ANNALI DI GEOFISICA, VOL. 44, N. 2, April 2001

Properties of the geoelectric structure that promote the detection of electrotelluric anomalies: the case of Ioannina, Greece

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Abstract
The reliable detection and identification of electrotelluric anomalies that could be considered as precursory phenomena of earthquakes become fundamental aspects of earthquake prediction research. Special arrangements, in local and/or regional scale, of the geoelectric structure beneath the measuring point, may act as natural real-time «filters» on the ULF electrotelluric data improving considerably the signal to «magnetotelluric-noise» ratio of anomalies originated by probably non-magnetotelluric sources. Linear polarization, *i.e.* local channelling of the electric field on the surface is expected in cases where 3D-local inhomogeneities, producing strong shear distortion, are present in the vicinity of the monitoring site and/or when a 2D-regional geoelectrical setting exhibits high anisotropy. By assuming different generation mechanisms and modes of propagation for the electrotelluric anomalies that could be considered earthquake precursory phenomena, a rotationally originated residual electrotelluric field results, eliminating background magnetotelluric-noise and revealing «hidden» transient variations that could be associated to earthquakes. The suggested method is applicable in real-time data collection, thus simplifies and accelerates the tedious task of identification of suspicious signals. As an indicative example, the case of Ioannina (located in Northwestern Greece) is presented. The local polarization of the electrotelluric field varies dramatically even at neighboring points although the regional geoelectric strike direction does not change.

Key words *electrotelluric – Greece – magnetotelluric – Mohr circles – noise reduction – seismic precursor – tensor decomposition*

1. Introduction

In recent years, the research for earthquake precursory phenomena gained new dynamics by focusing on electric, magnetic and electromagnetic transient variations that precede seismic activities. Such anomalous effects have been repeatedly reported from field observations (Gokhberg *et al.*, 1982; Fraser-Smith *et al.*, 1990; Park, 1994; Di Bello *et al.*, 1996; Cuomo *et al.*, 1997; Varotsos and Lazaridou, 1991; Varotsos *et al.*, 1993, 1996a; Nomikos and Vallianatos, 1996, 1997; Vallianatos and Nomikos, 1998) and measurements in laboratory experiments. Furthermore, a number of theoretical models in the literature have been suggested for the description and explanation of the generation mechanisms and propagation modes of seismic forerunners (Varotsos and Alexopoulos, 1986; Dobrovolsky *et al.*, 1989; Enomoto and Hashi-

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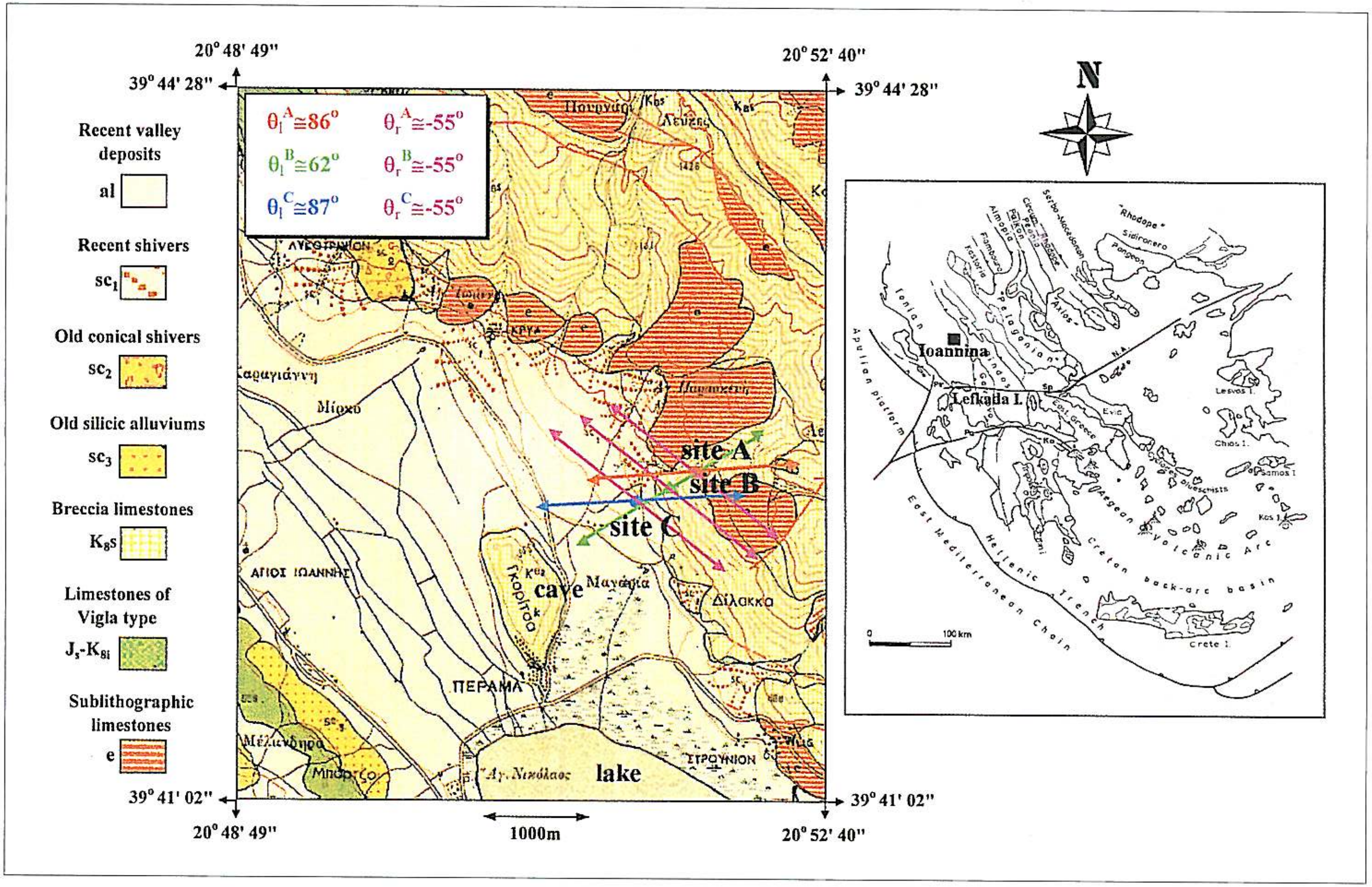

Fig. 1. Geological map of Ioannina region where the measuring sites A, B and C are located. For each site, the local and regional strike-directions of the measured electrotelluric field are depicted. The respective angles (θ_l and θ_r), deviating clockwise from the NS-direction, resulted from the application of the impedance tensor decomposition methodology and the Mohr circles analysis to the MT-data from each site.

moto, 1990; Slifkin, 1993; Park *et al.*, 1993; Honkura and Kuwata, 1993; Varotsos *et al.*, 1996b; Teisseyre, 1997; Vallianatos, 1997; Molchanov and Hayakawa, 1994, 1998; Molchanov, 1999; Vallianatos and Tzanis, 1998, 1999).

