretations

During the years 1972-1984 four automatic recording systems were used to study an area in the northwestern part of Italy. Seven MV stations were located between 44°13′ and 45°40′N in latitude and between 6°58′ and 8°11′E in longitude. A number of events were selected after having applied a low-pass filter on the 30 s sampling rate. The graphic representation of the induction arrows as shown in fig. 2a for the three periods 8, 20 and 60 min

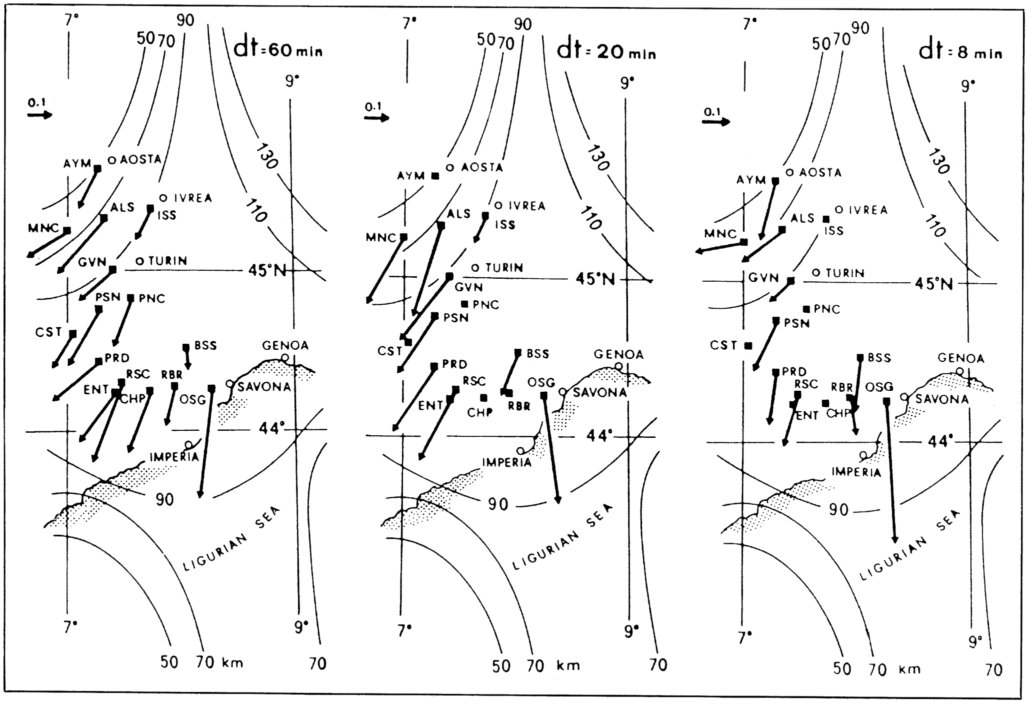

Fig. 2a. Induction arrows (real and imaginary) for 60, 20 and 8 min. Isolines of the Sub-Moho layer depths (in kilometers) are also indicated.

derives from the computation of the power spectra of vertical magnetic component in the complex frequency domain.

The induction arrows of the southern stations of the investigated area point toward smaller lithospheric thickness and seem also in accordance with a possible «coast effect» (Parkinson and Jones, 1979). The arrows of the northern stations are almost tangent to the lithospheric thickness isolines (Panza, 1984). This could be caused by the presence of strong vertical inhomogeneities associated with more conductive intrusions into the root of the Alpine system, as well as the features of the mantle upheaval in the Ligurian Sea (Bozzo and Meloni, 1989). It is also worth noting that a 3D conductivity anomaly appears from the Fourier maps covering the area in which is partially present the gravity anomaly called the Ivrea body (Laubscher, 1985), (fig. 2b).

From Summer 1988 to Spring 1991 a quasi-simultaneous MV array with 13 stations was installed in Sardinia (Italy) and Corsica (France) over an area located between 42°5′ and 39°N and between 8°40′ and 9°60′E. As known, these two islands form a unique block-system (Corso-Sardinian microplate). Locally, it is influenced by a thinned continental crust and the formation of new oceanic crust under the Tyrrhenian Sea, as confirmed by strongly positive values of heat flow density as well as magnetic and gravimetric anomalies in that area (Lavecchia, 1988; Della Vedova *et al.*, 1991; Červ *et al.*, 1993). Using the analysis seen in the previous paragraph, and in particular the hypothetical event technique with N-S and E-W directions of polarization, two zones of high conductivity were clearly recognized: one more shallow area, in the Bonifacio Strait, connected with the presence of an enhanced den-

