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Discussion on telluric field and seismic activity in Central Greece

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Abstract
Two stations were installed in the Southeastern Thessaly basin (Central Greece), recording the geomagnetic and telluric fields from 1993 to 1996. The aim was to detect long-term abnormal changes of the telluric field, which were possibly related to imbedding earthquakes. Between January 1993 and October 1996, 213 and 185 (Neraida and Mavrolofos stations respectively) abnormal changes of the telluric field were observed in association with the seismic activity. The duration of these changes varied from several minutes to 24 days and the maximum amplitude was 3.8 mV/m. Data recording detected 625 and 917 seismic events for Neraida and Mavrolofos station respectively. The percentage of the earthquakes associated with the telluric anomalies is 27% and 16% respectively for each station. Both percentages are considered to be very low. Telluric activity was followed by a burst of seismic activity in areas spreading to different directions from the stations. A correlation of the characteristics of the telluric field with the earthquake magnitude was attempted, but no reliable relationship was obtained.

Key words *telluric – earthquake precursors – prediction*

1. Introduction

During recent decades, long-term period changes (days or weeks) of the telluric field have been observed and attributed to forecoming earthquakes (Fedotov *et al.*, 1970; Sobolev, 1975; Yamazaki, 1977; Raleigh *et al.*, 1977; Di Bello *et al.*, 1994). Short-term changes (several minutes), considered as pre-seismic signals, have also been reported (Varotsos and Alexopoulos, 1984a,b; Ralchovsky and Komarov, 1988, 1989; Tate and Daily, 1989). However, the morphology of these signals varies widely. The broad variety of signal morphologies could be related to different mechanisms, which produce the observed seismotelluric signals described by several authors (*i.e.* Meyer and Teisseyre, 1989; Dobrovolsky *et al.*, 1989; Scholz, 1990).

The data used in this study were collected from January 1993 to October 1996 at two stations which recorded the Earth's telluric and magnetic fields. The stations were installed in the southeastern margins of the Thessaly basin, in Central Greece. In Neraida station, the Geophysical Laboratory of the Aristotle's University of Thessaloniki recorded the three components of the magnetic field and the horizontal telluric field in the E-W and N-S magnetic directions (fig. 1). In Mavrolofos station, located 11 km away to the east, the Geophysical Laboratory of Orleans (CNRS, France) recorded both horizontal magnetic and telluric fields in the E-W and N-S magnetic directions (fig. 1).

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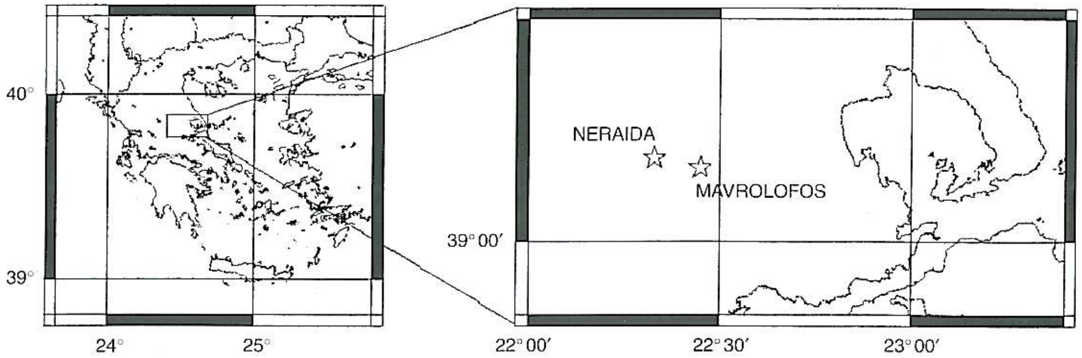

Fig. 1. Location of the MT stations.

2. Data collection

The southern part of Thessaly, and its surroundings, is one of the most seismically active zones in Greece (Papazachos and Papazachou, 1989). For these reasons, the two stations were installed along the major seismogenic fault (Anchialos) in an east-west direction (Papazachos *et al.*, 1993).

The instrumentation at Neraida station consists of a triaxial magnetometer (Bartington 0.1 nT resolution type), two orthogonal telluric lines and the recording PC unit. At the beginning of our study, non-polarised electrodes Cu-CuSO$_4$ were used to measure the horizontal telluric components. On May 1995 these electrodes were replaced by solid solution Pb-PbCl$_2$ electrodes (Petiau and Dupis, 1980). Both telluric lines are 50 m long and oriented N-S and E-W directions. The magnetic and telluric fields were sampled every 30 s and stored in a PC computer every three hours.

In Mavrolofos station Pb-PbCl$_2$ electrodes were used. In each orthogonal direction the spacing between probes was 100 m. This autonomous station, recharged by solar panels, picked up data every 12 s, and stored them on a 10 or 20 Mb flash card.

The horizontal components of the telluric field were recorded at both stations. The three geomagnetic components in Neraida station and the two horizontal ones in Mavrolofos station were also recorded. Most of the magnetic data were used from Mavrolofos station, which was more stable with time.

Figures 2 and 3 show the telluric data for the recording period.

Many gaps in the data collection were observed during the experiment (fig. 2 and 3). Nevertheless, changes of long-term duration and large amplitude can be noticed.

Therefore, we studied the telluric variations of different time scales in order to discriminate short-term signals ($\leq$ 3 h).

3. Data processing

The telluric field recorded as a potential difference between two electrodes buried at the earth's surface, consists in general in: a) the main telluric field; b) the magnetotelluric signal; c) the effect due to meteorological changes; d) the artificial or anthropogenic noise and e) the seismoelectric signal, if any. The aim of any processing scheme applied on the data is the removal of all the components except the last one, *i.e.* the seismoelectric signal.