In spite of the considerable improvement of the sensors and the measuring systems, the data quality is still a problem because usually the records are contaminated with natural and/or artificial noise-signals. In particular, major and continuously existing noises are the magnetotelluric (MT) disturbances that aggravate the electrotelluric records and hinder the reliable detection and identification of pre-seismic signals. The inductive component of the electrotelluric field can be efficiently reduced by applying the warm method of the residual electric field (Chouliaras and Rasmussen, 1988; Arvidsson and Kulhanek, 1993; Hadjioannou *et al.*, 1993; Vallianatos and Nomikos, 1994).

In the present work, it is shown that when near-surface local inhomogeneities, embedded in the Earth's regional geoelectric structure (in the vicinity of the monitoring site) and/or a 2D-regional geoelectric structure with high anisotropy, produce strong local channelling of the electric field measured on the surface, a «natural real-time filter» is operating. In such cases, a very simple, straightforward method is suggested that during real-time data collection reveals electrotelluric anomalies originated by probably non-magnetotelluric sources, *e.g.*, earthquake preparation physical mechanisms.

The presentation of the aforementioned issues proceeds through the study of the indicative, characteristic case of Ioannina located in Epirus, Northwestern Greece.

The Ioannina region lies within the Ionian zone at the edge of Pindus thrust, where the surround area consists of highly karstified limestones. Furthermore, it lies between the subduction zone located south of the Ionian Islands and the continent collision zone in Apulia and Northern Greece. Microseismicity studies in Northwestern Greece (Kiratzi *et al.*, 1987; Hatzfeld *et al.*, 1995) revealed complicated patterns for the seismicity and the focal mechanisms but no prevailing deformation model was determined.

The geological setting of Ioannina comprises a high mountain trending NW-SE and consisting primarily of Paleocene to Eocene age limestones and an adjacent basin (SW-side) with alluvium and lake sediments. Many of the limestones are faulted and a few isolated outcrops occur within the basin, with more significant the extensive cave of Perama village (fig. 1). Also, small outcrops of Eocene to Oligocene age flysch occur along the alluvial-limestone contrast.

MT-measurements were carried out at three neighboring sites hereafter cited A, B and C respectively (fig. 1). Preliminary, but important information is extracted from the electric field polarization diagrams (fig. 2), which indicate a local strong linear polarization (channelling) of the regionally induced electric field exists but at different directions from site to site.

2. Tensor decomposition and Mohr circles analysis of Ioannina MT-data

The aforementioned result suggests the presence of small-scale near-surface 3D-inhomogeneities embedded in a 2D-geoelectric structure, which also can be characterized from high anisotropy. In such cases, a decomposition of the measured impedance tensor may conduce to separate, if possible, local distortion parameters and regional 2D-parameters. Then, the measured impedance tensor is described by the equation

$$\ddot{Z}_m = \hat{R} g \ddot{T}\ddot{S}\ddot{A}\ddot{Z}_{2D}\hat{R}' = \hat{R}\ddot{T}\ddot{S}\ddot{Z}'_{2D}\hat{R}' \qquad (2.1)$$

with

$$\ddot{C} = g\ddot{T}\ddot{S}\ddot{A} = g\begin{pmatrix} 1 & -t \\ t & 1 \end{pmatrix}\begin{pmatrix} 1 & e \\ e & 1 \end{pmatrix}\begin{pmatrix} 1+s & 0 \\ 0 & 1+s \end{pmatrix} \qquad (2.2)$$

and

$$\ddot{Z}'_{2D} = g\begin{pmatrix} 0 & (1+s)Z^E \\ -(1-s)Z^H & 0 \end{pmatrix} \qquad (2.3)$$

where $\hat{R}$ is the operator of clockwise rotation of the measuring coordinate system, in order to coincide with the principal axes of the 2D-structure, $\ddot{C}$ is the distortion tensor, g is the gain of

