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Central Italy magnetotelluric investigation. Structures and relations to seismic events: analysis of initial data

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Abstract
A scientific collaboration between the Warsaw Academy of Science, (Poland) and the National Institute of Geophysics (Italy), gave rise to the installation of few stations for the long term measurement of magnetotelluric fields in central Italy. The selection of investigation sites was determined by the individual seismic interest of each location. The project began in the summer of 1991, with the installation of 2 magnetotelluric stations in the province of Isernia, (Collemeluccio and Montedimezzo). In 1992, 2 more stations became operative, one in the province of Rieti, (Fassinoro), the other in the province of L'Aquila, (S. Vittoria). For the purpose of this project, the magnetic observatory in L'Aquila was also equipped with electric lines, for the measurement of the telluric field. The aim of the analysis here presented, is to show that is possible to follow the temporal evolution of magnetotelluric characteristic parameters. At Collemeluccio this evolution was compared with the seismic released energy for events recorded within the study area.

Key words *magnetotellurics – modelling – seismicity*

1. Introduction

Natural electromagnetic phenomena can be caused by the electromagnetic induction, of external origin of the Earth's magnetic field time variations, within the Earth. The observation of these phenomena, can be made by the measurement of the time variations of each magnetic and electric component in a given area. The resulting measurements can then be used to determine the distribution of underground electrical conductivity. The name magnetotelluric was given to the technique that specifically uses horizontal electric and magnetic components for such measurement; (Tikhonov, 1950; Cagniard, 1953).

Electromagnetic phenomena can also be observed on the Earth's surface, (where the noise level allows this), the origins of which lie deep within the complex mechanisms of rock fracture caused by tectonic stress, therefore this type of electromagnetic phenomenon should not be influenced by induction due to variations in the terrestrial magnetic field. Several observations appear to confirm the correlation of electromagnetism with tectonic and seismic phenomena occurring in the study area (Rikitake, 1976; Honkura, 1981; Mogi, 1985). These phenomena overlap those of so-called «traditional» magnetotellurics, however, they can be separated out with the aid of specific mathematical analyses.

Many results obtained from the study of observation installations, generally demonstrate the clear existence of a connection between electromagnetic phenomena and seismic activity. The correlations between seismic activity and the fluctuations in the telluric electric field, the magnetic field, the impedance of the soil and the radio-emissions, are of particular interest. It is, however, necessary to point out that, due to inherent interpretational difficulties, the results obtained from these observations are not always definitive, therefore it is not possible to state the absolute existence of a clearly defined systematic phenomenologic correlation between telluric electromagnetic «anomalies» and seismic activity. However, having stated this, significant results can be found in: Corwin and Morrison (1977), Morrison *et al.*, (1979), Gokhberg *et al.* (1982), Warwick *et al.* (1982), Varotsos and Alexopoulos (1984, 1987), Drakopulos *et al.* (1989), Fraser-Smith *et al.* (1990), Zhao *et al.* (1991), Uyeda *et al.* (1992). A recent experimental review paper on this phenomenology is available in Park *et al.* (1993).

It is, therefore, natural that the scientific community pays particular attention to the variations of the parameters linked to the electric and magnetic properties of lithoid material exposed to stress and fracturing. Several laboratory test have demonstrated the existence of a close correlation between the stress tensor and the impedance tensor (electric), for various rock types. Similar correlations have been found in other physical quantities, in which magnetization and electric fields have been generated under the application of stress (Nagata, 1970; Stacey and Johnston, 1972; Tuck *et al.*, 1977).

In this paper we aim to direct the results gained from a series of magnetotelluric measurements to the study of the above mentioned phenomena (see also Ernst *et al.*, 1994). The observation installations used in this series of measurements consisted of an instrumental network formed by magnetometers and telluric lines for the measurement of time variations of the magnetic and electric fields. In particular, a torsion magnetometer with a photoelectric transducer was used for the measurements of the time variations of the three components of the geomagnetic field; whilst for the measurement of potential spontaneous phenomena, 2 electric lines were used for each site at around 100 m apart placed in a NS-EW direction; the instrumentation was completed by low noise and linear filter preamplifiers. The polar electrodes consisted of a porous porcelain element containing a cupric sulphate gel. Data were gathered using a 14 bit A/D converter and a cassette recorder (fig.1). The systematic sampling took place every 20 s; every 10 days it was speeded up by 4 s per 24 h (Jankowski *et al.*, 1984).

The siting of this type of long term phenomenologic observation network had to be located in an area in which the noise level was compatible with the phenomena under observation.

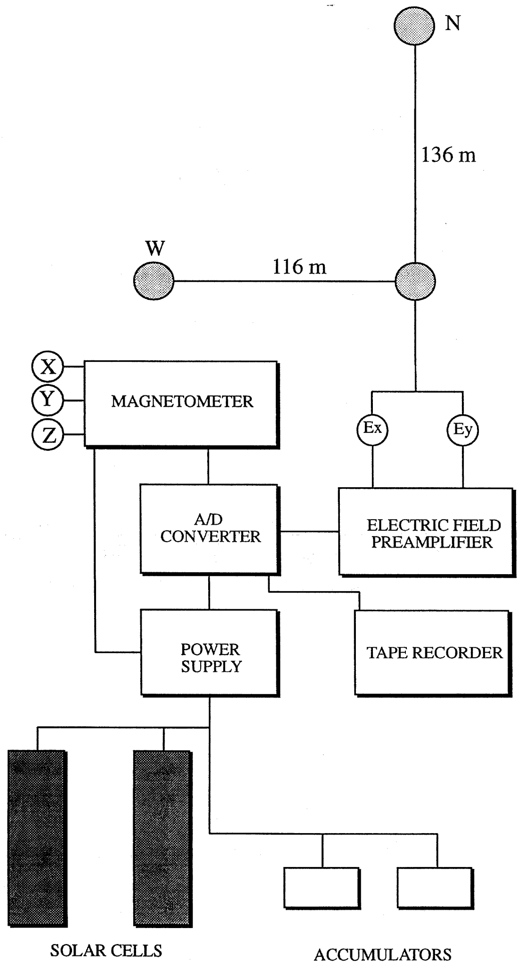

Fig. 1. Magnetotelluric instrumentation utilized in the field measurements.

2. Geological-structural features and seismicity in the area

The geological setting of the Central and Central-Southern Apennines is characterized by the presence of large carbonate platforms separated by pelagic basins. The carbonate deposition began during the Late Triassic, on the southern border of the expanding Tethys. In the Middle Liassic, a major tectonic crisis produced the disarticulation of large sectors of the shelf platform, whilst the higher sectors were undergoing shelf sedimentation, vast low-lying areas were subjected to pelagic sedimentation.

