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A. ZAJA [1], A. GALGARO [1] and R. POLINO [2]

MAGNETOTELLURIC SURVEY ON THE ALPS-APENNINES BOUNDARY (TERTIARY PIEMONTE BASIN - NORTH-WESTERN ITALY)

Abstract. A 60-kilometre-long magnetotelluric profile was carried out across the south-western part of the Po plain from Monferrato through the Asti-Alessandria Plio-Quaternary infillings, the Langhe Tertiary Basin and into the Maritime Alps (Voltri Group). Recent works suggest that in this region the step-like geometry of the top of the basement is due to the northward overthrust of an Alpine basement wedge onto the Apenninic sedimentary nappes and the underlying Padane basement. The spatial distribution of the major tectonic discontinuities was well constrained, at crustal scale, by seismic survey and gravimetric modelling. The aim of the magnetotelluric survey was to detect the electrical behaviour of this structure, thus defining the geometric relationship between the overthrusting resistive basement (Alpine crystalline basement, ophiolites, Mesozoic cover) and a less resistive sedimentary thrust belt (Apenninics). Data were collected with an M.S.P.M. (Medium Short Period Magnetotellurics) instrument, which is a real-time data processing system in the frequency range 100 Hz - 1/64 Hz. The 2-D magnetotelluric interpretation shows an evident rise in the resistive basement southeastwards: it confirms the existence of tectonic discontinuities constraining the geometries of the Tertiary Basin.

INTRODUCTION

One of the problematic features of the western Po plain was the grafting, at a crustal scale, of the Tertiary Apenninic thrust belt on to the inner part of the Cretaceous- Paleogene collisional Alpine chain. Recent works (Biella et al., 1992; Polino et al., 1992) show, in this region, a complex crustal structure due to the reworking of the Alpine Cretaceous/Paleogene structures by the Apenninic-related Neogene tectonics. This leads to the present day complex structure, whose peculiar feature is the overthrusting of both Alpine and Apenninic domains onto the Padane foredeep along the north-vergent Apenninic sole thrusts. Structural relationships between these mountain chains form a complex feature located at depth and masked by the sediments of the Po plain and Piemonte Tertiary Basin.

The area of transition from Alps to Apennines is located, on the crustal scale, in the Langhe and Monferrato districts (Fig.1). Due to the scarcity of superficial geological data, the interpretation of crustal geometries and tectonic evolution of this area must be derived mainly from geophysical studies.

Geophysical data come from general investigations of the entire Po plain (see e.g. Cassano et al., 1986), from the EGT-southern segment projects (for a review see Cassinis, 1986; Morelli and Nicolich, 1990) and from some geophysical studies carried out in limited areas (Loseke and Scheelke, 1978; Armando et al., 1984).

Subsurface data show that the crystalline basement, below the Po plain, is considerably

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[1] Dip. Geologia, Paleontologia e Geofisica, Via Rudena 3, 35123 Padova, Italy.

[2] CNR - C. S. Geodinamica Catene Collisionali, Via Accademia delle Scienze 5, 10123 Torino, Italy.

Table — Coordinates of the MT sounding stations.

SITE	N.	LATIDUDE	LONGITUDE
Val Grana	1	44°59'15"	8°25'08"
Piepasso	2	44°55'40"	8°22'18"
Roncaglia	3	44°50'29"	8°24'48"
Quaglio	4	43°53'09"	8°20'15"
Rocchetta Palafea	5	44°42'00"	8°21'08"
Bubbio	6	44°39'00"	8°17'20"
Cartosio	7	44°35'48"	8°24'26"
Cavalli	8	44°32'48"	8°22'23"
Giusvalla	9	44°27'48"	8°22'56"
Castino	10	44°37'11"	8°11'17"
Violette	11	44°33'46"	8°08'36"
Pian Soave	12	44°31'45"	8°14'34"
Gottasecca	13	44°27'43"	8°11'15"

deeper than the basement below the Langhe Tertiary Basin. Historically, the interpretation of this step-like geometry has continued to change considerably : normal fault (Carta Geologica d'Italia, 1968; Gunter and Reutter, 1978; Loseke and Scheelke, 1978), reverse fault with minor overthrusting component (Pieri and Groppi, 1981; Cassano et al., 1986) or wedge effect of the Apenninic basement (Roure et al., 1990).

Recent interpretations suggest that this geometry is due to the existence of an intracontinental sedimentary wedge of Tertiary age at the Monferrato thrust front. This hypothesis was suggested by gravity modelling (Miletto and Polino, 1992) and has recently been confirmed by seismic refraction and reflection experiments (Biella et al., 1992; Polino et al., 1992, Biella et al., 1993).

The N-S magnetotelluric profiles here presented span from the Monferrato and the Langhe up to the Maritime Alps (Voltri Group): they run across superficial geological domains that are related at the crustal scale to both Alpine and Apenninic structural domains.

- Monferrato is considered as the north-western prolongation of the Apennines; to the north it is bounded by a basal thrust related to the Apenninic thrust fronts (Pieri and Groppi, 1981; Castellarin et al., 1985, 1992; Biella et al., 1988). To the south it is bounded by a left-lateral deformation zone (Piana and Polino, 1994) which is the superficial expression of the crustal discontinuity separating the Apenninic-related domain from the Alpine-related domains (Biella et al., 1992; Polino et al., 1992);
- The Langhe is considered part of the "Piemonte Tertiary Basin", a comprehensive term used to indicate the molasses deposited on Alpine-related structural domains (Torino Hill, Langhe, Lemme-Staffora and Alto Monferrato, sensu Polino et al., 1992; see Fig. 1);
- The Maritime Alps correspond to the outcropping part of the Alpine metamorphic belt, where the MT survey was carried out.

The aim of the MT survey was mainly to detect, from the electrical behaviour of the geological structure, the geometric relationships between the resistive basement and the more conductive sedimentary cover.

MAGNETOTELLURIC MEASUREMENTS AND DATA ANALYSIS

Thirteen magnetotelluric soundings along two N-S profiles were carried out in the Tertiary Piemonte Basin: given the E-W regional strike, the N-S direction was chosen as principal direction

