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A MT 2D modelling of the Apenninic margin and Bradanic trough after identification of an artificial e.m. wide-band source on the natural MT data

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Abstract

In the frame of Italian research project «CROP», a magnetotelluric (MT) survey was carried out in Southern Italy, above the Apulian platform, with the aim to investigate its transition beneath the Apennine chain. The MT stations were divided into two areas, the first around Lavello town, the second south of Mount Vulture inactive volcano. The standard processing of MT raw data, collected with the single-site scheme, gave fairly non-plane wave response as concerns data of Lavello area, while the volcano's area data were compatible with a natural plane-wave e.m. field response. The Lavello area results were shown to be heavily affected by a near field effect of a strong wide-band electromagnetic source located several kilometers NE of Lavello. After the identification of this effect and an attempt to interpret these data, a 2D interpretation of the whole survey was then possible and the main result can be summarized as follows: a) the «electrical» boundary of the Bradanic trough should be displaced about 4 km toward SW; b) in the area south of Melfi town, the carbonatic platform should lie at a depth of about 8 km.

Key words *magnetotellurics – artificial noise – structural modelling*

1. Introduction

Among the many problems linked to understanding the evolution of the Italian peninsula, a major one is the knowledge of how and to what extent the Apulian platform immerses under the Apenninic chain. In fact, terrain evidence, drill hole information as well as seismic reflection data cannot always give a satisfactory picture of the buried structures in this area, due to recent chaotic formation overlappings, often poorly differentiated from the seismic point of view.

In this situation, non-seismic methods, like those based on the electrical resistivity, may help in resolving lack of geo-structural information.

In the frame of the Italian strategic project devoted to the study of the deep crust (CNR's «CROP» project), several magnetotelluric surveys were carried out by Italian teams. The magnetotelluric (MT) method, based on measurements of the oscillations of the geomagnetic field and the correlated electric or telluric field at frequencies above $10^{-4} - 10^{-3}$ Hz, gives quantitative information on the distribution of the electrical resistivity within the Earth from

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the shallowest depths (some meters) to hundreds of kilometers, by recording and processing the natural electromagnetic field oscillations in suitable frequency ranges.

This paper describes the results and, to some extent, the problems encountered during an MT survey carried out in the neighborhood of the inactive volcano «Mount Vulture».

MT measuring stations were distributed in two different areas, several km apart, *i.e.*, 5 stations within the Bradanic trough and 5 stations in the external front of the Apenninic chain around and south of the volcano.

The aim was to characterise the transition zone of the Apulian platform under the chain in an area where seismic reflection data failed to give reliable information.

2. Geological outline

The investigated area (a geological map, simplified from Bigi *et al.*, 1992, is reported in fig. 1) is located roughly around Lavello and Melfi towns (Southern Italy), where the main superficial structure is the inactive volcano Mount Vulture, with its eruption products (mainly potassic tuffs). At the far east of the area, the Apulian platform outcrops with its most recent (mainly Cretaceous) carbonatic formations; toward West, it immerses under recent (Plio-Quaternary) deposits which fill the Bradanic trough. This is a very elongated structure, with strike parallel to the main Apennine axis (about N310), which is confined on its western side by the tertiary formations and deposits of the chain, characterised by various shaly and silty facies, locally covered by the Mount Vulture lavas and clastic products.

3. Data collection and processing

MT data were collected with the single-site acquisition scheme in 10 stations; 5 of them were located around the town of Lavello in order to determine the depth to the carbonatic platform and possibly its thickness. The others were placed in suitable points around and south of Melfi town, to achieve information on the depth of the Apulian platform. A calibration MT sounding was performed at the «Puglia 1» AGIP deep well during the night to reduce cultural noise, suspected to be very strong in that area. Measuring directions were aligned with the Apenninic strike (y-axis: N310) and its normal (x-axis: N40)

The area was carefully chosen on the basis of an *a priori* evaluation of a low-level cultural noise (Italian d.c. powered railways, power and industrial plants). MT data were collected in the frequency range roughly 0.003 Hz to 300 Hz, which was thought to be suitable for the proposed exploration target.

Recorded data at the Puglia 1 site look significantly different from the other ones, as they contain a lot of noise in the form of spikes, steps and sawteeth-like signals.

Evaluation of such raw field data could give, even using robust processing algorithms, heavily biased results. Therefore all recorded data were preprocessed to increase signal-to-noise ratio by using the procedure suggested by Santarato and Spagnolini (1995). This technique, named Directional Noise Cancelling (DNC), is based on a Bayesian approach for the estimation (and cancellation) of the polarized noise from noisy signal in the time domain. DNC is able to remove (or in the worst cases, to reduce) the noise due to one or more fixed sources by substituting noisy data with their linear prediction. The prediction is computed by weighting the data surrounding the noisy datum by means of a short prediction filter. The coefficients of this filter are iteratively computed and adaptively improved. This approach, in the single site acquisition scheme, can be successfully applied only to impulsive noise, based on the assumption of a smooth character of the natural signal. In fact, because a «reference clean» signal is not available, the only possible prediction of the signal within the noise is based on the noisy signal itself.