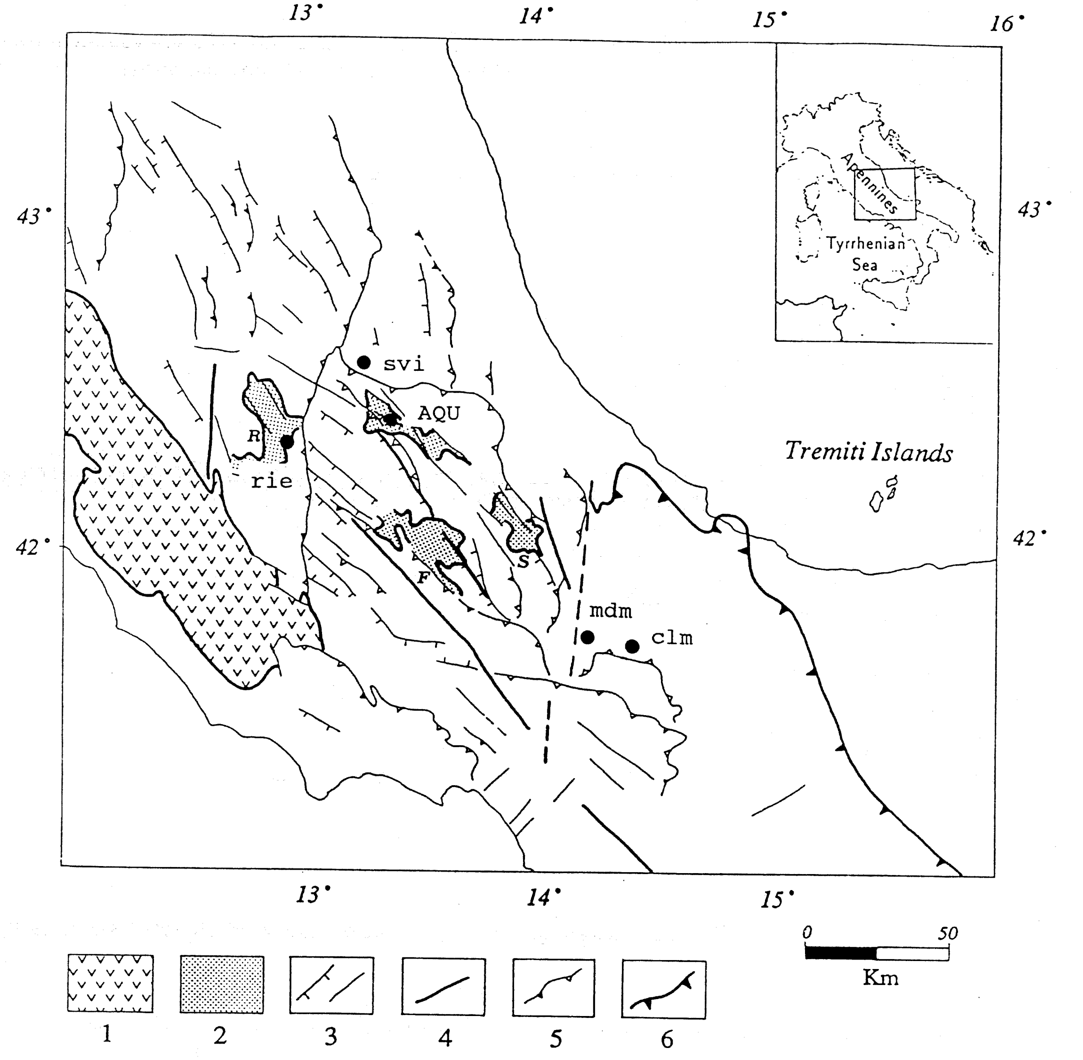

Fig. 2. Structural scheme of the Central-Southern Apennines. 1 = Quaternary volcanic deposits; 2 = Plio-Quaternary extensional basins: L'Aquila (L), Fucino (F), Sulmona (S) and Rieti (R); 3 = extensional faults; 4 = strike-slip faults; 5 = thrust faults; 6 = Apennine thrust front.

Thus large paleogeographic-domains were born, among which are the Laziale-Abruzzese carbonate platform, the Umbro-Marchigiano and Marsicano-Molisano basins. The principal tectonic phases, Tortonian-Pliocene in age, accompained by the appearance of abundant terrigenous sediments, have disarticulated the antique carbonate platform generating folding and thrusting phenomena

Extensional activity followed the compressive phases in the Tyrrenian area since Late Miocene. Extensional tectonics determined the regional formations of uprised and collapsed structures, horst and graben, limited by large normal faults. This process was accompained by plio-pleistocenic volcanism. The principal tectonic features related to this extensional phase, are characterized by NW-SE orientation (fig. 2) (Parotto and Praturlon, 1975).

The sites chosen for this magnetotelluric study all fall within an area of the Apennines characterized by its high level of seismic activity, (intensities of up to X MCS and magnitudes up to 6.9), with localized events at a hypocentral depth principally contained within 20 km (Istituto Nazionale di Geofisica, 1995).

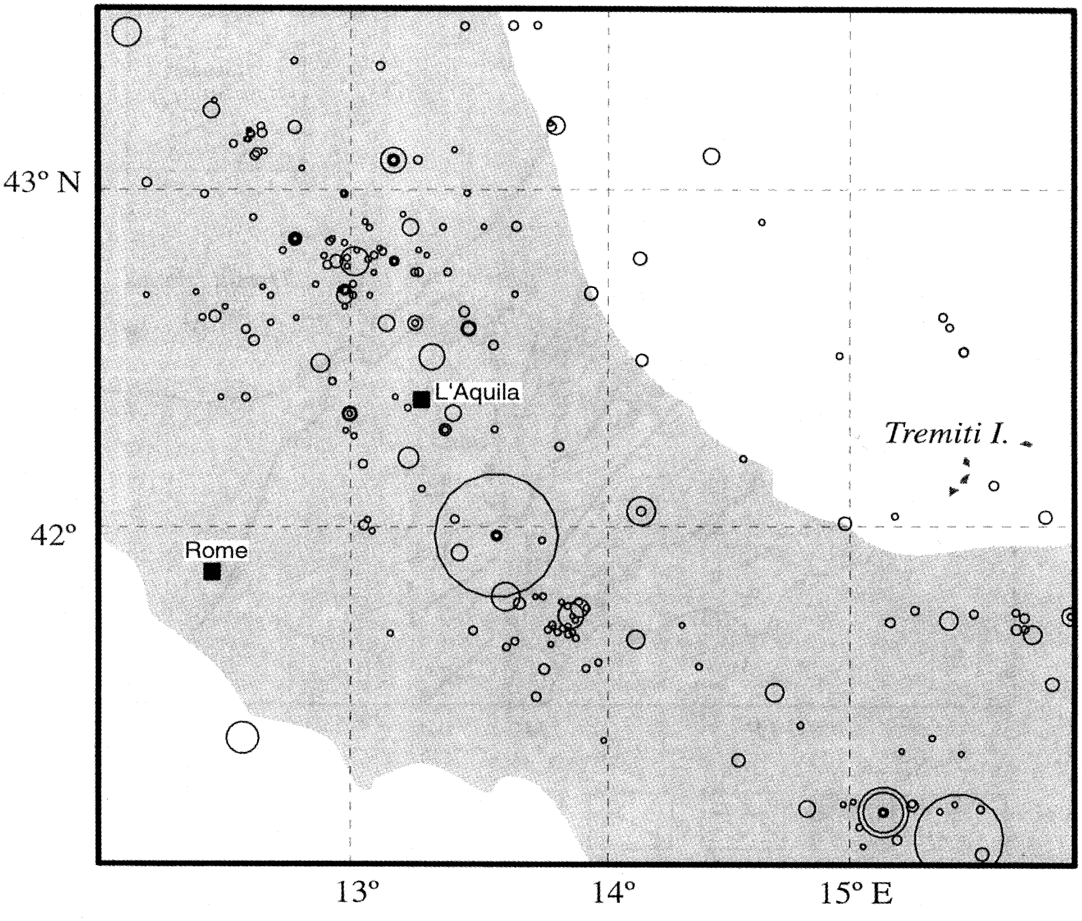

Fig. 3. Historical seismicity in Central Italy (this century). Reported events are $M > 4.0$ and proportional to circle radius.

The focal mechanisms are mainly linked to an extensional movement, associated with minor strike slip components, in either an apenninic or anti-apenninic direction (Gasparini and Praturlon, 1981).

The principal seismogenetic centers that occur in the study area (fig 3), are Piana del Fucino, noted for the powerful earthquake (M = 6.9) at Avezzano in 1915 (Ward and Valensise, 1989); the Reatine area (for which the ING records report historic events of up to VII-IX MCS); and the territory of L'Aquila (intensity up to X MCS). The southern zone of the study area contains the seismogenetic centers of Monte della Meta, (intensity levels of up to VI-VII MCS), recently affected by the Val Comino earthquake 1984 $M = 5.4$ (Console *et al.*, 1989); Isernia (intensities of up to VI-VII MCS); and the center of Matese (intensities of up to X MCS). The present seismicity of the area is manifested in a moderate but persistent activity, with events of medium magnitude, varying around $M = 3.0 \div 4.0$.

3. The observational sites selection and the electromagnetic noise level

In the study of magnetotellurics and its correlation with seismotectonic events, the non-inductive electromagnetic noise level originating from within the Earth is deemed to be generated by determined internal physical and chemical processes. To demonstrate this, physical models have been developed in which the natural ground noise is modulated by the stress of the internal and superficial rock (Igoshin and Sholpo, 1979; Anghel, 1979; Corwin and Morrison, 1977; Lockner and Byerlee, 1986). However, electromagnetic disturbances (due to anthropic activity) can hamper the signal monitoring. The natural noise can in fact be overcome by the artificially generated noise of large technological systems, the intensity of which is notably larger than that of the target signals.

In Central Italy, the principal source of artificial noise is that of the railways, being fed by direct current. The choice of measurement points was therefore, primarily conditioned by the position of the rail network. The magnetotelluric monitor stations were installed at a minimum distance larger than 20 km away from any railway. However, due to the possible effects generated by the rail network, even over long distances, an extra precaution was taken, *i.e.* the frequency band explored was limited to a maximum frequency of 0.01 Hz. This limit was computed considering that for a wave period of T = 100 s the apparent wavelength of an electromagnetic signal in a vacuum is 10^7 km, within the Earth, with an average resistance of ρ = 10 Ohm.m, it is less than 20 km (skin depth). Therefore, the observational points were located in the «far field» of rail noise for $T < 100$ s. Thus, for waves of $T < 100$ s the artificial magnetic field interacts with the medium and the electric and magnetic signals result as correlated and therefore indistinguishable from the natural signals. For $T > 100$ s, the measurement points result in the near field in relation to the artificial sources; thus the relative magnetic and electric fields are not correlated for electromagnetic induction, most importantly in terms of phase and polarization, therefore their effect is easily demonstrable, with the application of magnetotelluric algorithms.