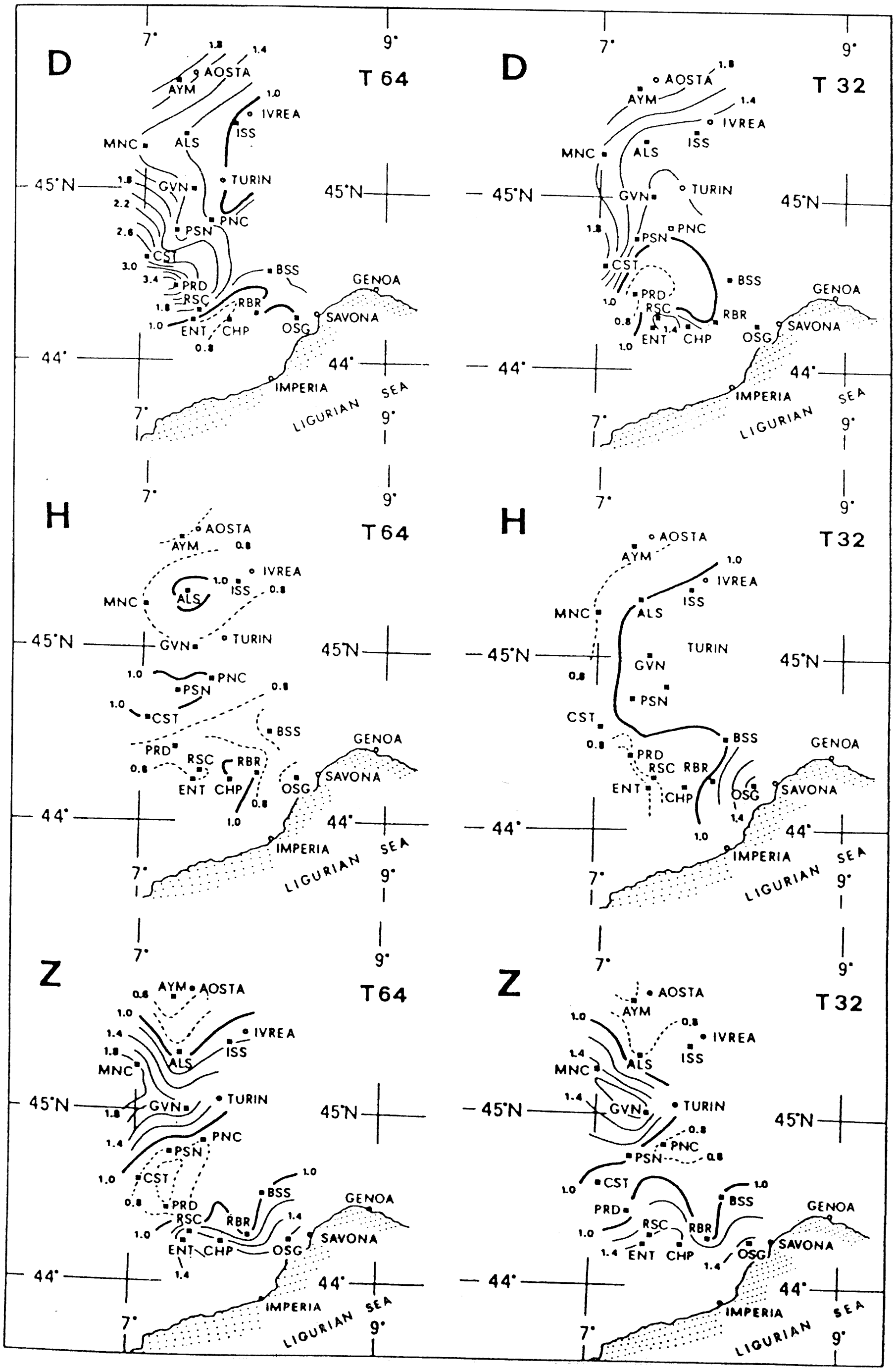

Fig. 2b. Real and imaginary Fourier amplitude maps.