The seismoelectric signal is considered as «noise», since, it is unpredictable (it is supposed to be precursor in itself), and its main characteristics (amplitude, duration, frequency) are unknown. That is because the source of these signals is in most cases unknown as well as the mode of their generation and propagation.

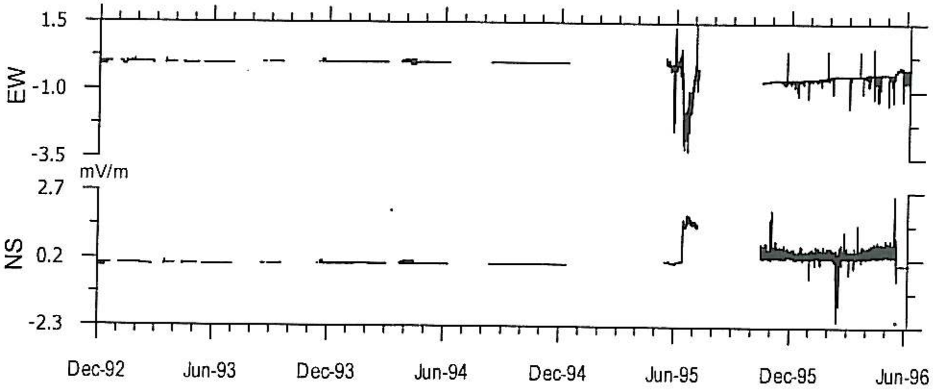

Fig. 2. Telluric records at Neraida station between February 1993 and June 1996.

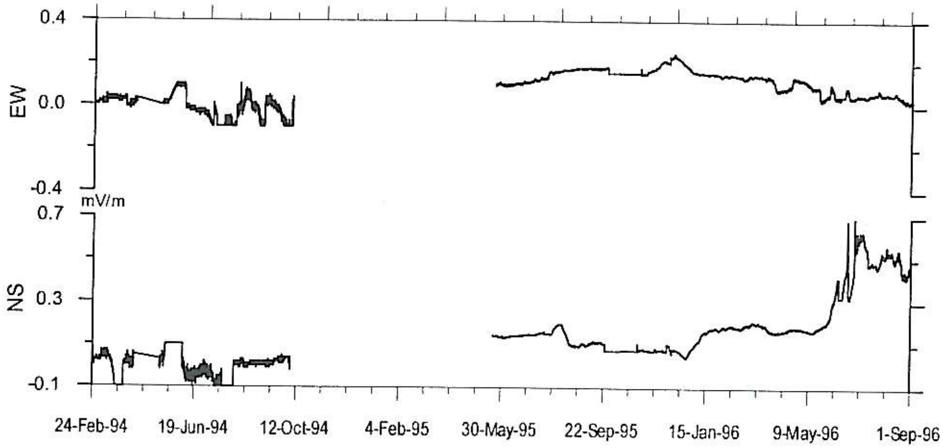

Fig. 3. Telluric records in Mavrolofos station for the period February 1994 - September 1996.

The magnetotelluric effect and the influence of various meteorological changes (*i.e.* humidity, temperature, and pressure) are phenomena that can be quantified and thus they are considered as «non random» noise.

The electrodes used in the stations are Cu-$CuSO_4$ (for the short-term) and solid solution Pb-$PbCl_2$. Temperatures influencing these electrodes are – 360 μV/°C and – 40 μV/°C (Petiau and Dupis, 1980) respectively. The monthly variation of the temperature recorded at the meteorological station in Farsala, 20 km away from the stations, can reach 38 °C. Consequently, the maximum change in the potential at each electrode could be 14 and 1.5 mV. Since the influence on both the electrodes of a dipole is supposed to be the same, the potential difference due to temperature must be very low since it is divided by a the factor of 50 in Neraida and 100 in Mavrolofos station which are the dipole separation in meters respectively. That is because the depth of the probes (30-40 cm) is not considered to be enough to ensure isolation from temperature changes.

Changes in the electrode potential due to atmospheric changes have been reported (Morat and Le Mouël, 1992) having the value of 10 mV for a pressure change of 10 mbars.

The first major problem comes from the effect of the rainfalls. This effect is practically unpredictable since it depends on many parameters. The main problem is the type of probes, the way to bury them, and the nature of the ground. The Pb-PbCl$_2$ probes look very stable with respect to the rain effect (Ruzie, 1995). In the area rainfall is recorded at the meteorological station of Almyros (10 km east from Mavrolofos station). A comparison of the telluric signal with rainfalls was done in order to identify simultaneous changes showing the probable meteorological origin of some telluric changes (fig. 4).

The second major problem to solve is the removal of the effect of magnetic changes. Therefore, a program for the estimation and removal of the magnetotelluric effect was built. The estimation of the impedance tensor can be done either in the time domain (Yee *et al.*, 1988) or in the frequency domain (Sims *et al.*, 1971; Grillot, 1975; Eggers, 1982; Travassos and Beamish, 1988; Pedersen and Rasmussen, 1989; Larsen *et al.*, 1996). Our program is based on the procedure proposed by Chouliaras and Rasmussen (1988). The program was tested on synthetic data where the telluric components were calculated from real magnetic data and the use of known elements of the impedance tensor. The same procedure was followed once again but a sudden change had been added on the NS component. The sudden change represents a transient signal superimposed on the records. The results of these tests are shown in fig. 4.

In fig. 5a,b the input data (at the bottom of the figures) were calculated from original magnetic components and elements of the impedance tensor having the following values:

$$Z_{xx} = Z_{yy} = 0.1, \quad Z_{xy} = Z_{yx} = 1.$$

In fig. 5a the residual telluric field is equal to zero as it was accepted since a pure magnetotelluric signal was considered. In the upper part of the figure, the computed values of the impedance tensor correspond to the correct values, showing the proper function of the program. Figure 5b shows that the elements Z_{xx} and Z_{xy} of the impedance tensor were not correctly estimated. The «signal» added to the NS component of the telluric field cannot be clearly identified in the residual field (fig. 5b). The artificial signal affects the estimation of the impedance tensor for all frequencies. In case of a single squared pulse signal, it can be exactly recovered in the residual field. Different types of signals in both components have been studied and the result was the same, that is, the wrong calculation of the impedance tensor and noisy residual telluric field.