The series of measurements used in this study, begun in the summer of 1990, in the province of Isernia, with the installation of a magnetotelluric station (Collemeluccio clm) and a telluric station (Montedimezzo, mdm). In 1991 another 2 magnetotelluric stations became operative in the province of Rieti (Fassinoro, rie) and in the province of L'Aquila (S. Vittoria, svi), in addition to the geomagnetic Observatory of L'Aquila which was rigged with telluric lines for the purpose of this study.

4. Signal treatment and the revelation of non inductive phenomena

In order to understand exactly whether an active tectonic process can influence the electrical resistivity in the area near to the measurement station, it is necessary to expose the electric and magnetic signals to a mathematical treatment. Greater protection against interference is gained however with the recognition and isolation of artificial noise from the signal itself.

In the «near field» the magnetic disturbance produced by the railway is plane-polarized roughly on the vertical of the observation site: therefore, the noise results as present mainly on the Z magnetic component (Palangio *et al.*, 1991). An attempt to remove this noise comprises the consideration that the vertical magnetic signal measured $H_z(t)$ is a result of the overlaying of a undesirable component $H_z a(t)$ and a natural component $H_z n(t)$:

$$H_z(t) = H_z n(t) + H_z a(t).$$

In the hypothesis that the $H_z n(t)$ component is produced by induction of the horizontal $H_x(t)$ and $H_y(t)$ and that all other natural signals are reasonably negligible, it is possible to separate the induced part of the measured signal $H_z n(t)$, via the use of the «impulse response» function of the medium $T_x(t)$ and $T_y(t)$:

$$H_z n(t) = T_x(t) * H_x(t) + T_y(t) * H_y(t).$$

Where $*$ represents the convolution operator. Once the functions T_x and T_y have been determined (a normal process in the study of geomagnetic depth sounding, *e.g.* Parkinson and Hutton, 1989), it is possible to determine the structural characteristics of the site.

As well known is possible to determine the tensor, «the impedance of the medium», $\hat{Z}_{ij}(\omega)$, traditionally used in magnetotellurics (see Kaufman and Keller, 1981). This may be expressed in frequency domain if E_x and E_y indicate the electric fields in the direction of x and y, with

$$\hat{E}_x(\omega) = \hat{Z}_{11}(\omega)\,\hat{H}_x(\omega) + \hat{Z}_{12}(\omega)\,\hat{H}_y(\omega) \quad (4.1)$$

$$\hat{E}_y(\omega) = \hat{Z}_{21}(\omega)\,\hat{H}_x(\omega) + \hat{Z}_{22}(\omega)\,\hat{H}_y(\omega). \quad (4.2)$$

As has already been seen, the measured electric field, in addition to inductive signals, contains natural non inductive signals produced by artificial and natural sources. In the time domain the non inductive part of the electric fields $E_{ni}(t)$ can be separated:

$$E_{ni}(t) = E_m(t) - E_p(t)$$

in which $E_m(t)$ is the recorded signal and $E_p(t)$ is the predicted signal via the impulse response function $Z_{ij}(t)$:

$$E_{px}(t) = Z_{11}(t) * H_x(t) + Z_{12}(t) * H_y(t)$$

$$E_{py}(t) = Z_{21}(t) * H_x(t) + Z_{22}(t) * H_y(t).$$

Figures 4 and 5 illustrate several examples of the separation of non inductive signals from the recorded signals, in the case of the horizontal components of the electric field for the S. Vittoria site.

The predicted signal, computed using the impulse response functions of the medium, constitutes the inductive contribution; *i.e.* this represents the electric field produced via induction, by the variations of the horizontal geomagnetic field components. From the difference between the recorded and the predicted signal, it is possible to decontaminate the ground noise, thus revealing the Earth's natural electric field.

Returning now to the magnetic transfer functions, being the currents that generate the anomalous contribution on the vertical component $H_z a(t)$, due to the presence of non inductive electric fields $E_{ni}(t)$, it is possible to write

$$E_{ni}(t) = T_e(t) * H_z a(t)$$

and thus, theoretically possible to isolating the anomalous magnetic contribution.

It is clear that the function $Te(t)$, or its correspondent in the frequency domain, becomes a very useful parameter, in establishing the nature of anomalous signals.

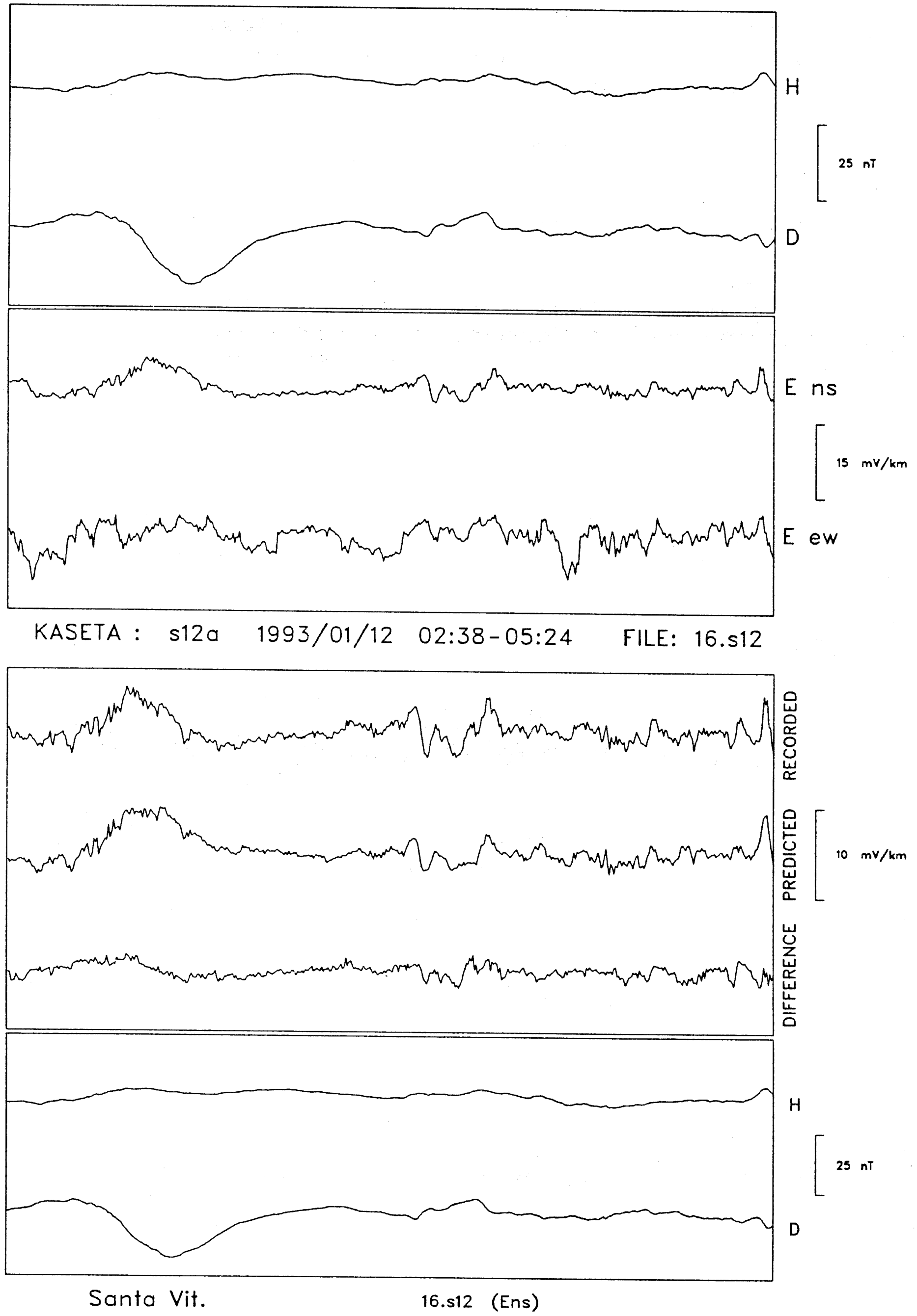

Fig. 4. An example of the separation of predicted and recorded horizontal electric signal for the site at S. Vittoria: medium to low magnetic activity. Horizontal magnetic field is reported on the top and the bottom.