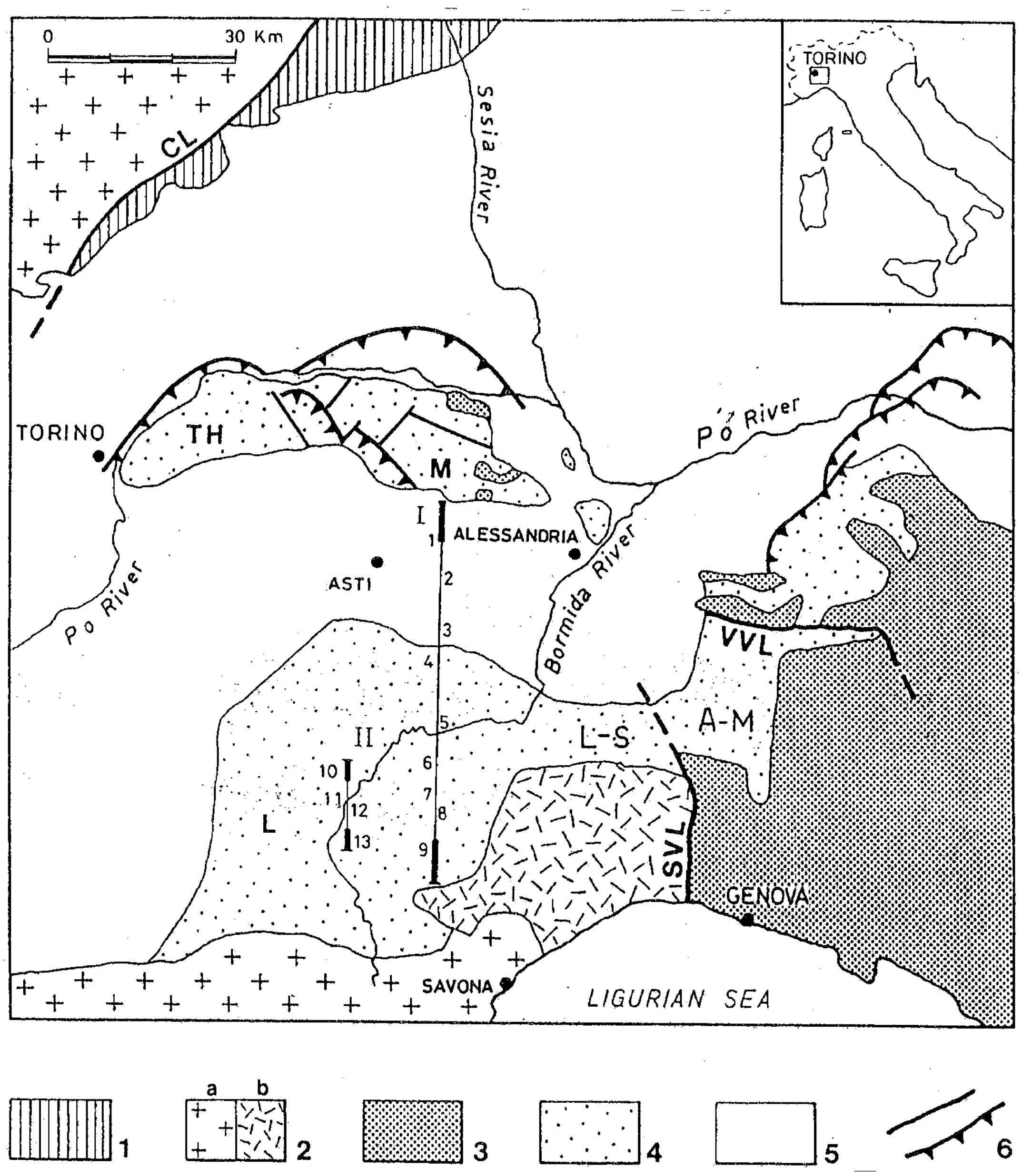

Fig. 1 - Geological sketch map of the Western Po plain, Piemonte Basin.
Symbols: 1) South Alpine domain and Canavese Zone, 2) Penninic-Austro-Alpine domain: a-basement nappes, b-ophiolitic units of the Voltri Group, 3) Cretaceus-Paleogene flysch units of the Apenninics, 4) Tertiary infillings of the Piemonte Tertiary Basin: (L: Langhe, L-S: Lemme-Staffora; AM: Alto Monferrato), Torino Hill (TH) and Monferrato (M) domains, 5) Pliocene-Quaternary infilling of the Po Plain, 6) Heavy lines: main tectonic lines; CL Canavese Line, VVL Villavernia-Varzi Line, SVL Sestri-Voltaggio Line. Heavy lines with triangles: Torino Hills, Monferrato and Apenninic thrust fronts.
(I) e (II): Magnetotelluric profiles.

for the two MT profiles (I and II).

Locations and coordinates of the MT sites are shown in Fig. 1 and in the Table.

MT data were recorded with an M.S.P.M., a real-time data processing system (Bon et al., 1987): it can operate in different frequency bandwidths, depending on the high- and low -pass analogical filters used.

During the fieldwork, data were recorded in three different overlapping frequency ranges: 100 - 1 Hz, 8 - 1/8 Hz, and 1 - 1/64 Hz, and the sampling rates were respectively 400, 32 and 4 Hz.

Data were of good quality, with the predicted coherencies usually 0.8 or higher; resistivity and phase curves show a continuous trend, without shifting from range to range, even if the acquisition was performed with different overlapping frequency bandwidths. Examples of the MT data are shown in Figs. 2, 3 and 4.

MT soundings (1-4), at the northern part of the profile I, show isotropic apparent resistivity curves for almost all considered periods; the very low resistivity values (1-50 Ω · m) of the shallow formations are due to a high terrigenous fraction, which is always very conductive. Some central and southern sites show a 2-D behaviour in the apparent resistivity curves.

Azimuth directions of the southern soundings of profile I prove the E-W geological strike direction.

Some apparent resistivity curves from the southern sites on both profiles are affected by static shift phenomena, perhaps due to the horizontal and vertical current gathering in three-dimensional resistivity heterogeneities (Park, 1985).

In order to perform a 2-D interpretation the apparent resistivity and phase curves were derived for TM and TE polarization modes from the magnetotelluric time series.

Rho TM (N-S direction) and Rho TE apparent resistivity pseudosections, and phase TM and phase TE pseudosections for profile I are presented with logarithmic period vertical scale in Figs. 5, 6, 7 and 8. Apparent resistivity pseudosections evidence three different sectors: the northern area (sites 1-4) characterized by a very conductive sequence (1-20 Ω · m) of Pliocene-Quaternary Asti-Alessandria Basin infilling; the central part (sites 5-6), which represents a transition zone of middle conductivity (20- 250 Ω · m), with Pliocene-Quaternary layers covering Tertiary sediments; and the southern area (sites 7-9) with high to very high (100 -> 1000 Ω · m) apparent resistivity values, in which Tertiary sediments probably cover a resistive Alpine basement.

The 2-D model search was done by trial and error with the forward program of Wannamaker at al. (1987).

The 2-D resistivity model along profile I is presented in Fig. 9. Rho TM experimental apparent resistivity curves and the model response curves are shown in Fig. 10.

The best-fit was recognized for TM polarization, while the poorer TE polarization fit, for the southern sites, could be due to the proximity of lateral resistivity variations in an E- W direction. Different geological formations are, in fact, detected to the west: apparent resistivity curves, along with different strike directions for sites 10-11-12-13, confirm shallow lower resistivity values along profile II, due to the extension of the Langhe Basin in a NE-SW direction.

The presence nearby of a coast and thus a deepening sea-bottom lead to the suggestion of considering the coast-effect on the MT data interpretation, but 2-D modelling of the magnetotelluric section along profile I didn't show appreciable changes by its introduction.

GEOPHYSICAL MODELLING: DISCUSSION AND COMPARISON

The modelling of the MT profiles shows marked differences along the strike: to the north the main feature is a succession of very conductive layers down to a depth of several kilometres; while to the south, the detected resistive basement is at a shallower depth in both profiles, suggesting an important tectonic discontinuity constraining the geometry of the whole section.

The 2-D model of profile I (Fig.9) shows three different sectors:

a) low resistivity values (1-50 Ω · m) for the northern sites;

b) medium resistivity values (200-400 Ω · m) in the central part of the profile;

c) high resistivity values (20000 Ω · m) for the southern sites.