The correct estimation of the elements of the impedance tensor of the telluric signal implies a pure magnetotelluric origin. Therefore, any noise component in the original data must be removed before any processing of the data. That makes the whole procedure (removal of MT signal) meaningless because the interest is in the «noise». The eventual seismoelectric signal is superimposed on that «noise» and the problem becomes like a vicious circle. So, the inferred conclusion is that no attempt for the removal of the magnetotelluric signal should be made. The most effective way to disclose an MT change seems to be to compare the telluric and the magnetic components simultaneously.

Filtering in certain frequencies could be applied in order to avoid characterization of magnetotelluric (MT) changes as seismoelectric signals. A main problem coming from the magnetotelluric signal is that it varies in a significant range of frequencies. In order to study the behavior of the magnetic and telluric field in long-term recordings, the continuous data set from Mavrolofos station has been used. This data set covers the time period from May to September

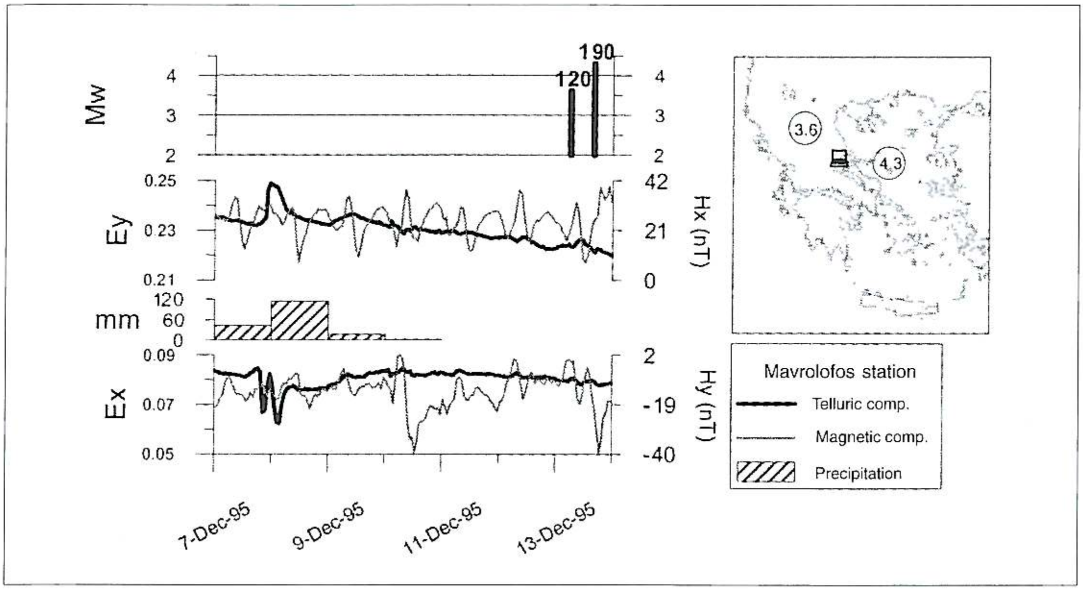

Fig. 4. Relation between changes on the telluric field and rainfall. On the upper side of the figure the seismicity is shown. At the right side the map of Greece showing the location of the epicenters and the station is shown.

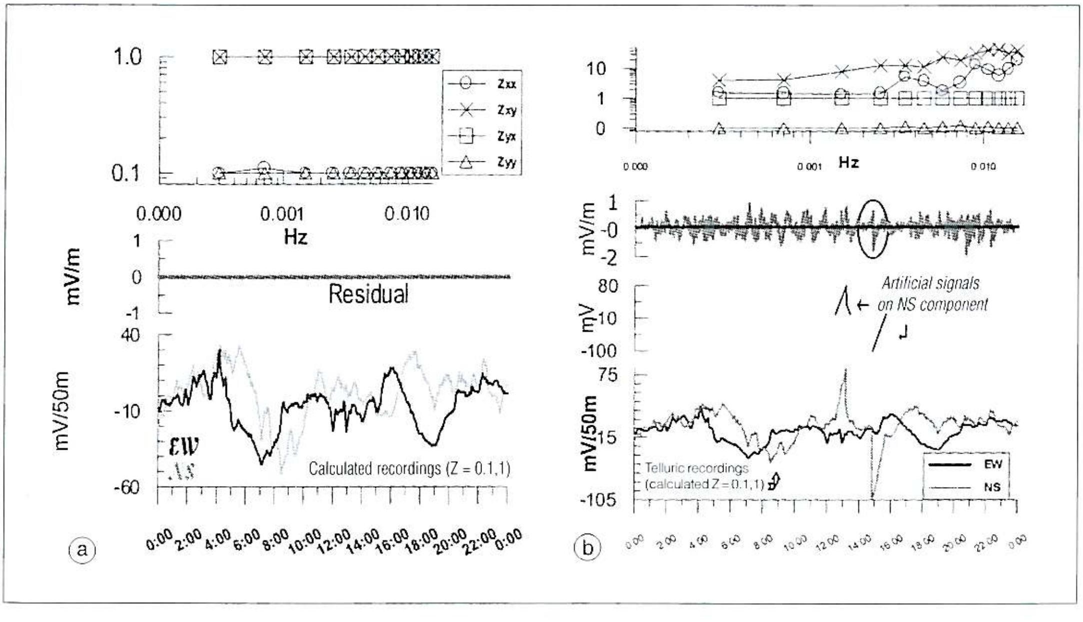

Fig. 5a,b. Removal of the MT signal from the telluric recordings.