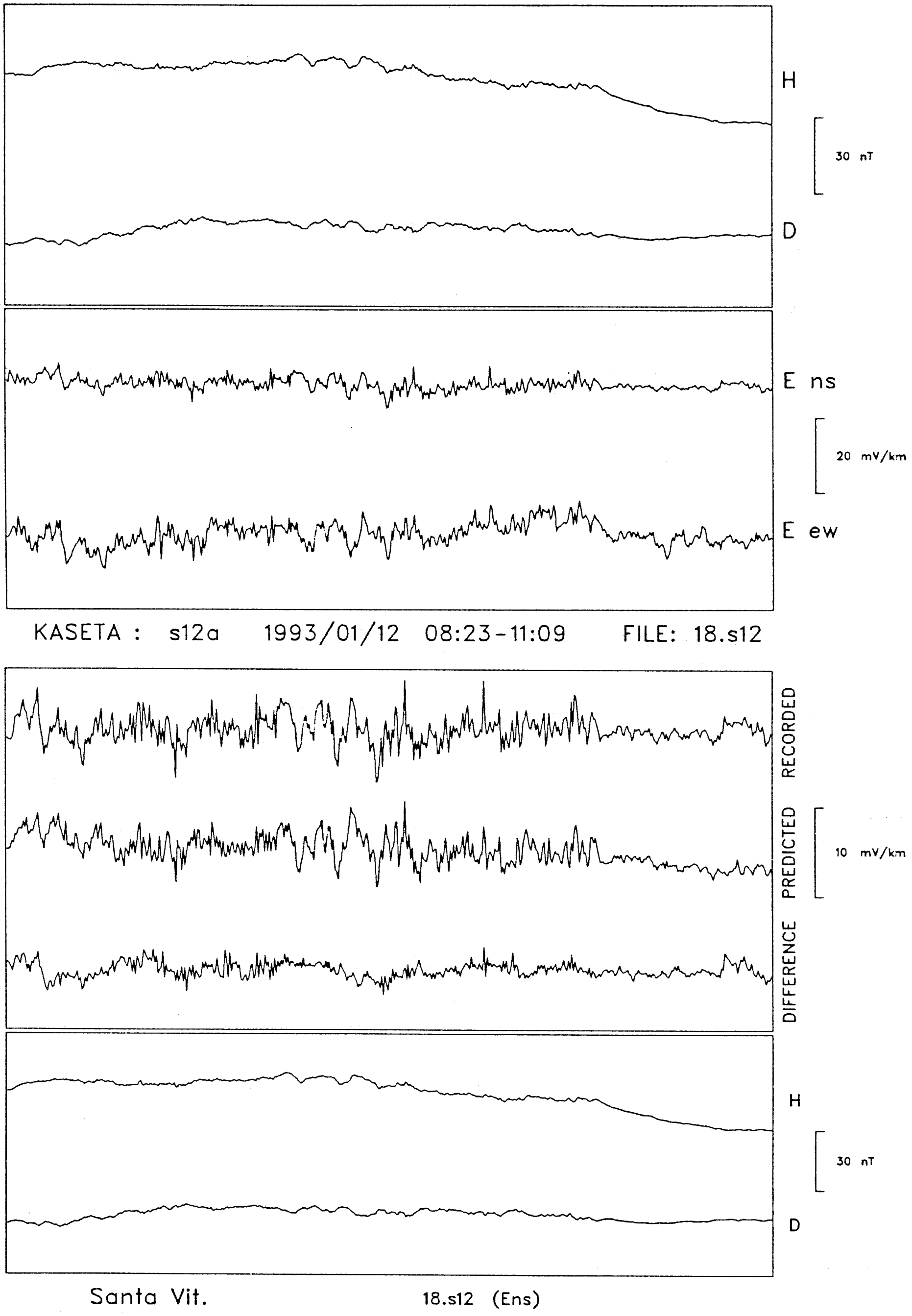

Fig. 5. An example of the separation of predicted and recorded horizontal electric signal for the site at S. Vittoria: medium to low magnetic activity. Horizontal magnetic field is reported on the top and the bottom.

5. Experimental computation of the impedance tensor at Rieti and S. Vittoria

The elements of the impedance tensor Z_{ij} are defined using eqs. (4.1) and (4.2); the apparent contradiction of the resolution of a system with two equations of 4 unknowns, is resolved considering that since the elements of $\hat{Z}_{ij}$ vary slowly with the frequency, they can be calculated on a number of points with a lower point value than the transformed values. Therefore, it can be said that the elements Z_{ij} are calculated, as an average, on limited frequency bands. One of the most common methods of calculation of the impedance tensor, is described by Madden and Nelson (1964). In this study, the Wieladeck and Ernst (1977) formula is utilized, based on a least squares algorithm in time domain. Applying the Cartesian matrix of rotation $R_{ij}(\theta)$ to the elements of the tensor $Z_{ij}(\omega)$:

$$Z'_{ij}(\omega) = R_{ik}(\theta)\ Z_{kp}(\omega)\ R_{pj}(\theta) \qquad (5.1)$$

the elements $Z_{ij}(\omega)'$ can be obtained, in a reference system rotated on the horizontal plane at an angle of θ. The Z_{ij} elements as a function of θ, give the useful graphic representation from which the type of conductivity structure present in the investigated area emerges.

In the ideal case of pure two-dimensional conductivity, the impedance tensor can be rotated to the point of uncoupling the eqs. (4.1) and (4.2) ($E'_x = Z'_{12} H_y$; $E'_y = Z'_{21} H_x$). Generally, a maximum and a minimum impedance value is obtained for a given angle θ.

The graphs in figs. 6 and 7 refer to the stations of Rieti and S. Vittoria, they display the rotation of the impedance tensor as a function of the angle θ and period T. These areas seem to show a conductivity structure, far from the one-dimensional model. The minimum conductivity value corresponds to an angle θ, about 40°÷ 50°. Even though an exact interpretation of this anisotropy is not possible, it is interesting to note how this angle appears to correlate with the main tectonic features in Central Italy.

After a year or so of measurements, the stations at Rieti and S. Vittoria were abandoned, due to an increase in the noise, to an extent that the levels reached were utterly incompatible with this type of measurement. Since both stations were used for a lengthy period, the recorded data was used to attempt an interpretation of the conductivity structure of the two areas. The subsequent resistivity curves and phases are shown in figs. 8 and 9. The resistivity curves were utilized to resolve a problem of one-dimensional inversion; the results of which are also illustrated at the bottom of figs. 8 and 9.

6. Analysis of data relating to the station at Collemeluccio

In this first phase, the area of Collemeluccio presented the lowest electromagnetic ground noise level of all the test sites. Consequently, only this station was kept on in order to undertake long term studies on the possible association of electromagnetic phenomena with seismic events.

In magnetotellurics, frequent use is made of the apparent resistivity ρ_a, or rather, the resistivity that a uniform Earth should have, in order to give the measured impedance value Z. If the conductivity varies with the depth, then ρ_a must change with the frequency. Laterally varying conductivity, however, leads to conditions of anisotropy, as described previously. The most complex case is that of a variation over three spatial coordinates, (three-dimensional case), for which a solution cannot be given. The apparent resistivity is derived from the non diagonal elements of the impedance tensor $\hat{Z}_{ij}(\omega)$, for example using the formulation of Kaufman and Keller, 1981:

$$\hat{\rho}_{ij}(\omega) = \frac{|\hat{Z}_{ij}(\omega)|^2}{\omega\mu}.$$

Data concerning the apparent resistivity of the site at Collemeluccio, produced interesting results. The calculations of which, were made using $E_x - H_y$ and $E_y - H_x$ during periods characterized by a good magnetic activity. The curves represented in fig. 10, refer to average monthly