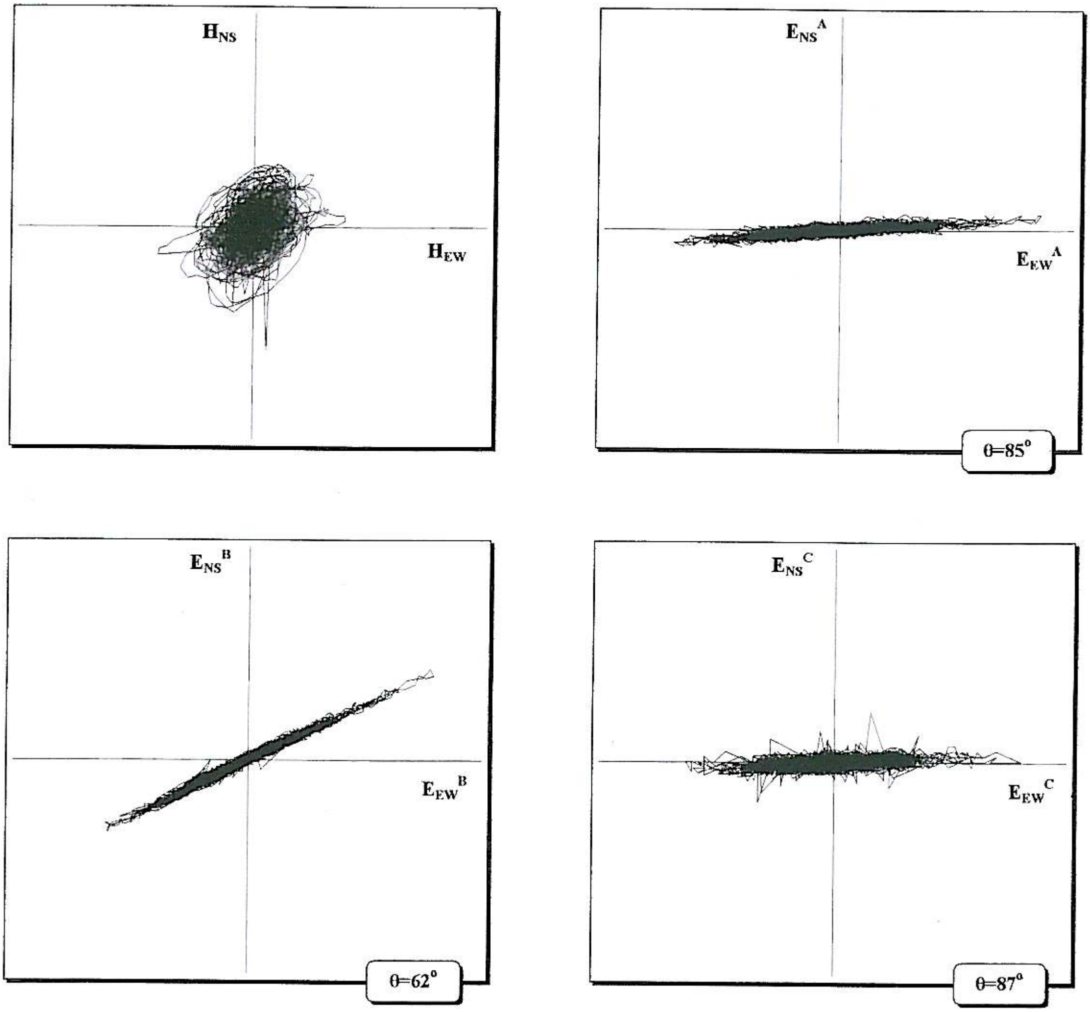

Fig. 2. Observed polarization diagrams of the electric field measured at the sites A, B and C of Ioannina region. For each site, the local polarization angle (deviating clockwise from NS-direction) of the electric field is depicted. The same diagram of the simultaneous magnetic field is given for reference. Electric and magnetic data were collected at all the sites using low pass active filters with cut-off frequency 1 Hz and were sampled every 1 s.

the measuring site, $\ddot{T}$ is the twist tensor, $\ddot{S}$ is the shear tensor, $\ddot{A}$ is the anisotropy tensor and $\ddot{Z}'_{2D}$ is the tensor that refers to an ideal 2D- regional structure at its principal coordinate system, but includes also $g\ddot{A}$, which does not destroy its ideal form (Bahr, 1988, 1991; Groom, 1988; Groom and Bailey, 1989; Groom *et al.*, 1993). The MT-tensor decomposition successfully determines the dimensionality of the dominant geoelectric structure and recovers the regional impedance responses except for the «static-shift» influence (in cases, of course, where the regional structure can be characterized approximately as 1D or 2D). Moreover, the principal directions of the regional induction are determined but with the ambiguity concern-

Table I. Skew angles (in degrees) for various periods (in seconds) determined from the MT-data of the sites A, B and C at Ioannina.

T	β_1^A	β_2^A	β_2-β_1^A	β_1^B	β_2^B	β_2-β_1^B	β_1^C	β_2^C	β_2-β_1^C
13	– 43.4	46.7	90.1	– 52.3	20.7	73.1	– 27.5	66.2	93.7
15	– 41.0	54.5	95.6	– 51.0	38.2	89.1	– 25.0	72.4	97.4
19	– 41.7	48.8	90.5	– 51.0	39.2	90.3	– 25.1	64.1	89.2
26	– 41.6	41.4	83.0	– 50.8	38.6	89.4	– 25.2	62.2	87.4
31	– 41.5	44.3	85.8	– 50.8	38.2	89.0	– 25.2	60.2	85.4
37	– 41.7	43.6	85.2	– 50.8	38.0	88.7	– 25.4	60.9	86.3
53	– 41.8	44.5	86.2	– 50.8	35.5	86.3	– 25.4	60.7	86.1
58	– 41.8	45.5	87.3	– 50.8	35.1	86.0	– 25.3	56.4	81.7
75	– 41.7	39.2	80.9	– 50.8	35.2	86.0	– 25.3	47.0	72.3
107	– 41.8	40.7	82.5	– 51.4	36.0	87.4	– 25.4	53.1	78.4
128	– 42.1	50.0	92.1	– 51.9	38.4	90.4	– 24.8	56.3	81.1
192	– 42.1	38.6	80.7	– 52.3	39.3	91.6	– 23.8	48.7	72.5

ing the strike-direction. The decomposition analyses, introduced by Bahr and Groom *et al.*, were implemented to the MT-data from the measuring sites A, B and C (Makris, 1997; Makris *et al.*, 1997). We summarize here the conclusions drawn: i) The model of the geoelectric structure beneath Ioannina that better fits the MT-data is 2D-(regional)/3D-(local). The same conclusion is obtained when independently analyzing the MT-data from sites A, B and C. The apparent resistivities, that correspond to the regional principal directions, seem to have a ratio of the order of 10, but note that the decomposition of the impedance tensor does not allow an accurate determination of the 2D-basement apparent resistivities, thus a higher order of anisotropy cannot be excluded. ii) The regional principal axes found to deviate from the measuring coordinate axes ($x \rightarrow$ NS, $y \rightarrow$ EW) 40° to 50° counterclockwise at all the sites A, B and C. iii) Strong shear distortion of the regionally induced electric field is a remarkable characteristic, common for the three sites. The relevant shear-parameter is close to unity ($|e| \rightarrow 1$). Furthermore, by applying the technique of the telluric vectors (Bahr, 1991) and calculating the skew angles β_1 and β_2 and their difference β_2-β_1 (Vallianatos, 1995; Makris, 1997; Makris *et al.*, 1997) we found that β_2-$\beta_1 \approx 90°$ in a wide range of periods and for all the measuring sites (see table I). The two latter results indicate strong local channelling of the regional inductive currents, so the measured electric field is linearly polarized.