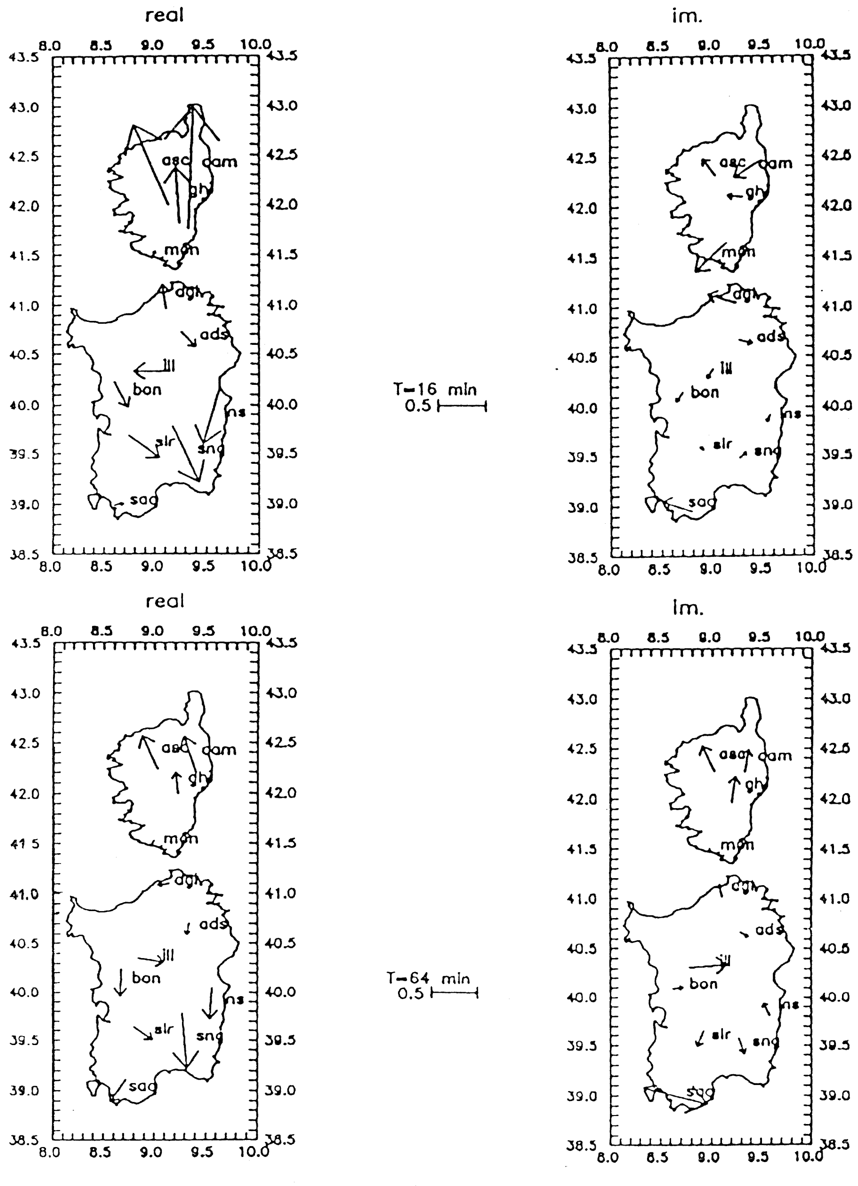

Fig. 3a. Induction arrows (real and imaginary) for 16 and 64 min.

sity of heat flow; the other one, in the Sardinia channel, probably due to a thin layer of sediments (figs. 3a and 3b). Two dimensional inversion modelling (Červ and Prauss, 1978; Červ and Pek, 1981; Pek, 1987) was carried out to find the global conductivity distribution suggested by the induction arrows, Fourier maps and pseudosections. The final model is shown in fig. 4.

Another quasi-simultaneous MV survey was performed in Central Italy from 1992 to 1994