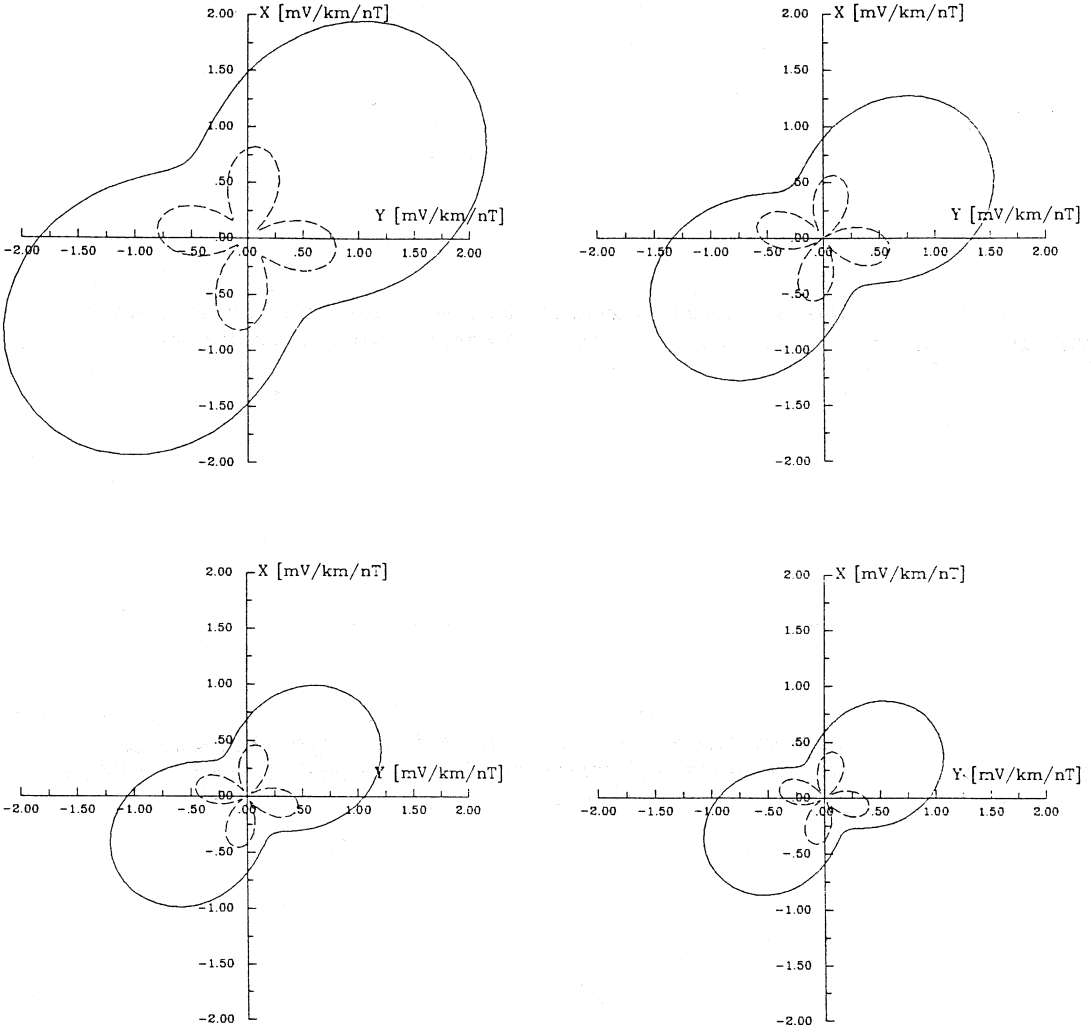

Fig. 6. Rotation of the impedance tensor in the S. Vittoria station. The four panels refer respectively to T = 200 s, 400 s, 600 s and 800 s. Solid line represents Z_{xy} and dashed line represents Z_{xx}.

calculations, for the period between January 1992 and February 1993. Each curve of 20-50 measurement intervals is made up of 499 samples (about 10^4 s). The apparent resistivity is shown on the left and the phases, in order of period relating to Z_{xy} (above) and Z_{yx} (below) are on the right. The values of apparent resistivity vary around 5 and 10 Ohm.m, relating to a period of between 300 and 1200 s, that is equal to a depth of *circa* 20-30 km ($p = \frac{1}{2\pi}\sqrt{10\rho T}$ with ρ in Ohm.m and T in s).

Three quantities, invariant with respect to the rotation can be calculated from the elements of the impedance tensor, via the $R_{ij}(\theta)$ matrix. Consequently, these quantities do not

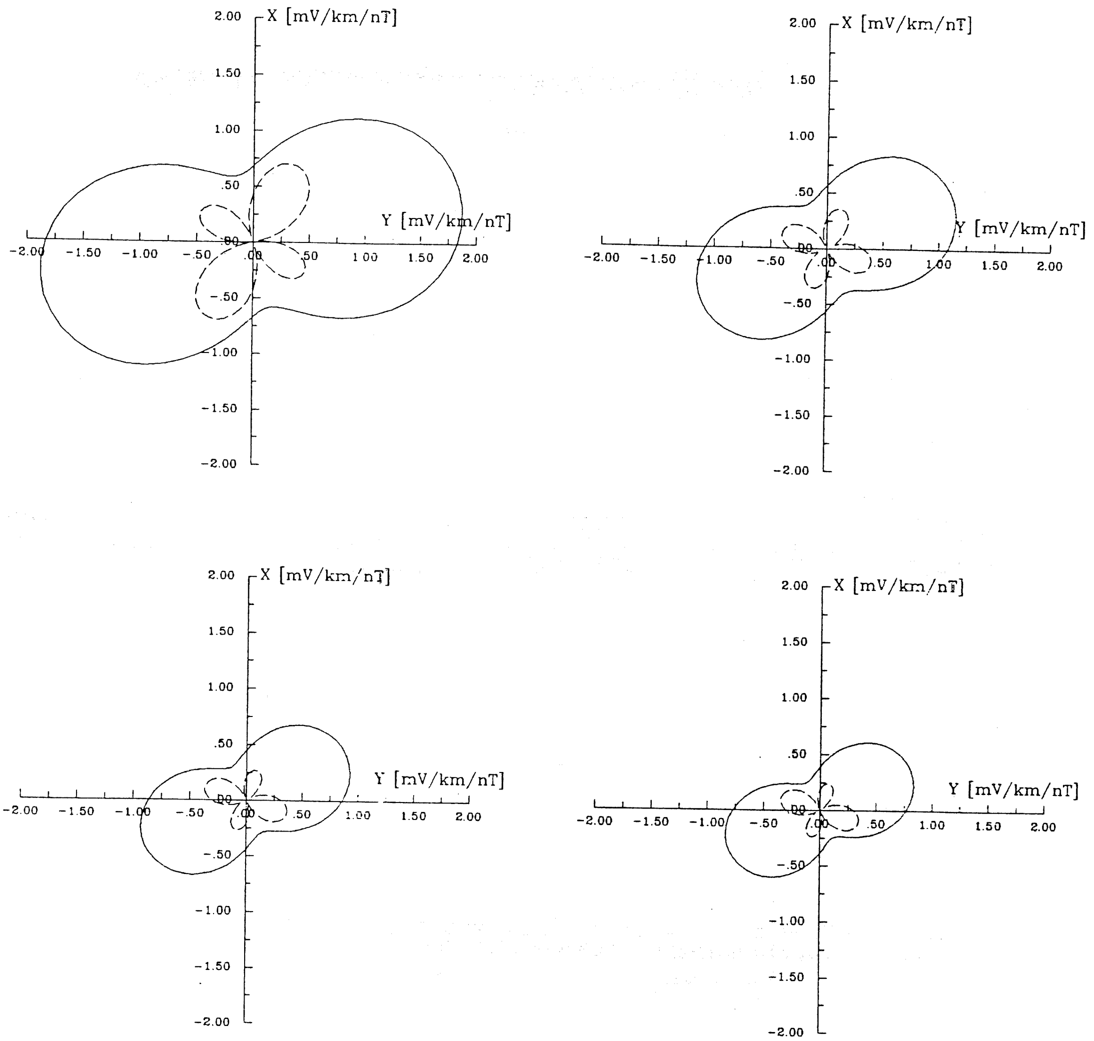

Fig. 7. Rotation of the impedance tensor in the station at Rieti. The four panels refer respectively to $T = 200$ s, 400 s, 600 s and 800 s. Solid line represents Z_{xy} and dashed line represents Z_{xx}.

depend on the reference system in which they are measured:

$$G_1 = \hat{Z}_{xx}(\omega)\,\hat{Z}_{yy}(\omega) - \hat{Z}_{xy}(\omega)\,\hat{Z}_{yx}(\omega)$$

$$G_2 = \hat{Z}_{xx}(\omega) + \hat{Z}_{yy}(\omega)$$

$$G_3 = \hat{Z}_{xy}(\omega) - \hat{Z}_{yx}(\omega).$$

The ratio G_2/G_3, the so-called «skew ratio», supplies a useful parameter in the interpretation of the conductivity structure.