The MT processing problem consists in the estimation of the Z impedance tensor elements relating the electric induced field to the magnetic source field:

$$E_x = Z_{xx}H_x + Z_{xy}H_y$$

$$E_y = Z_{yx}H_x + Z_{yy}H_y.$$

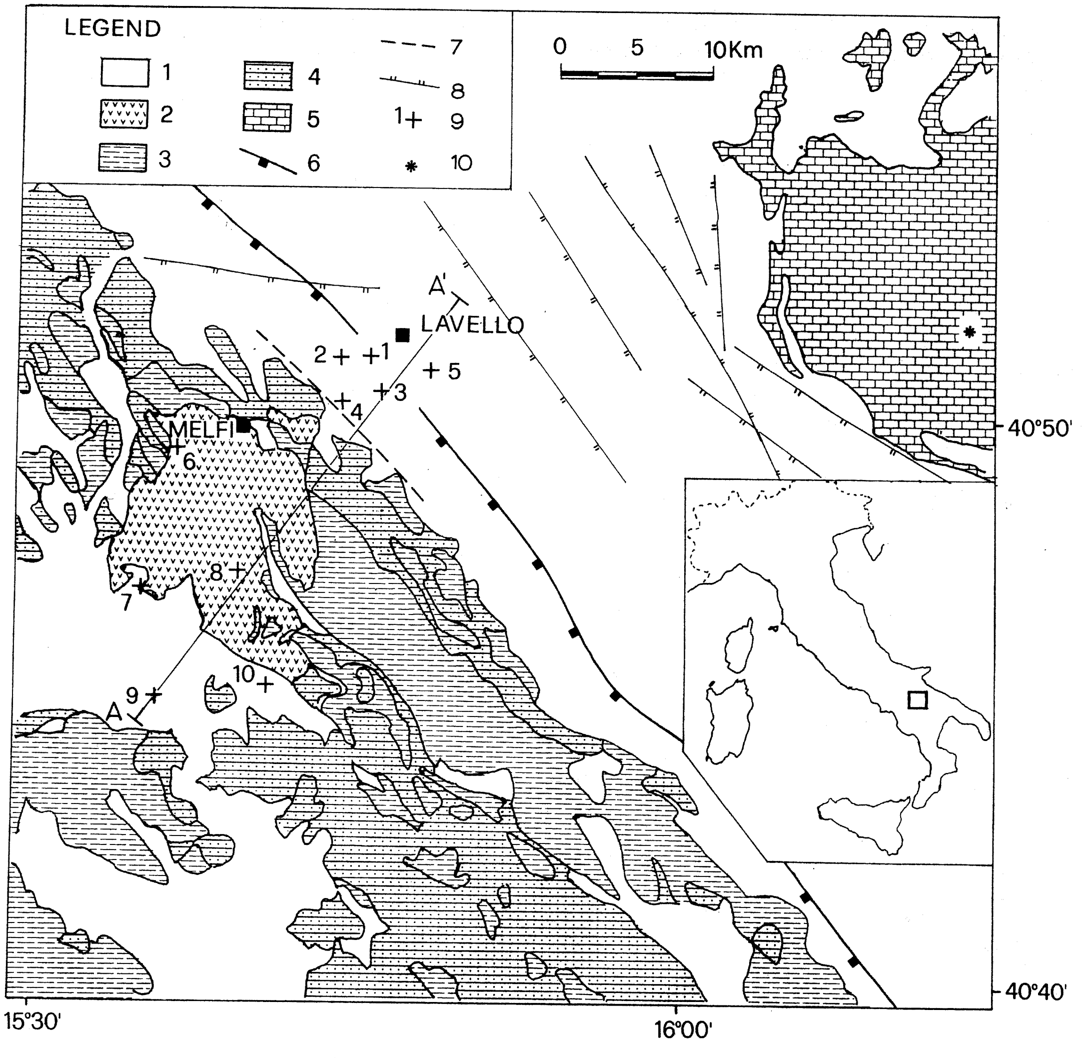

Fig. 1. Geological sketch of the measurement area: 1) Plio-Quaternary deposits; 2) Plio-Quaternary potassic volcanics; 3) Irpinian Units (Miocene): turbidites of variable origin; 4) Sicilide units (Eocene); mainly clays and shales including arenaceous and calcareous turbidites; 5) Apulian platform: Jurassic and Cretaceous neritic carbonates; 6) boundary of the allochtonous Apenninic units; 7) electrical boundary; 8) normal fault (outcropping or buried); 9) MT sounding; 10) «Puglia 1» deep AGIP well.

Many authors have tried to solve the above system of two equations with four unknowns. We present results applying two independent «robust» methods: *i.e.*, the time-domain approach by Spagnolini (1994) and the popular frequency-domain algorithm by Chave (*e.g.*, Chave and Thomson, 1989).

The usual way of presenting MT results is to plot the apparent resistivity and phase curves as a function of period *T*, *i.e.*:

$$\rho_{axy} = 0.2T\,|\,Z_{xy}\,|^2 \qquad \phi_{xy} = \arctan\,(Z_{xy})$$

$$\rho_{ayx} = 0.2T\,|\,Z_{yx}\,|^2 \qquad \phi_{yx} = \arctan\,(Z_{yx}).$$

As mentioned above, the measuring sites were chosen in connection with previous noise level evaluation, while we were already aware of a probably high noise level Puglia 1 site.

The apparent resistivity and phase curves computed for one of the 3 frequency recording bands, obtained at Puglia 1 site before (fig. 2) and after (fig. 3) impulsive noise removal by DNC technique display a remarkable improvement in MT parameters. Nevertheless some features remain incompatible with the true natural signal: note in fig. 3 the abnormally high slopes in apparent resistivity curves and the equally anomalous flat, near zero phase curves. These phenomena are due to artificial contributions, that cannot be removed from the DNC algorithm, because of their «smooth» nature; the DNC technique is intrinsically blind to smooth noise (*i.e.*, low-pass type) when single site data are concerned.