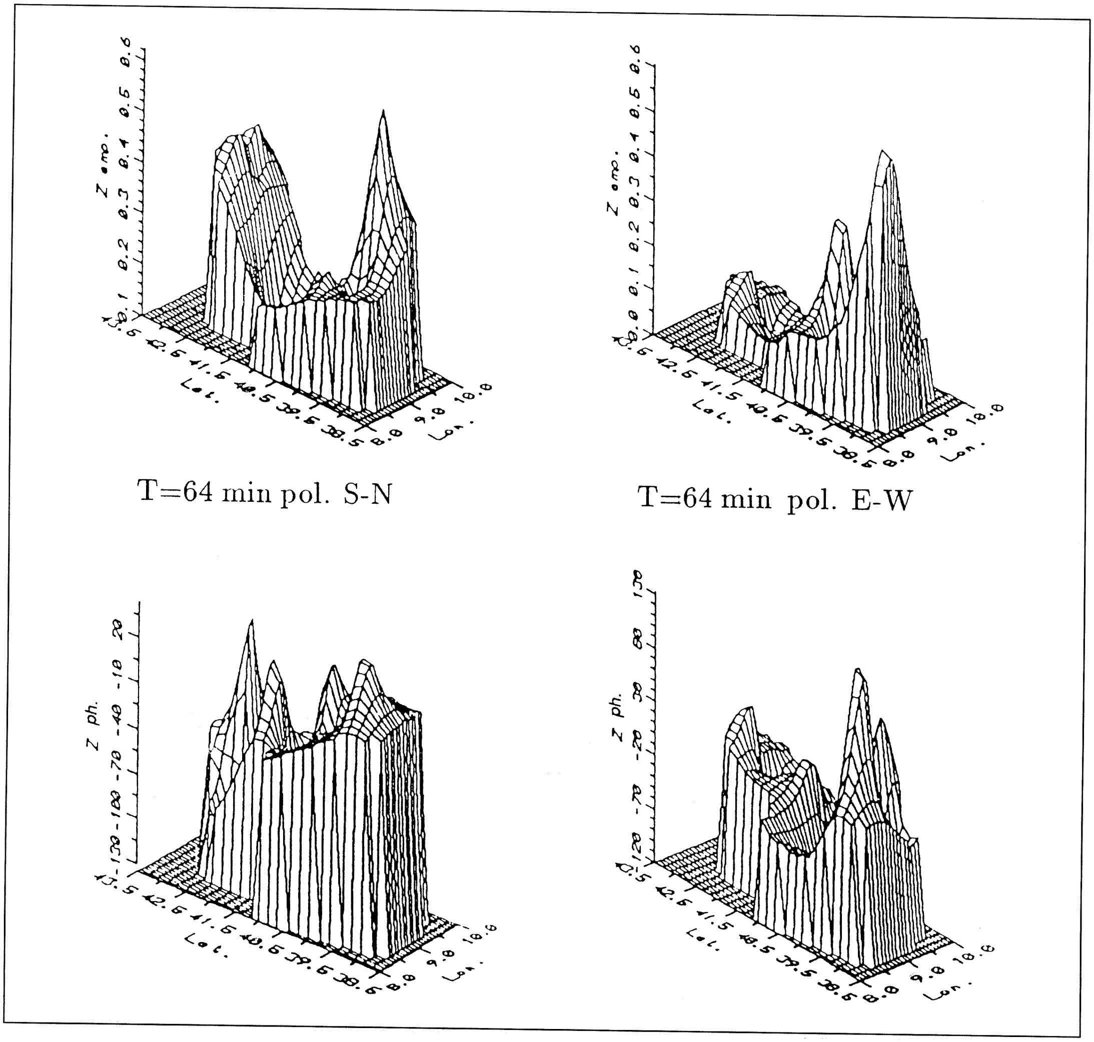

Fig. 3b. Real *Z* amplitude and phase Fourier maps in the hypothetical event technique for a period $T = 64$ min. Polarizations S-N and E-W on the left and right side, respectively.

by means of a magnetometer array covering an area of 40000 km^2, between the latitudes 42° and 44°N and longitudes 11° and 14°E. The position of the 14 sites (including L'Aquila Geomagnetic Observatory) was chosen to better detect possible underground electrical conductivity contrasts (laterally and/or in depth) along profiles crossing the Apennine chain. In each site the accuracy of measurement was 0.5 nT and the sampling rate was 10 s. After the application of an averaging and filtering process to eliminate unwanted noise, the recording system stored 1-min mean values. The shortest period of data recording at each site was 4 months since the low solar activity caused a longer time of data acquisition for the collection of events (Di Mauro *et al.*, 1996).

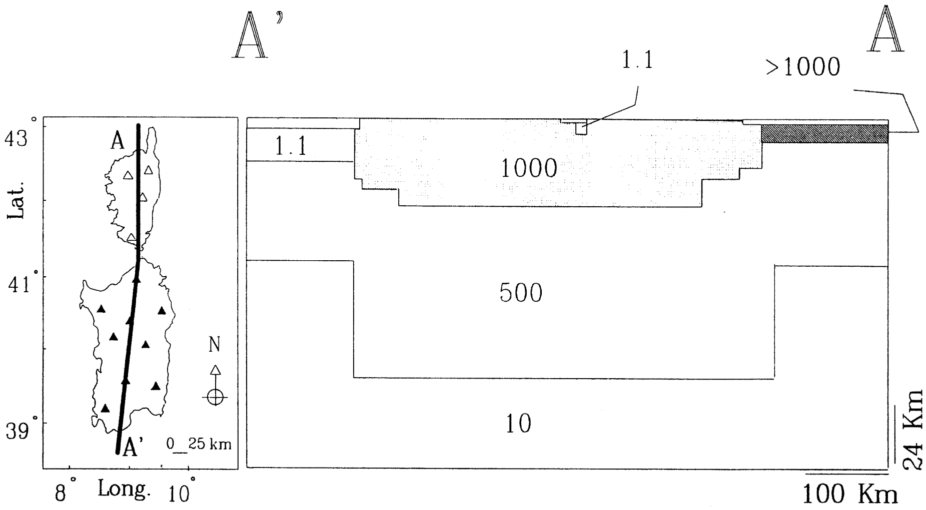

Fig. 4. The final 2D resistivity model of the Sardinian-Corsica block along S-N profile AA′ shown at the left side. Values are in Ω · m.

A multivariate technique based on statistical analysis of the eingevalues and eingenvectors of the spectral density matrix (Egbert and Booker, 1989) was applied to verify the validity and applicability of the assumption about the uniformity of the EM field. A test over 46 events, simultaneously recorded at the northernmost four sites, confirmed that the most dominant eingevalues numbers are the first two justifying the validity of assuming a plane wave as EM inducing field (Armadillo *et al.*, 1995). Two different induction arrow maps are shown in fig. 5, taking into account the harmonics corresponding to periods of 85.3 and 16 min. The induction arrows seem to point away from the central axis of the Italian peninsula, towards the sea both in the west and east side and the directions of the imaginary arrows are often in accordance with the real ones. Although the evident 'coast effect' (Parkinson and Jones, 1979) could explain the behaviour of the arrows associated to the smallest period, the amplitudes and the directions of arrows, for the longer periods, reflect the influence of the main three tectonic structures of the investigated area: the Tyrrhenian domain, the Adriatic domain and the Apennines.