We draw the attention of the reader to the fact that the directional angles (local strikes) of the local channeling, determined by the decomposition, *i.e.* $\vartheta_1^A \approx 81°$, $\vartheta_1^B \approx 62°$ and $\vartheta_1^C \approx 90°$, are in full agreement with the gradients of the trend lines of the relevant observed polarization diagrams (fig. 2) and are diversified from site to site, although these sites are very close to each other (see fig. 1). The latter implies that the area under study is strongly inhomogeneous.

Mohr circles is a convenient method in order to derive information from the measured impedance tensor concerning the dimensionality of the geoelectric structure and to determine the characteristic strike-directions at local and/or regional scale (Lilley *et al.*, 1989; Lilley, 1993a,b; Makris *et al.*, 1999). Figure 3a,b depicts, for different frequencies, the Mohr circles $Z'_{xx}(\vartheta)$ *versus* $Z'_{xy}(\vartheta)$ – solid line circle groups – constructed separately for the real and imaginary parts, for site B of Ioannina region (similar diagrams were constructed also for sites A and C). For the frequency range under consideration, all these circles pass approximately through the origin. The latter result implies that irrespec-

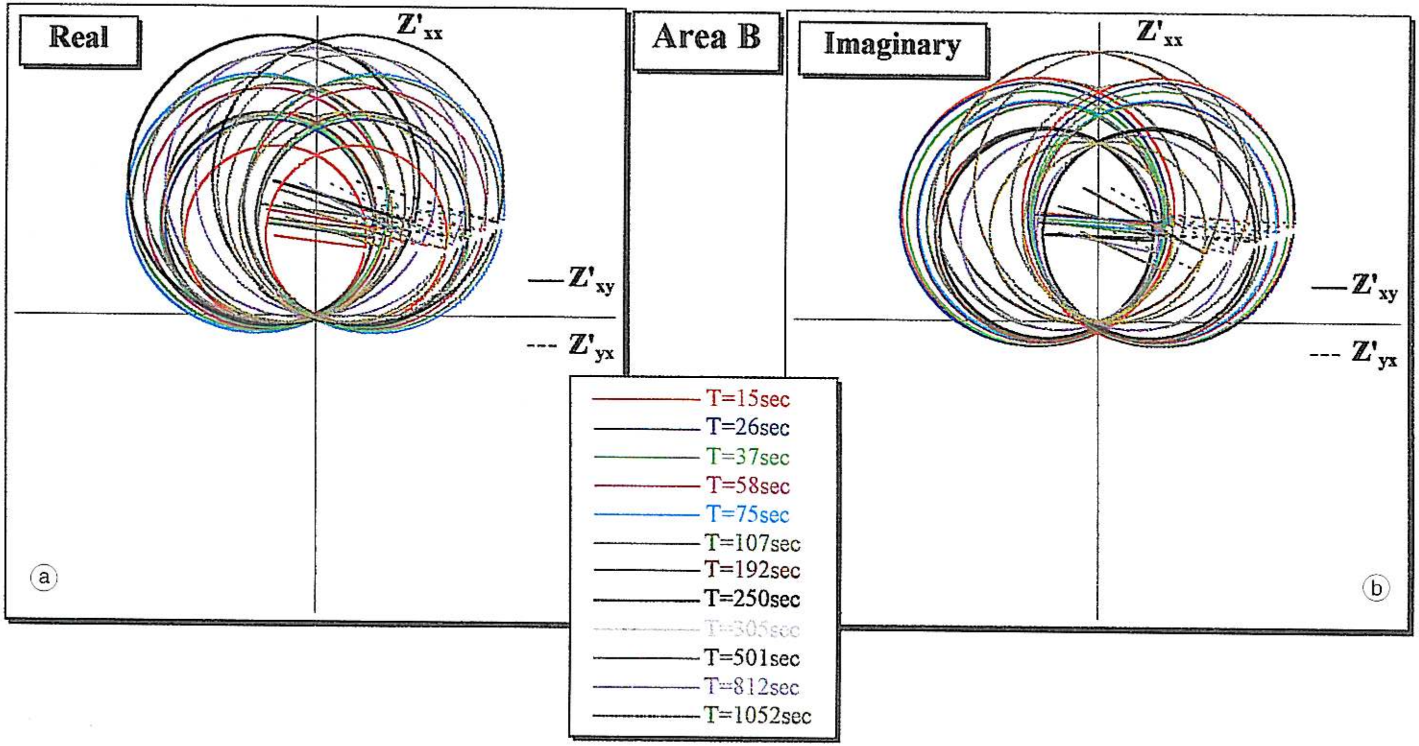

Fig. 3a,b. Mohr circles for various periods, by taking (a) the real and (b) the imaginary parts respectively of the Z'_{xx} and Z'_{xy} impedance tensor elements [left swarm of circles at diagrams (a) and (b)] and of the Z'_{xx} and Z'_{yx} impedance tensor elements [right swarm of circles at diagrams (a) and (b)], constructed using the MT-data from site B of Ioannina region (IOA). [*cf.* a line connects the center with the respective first point (which corresponds to a rotation angle equal to 0°) of each circle. Also the last two points, which correspond to the rotation angles 179° and 180° respectively, are intentionally omitted in order to depict the counterclockwise direction of circle construction].

tively of the polarization of the incident magnetic field, the electric field is linearly polarized in the direction of the $y'(\vartheta_1)$-axis. Consequently, the local electric field is strongly (linearly) polarized at sites A, B and C in the directions ~ N80°E, ~ N60°E and ~ N90°E respectively, which also coincide with the gradients of the trend lines of the relevant experimental polarization diagrams (fig. 2).