The temporal fluctuations of G_1, G_2 and G_3, as well as the other Z_{ij} elements of the impedance tensor, being clear of inductive phenomena due to natural magnetic signals of external origin, can be correlated with stress vari-

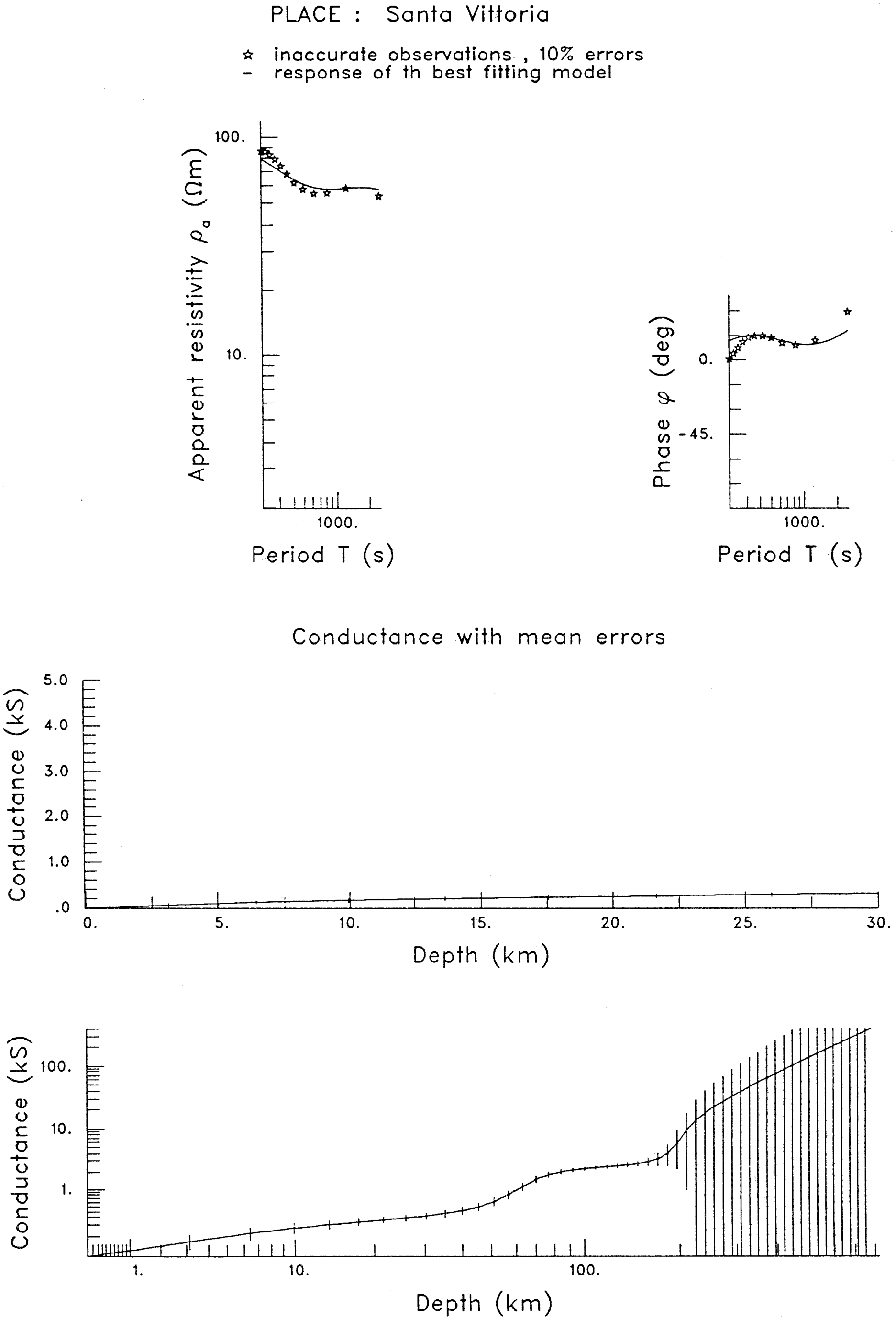

Fig. 8. Conductivity model for the station at S. Vittoria.

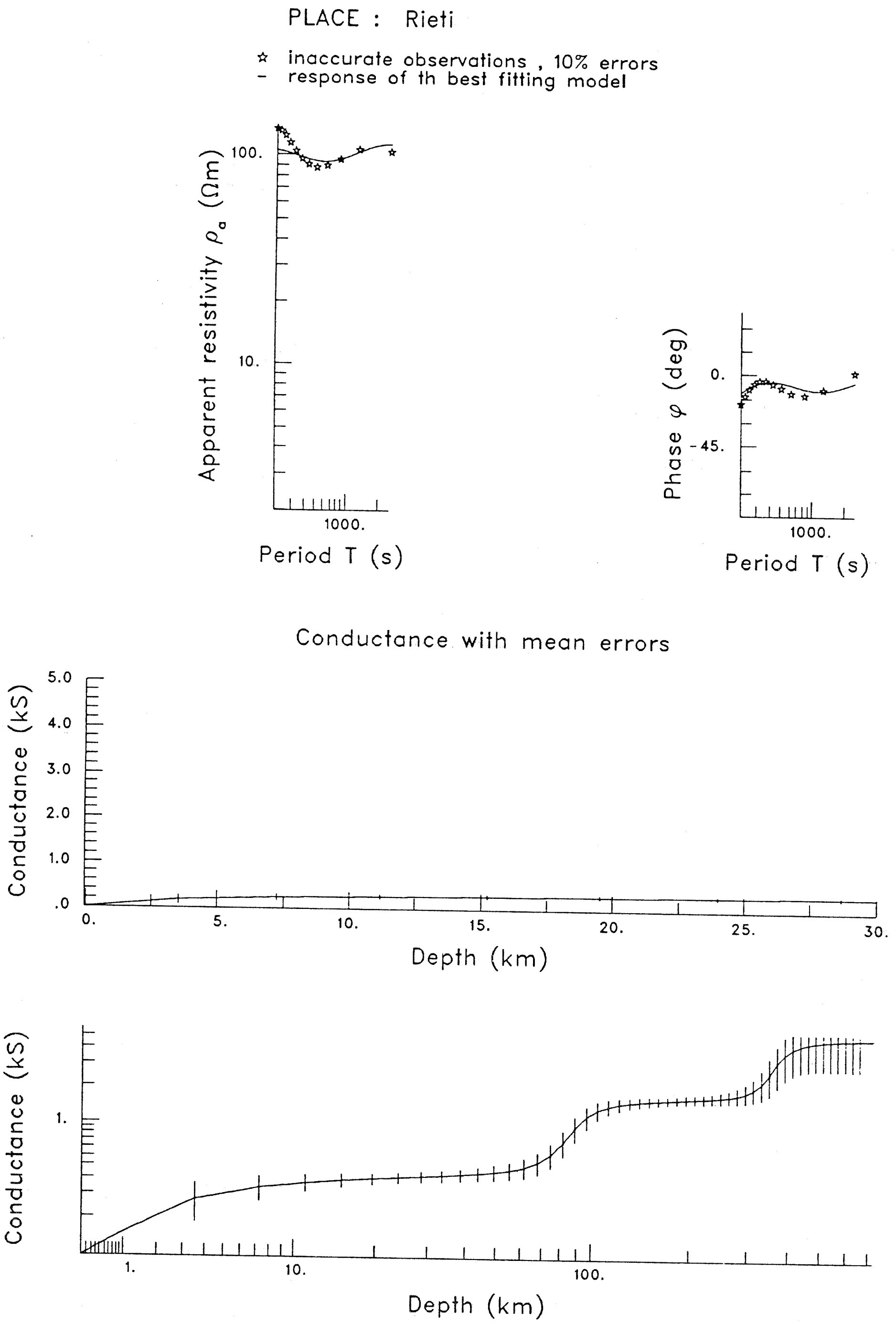

Fig. 9. Conductivity model for the station at Rieti.