In all other soundings, Puglia 1 sounding apart, impulsive noise was also present in terms of spikes (variable in amplitude, occurrence and direction, from site to site). Removal of this kind of noise before robust estimation of Z tensor elements yielded generally «cleaner» results.

It is interesting to compare the apparent resistivities from two fairly distant sites, *i.e.*, site No. 4 (fig. 4; Lavello surroundings) and site No. 9 (fig. 5). The apparent resistivity curves of site No. 4 are again characterised by abnormal slopes in the period range 1 to 100 s, while corresponding phase curves, although of some worse quality, fairly fall to near zero values in the whole period band above 1 s. Results pertaining to both orthogonal measuring directions look quite similar, as usual in one-dimensional (1D) earth conditions. On the contrary, results of site 9, while of some better quality, show a more «natural» behaviour, *i.e.*, without the above-mentioned anomalous features. Divergences of apparent resistivity and phase curves above 1 s are most probably related to a 2D earth response.

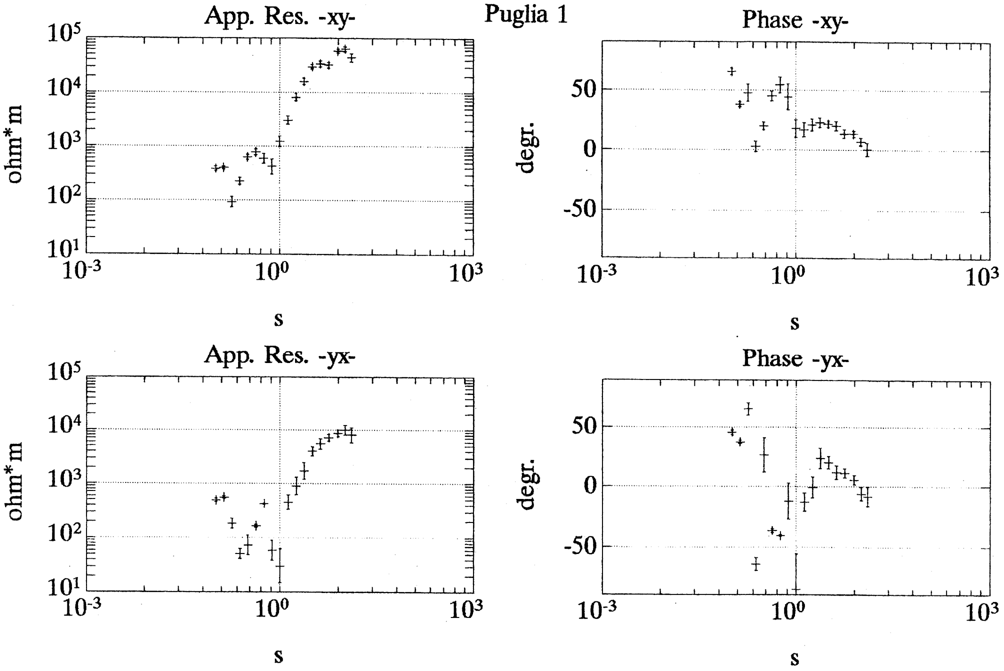

Fig. 2. Apparent resistivity and phase curves of MT sounding at Puglia 1 AGIP well before time domain data preprocessing.

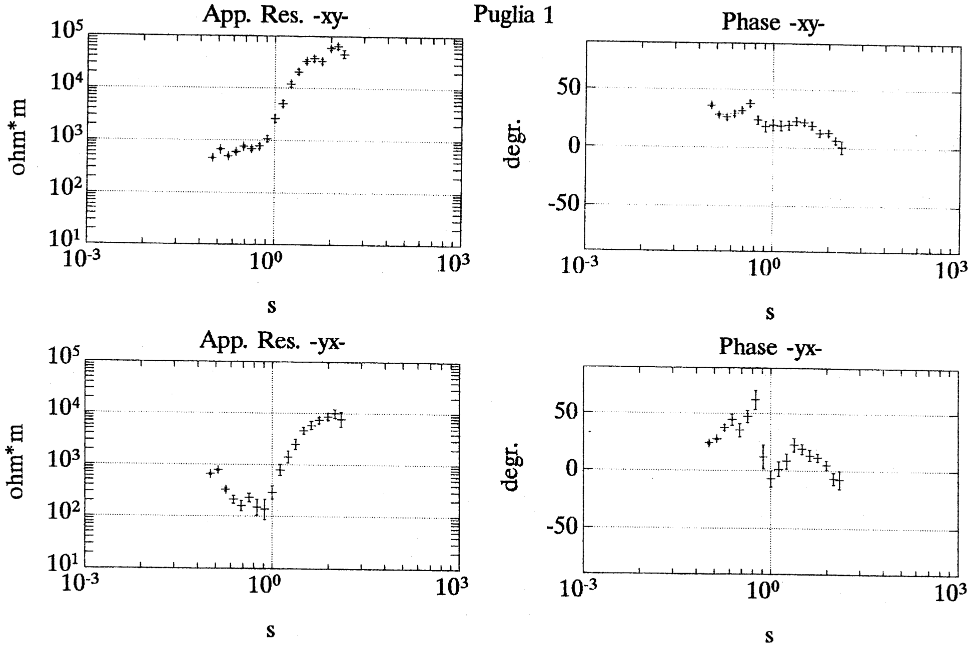

Fig. 3. Apparent resistivity and phase curves of MT sounding at Puglia 1 AGIP well after time domain data preprocessing.