1995. The recordings of the components of the horizontal magnetic and telluric fields are shown in the fig. 6.

It can be seen from fig. 6 that magnetotelluric (MT) amplitude spectrum peaks clearly in frequencies of 24, 12, 10, 8 and 6.7 h. This means that even a change of seismoelectric origin of the telluric field that peaks in the same frequencies could not be distinguished from an MT effect. Nevertheless, the long period recordings were low pass filtered using the frequency threshold of 1.11×10^{-5} Hz (25 h period). They were also high pass filtered that all frequencies above 6.94×10^{-5} Hz were kept for further study (4 h period).

The magnetic field has natural variations of internal and external origin, so, in case the magnetic field is studied itself, these variations should be taken into account. In that case these variations should be reduced considering the residual of the data with respect to a reference magnetic observatory. The present study focussed on the magnetotelluric effect, so, this reduction is not necessary since the procedure that has been followed is the simultaneous study of the telluric and magnetic data in order to observe any concomitant changes.

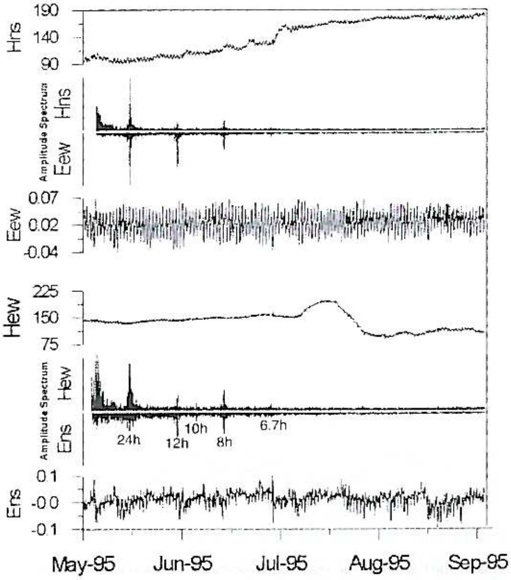

Fig. 6. Recordings of the horizontal components of the magnetic and telluric fields. FFT amplitude spectrum of magnetic and telluric components appears in the middle of each coupled pair (*e.g.*, Ens, Hew).

4. Earthquakes occurring during the monitoring interval

Greece and the surrounding area are well known as a highly seismic area. Many events were recorded during the monitoring period. From February 2, 1993 to June 19, 1996 a total number of 13 167 seismic events were recorded within a distance of less than 500 km from Neraida station. For Mavrolofos station the number of the events between February 14, 1994 and October 31, 1996 was 10 283. This information is drawn from the bulletin of the seismological station of the Geophysical Laboratory of the Aristotle University of Thessaloniki.

Some of these earthquakes had very small magnitude (less than 3.0) or were located at a relatively large distance from the MT stations (according to their magnitude). In both cases, the shocks cannot cause detectable signals. The earthquakes considered in the present study were chosen having the following properties:

A – events with $M_w \geq 3.5$ and $\Delta < 160$ km,

B – events with $M_w \geq 4.0$ and $\Delta < 330$ km,

C – events with $M_w \geq 4.7$ and $\Delta < 500$ km,

where M_w is the moment magnitude and Δ is the distance from Neraida.

These criteria are arbitrary and under examination.

For Neraida station 625 earthquakes were selected for the referred period and for Mavrolofos station 917 events were chosen accordingly. Figure 7a,b shows the location of the epicenters. Symbols of three sizes are used to denote the three magnitude zones (A, B, and C). It must be noted that recording was interrupted for some time periods because of technical problems. For these periods, the seismic events of the following months were considered.

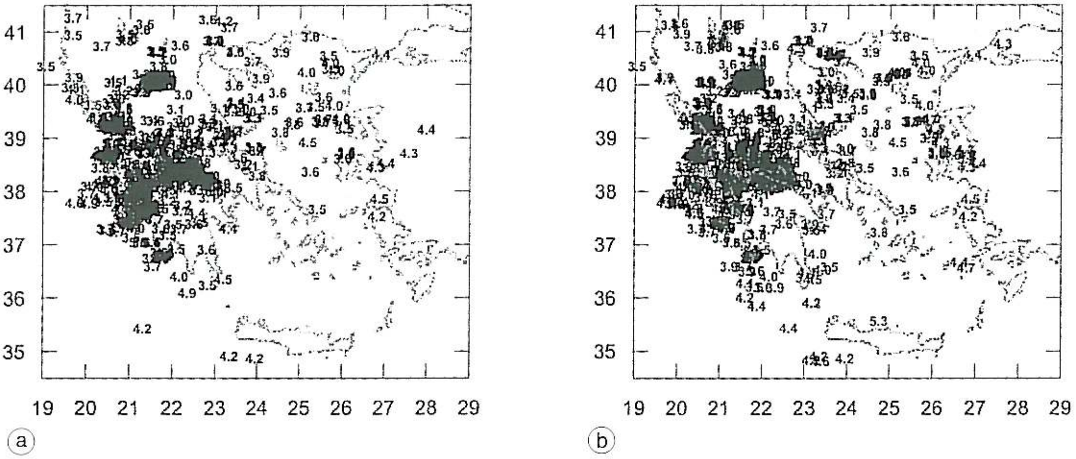

Fig. 7a,b. Location of the epicenters of the earthquakes correlated with the telluric activity: a) Neraida; b) Mavrolofos.

5. Correlation between abnormal changes and seismic activity

The abnormal changes were listed according to their main characteristics (amplitude, starting time, duration).