A hypothetical event technique was used to simulate a virtual array with two polarizations at 57° and 147°. These two directions correspond to the angles of the central axis of Italy (or the axis of the Apennine chain) and its orthogonal angle with respect to the geographic meridian. The isolines from the real Z-Fourier values and phase identified conducting media and the localization of possible anomaly bodies (figs. 6 and 7) which were used to constrain the model parameters. The 2D inversion model, based on the same technique used for the Corso-Sardinian system, and the 3D inversion model, based on a code developed by Mackie *et al.* (1993), seem to confirm that a complex interdependence between the conductive media (the sea waters) and the main tectonic structures could control the conductivity character in that region. In fact, in the final models, shown in figs. 8 and 9, a deep resistive root (at a depth of around 10 km) of the Apennines chain appears surrounded by a medium conductive background, in which some conductive structures are also present. That combination could explain the evident 3D character of the investigated area and, moreover the behaviour of the induction arrows even for the

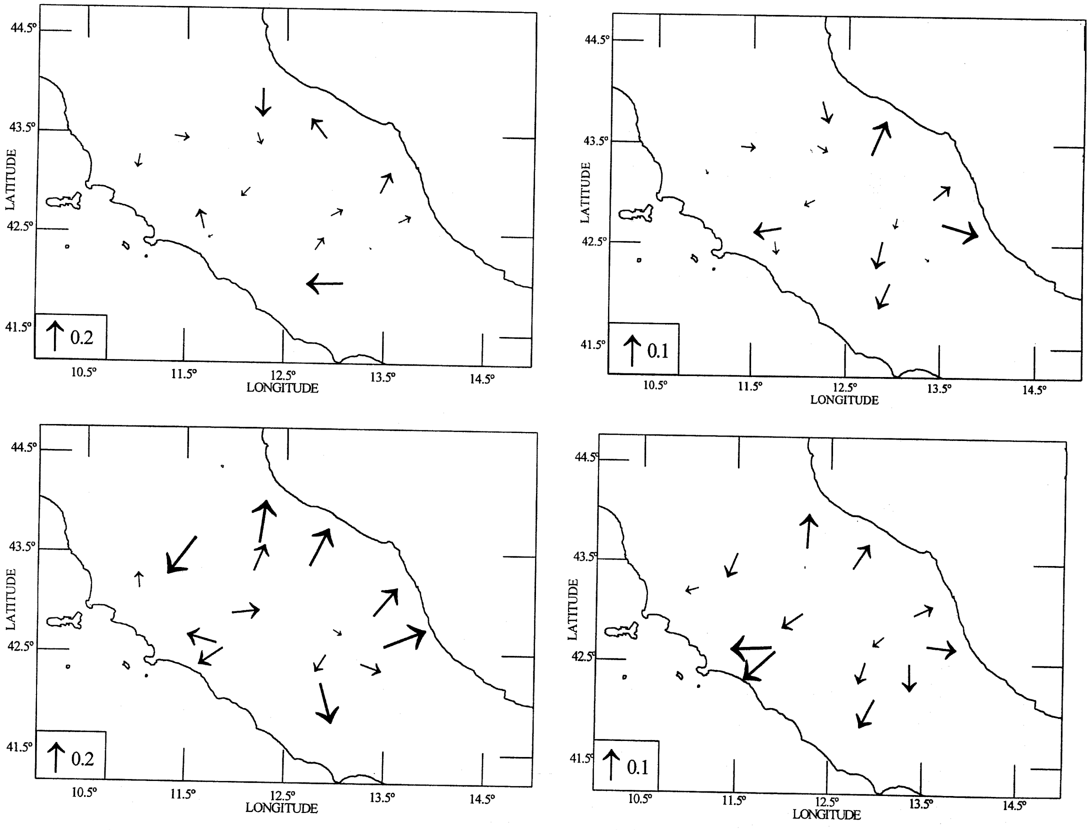

Fig. 5. Induction arrows (real - top and imaginary - down) for 16 min (left side) and 85.3 min (right side) in Central Italy.

period of 85.3 min: for such a period the influence of the coast effect (essentially the seas) should be negligible. However that mainly 3D attribute was well correlated with other geophysical results (Lavecchia, 1988; Minelli *et al.*, 1991; Serri *et al.*, 1993; Spakman *et al.*, 1993; Amato *et al.*, 1993).