Most superficial resistivities in sector a) are related to the Pliocene-Pleistocene sediments with typical resistivity values of shales and clays; sector b) can be associated with the undifferentiated Tertiary cover, and the high resistivity value of the electrical basement could be interpreted as due to a "granitic" basement: similar resistivity values have been detected

SITE: 1

1) BAND : 0 1 2
2) SAMPLE/WINDOW : 512 512 512
3) NUMBER WINDOWS: 38 47 20
4) SAMPLE RATE Hz : 400 32 4
5) MIN COHERENCY : 0.80 0.80 0.80

SITE: 2

1) BAND : 0 1 2
2) SAMPLE/WINDOW : 512 512 512
3) NUMBER WINDOWS: 38 41 34
4) SAMPLE RATE Hz : 400 32 4
5) MIN COHERENCY : 0.80 0.80 0.80

SITE: 3

1) BAND : 0 1 2
2) SAMPLE/WINDOW : 512 512 512
3) NUMBER WINDOWS: 31 28 38
4) SAMPLE RATE Hz : 400 32 4
5) MIN COHERENCY : 0.80 0.80 0.80

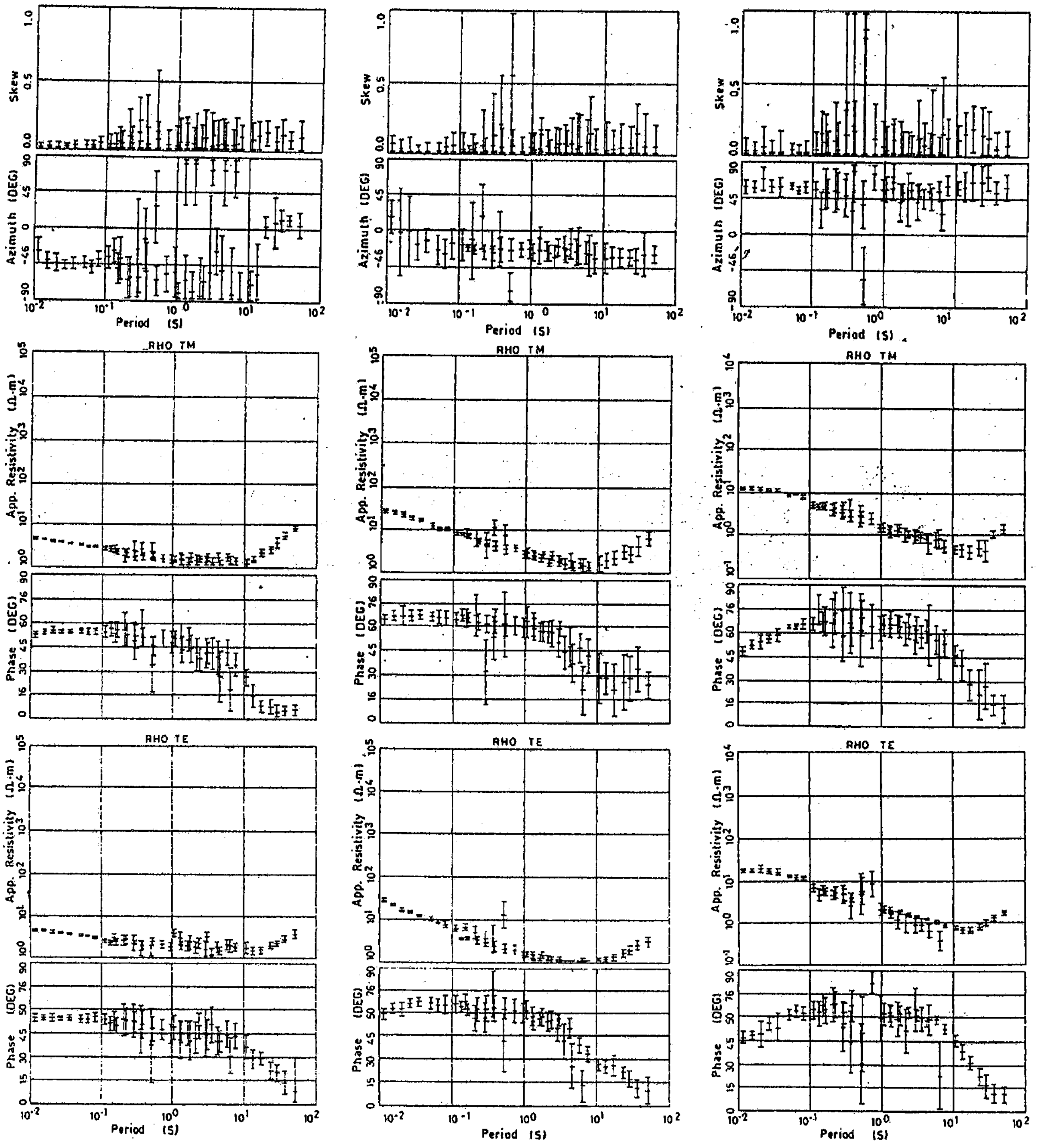

Fig. 2 - MT response curves vs. period for sites 1,2,3.

SITE: 4

1) BAND	: 0	1	2
2) SAMPLE/WINDOW	: 512	512	512
3) NUMBER WINDOWS:	45	24	30
4) SAMPLE RATE Hz	: 400	32	4
5) MIN COHERENCY	: 0.80	0.80	0.80

SITE: 5

1) BAND	: 0	1	2
2) SAMPLE/WINDOW	: 512	512	512
3) NUMBER WINDOWS:	38	43	39
4) SAMPLE RATE Hz	: 400	32	4
5) MIN COHERENCY	: 0.80	0.80	0.80

SITE: 6

1) BAND	: 0	1	2
2) SAMPLE/WINDOW	: 512	512	512
3) NUMBER WINDOWS:	88	30	21
4) SAMPLE RATE Hz	: 400	32	4
5) MIN COHERENCY	: 0.80	0.80	0.80