The final file where the correlation was made contained both the «signals» and the seismic events sorted by the time of occurrence beginning on January 1, 1993. The correlation was made following the rule that every telluric signal corresponds to one seismic event and in particular, the event that immediately follows the signal. This imposed assumption is necessary to continue the work since the high seismicity of Greece produces a cluster of events almost at any time.

Plots with telluric and seismic activity were produced in order to facilitate the correlation procedure. Hourly averages were estimated and the data plotted for different time scales, in order to observe different forms and periods of telluric signals with isolated seismic events or seismic swarms. Typical examples of monthly plots of the telluric horizontal components are shown in figs. 8 and 9.

Abnormal variations with various patterns can be observed on these figures. Short-term signals are superimposed over long-term changes. That makes any correlation difficult since during the evolution of a telluric change seismic activity can be burst in different areas.

The construction of the referred figures aims to have a visual expression of all the information available concerning the electrotelluric field, precipitation and seismicity. Figures similar to figs. 10 and 11 have been drawn for all the data.

After the construction and study of these figures, specific time periods of telluric activity (or special seismic activity) were isolated and studied further. This procedure resulted in the selection of 45 specific time periods for the Neraida station and 41 ones for Mavrolofos station. Examples of short-term recordings are shown in figs. 12 and 13.

The following comments result from the visual inspection of these plots.

– Abnormal changes vary widely in their form. Generally, they look like sharp changes with smooth restoration or like mild changes with sharp or smooth restoration.

– In some cases abnormal variations appear related to rainfall. An example is shown in fig. 13 (lower part) where an obvious anomaly on both telluric components starting at the end of December 7, 1995 is followed by rainfall having

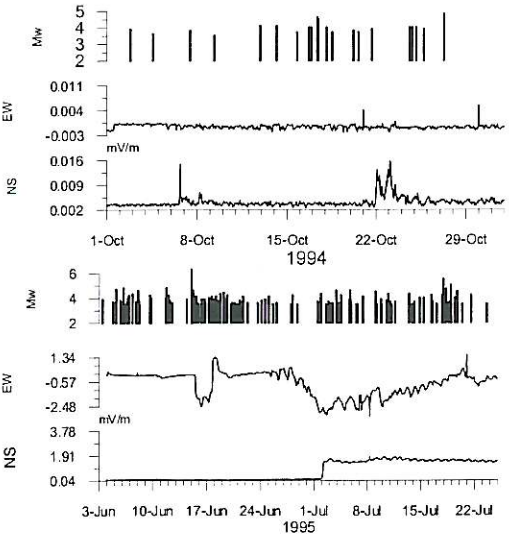

Fig. 8. Monthly variation of the telluric horizontal components (station Neraida). The seismic activity during the same period is represented by dark bars.

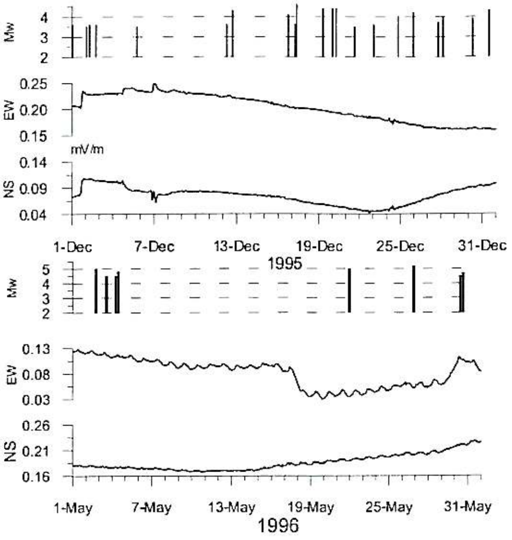

Fig. 9. Monthly variation of the telluric horizontal components (station Mavrolofos). The seismic activity during the same period is represented by dark bars.

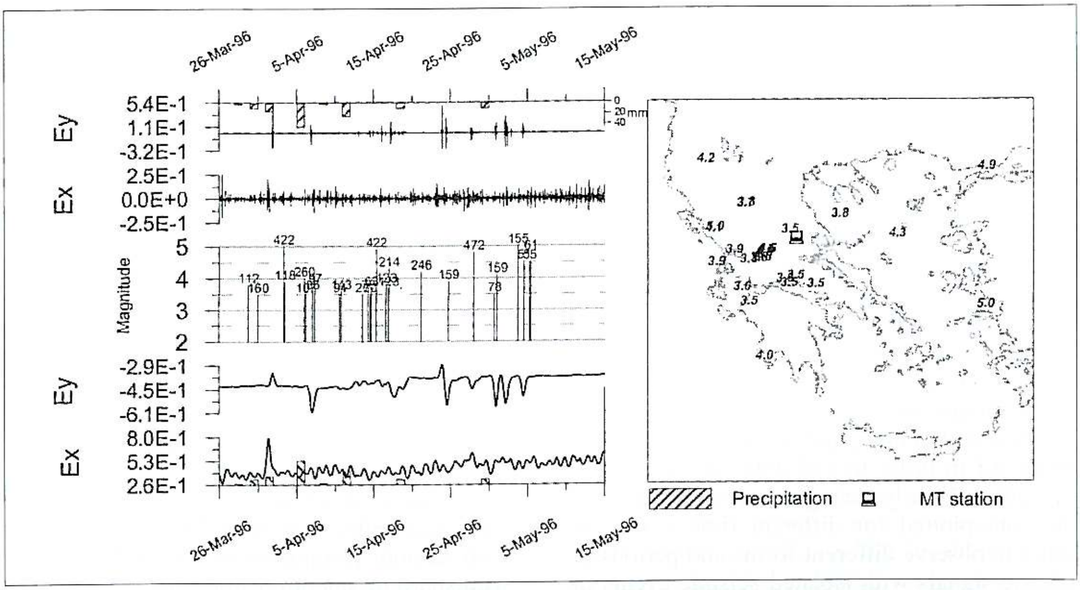

Fig. 10. Recordings during period of telluric activity (Neraida station). On the left upper part the high frequencies variations are shown ($T < 4$ h), in the middle part the earthquakes (the dark bar shows the magnitude), and on the lower part the low frequency variations are shown ($T > 25$ h). The map on the right shows the epicenters of the shocks which occurred during the same time period. The epicenters are annotated by a number corresponding to the M_w magnitude of the earthquake.