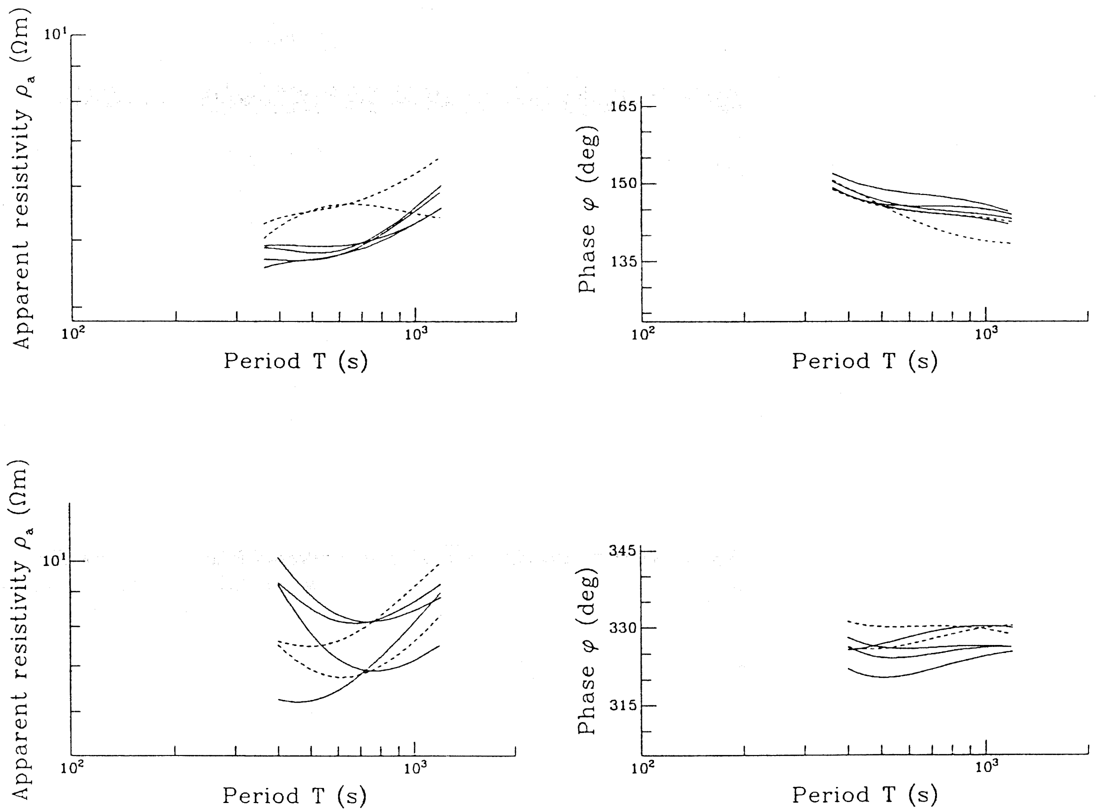

Fig. 10. Representation of ρ_a and φ for the station at Collemeluccio for Z_{xy} and Z_{yx} respectively.

ations in the rock at depth. Investigations of this type have been conducted all over the world in areas characterized by high seismic activity, *e.g.* see Sadowsky *et al.* (1972), Honkura *et al.* (1976).

Figure 11 displays the pattern of the Z_{ij} elements in function of angle θ and period T. It appears evident that the ratio G_2/G_3 is different from zero in every frequency interval considered. Thus it appears that the Collemeluccio area is of a three-dimensional character. Although some doubt still remains as to the validity of this interpretation, due to the consistent variance of θ by the elements of the impedance tensor.

An attempt to interpret the conductivity structure of the area as done for S. Vittoria and Rieti, is shown in fig. 12. The time variations of the apparent resistivity ρ_{xy} and ρ_{yx}, were compared to the seismic activity, quantified by the seismic energy produced each month, during the period of January 1992 to February 1993 according to Basili *et al.* (1980), (see fig. 14).

7. Conclusions

The wide panorama of research into electromagnetic precursors of seismic events, a place is devoted to the study of parameters linked to measurements of a magnetotelluric type. Several experiments have provided encouraging results. It must be remembered that the technique that utilizes the electrotelluric fields to this end, must include a scheme of calculation containing an algorithm that can distinguish the «noise» of the electrode from the tectonic signal. Resistivity is one of the typical properties observed in the study of seismic precursors, since its variations in response to stress and deformation have been revealed in the laboratory. As well known magnetotellurics uses a passive system of measurement of the fluctuations in the electric and magnetic fields at an observation site; the analysis of the consequent data reveals the resistivity, via a complex impedance computation.

In this study after having discussed the inherent problems of magnetotelluric installations and their limits in resistivity analysis, an

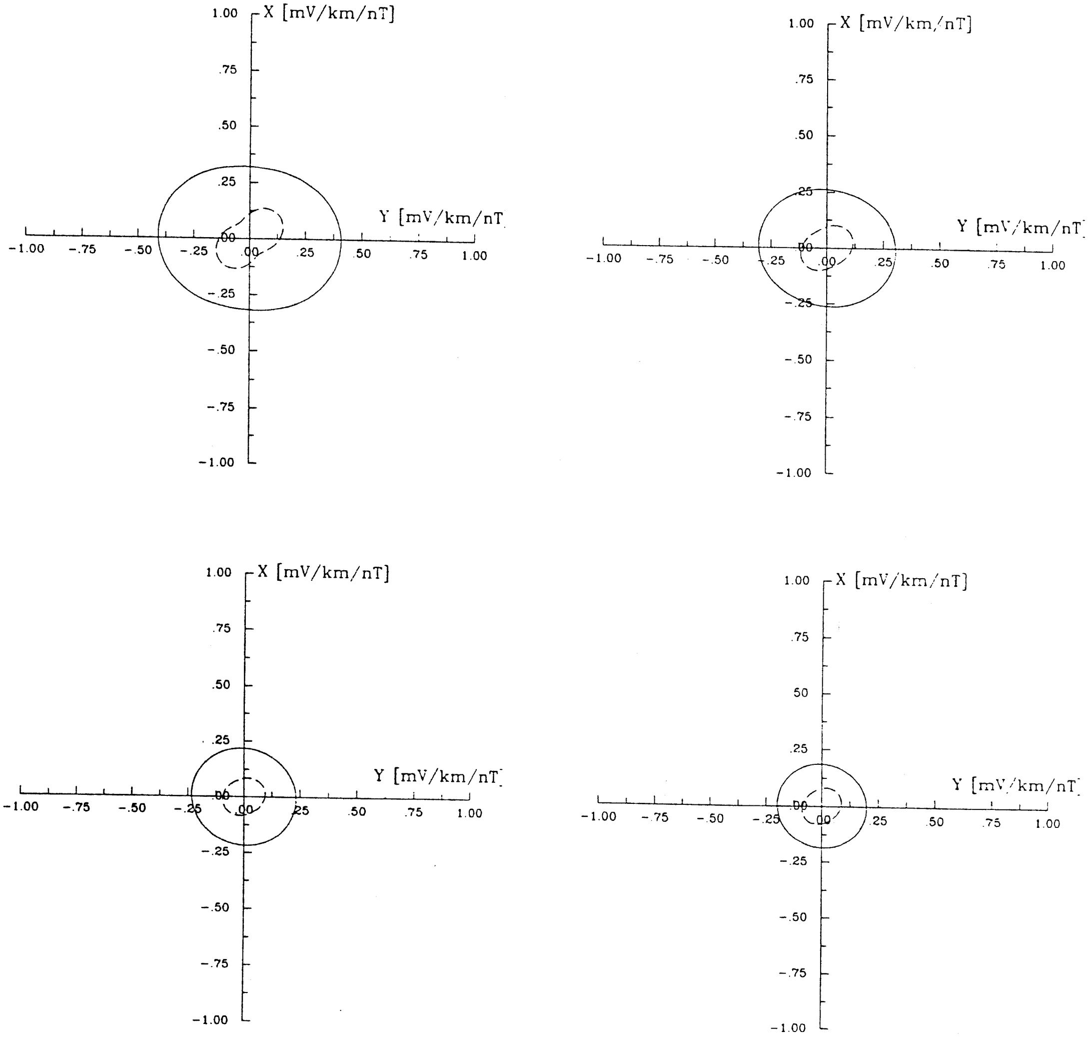

Fig. 11. Rotation of the impedance tensor for the station at Collemeluccio. The four panels refer respectively to T = 200 s, 400 s, 600 s and 800 s. Solid line represents Z_{xy} and dashed line represents Z_{xx}.