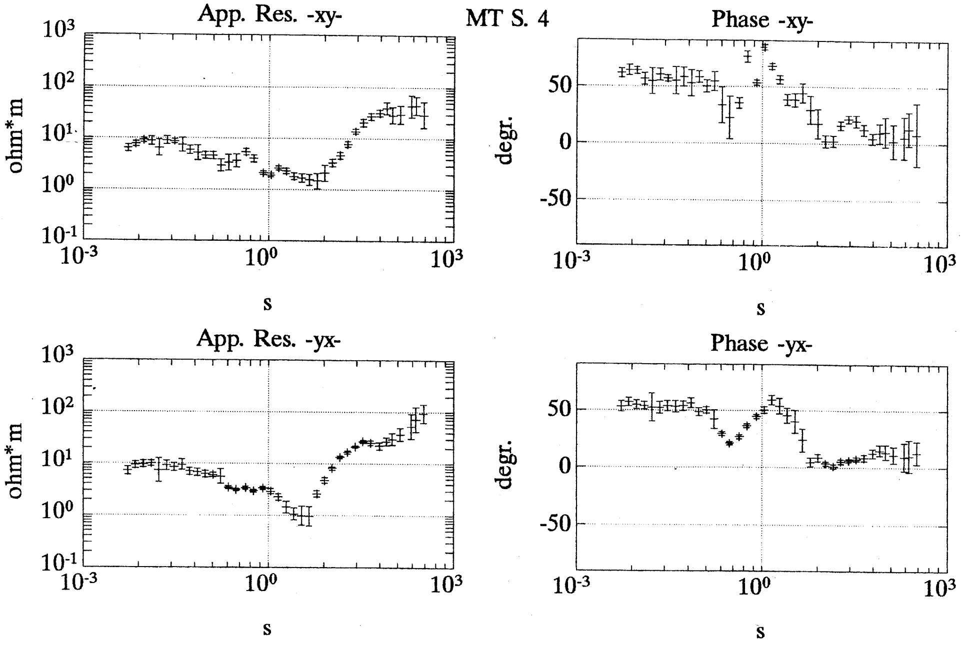

Fig. 4. Apparent resistivity and phase curves of MT site No. 4.

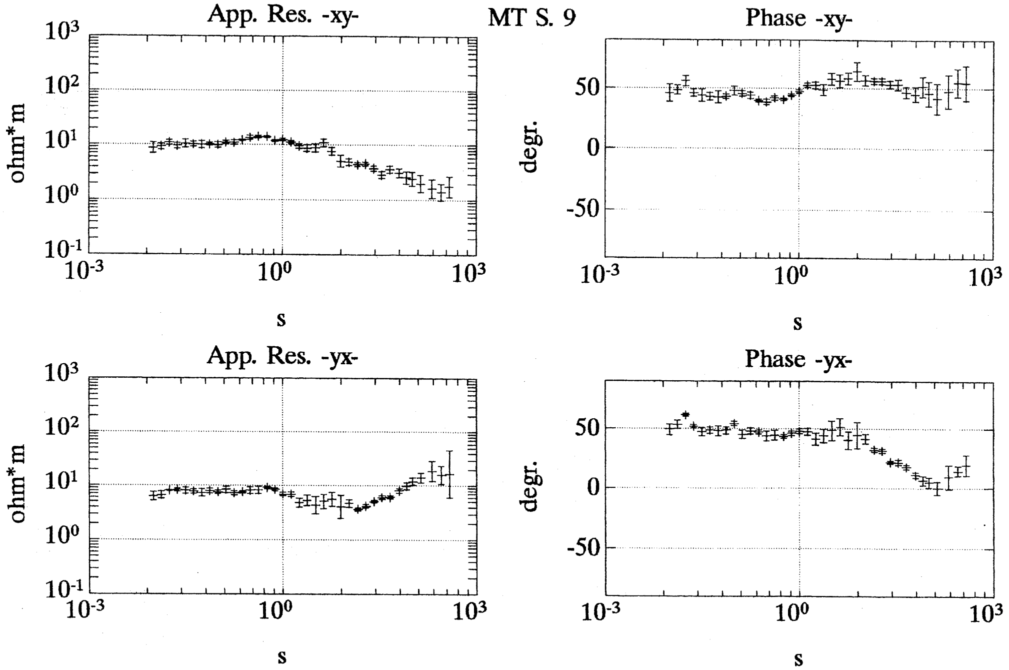

Fig. 5. Apparent resistivity and phase curves of MT site No. 9.

4. Data interpretation

4.1. *Lavello area*

All other soundings around Lavello show quite similar characteristics with the response of site No. 4, while soundings pertaining to the chain seem to be free from the problem which affects Lavello area data and they have a similar character to results of the site no 9. Data of site No. 6 show apparently 1D behaviour. A deeper insight into the polar diagrams of Z_{xy} impedance element, skewness and random results in strike determination, even using Groom and Bailey's decomposition (1989), reveals that they most probably pertain to a 3D earth response. This is in fair agreement with the neighbouring local volcanos' structure.