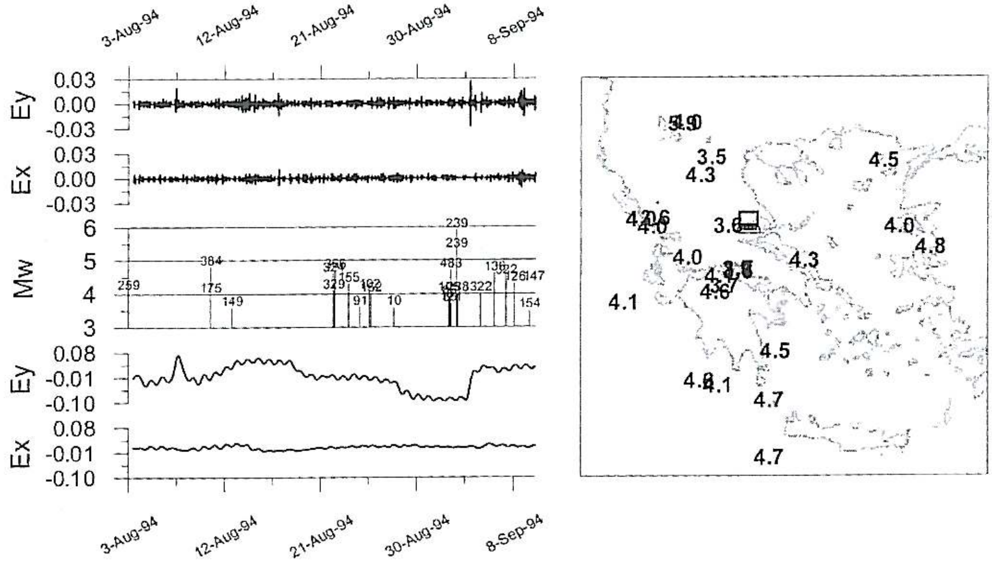

Fig. 11. Recordings during a period of telluric activity (Mavrolofos station). The annotations are the same as in fig. 10.

the same duration. There is no «one to one» correlation between rainfall and telluric abnormal variations. On the other hand, signals having sudden build up are not associated with rainfalls. That means that even if disturbances and rainfalls appear simultaneously, it is not certain that they are related.

– Seismicity is continuously present in a manner that is difficult to distinguish if telluric anomalies precede or follow seismic events.

The next step was the detection of solitary abnormal changes of the telluric field and the estimation of their characteristics (starting time, duration, and amplitude). About 213 abnormal changes were shaped for Neraida station and about 185 for the Mavrolofos station. The statistics of these changes are presented in figs. 14 and 15.

The percentage of the most common values of the amplitude and the duration of these changes is represented in table I.

Such isolated abnormal changes were correlated with seismic activity. The correlation was estimated after carrying out a selection of pairs of every abnormal variation with its next earthquake, *i.e.* by assuming a «one to one» correspondence except in the case of an earthquake swarm, in which case the major shock was considered. Abnormal variations that were not followed by earthquakes were denoted as «non correlated anomalies». The results of such correlation analysis are presented in tables II and III.

It is evident that the parameters which determine the telluric signal characteristics vary widely. However, the most important comment on the presented correlation is the very low percentage of seismic events, which are associated with the telluric activity. It is very encouraging that even if we accept the telluric anomalies as precursory phenomena, we must accept that the majority of the earthquakes are not associated with telluric precursors.

Since the criteria for the selection of the earthquakes were arbitrarily chosen, a second catalogue of earthquake candidates for correla-