The «conjugate» form of the aforementioned Mohr circles was introduced by Makris (Makris, 1997). The relevant Mohr circles for site B are also depicted in fig. 3a,b (dashed-line circle groups). They exhibit the same peculiarity, *i.e.* they pass through the origin independently of the measuring site, the frequency and the consideration of either the real or the imaginary parts. This result can be considered as a «signature» of the regional geoelectric structure as it refers to the *H*-polarization mode of an ideal 2D-regional structure (*e.g.*, a vertical boundary), provided that the measuring site lies on the conductive medium but close to the resistivity contrast (Fischer *et al.*, 1992). The angle ϑ_r was found to be approximately 125°, at all the measuring sites and for the whole the frequency range under study, implying a regional direction striking ~ N55°W in accordance with one of the principal directions of the regional structure inferred by the decomposition.

3. Real-time MT-noise reduction

There is a continuous effort to find tools to increase the identification and discrimination of ELF, ULF and/or VLF anomalous signatures of the electrotelluric field that could be associated to earthquakes (Park, 1994; Tzanis and Gruszow, 1998; Tzanis *et al.*, 2000). Reliable recognition of such transient electrotelluric phenomena is the primary and most crucial step before any further interpretation. Electrotelluric background noise is dominated (especially at low frequencies) by magnetotelluric signals, which severely and almost continuously aggravate electric and magnetic field records even at measuring sites unaffected by any kind of artificial and/or man-made noises. MT-disturbances should very often interfere with and/or overlap existing pre-seismic electric field variations, thus hindering their recognition. A conventional method for MT-noise reduction from the electric field records usually applied is that of the residual field (Chouliaras and Rasmussen, 1988; Arvidsson and Kulhanek, 1993; Hadjioannou *et al.*, 1993; Vallianatos and Nomikos, 1994). However, in order to efficiently implement this analysis the following criteria are imposed: i) the simultaneous recordings of the horizontal components of the magnetic field must be also available; ii) the magnetic field data must be free from local anthropogenic or other type of noises, and iii) the method operates in the frequency domain. These criteria are difficult to fulfill continuously in time and in measuring conditions.

Based on specific arrangements of the regional and/or local geoelectric structure underneath the measuring sites, we suggest a straightforward method to diminish the magnetotelluric signals from the electrotelluric records (in one measuring direction) that allows the emersion of «hidden» electrotelluric anomalies. The method supposes that ELF and ULF transient electrical seismic precursors are characterized by different generation mechanisms, modes of propagation, nature and properties – though still poorly clarified and understood (Varotsos and Alexopoulos, 1986; Dobrovolsky *et al.*, 1989; Enomoto and Hashimoto, 1990; Bernard, 1992; Slifkin, 1993; Park *et al.*, 1993; Honkura and Kuwata, 1993; Varotsos *et al.*, 1996b; Teisseyre, 1997; Vallianatos, 1997; Molchanov and Hayakawa, 1994, 1998; Molchanov, 1999; Vallianatos and Tzanis, 1998, 1999) in comparison with the MT-disturbances. Therefore, it is expected that pre-seismic electrotelluric signals, observed at a measuring site on the surface, should generally have different directional properties from MT-signals (Uyeshima *et al.*, 1998; Kanda *et al.*, 2000).

Based on the results presented in the previous section of this paper it is concluded that if a measuring site is located close to a local near-surface inhomogeneous structure producing strong shear distortion or/and over a 2D-regional geoelectric structure with high conductivity contrast but close to the geoelectrical discontinuity, the observed horizontal electric field would be linearly polarized in a preferred direction imposed by the geoelectric structure whereas the magnetic field would fluctuate in all directions (fig. 2). Of course, this site is supposed to be sensitive to the collection of electric field variations of seismic origin (Varotsos *et al.*, 1993, 1996b).

At the selected (taking into account the aforementioned considerations) monitoring point the horizontal components of the electrotelluric field are measured by installing grounded electric dipoles (using non-polarized electrodes), having the same moderate dipole length (of the order of a few tens of meters), at two perpendicular directions (*e.g.*, NS and EW). As explained above, it is expected that the measured horizontal electric field will be linearly polarized in a specific direction (local strike) that could be determined either by applying the methods, presented in the previous section of this paper, to an MT-database of the site under consideration, or by constructing the relevant polarization diagrams of the electrotelluric field in the presence of a strong magnetotelluric activity (fig. 2).

By analytically rotating the measuring coordinate system, in order one of the measuring directions to be aligned with the direction that is normal to the local strike, we successfully diminish the MT-noise superimposed on to the electrotelluric field component at that direction (whereas it is maximized at the other direction, aligned with the local strike). For example, in fig. 4 inspect the electric field records from site B (in the presence of strong MT-signals) before and after the rotation of the measuring coordinate system ($x \rightarrow$ NS, $y \rightarrow$ EW). Another way is to intentionally install the horizontal dipole-array to coincide with the directions that correspond to the MT-noise reduction direction and to the MT-signal maximization (*i.e.* the direction that is perpendicular to the other). In such a case, we shall have a monitoring channel continuously insensitive to the electric field variations of magnetotelluric origin.