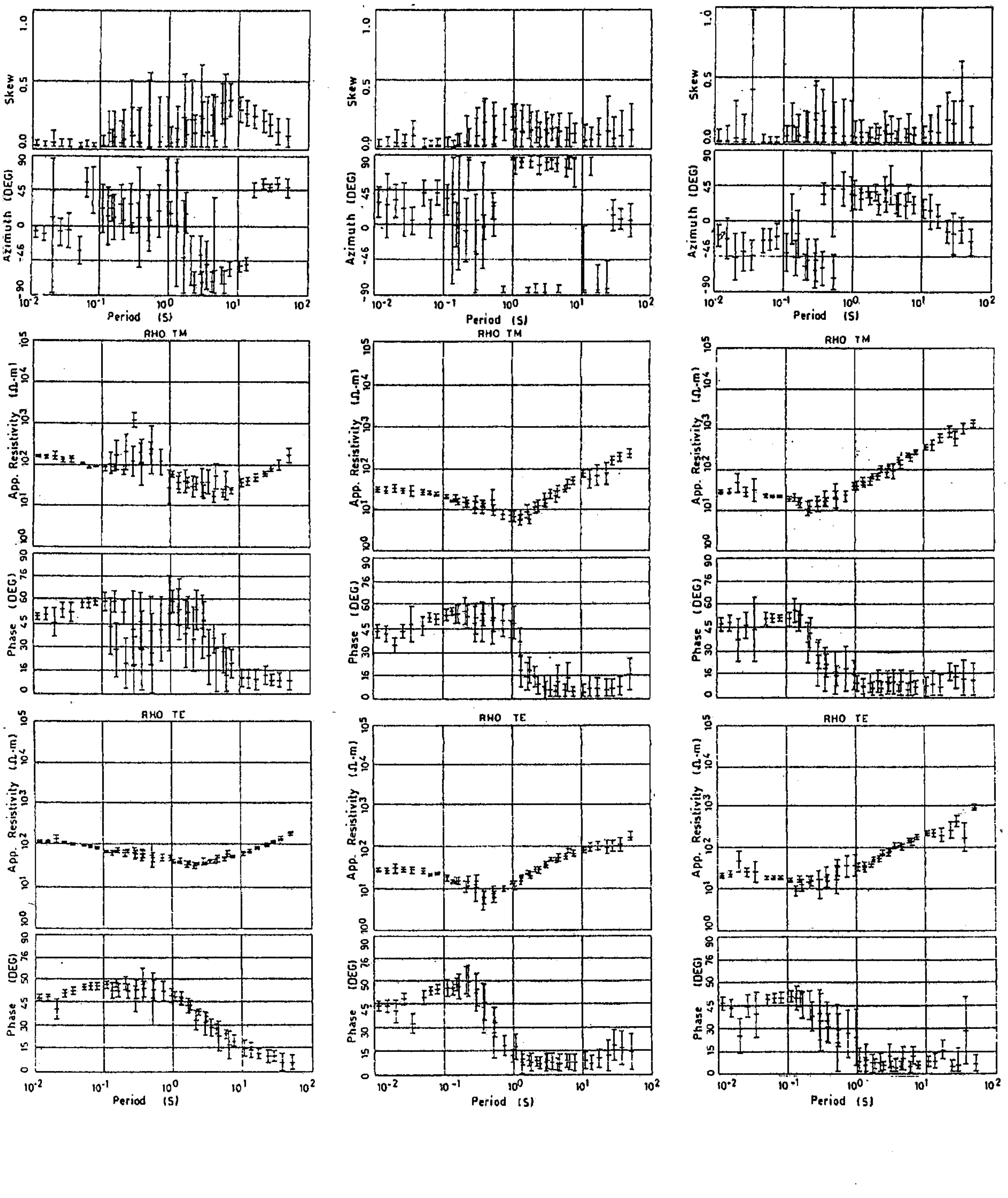

Fig. 3 - MT response curves vs. period for sites 4,5,6.

SITE: 7

1) BAND	: 0	1	2
2) SAMPLE/WINDOW	: 512	512	512
3) NUMBER WINDOWS:	52	23	40
4) SAMPLE RATE Hz	: 400	32	4
5) MIN COHERENCY	: 0.80	0.80	0.80

SITE: 8

1) BAND	: 0	1	2
2) SAMPLE/WINDOW	: 512	512	512
3) NUMBER WINDOWS:	43	13	20
4) SAMPLE RATE Hz	: 400	32	4
5) MIN COHERENCY	: 0.80	0.80	0.80

SITE: 9

1) BAND	: 0	1	2
2) SAMPLE/WINDOW	: 512	512	512
3) NUMBER WINDOWS:	34	23	47
4) SAMPLE RATE Hz	: 400	32	4
5) MIN COHERENCY	: 0.80	0.80	0.80

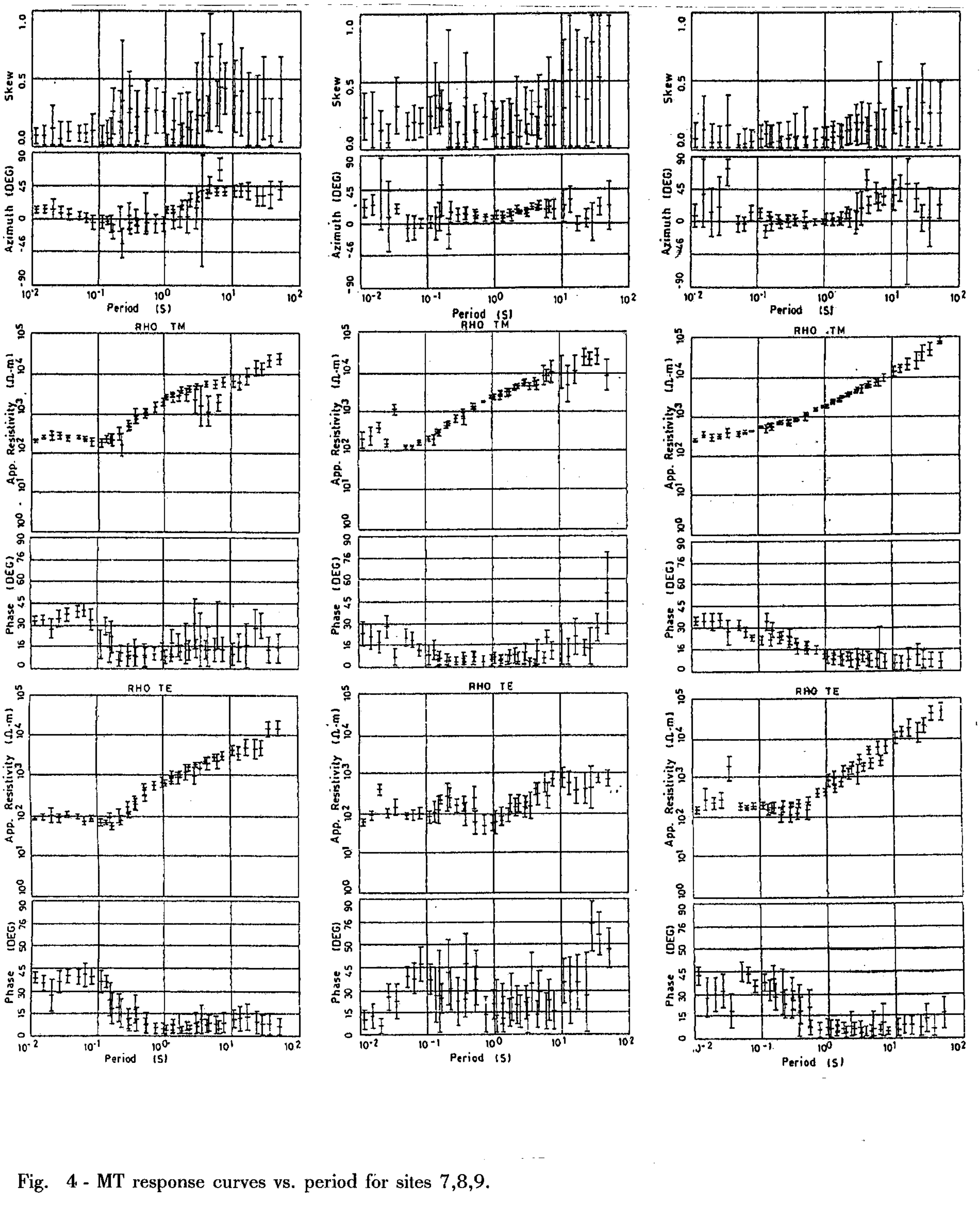

Fig. 4 - MT response curves vs. period for sites 7,8,9.