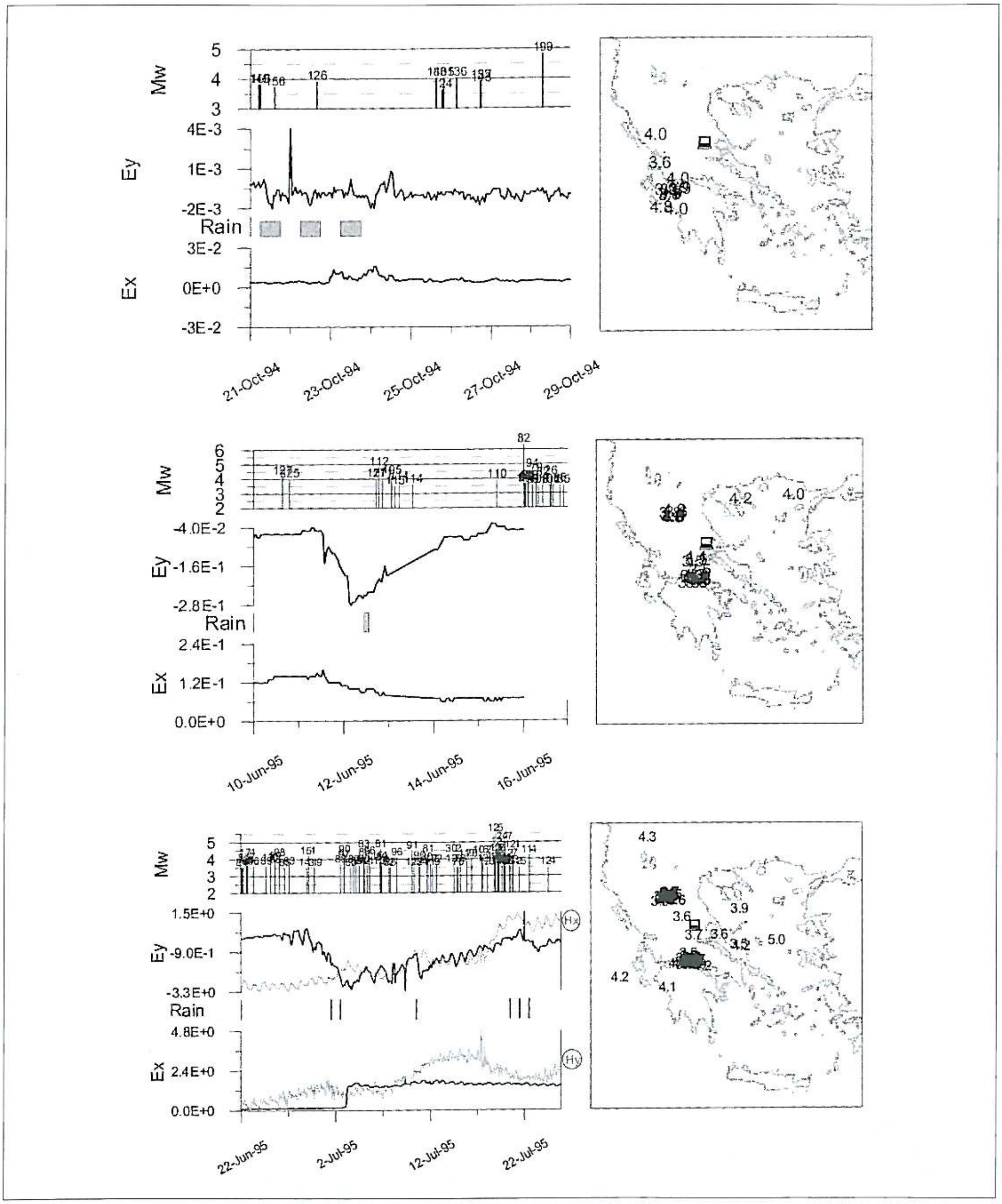

Fig. 12. Detailed plots of recordings during telluric activity (Neraida station). On the left hand side the seismicity (upper part), the telluric components (E_x and E_y) and the precipitation are shown. The epicenters of the earthquakes which occurred during the same time interval are shown on the map on the right hand side. They are annotated by numbers which also denote the magnitude of the shock.

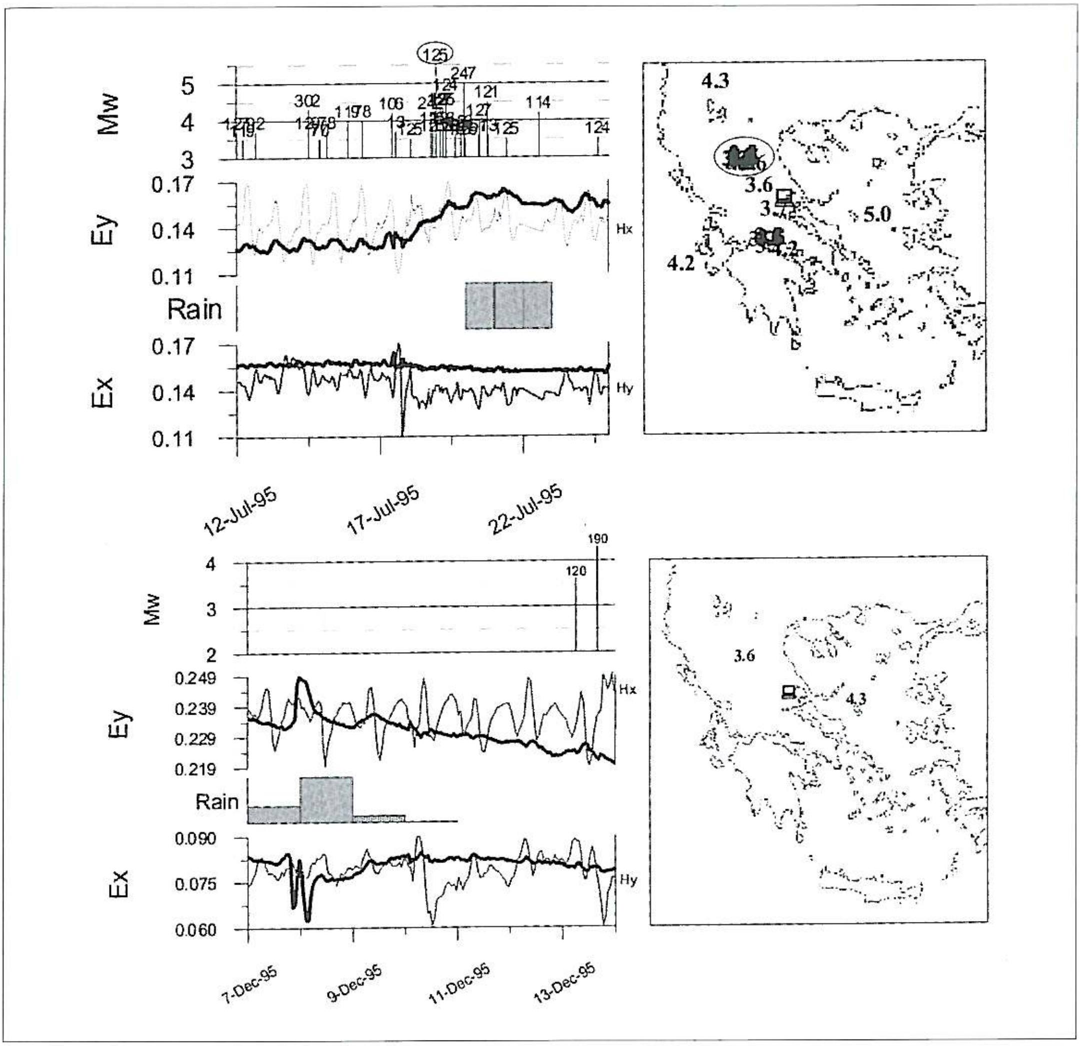

Fig. 13. Detailed plots of recordings during telluric activity (Mavrolofos station). On the left hand side the seismicity (upper part), the telluric components (E_x and E_y), the magnetic components (H_x and H_y) and the precipitation are shown. The epicenters of the earthquakes which occurred during the same time interval are shown on the map of the right hand side. They are annotated by numbers which also denote the magnitude of the shock.