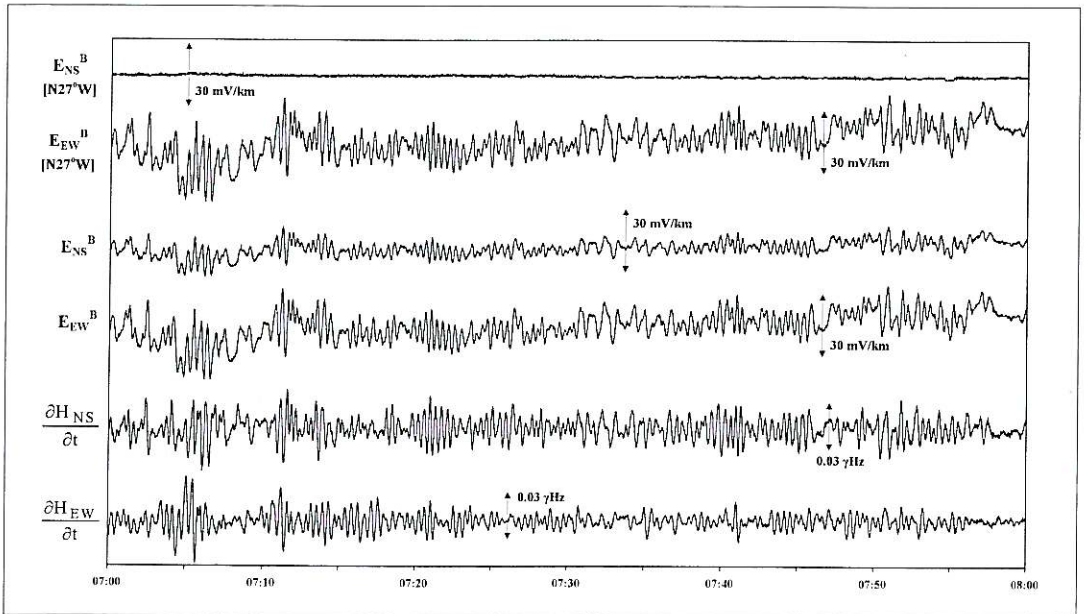

Fig. 4. One hour electric and magnetic data collected (low-pass filtered at 1 Hz and sampled every 1 s using a dipole array deployed EW and NS) at site B on September 18, 1994 during the presence of intense magnetotelluric disturbances. The upper two time-series represent the electric field components at a rotated measuring coordinate system (27° counterclockwise).

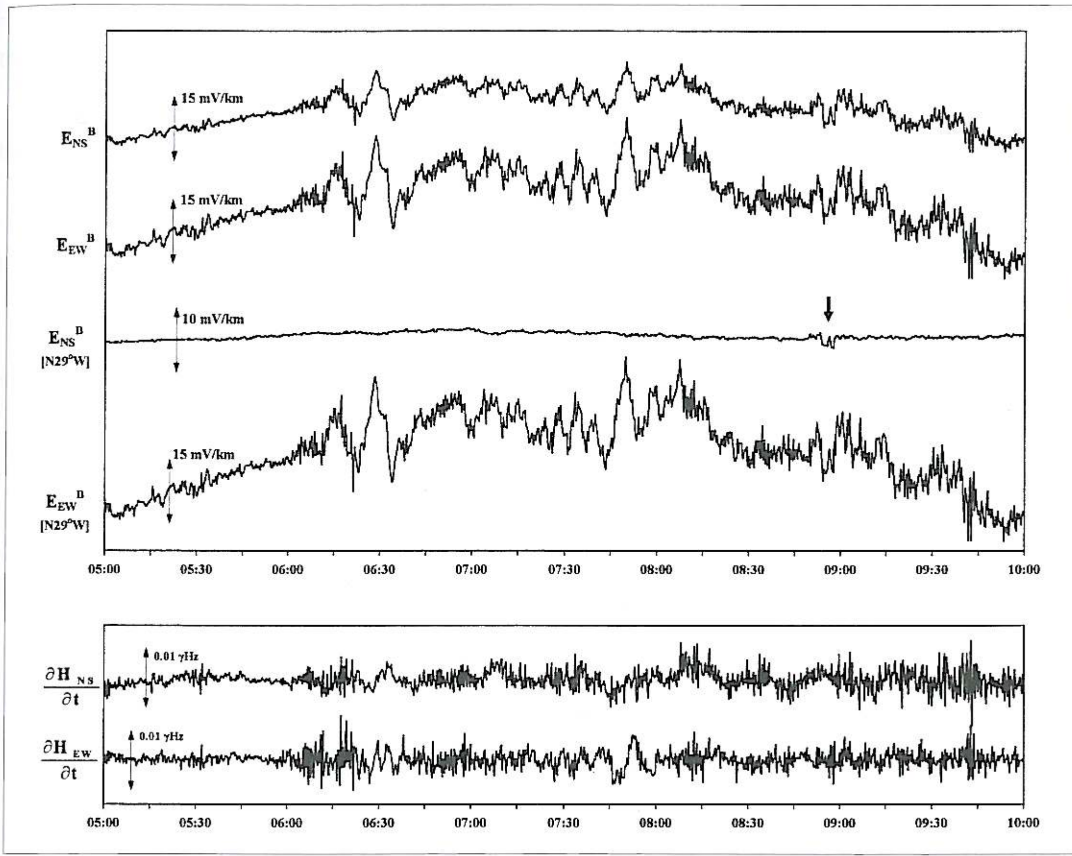

Fig. 5. Electric and magnetic field variations recorded on October 16, 1994 at site B of Ioannina. The measuring directions (NS and EW) at site B were analytically rotated N29°W, revealing a transient electrotelluric anomaly that was interpreted by Varotsos *et al.* (1996a, 1997) as a pre-seismic electrical activity and was associated to the seismic activity close to the Lefkada Island, Greece (November 29 and December 1, 1994).

Consequently, any overlapped («hidden») anomalous signature will be revealed at the residual electric field in the direction where the MT-noise is minimized provided that it has different directional properties.

Figure 5 depicts an implementation of the suggested method in order to emerge a «hidden» electrotelluric anomaly (of probably non-magnetotelluric origin) by applying the same technique to the electric field data of site B (recorded on October 16, 1994). The latter anomaly was interpreted by Varotsos *et al.* (1996a, 1997) as a pre-seismic electrical activity and was associated with the seismic activity close to the Lefkada Island, Greece (November 29 and December 1, 1994). It is far beyond the scope of this paper to argue on the identification criteria of electrotelluric earthquake precursors.

Furthermore, it is evident that the suggested procedure can be very easily incorporated into a real-time data collection system in order to continuously provide the residual electrotelluric field, thus enhancing the reliable recognition of suspicious electrotelluric anomalies and leading towards the development of automated detection real-time systems.

4. Conclusions

Linear polarization of the horizontal ULF electric field, observed on the Earth's surface, is expected in cases where 3D-local near-surface inhomogeneities, producing strong shear distortion, are present in the vicinity of the monitoring site and/or when high anisotropy characterizes a 2D-regional geoelectric structure. Such arrangements, in local and/or regional scale, of the underlying geoelectric structure, act as natural real-time «filters» on the electrotelluric data considerably improving the signal to MT-noise ratio. In such cases, magnetotelluric impedance tensor decomposition techniques as well as Mohr circles analysis successfully determine the local strike direction of the electrotelluric field and/or the principal axes of the regional structure.