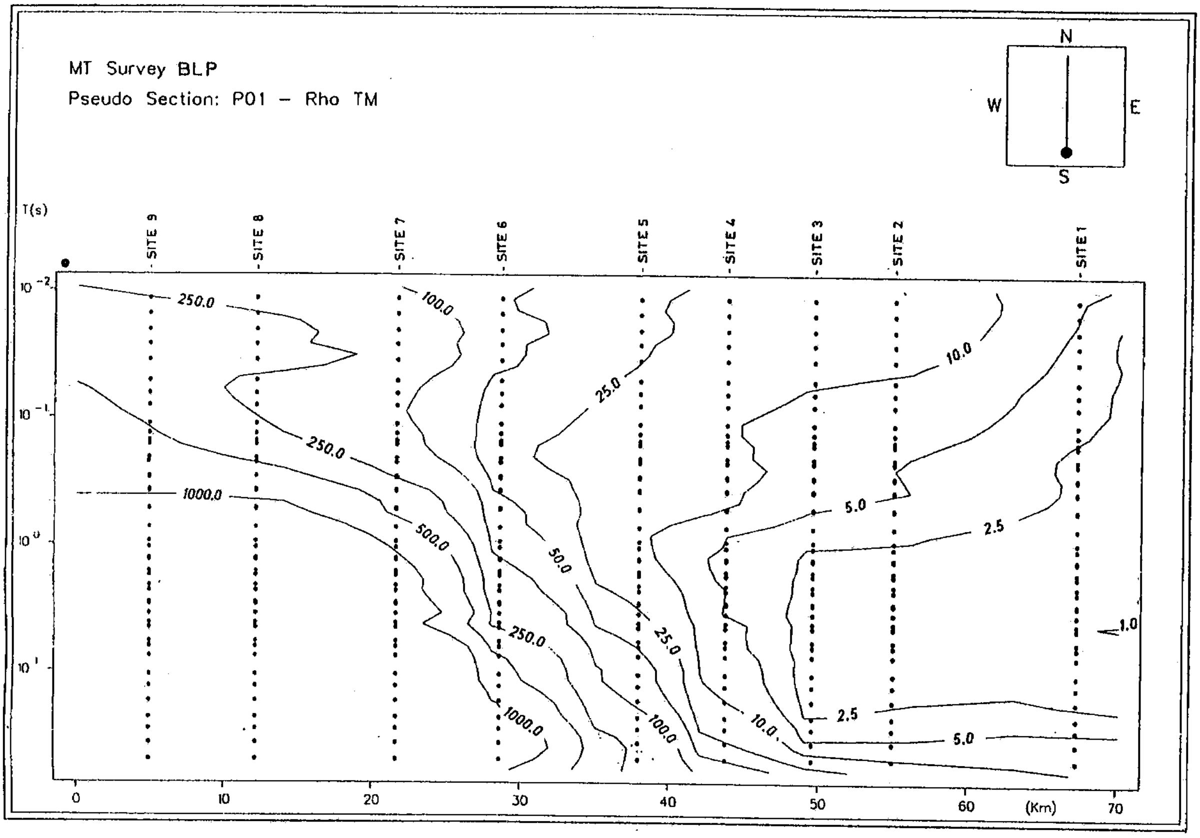

Fig. 5 - Pseudosection of TM apparent resistivity.

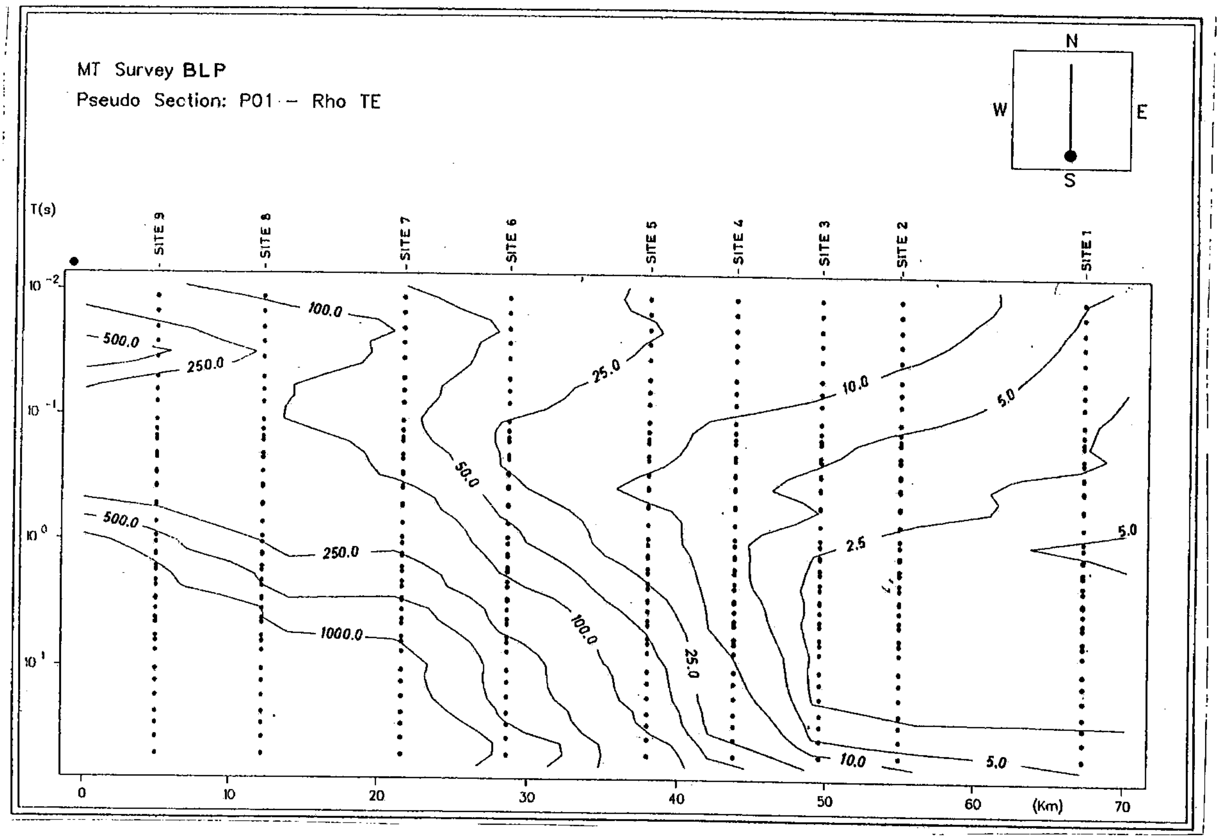

Fig. 6 - Pseudosection of TE apparent resistivity.