The inversion of Lavello area soundings clearly fails when carried out with a 1D algorithm, since it cannot take into account the V-shaped minimum of ρ_a curves around 1 s and corresponding steep slopes both in ρ_a's and phases. These features cannot be explained in terms of a response to a natural eloctromagnetic field excitation, but clearly indicate the presence in the area of a wide band artificial noise source.

In fact, as electromagnetic theory in the quasi-static approximation shows (see *e.g.*, Zonge and Hughes, 1987), the V-shaped minimum and corresponding steep phase slope pertain to the «transition zone» of an electric dipole excitation over a layered earth with a resistive basement at a suitable depth. In this band the frequency-source distance and electric structure of the underlying earth give an induction number value $|kr|$, where $k = \sqrt{i\mu\omega\sigma}$ (the meaning of symbols is as usual) is the wavenumber and r the distance to the source, roughly between 1 and 3. Greater $|kr|$ values characterise the far field plane wave approximation, where MT works, *i.e.*, in our case the period band below 1 s. Values of $|kr|$ less than

1 pertain to the near field values, in our data above 10 s, where the magnetic field «saturates», *i.e.*, it is no longer structure sensitive.

Therefore, because of the low-pass filter effect of the conductive earth, artificial signals, though impulsive at the source, can appear as a smooth signal, *i.e.*, a natural-shape signal, not removable from DNC in the single site context.

At greater distances from the noise source, as is the case of the remaining sites No. 6 to 10 (*i.e.*, the source is most probably located some tens of kilometers NE of Lavello town), computed Z-tensor estimates can be recognised as the response to a natural field excitation.

Inversion of measured responses at sites 1 to 5 can now be performed as the response to an oscillating electric dipole. These computations were carried out using a 1D model of the buried structure of the area.

The best-fitting model and its 1D response to an electric dipole excitation are reported in fig. 6. The deepest interface is at a depth of about 1 km. MT data fail to give any deeper information because of near field saturation, that is, they are not useful to achieve the proposed aim to explore the carbonatic platform internal electric structure, its bottom and possibly the whole crust.

A possible strategy can nevertheless be devised to recover information in this saturation band by resorting to the model response of fig. 6. The computed phases, after having crossed the 0 degree axis become negative and subsequently they reach nearly zero values. If the buried structure can be deemed 1D, then the site response to the dipole excitation at the estimated distance can only be of the kind of fig. 4, whichever is the structure evolution beneath the estimated sequence of layers. If computed Z tensor Z_{mis} can be deemed the sum of two contributions, the first natural Z_{nat}, the second artificial Z_{art}, which is always feasible be-

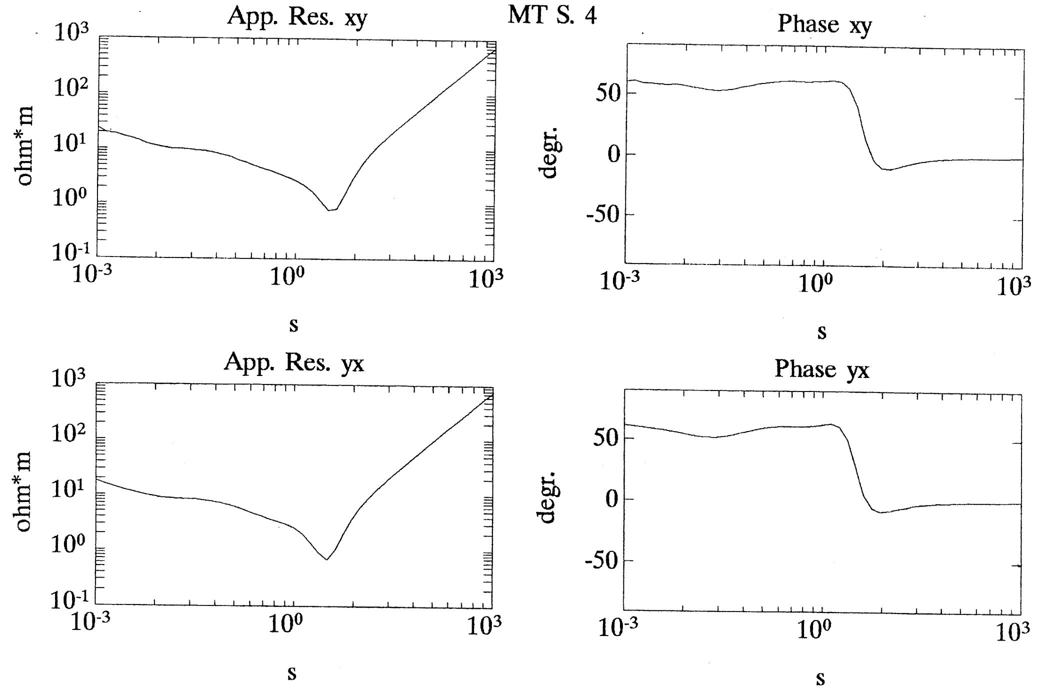

Fig. 6. Best-fitting 1D model responses of MT site 4 data to an electric dipole excitation. Resistivity sequence: 40-6-1.2-1000 Ωm; thicknesses: 30-270-900 m.

cause of causality of the system, then

$$Z_{\mathrm{mis}} = Z_{\mathrm{nat}} + Z_{\mathrm{art}} =$$

$$= \mathrm{Re}(Z_{\mathrm{nat}}) + \mathrm{Re}(Z_{\mathrm{art}}) + i^* \, [\mathrm{Im}(Z_{\mathrm{nat}}) + \mathrm{Im}(Z_{\mathrm{art}})].$$