4. Conclusions

In the past two decades the Ivrea body in the Northwestern Alps and their junction with the Apennine chain, the micro-plate of the Sardinian-Corsican system and, recently, the central part of the Italian peninsula along Tyrrhenian-Adriatic lithospheric transects were investigated by means of geomagnetic depth soundings to detect the underground electrical conductivity contrasts. Studies in time and frequency domain were applied in the first investigations. More refined analysis involving tests on the induced EM field dimension, computations of Transfer Functions of single-site through induction arrows and Fourier maps in the Hypothetical Event technique were applied to the latter studies. Independently from other geophysical methods, it was possible to confirm the presence of the lithospheric and asthenospheric gravity anomaly found over the Ivrea

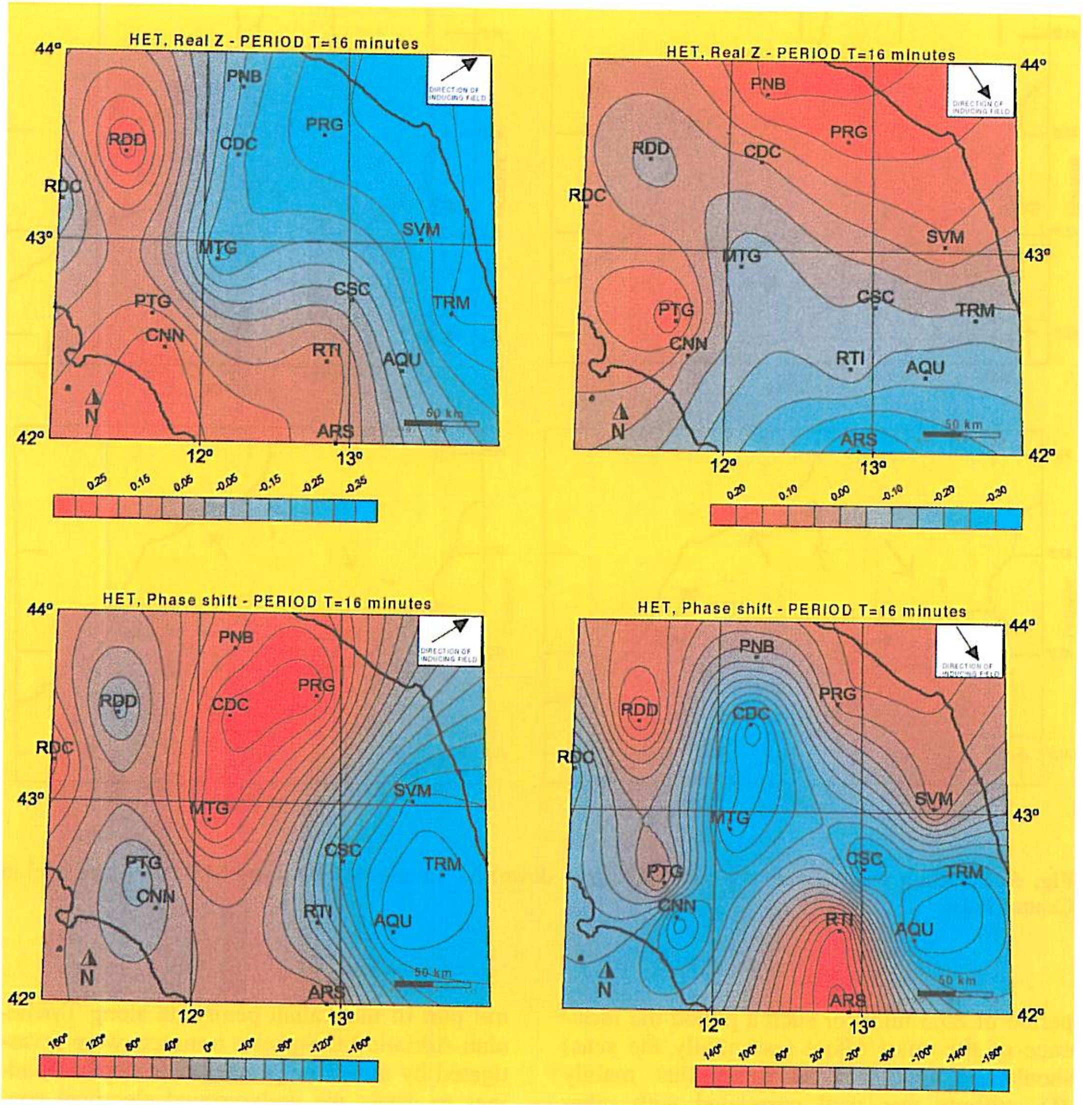

Fig. 6. Real *Z* values and phase Fourier maps in the hypothetical event technique for the period T = 16 min. Polarization 57° (left side) and 147° (right side).

area; it was also possible to describe the electrical conductivity distribution in the inner part of the SW Alpine arc. In the Sardinian-Corsican system, inversion models carried out the existence of two major electrical conductive bodies, one north of Corsica, and the other south of Sardinia.

In Central Italy, the regional electrical conductivity distribution pointed out, as the most evident result from 2D and 3D inversion models, a deep conductive structure beneath the Apennines and a very resistive root (up to a depth of some 10 km) for this part of the mountain chain.