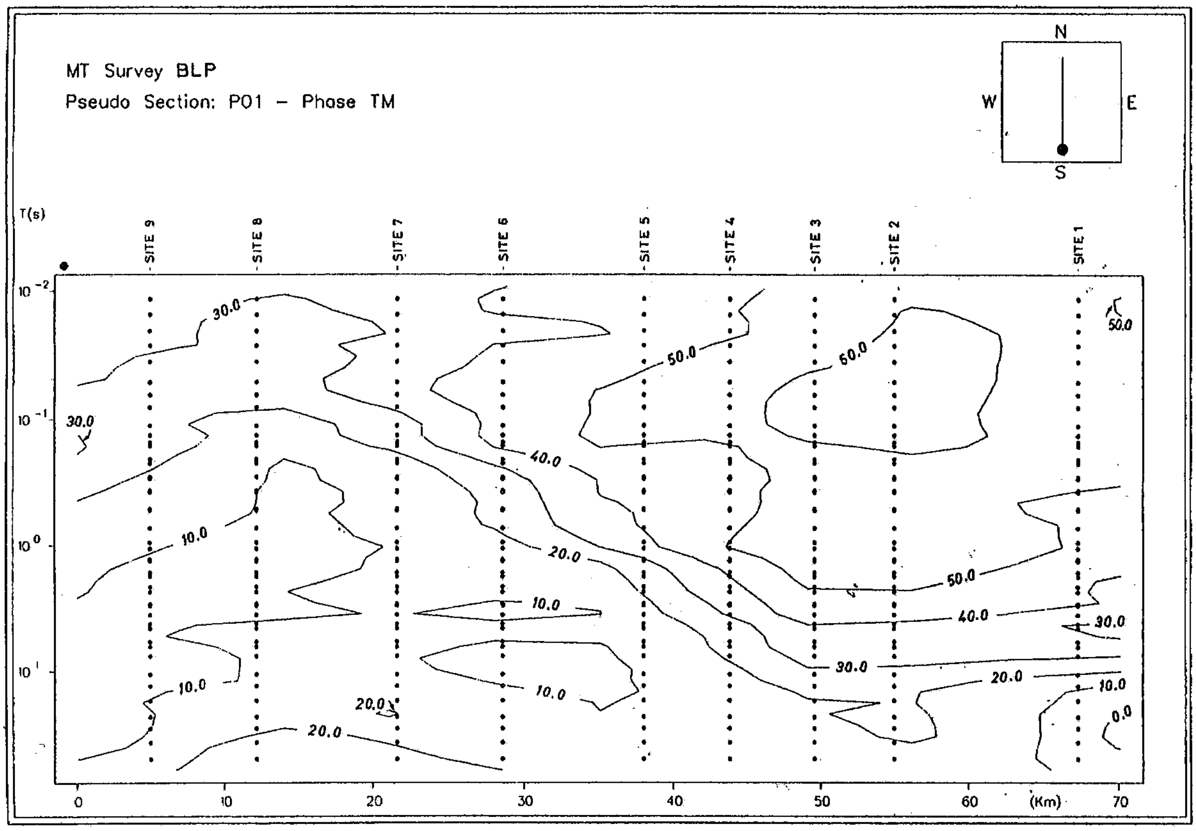

Fig. 7 - Pseudosection of TM phase.

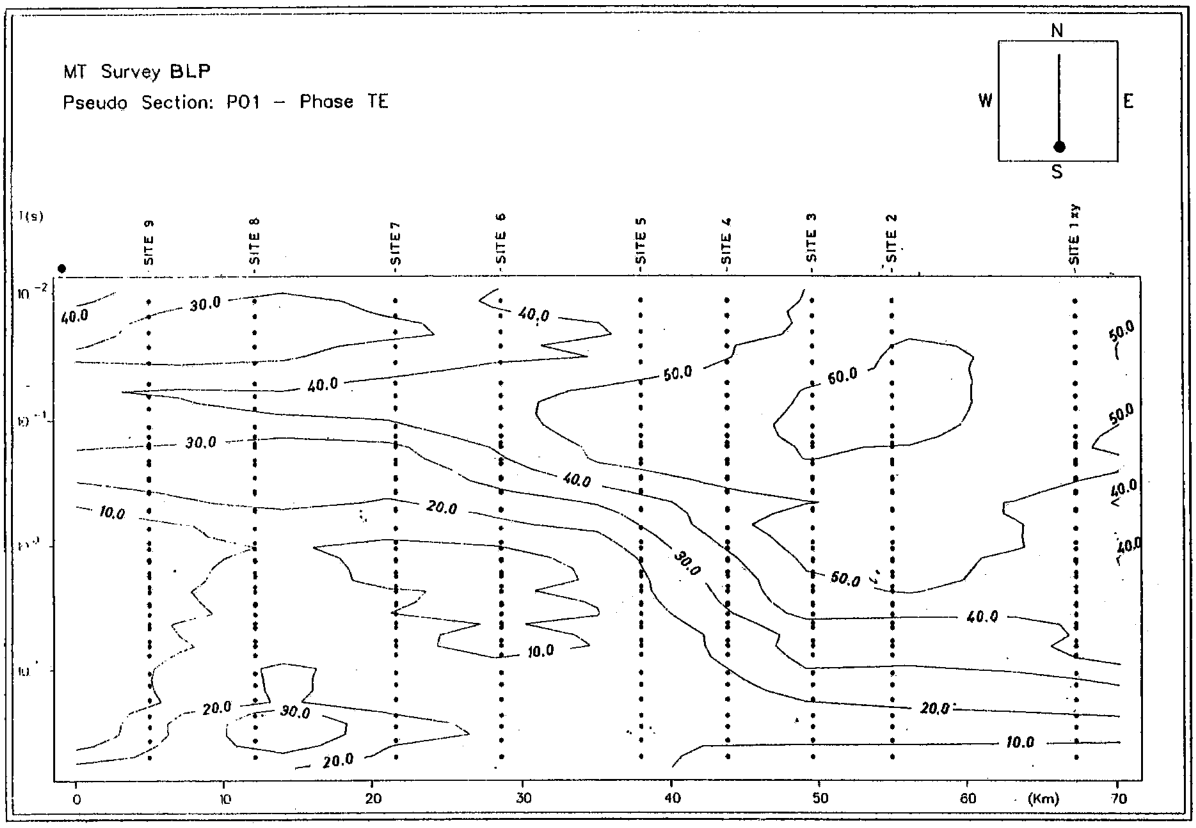

Fig. 8 - Pseudosection of TE phase.