In Z_{nat}, sign(Re) = sign(Im), while in Z_{art} the imaginary part has an opposite sign in the intermediate and near field (phase changes of sign). We may thus presume that in the near field range $\mathrm{Im}(Z_{\mathrm{mis}})$ is biased toward zero because of $\mathrm{Im}(Z_{\mathrm{art}})$:

$$\mathrm{Im}(Z_{\mathrm{nat}}) = \mathrm{Im}(Z_{\mathrm{mis}}) - \mathrm{Im}(Z_{\mathrm{art}}). \qquad (4.1)$$

Because $\mathrm{Im}(Z_{\mathrm{art}}) \leq \mathrm{Im}(Z_{\mathrm{mis}})$ we can obtain an estimate of $\mathrm{Im}(Z_{\mathrm{nat}})$ by using eq. (4.1). Therefore, $\mathrm{Im}(Z_{\mathrm{nat}})$ becomes interpretable quantitatively, although this parameter is the worst possible for inversion among the several ones available (Spies and Eggers, 1986).

It is equally true that

$$\mathrm{Re}(Z_{\mathrm{nat}}) = \mathrm{Re}(Z_{\mathrm{mis}}) - \mathrm{Re}(Z_{\mathrm{art}}), \qquad (4.2)$$

but in eq. (4.2) the contribution of Z_{art} dominates and thus a correction as in eq. (4.1) cannot give a reliable estimate of $\mathrm{Re}(Z_{\mathrm{nat}})$.

In fig. 7 the real and imaginary parts of Z_{yx} obtained at site No. 4 are reported together with the MT response of the 1D model used to compute the response reported in fig. 6. As can be seen, a nearer artificial source affects the data in the 0.1 to 1 s, both in real and imaginary parts. In fig. 8, while real data are unchanged, imaginary data have been corrected following eq. (4.1). A better fit to the computed MT response is evident in the transition zone band of the main artificial source.

4.2. *Apenninic chain area*

In this area MT results show a clear «natural» behaviour. A. Zerilli, in the frame of AGIP oil company explorations in Southern Italy, found a similar behaviour in MT data of a neighbouring area (personal communication). This area can thus be considered the «far field region» of the above noise source and no more sources seem to be present.

As already observed, data of sites 7, 8, 9 and 10 are essentially of 2D type. Regional

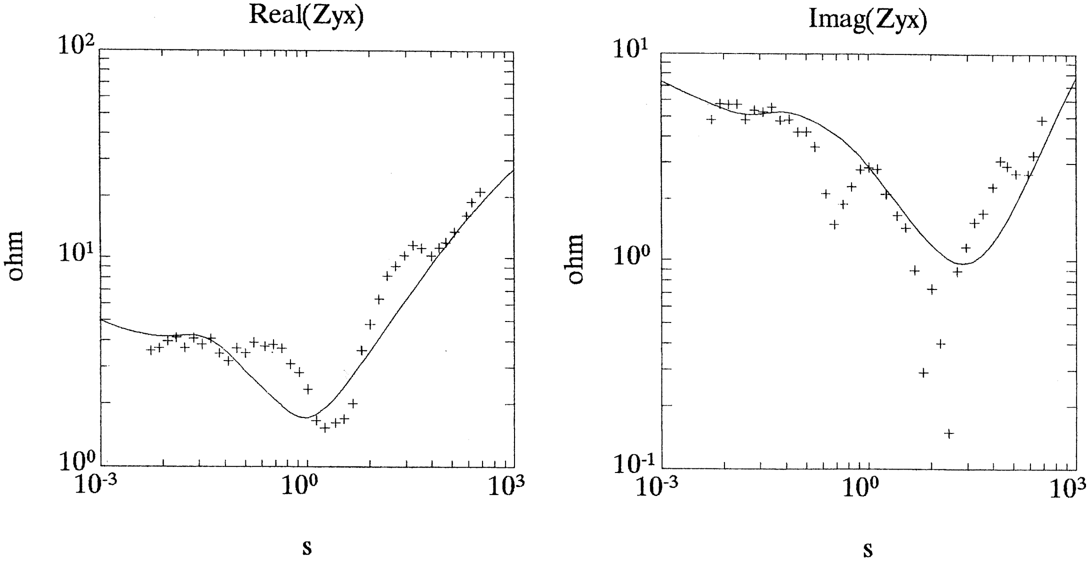

Fig. 7. Real (left) and imaginary (right) parts of Z_{yx} MT tensor component at MT site No. 4; the continuous line represents the plane wave excitation response of the model of fig. 6.