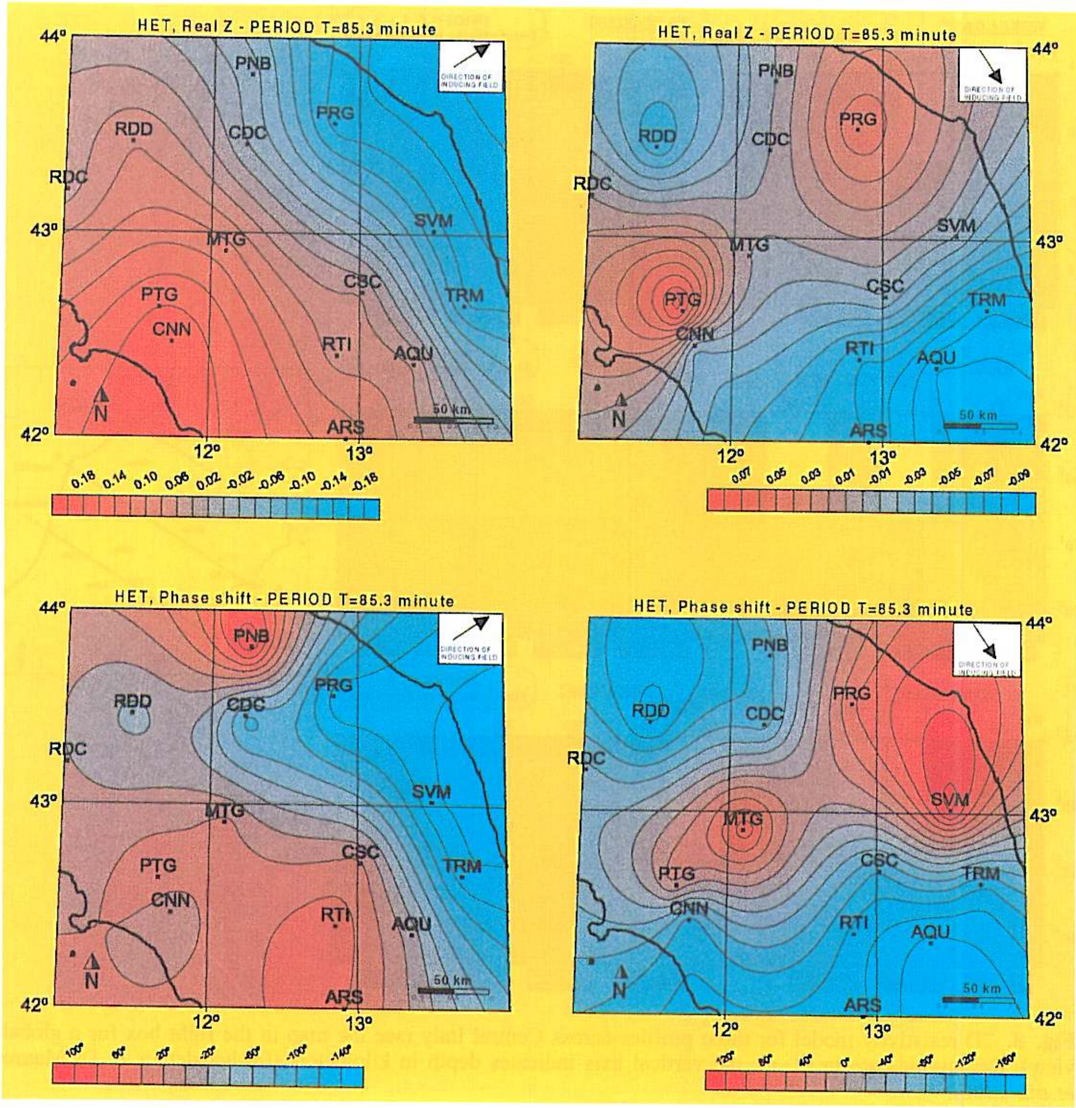

Fig. 7. As fig. 6 for the period $T = 85.3$ min.

The geophysical investigation by MV data represents a further self-consistent way to widen the knowledge of the interior of the Earth in a large range of length scales: from the crust to the mantle with particular regard to regional tectonodynamics. New strategies for each step in the MV method could be taken into consideration: from arranging the measurement arrays in more suitable spatial configurations, to using more refined analytical techniques on data both in the forward and inverse procedures. Investigations in other re-