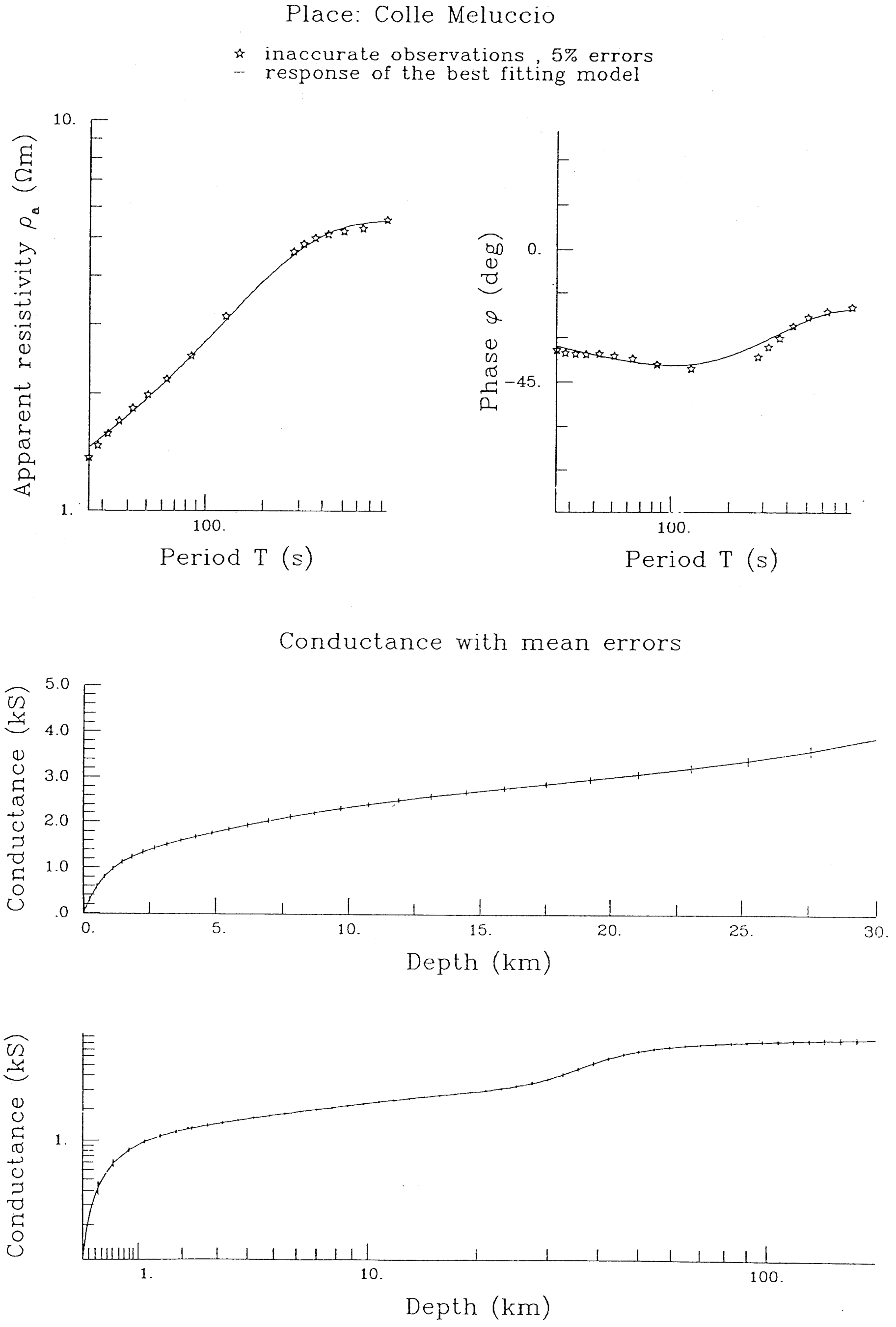

Fig. 12. Conductivity model for the station at Collemeluccio.

attempt was made to single out a site that would allow a long term investigation, so that variations in the magnetotelluric quantities could be observed over time.

The time interval considered for this study, was from January 1992 to February 1993, far too short a period to reveal any significant correlation between electromagnetic and tectonic phenomena. In addition to this limitation, there were no particularly intense earthquakes during this period: maximum magnitude of events taking place in the vicinity was 3.8 (fig.13). However, a useful part of this study was that of checking for possible variations in resistivity over time. An attempt was then made to place these temporal resistivity variations in relation to the total energy released in terms of seismicity. This check is shown in fig. 14, where the monthly averages of apparent resistivity ρ_{xy} and ρ_{yx} (dotted line) are related to the monthly seismic energy (continuous line), for the period January 1992 to February 1993.

The present belief, perhaps too pessimistic, is that the variation in terms of resistivity pre-

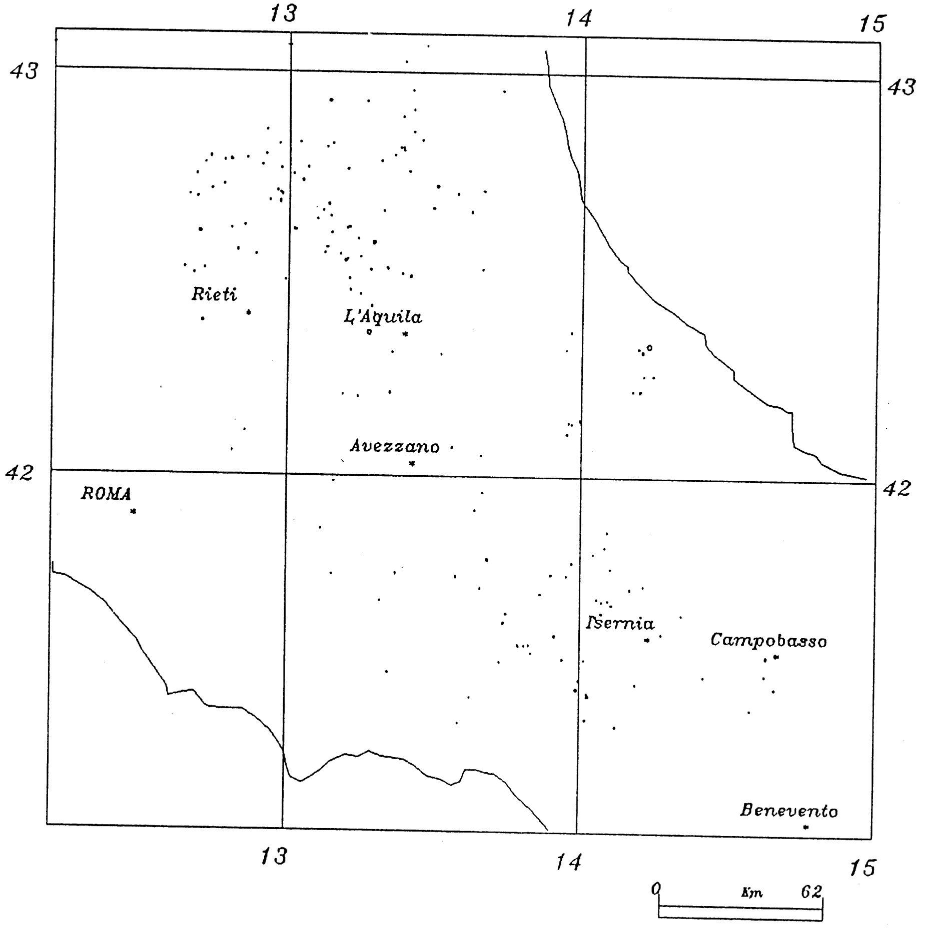

Fig. 13. Representation of localization of $M > 2.0$ seismic events occurred in the area during the period 1992-1993.

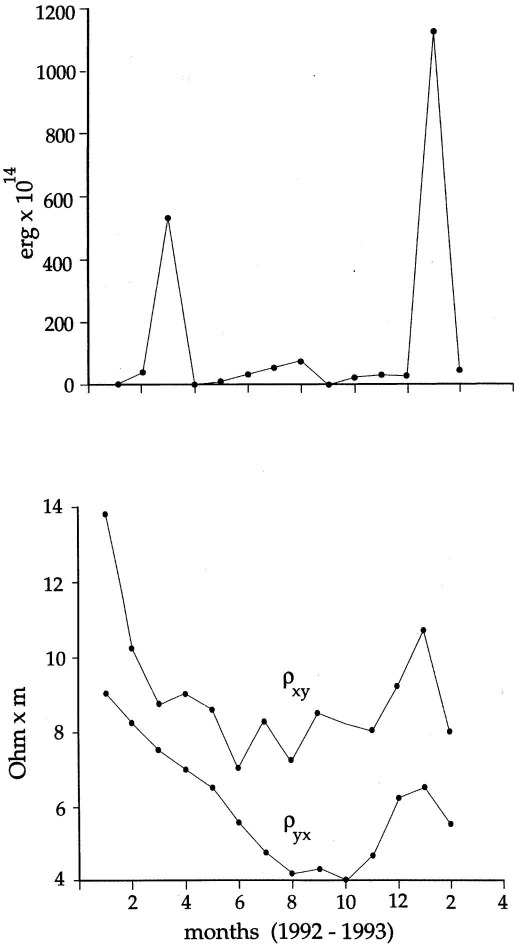

Fig. 14. Monthly total seismic energy (upper part) and monthly average ρ_{xy} and ρ_{yx} (lower part) for the study period.

ceeding a seismic event is minimal, just several percentage points (Park, 1991), and therefore the possibility of predicting these events using magnetotellurics is quite limited. The statistical approach taken in this phenomenologic investigation of a purely academic nature, and not intended as a proposal of possible earthquake prediction methods, has, however, revealed on the long term a possible correlation; further study using stronger events and more data, could be very interesting.

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