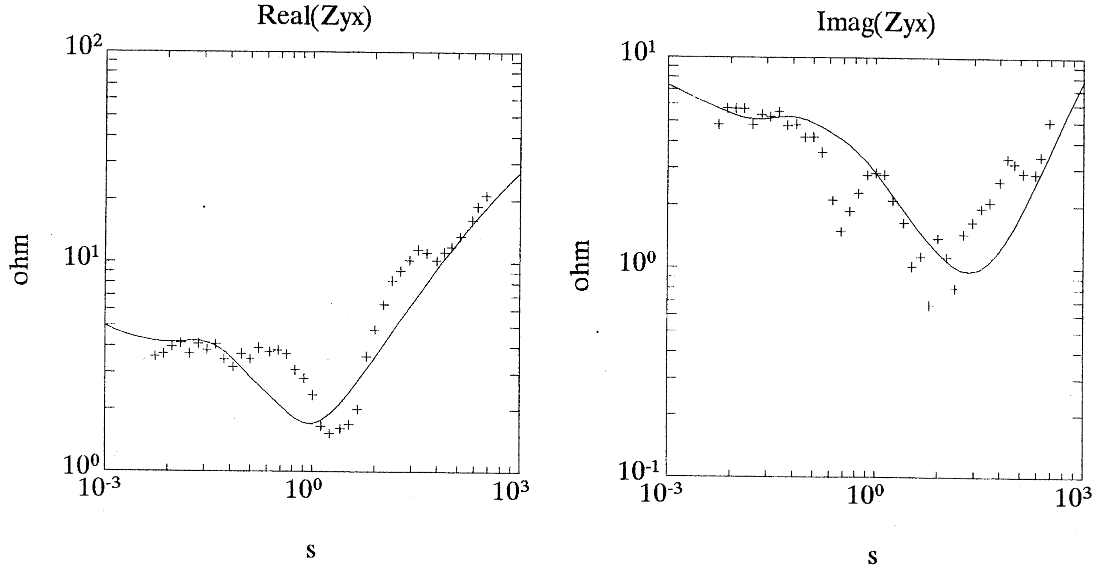

Fig. 8. Real (left) and imaginary (right) parts of Z_{yx} MT tensor component at MT site No. 4. The imaginary part is corrected for the artificial source contribution. The continuous line represents the plane wave excitation response of the model of fig. 6.

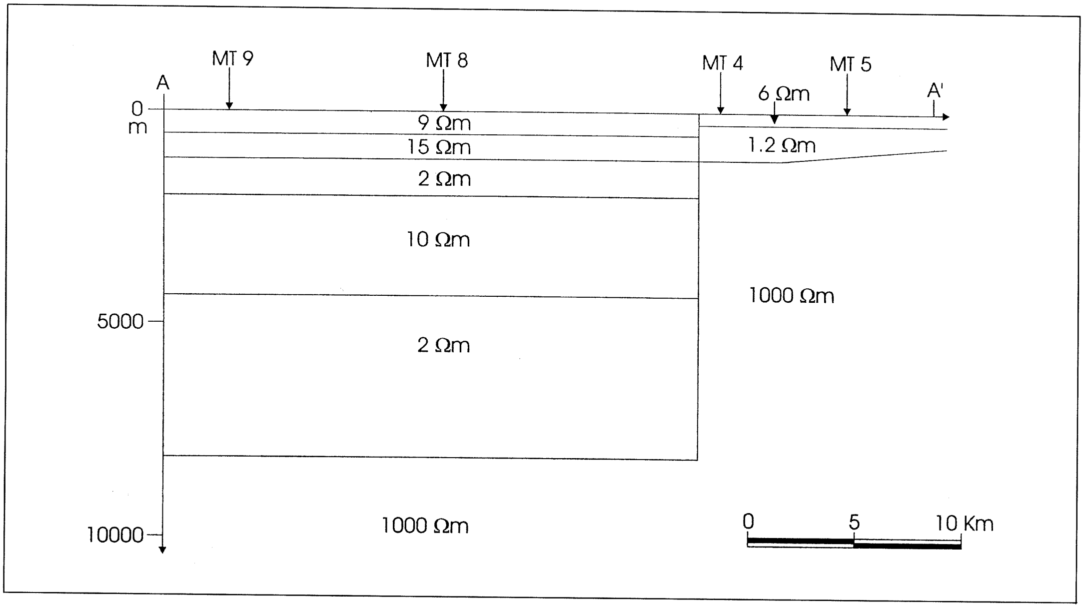

Fig. 9. The final 2D interpretative model.

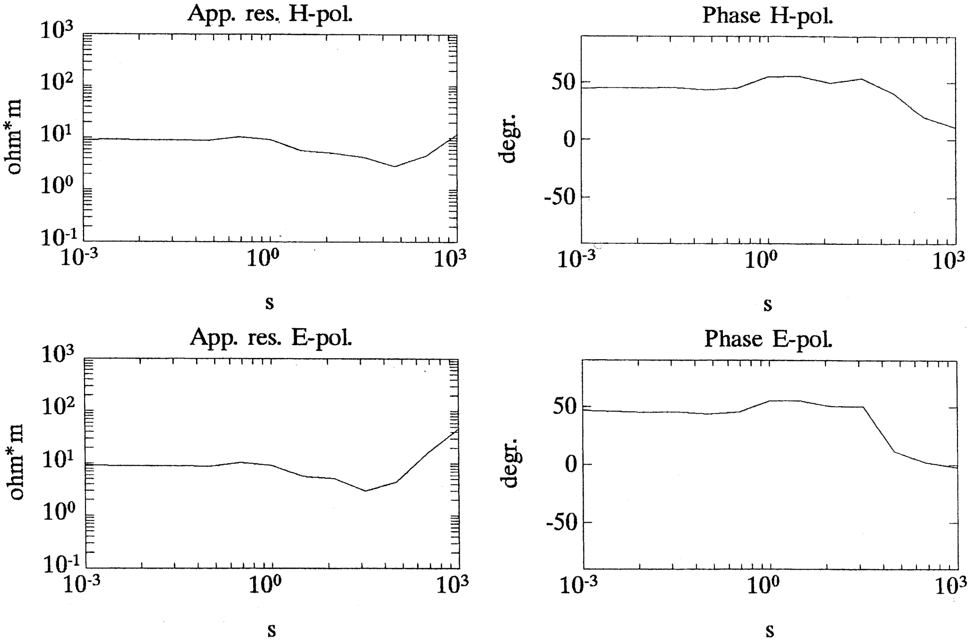

Fig. 10. Apparent resistivities and phases computed from final 2D model, pertaining to MT station No. 9.