Instead of applying to the electrotelluric records the warm and tedious method of the residual field in order to subtract the magnetotelluric noise, a straightforward method was suggested, that results in a rotationally originated residual electrotelluric field having the MT-noise eliminated at the direction which is perpendicular to the local strike, provided that the local horizontal electric field is linearly polarized. Consequently, any electrotelluric transient signal with directional properties different from those of the MT-signals can emerge from the background noise and thus be reliably recognized.

The method introduced in this work is applicable in real-time data collection, simplifying and accelerating the recognition of electrotelluric anomalies that could be associated with earthquakes and providing the possibility for the development of automatic real-time detection systems.

As an indicative example, the case of Ioannina (Northwestern Greece) was presented.

Acknowledgements

The author is indebted to and wishes to thank Dr. Vincenzo Lapenna and one anonymous referee for their constructive reviews and valuable comments to improve this paper.

REFERENCES

ARVIDSSON, R. and O. KULHANEK (1993): Enhancement of seismic electric signals using magnetotellurics, *Tectonophysics*, **224**, 131-139.

BAHR, K. (1988): Interpretation of the magnetotelluric impedance tensor: regional induction and local telluric distortion, *J. Geophysics*, **62**, 119-127.

BAHR, K. (1991): Geological noise in magnetotelluric data: a classification of distortion types, *Phys. Earth Planet. Inter.*, **66**, 24-38.

BERNARD, P. (1992): Plausibility of long distance electrotelluric precursors to earthquakes, *J. Geophys. Res.*, **97**, 17531-17546.

CHOULIARAS, G. and T.M. RASMUSSEN (1988): The application of the magnetotelluric impedance tensor to earthquake prediction in Greece, *Tectonophysics*, **152**, 119-135.

CUOMO, V., V. LAPENNA, M. MACCHIATO and C. SERIO (1997): Autoregressive models as a tool to discriminate chaos from randomness in geoelectrical time series: an application to earthquake prediction, *Ann. Geofis.*, **40** (2), 385-400.

DI BELLO, G., V. LAPENNA, M. MACCHIATO, C. SATRIANO, S. CARMINE and V. TRAMUTOLI (1996): Parametric time series analysis of geoelectrical signals: an application to earthquake forecasting in Southern Italy, *Ann. Geofis.*, **39** (1), 11-22.

DOBROVOLSKY, I.P., N.I. GERSHENZON and M.B. GOKHBERG (1989): Theory of electrokinetic effects occurring at the final stage in the preparation of a tectonic earthquake, *Phys. Earth Planet. Inter.*, **57**, 144-156.

ENOMOTO, Y. and H. HASHIMOTO (1990): Emission of charged particles from indentation fracture of rocks, *Nature*, **346**, 641.

FISHER, G., L. SZARKA, A. ADAM and J.T. WEAVER (1992): The magnetotelluric phase over 2D-structures, *Geophys. J. Int.*, **108**, 778-786.

FRASER-SMITH, A.C., P.R. BERNARDI, P.R., MCGILL, M.E. LADD, R.A. HELLIWELL and O.G. VILLARD (1990): Low-frequency magnetic field measurements near the epicenter of the 7.1 Loma Prieta earthquake, *Geophys. Res. Lett.*, **17**, 1465-1468.

GOKHBERG, M.B., V.A. MORGOUNOV, T. YOSHINO and I. TOMIZAWA (1982): Experimental measurements of electromagnetic emission possibly related to earthquakes in Japan, *J. Geophys. Res.*, **87**, 7824-7828.

GROOM, R.W. (1988): The effects of inhomogeneities on magnetotellurics, *Ph.D. Thesis*, University of Toronto, Canada.

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.*, **94**, 1913-1925.

GROOM, W.R., D.R. KURTZ, G.A. JONES and E.D. BOEMER (1993): A quantitative methodology to extract regional magnetotelluric impedances and determine the dimension of the conductivity structure, *Geophys. J. Int.*, **115**, 1095-1118.

HADJIOANNOU, D., F. VALLIANATOS, K. EFTAXIAS, V. HADJICONTIS and K. NOMICOS (1993): Subtraction of the telluric inductive component from VAN measurements, *Tectonophysics*, **224**, 113-124.

HATZFELD, D., I. KASSARAS, D. PANAGIOTOPOULOS, D. AMORESE, K. MAKROPOULOS, G. KARAKAISIS and O. COUTANT (1995): Microseismicity and strain pattern in Northwestern Greece, *Tectonics*, **14**, 773-785.

HONKURA, Y. and Y. KUWATA (1993): Estimation of electric fields in the conducting Earth's crust for oscillating electric current dipole sources and implications for anomalous electric fields associated with earthquakes, *Tectonophysics*, **224**, 257-264.

KANDA, W., M. UYESHIMA, J. MAKRIS, Y. ORIHARA, H. HASE, T. NAGAO and S. UYEDA (2000): Electric field polarization around Ioannina VAN-station, Greece, inferred from a resistivity mapping, *Phys. Earth Planet. Inter.*, **119**, 269-283.

KIRATZI, A.A., E.E. PAPADIMITRIOU and B.C. PAPAZACHOS (1987): A microearthquake survey in the Steno dam site in Northwestern Greece, *Ann. Geophys., Ser. B*, **5**, 161-166.

LILLEY, T. (1993a): Magnetotelluric analysis using Mohr circles, *Geophysics*, **58**, 1498-1506.

LILLEY, T. (1993b): Mohr circles in magnetotelluric interpretation (i) simple static shift (ii) Bahr's analysis, *J. Geomagn. Geoelectr.*, **45**, 833-839.

LILLEY, T., J.H. FILLOUX, I.J. FERGUSON, N.L. BINDOFF and P.J. MULHEARN (1989): The Tasman project of seafloor magnetotelluric exploration: experiment and observations, *Phys. Earth Planet. Int.*, **53**, 405-421.

MAKRIS, J. (1997): Electromagnetic study of the geoelectric structure of an area sensitive to the detection of pre-seismic electric signals, *Ph.D. Thesis*, Dept. of Physics, University of Athens, Greece.

MAKRIS, J., N. BOGRIS and K. EFTAXIAS (1997): Geoelectric structure of the VAN-Station at Ioannina sensitive to the detection of Seismic Electric Signals (SES), in *Proceedings of Athens Academy*, **72**, 303-421.