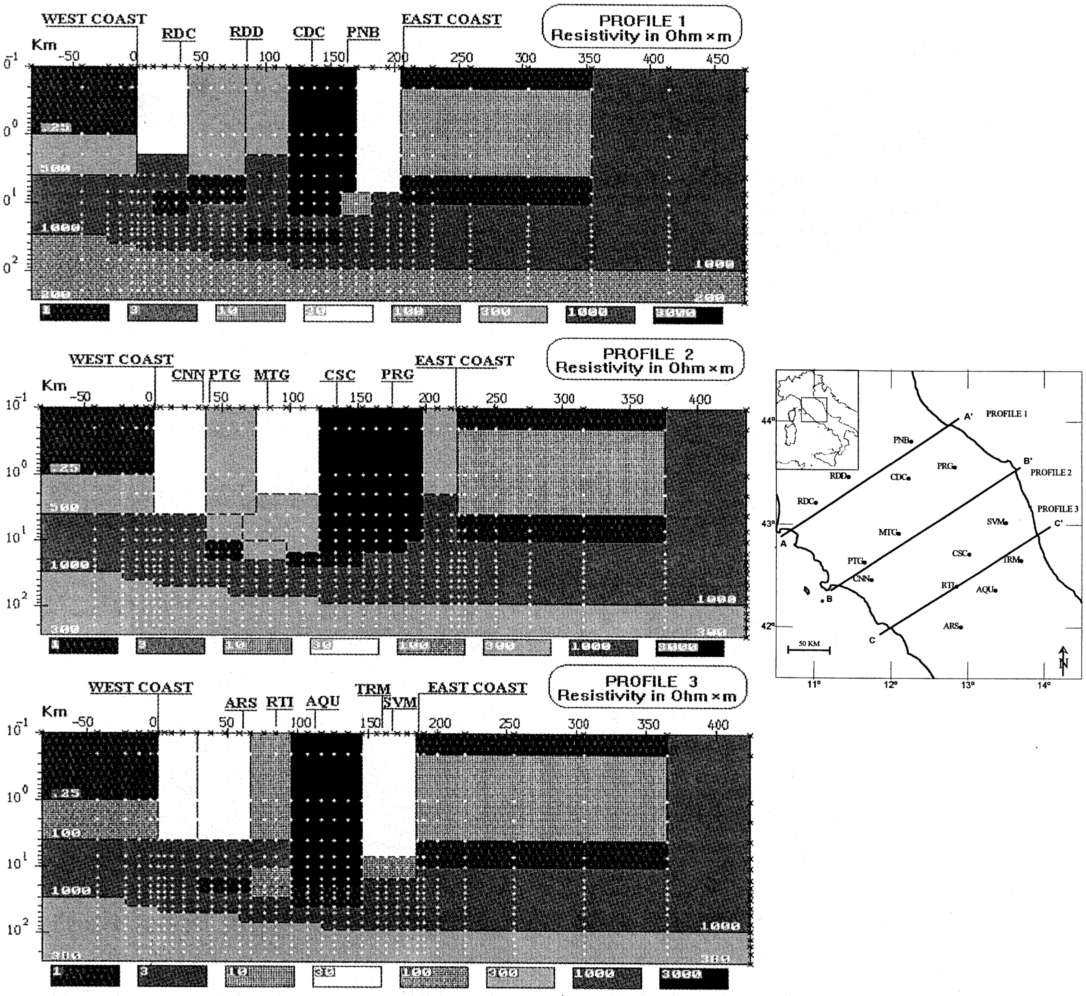

Fig. 8. 2D resistivity model for three profiles across Central Italy (see the map in the right box for a global view). Resistivities are in Ω · m; the vertical axis indicates depth in kilometers (further details in Di Mauro *et al.*, 1996).

gions of the Italian peninsula with complex tectonic settings and geodynamical history, represent a stimulating target for future MV studies.

The MV method was weakly sensitive (for the frequencies usually observed) to antropic noise and, in particular, to that produced by the Italian railway network, that extends over much of the country. Moreover, the easy installation and running of the instruments encourage the application of this method.

In the coming years an increase in solar activity is expected: this could provide a wide range of magnetic time variations in the geosphere system. The selection of the increasing number of events to be used in analytical step, as required for the MV method, will also be simplified. For a future improvement in the ap-

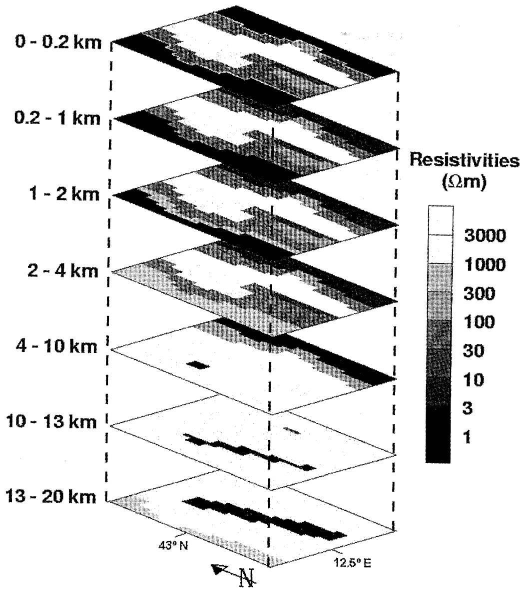

Fig. 9. 3D resistivity model with horizontal averaged values at selected band depth.

plication of the method, new strategies in the planning of survey campaigns will be taken into consideration (*e.g.*, by overlapping arrays and/or reference station array). Further progress on the analytical techniques for the determination of the transfer functions will be made such as imposing some physical constraints to the external sources, instead of a virtual configuration built by the hypothetical event technique. Finally, although being limited by the objective defeat of non-uniqueness in the solution of every algorithm of inversion, improvements could be made on 2D and 3D models, also using different numerical approaches by means of powerful modern computing systems.

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