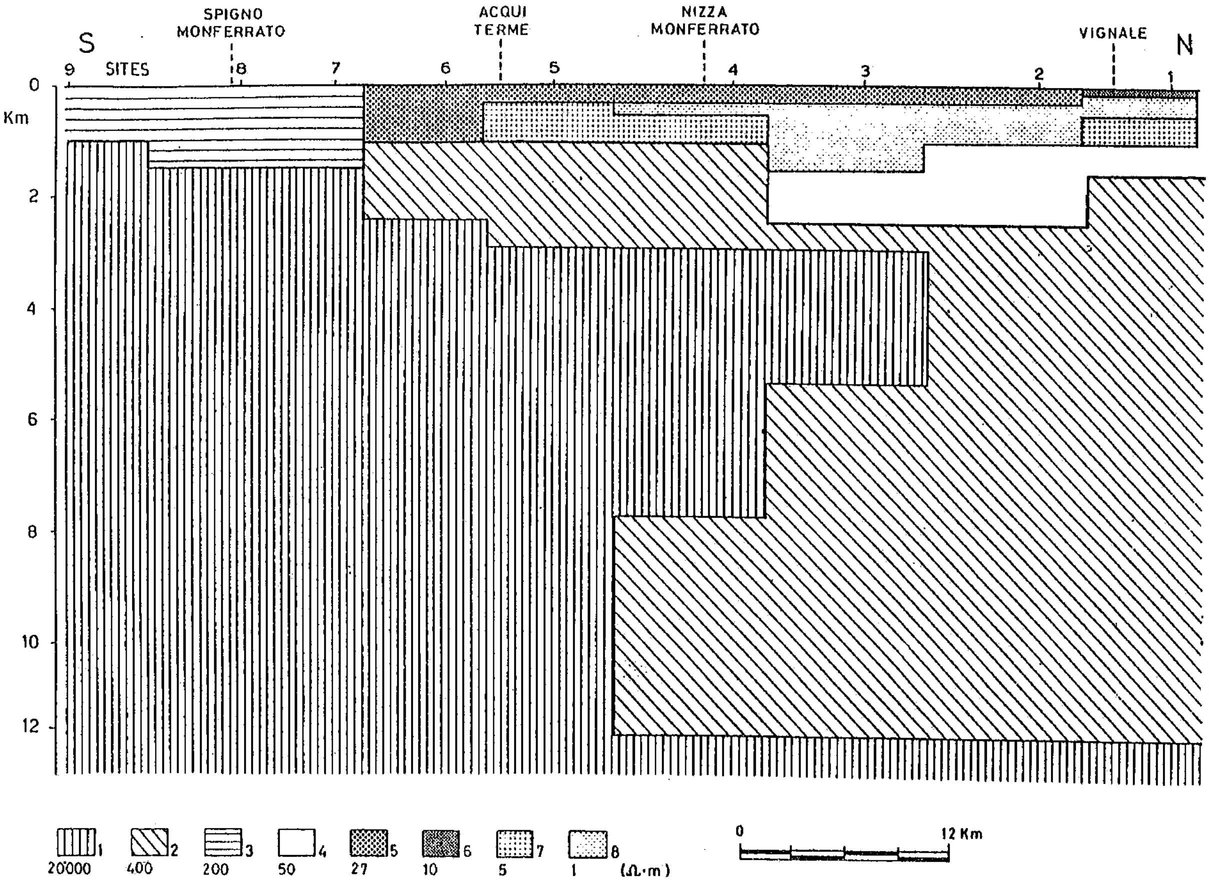

Fig. 9 - 2-D resistivity model along N-S direction (profile I).

on the same outcropping geological formation in the Central Alps (north of Italy) (Zaja, 1994).

The electrostratigraphic sequence below southern stations is very different from that detected in the northern section: shallow resistivities increase their values (10-200 Ω·m) towards the south; this behaviour is also recognized in the deeper layers and reflects a change in structural situation at depth.

In the southern part, the MT model shows a shallow basement dipping north whose geometry is in a good agreement with that depicted in the gravimetric model (Miletto and Polino, 1992) and detected by seismic survey (Biella et al., 1993).

The 2-D model for soundings along profile II is presented in Fig. 11: it confirms the geological situation along profile I. The electrostratigraphic sequence, similar to the one detected in profile I, confirms the westward prolongation of the 2-D model.

The proposed MT model does not contrast with gravimetric and seismic models and is in agreement with the suggested geological interpretation. Even if the resolution power of the MT sounding is not very high at a crustal scale, the proposed model agrees with the existence of an intracontinental sedimentary prism from Monferrato down to the crust southwestwards.

In addition, some remarks on gravity and magnetic anomaly maps are offered:

a) the Bouguer anomaly map (Fig. 12a) shows a minimum elongated south-westwards near Alessandria and suggests the extension of a low-density body in this direction: the higher thickness of the shallow cover and azimuth directions of the MT soundings, for the whole period band, along profile II, confirm the hypothesis of an intracontinental sedimentary prism;

b) magnetic anomalies had been detected (AGIP, 1983) in the southern area of the MT survey (Fig. 12b) and were interpreted to show the presence of ophiolite layers; this lithological type is not detectable in the MT model as it is probably masked by the high resistivity values of the basement.

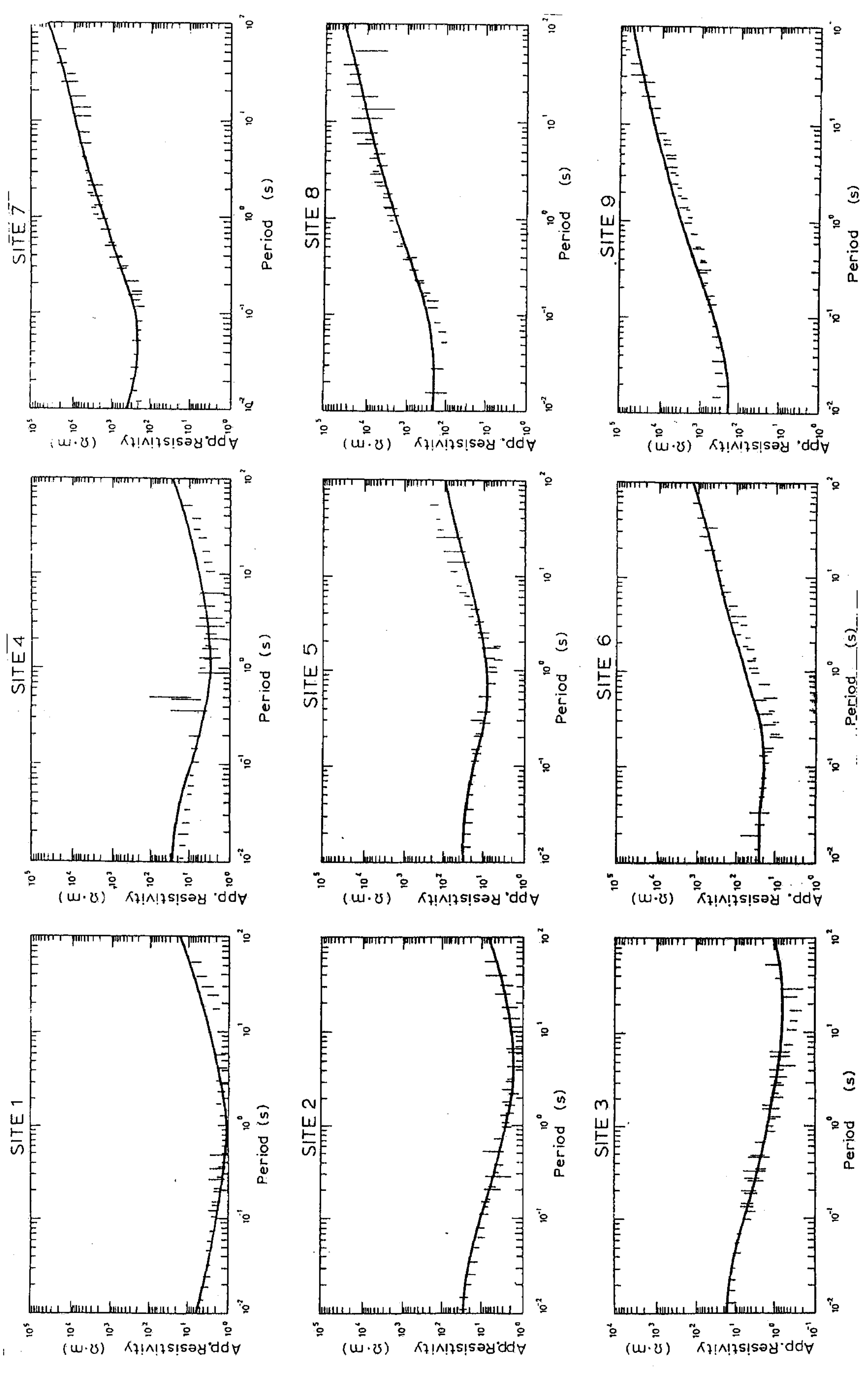

Fig. 10 - Rho TM apparent resistivity curves and computed 2-D model response curves (profile I).