MAKRIS, J., N. BOGRIS, N. and K. EFTAXIAS (1999): A new approach in the determination of characteristic directions of the geoelectric structure using Mohr circles, *Earth Planets Space*, **51**, 1059-1065.

MOLCHANOV, O.V. (1999): Fracturing as underlying mechanism of seismo-electric signals, in *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes*, edited by M. HAYAKAWA (Terra Sci. Pub. Co., Tokyo), 349-356.

MOLCHANOV, O.V. and M. HAYAKAWA (1994): Generation of ULF seismogenic electromagnetic emission: a natural consequence of microfracturing process, in *Electromagnetic Phenomena Related to Earthquake Prediction*, edited by M. HAYAKAWA and Y. FUJINAWA (Terra Sci. Pub. Co., Tokyo), 537-563.

MOLCHANOV, O.V. and M. HAYAKAWA (1998): On the generation mechanism of ULF seismogenic electromagnetic emissions, *Phys. Earth Planet. Inter.*, **105**, 201-210.

NOMIKOS, K. and F. VALLIANATOS (1996): Electromagnetic variations associated with the seismicity of the frontal Hellenic Arc, *Geologica Carpathica, special issue in «New trends in Geomagnetism»*, **49** (1), 57-60.

NOMIKOS, K. and F. VALLIANATOS (1997): Transient electric variations associated with large intermediate-depth earthquakes in South Aegean, *Tectonophysics*, **269**, 171-177.

PARK, S.K. (1994): Precursors to earthquakes: seismo-electro-magnetic signals, *Extended Abstracts for the 12th Induction Workshop, Brest*, 179-190.

PARK, S., M. JOHNSTON, T. MADDEN, D. MORGAN and F. MORRISON (1993): Electromagnetic precursors to earthquakes in the VLF band: a review of observations and mechanisms, *Rev. Geophys.*, **31**, 117-132.

SLIFKIN, L. (1993): Seismic electric signals from displacement of charged dislocations, *Tectonophysics*, **224**, 149-152.

TEISSEYRE, R. (1997): Generation of electric field in an earthquake preparation zone, *Ann. Geofis.*, **40** (2), 297-304.

TZANIS, A. and S. GRUSZOW (1998): On the problem of identification and discrimination of electrical earthquake precursors, *Phys. Chem. Earth*, **23**, 939-944.

TZANIS, A., F. VALLIANATOS and S. GRUSZOW (2000): Identification and discrimination of transient electrical earthquake precursors: fact, fiction and some possibilities, *Phys. Earth Planet. Inter.*, **121**, 223-248.

UYESHIMA, M., W. KANDA, T. NAGAO and Y. KONO (1998): Directional properties of VAN's SES and ULF MT signals at Ioannina, Greece, *Phys. Earth Planet. Inter.*, **105** (3-4), 153-166.

VALLIANATOS, F. (1995): Galvanic distortion of the MT-impedance tensor: application to Ioannina VAN-station (Greece), *Acta Geophys. Pol.*, **43** (2), 115-128.

VALLIANATOS, F. (1997): A generation mechanism for low frequency electric seismic precursors, in *Proceedings of the International Conference on Marine Electromagnetics, (MARELEC97) Imperial College, Dept. of Electrical and Electronic Eng.*, ch. 4.3.

VALLIANATOS, F. and K. NOMIKOS (1994): Description of a real-time system appropriate for the subtraction of the inductive component from electrotelluric recordings. An application to earthquake prediction, in *Proceedings XXIV ESC Gen. Assembly, Athens, Greece, 19-24 September*, 1121-1127.

VALLIANATOS, F. and. K. NOMIKOS (1998): Seismogenic radio-emissions as precursors to earthquakes in Greece, *Physics Chem. Earth*, **23** (9-10), 953-959.

VALLIANATOS, F. and A. TZANIS (1988): Electric current generation associated with the deformation rate of a solid: pre-seismic and co-seismic signals. *Phys. Chem. Earth*, **23** (9-10), 933-938.

VALLIANATOS, F. and A. TZANIS (1999): A model for the generation of precursory electric and magnetic fields associated with the deformation rate of the earthquake focus, in *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes*, edited by M. HAYAKAWA (Terra Sci. Pub. Co., Tokyo), 287-305.

VAROTSOS, P. and K. ALEXOPOULOS (1986): Stimulated current emission in the earth: piezostimulated currents and related geophysical aspects, in *Thermodynamics of Point Defects and their Relation with Bulk Properties* (North-Holland, Amsterdam), 136-142; 403-406; 410-412; 417-420.

VAROTSOS, P. and M. LAZARIDOU (1991): Latest aspects of earthquake prediction in Greece based on seismic electric signals, *Tectonophysics*, **188**, 321-347.

VAROTSOS, P., K. ALEXOPOULOS and M. LAZARIDOU (1993): Latest aspects of earthquake prediction in Greece based on seismic electric signals, II, *Tectonophysics*, **224**, 1-37.

VAROTSOS, P., M. LAZARIDOU, K. EFTAXIAS, G. ANTONOPOULOS, J. MAKRIS and J. KOPANAS (1996a): Short term earthquake prediction in Greece by seismic electric signals, in *A Critical Review of VAN*, edited by Sir J. LIGHTHILL (World Scientific), 29-76.

VAROTSOS, P., N. SARLIS, M. LAZARIDOU and P. KAPIRIS (1996b): Transmission of seismic electric signals at long distances. A plausible explanation of the selectivity effect, in *Proceedings of Athens Academy*, **71**, 283-354.

VAROTSOS, P., V. HADJICONTIS, K. EFTAXIAS, M. LAZARIDOU, M. MAVROMATOU, J. MAKRIS, N. BOGRIS and A. ABDULLA (1997): Short term earthquake prediction measurements in Greece at sites sensitive to observation of Seismic Electric Signals. *[EV5V-CT94-0439], Directorate General for Science Research and Development (DG XII/D-2) of European Commission, Joint Research Centre on Climatology and Natural Hazards, Review Meeting on Seismic Risk in the European Union, 23-24/5/1996*, Brussels (published in a report).