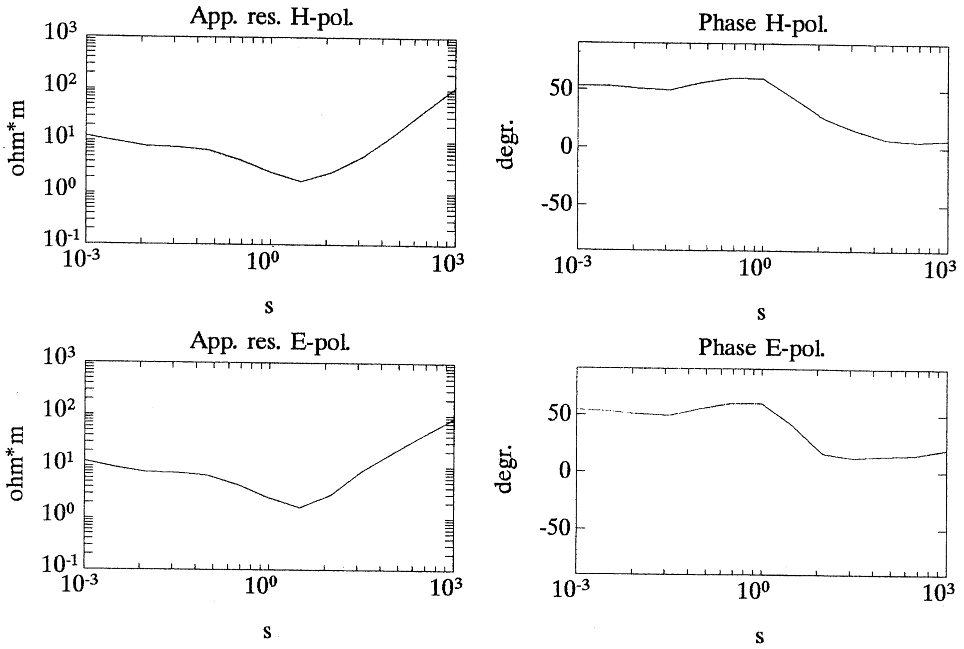

Fig. 11. Apparent resistivities and phases computed from final 2D model, pertaining to MT station No. 4.

strike computed with Groom and Bailey's algorithm (1989) coincides with the direction of the Apenninic main strike. A possible 2D profile connecting both areas can be drawn across MT stations 9-8-4-3-5.

5. Final model and concluding remarks

The best model compatible with experimental data is reported in fig. 9. As can be seen, the Apenninic chain area is characterised by a sequence of conductive layers, ranging between 2 and 15 Ωm, within a depth of 8 km, where a resistive basement has been achieved. The electrical boundary between the chain and the Bradanic trough has been recognised about 4 km W of the boundary of the allochthonous Apenninic units. The Plio-Quaternary sediments of the Bradanic trough were estimated as conductive layers. Their whole thickess was estimated to reach at most 1.2 km.

Figures 10 and 11 show the responses of the model at the positions corresponding to the above-mentioned sites Nos. 4 and 9.

The electrical structure of the Apulian platform is more complex than the one proposed here, as was shown by Iliceto and Santarato (1997), by resorting to data obtained in areas of Central Italy and in Istria (Croatia). Although this platform complex model fits Lavello's area data, too limited resolution of these MT data suggested presenting the simplest model which fits field results.

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REFERENCES

BIGI, G., D. COSENTINO, M. PAROTTO, R. SARTORI and P. SCANDONE (1992): *Structural Model of Italy* – Scale 1:500000. CNR, SELCA, Florence (Italy).

CHAVE, A.D. and D.J. THOMSON (1989): Some comments on magnetotelluric response function estimation, *J. Geophys. Res.*, **B92**, 633-648.

GROOM, R.W. and R.C. BAILEY (1989): Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion, *J. Geophys. Res.*, **B94**, 1913-1925.

ILICETO, V. and G. SANTARATO (1997): Characterisation of Apenninic tectonic environments (Trigno River Valley, Molise, Italy) by means of magnetotelluric measurements, in *Atti IX Congresso Nazionale Geologi, Roma, 17-20 Aprile 1997* (in press).

SANTARATO, G. and U. SPAGNOLINI (1995): Cancelling directional EM noise in magnetotellurics, *Geophys. Prospect.*, **43**, 605-621.

SPAGNOLINI, U. (1994): Time-domain estimation of MT impedance tensor, *Geophysics*, **59**, 712-721.

SPIES, B.R. and D.E. EGGERS (1986): The use and misuse of apparent resistivity in electromagnetic methods, *Geophysics*, **51**, 1462-1471.

ZONGE, K.L. and L.J. HUGHES (1987): Controlled source audio-frequency Magnetotellurics, in *Electromagnetic Methods in Applied Geophysics*, edited by M.N. NABIGHIAN, SEG, Tulsa (OK), vol. 2, 713-810.