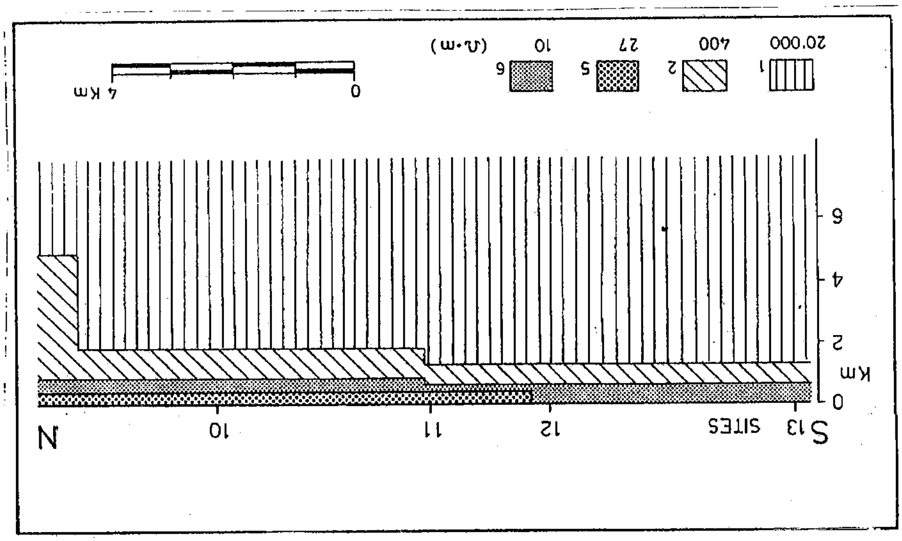

Fig. 11 - 2-D resistivity model along N-S direction (profile II).

CONCLUSION

Geological data, subsurface geophysics and gravimetric modelling suggest that the Monferrato ridge is the superficial expression of a major crustal rupture.

The MT survey along the two N-S profiles from Monferrato to the Maritime Alps (Voltri Group) supplies information mainly on the geometries of the upper crustal levels and on the depth of the basement. The latter gently deepens from south to north below the Langhe Basin to reach 3 kilometres below Asti. No significant variations in resistivity were observed in the southern part of the profiles, where ophiolitic bodies at shallow depth (Voltri Group) are inferred from superficial geology. This is probably due to the melange of ophiolites with more resistive lithologies at a scale not detectable with our scattered sampling.

In the northern part of the profile the basement descends to about 12 kilometres and has a flat shape in the MT model.

The nature of these basements at different depths is inferred from geological constraints:

a) the upper and southern one belongs to the Alpine domain and is partly formed from ophiolites (magnetic anomalies of Asti and Voltri Group);

b) the lower one is the southern prolongation of the entire Po plain basement and, according to AGIP interpretations, belongs to the south Alpine basement.

From site 2 to site 5, a low resistivity body could be modelled between the two basements. This body is coherent with the geological interpretation of the seismic image (Biella et al., 1992) of the crust, and the gravimetric modelling (Miletto and Polino, 1992): it is assumed to correspond to a major crustal boundary, and is interpreted as the intracontinental sedimentary prism in which the Apenninic/Ligurian Nappes are rooted and sandwiched between the underthrusting Padane domain and overthrusting Alpine domain.

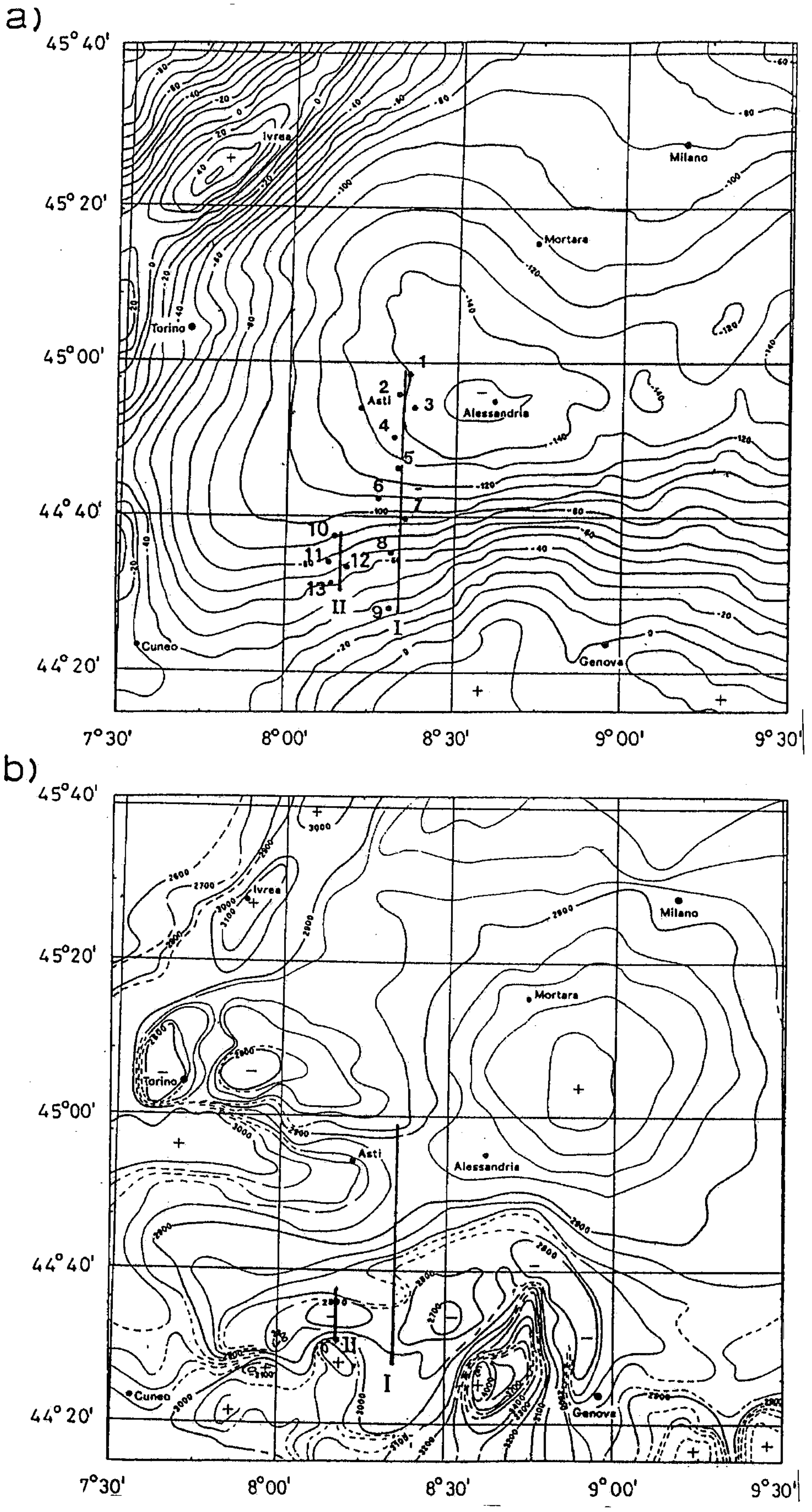

Fig. 12 - a) Bouguer anomaly map ($\delta = 2.4$ g / cm ^{3}, contour lines: 10 mGal) (Miletto et al., 1992).
b) Residual magnetic anomaly map (flight altitude: 1450m, thin contour lines: 20 nT; heavy contour lines: 100 nT) (Miletto et al., 1992).
I-II Magnetotelluric profiles.

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