tion has been composed. The selection of the earthquakes of the second catalogue was made after the equation

$$r = 10^{0.43M} \qquad \text{(Dobrovolsky } et\ al.\text{, 1979)}$$

where M is the magnitude of the forecoming earthquake and r is the distance at which the precursor is measured.

This catalogue is much shorter containing only 20 events. The problem arising from the

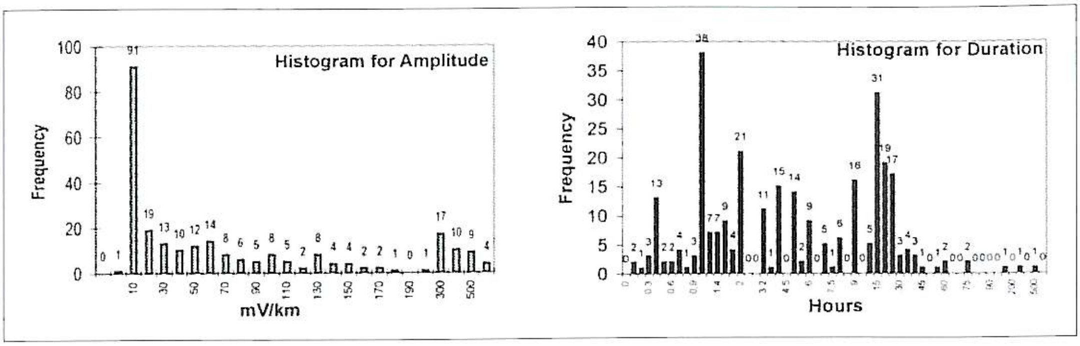

Fig. 14. Amplitude and duration distribution of the 213 telluric anomalies recorded to Neraida station.

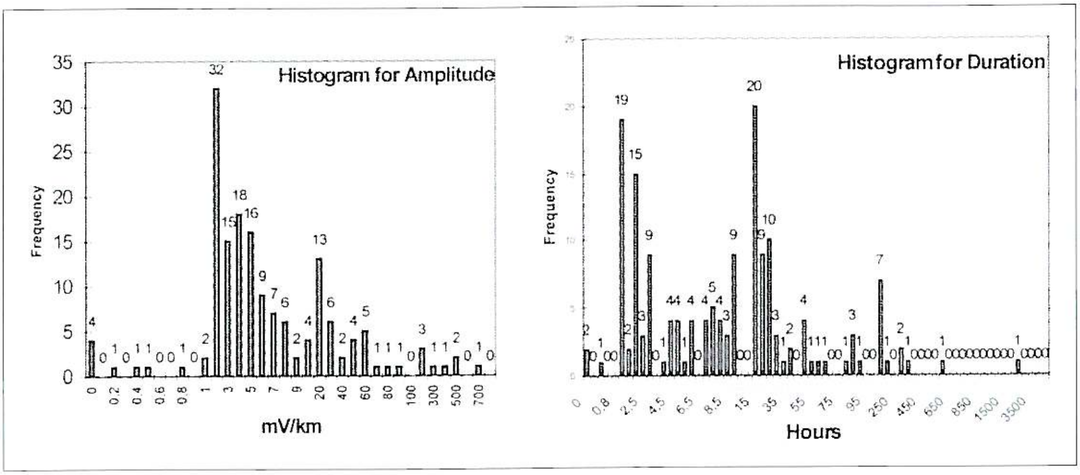

Fig. 15. Amplitude and duration distribution of the 185 telluric anomalies recorded to Mavrolofos station.

Table I. Percentage of the most common values of amplitude and duration of the abnormal changes in stations of Neraida and Mavrolofos.

Amplitude (mV/km)				Duration (h)			
Neraida		Mavrolofos		Neraida		Mavrolofos	
Range	%	Range	%	Range	%	Range	%
0-10	32	1-10	74	1-5	44	1-5	33
10-110	35	10-110	21	6-40	37	6-9	16
200-300	6	100-300	2.5			10-25	26

Table II. Results of the correlation between isolated anomalies and seismicity. The correlation is based on the assumption that the signal precedes only one shock.

Neraida station

Total telluric anomalies: 213

Total seismic events: 625

Correlated anomalies-seismic events: 166 (26.6% of earthquakes)

Non correlated seismic events: 459 (73.4%)

Non correlated anomalies: 47 (22.1%)

Correlation of seismicity and correlated telluric anomalies

Duration (h)		Amplitude (mV/km)		Lag time (h)		M_w		Distance from Neraida station (km)	
From	To	From	To	From	To	From	To	From	To
0.09	96	28	3800	0.0622	225	3.0	5.4	3	471

Table III. Results of the correlation between isolated anomalies and seismicity. The correlation is based on the assumption that the signal precedes only one shock.

Mavrolofos station

Total telluric anomalies: 185

Total seismic events: 917

Correlated anomalies-seismic events: 149 (16.2% of total number of earthquakes)

Non correlated seismic events: 769 (83.8%)

Non correlated anomalies: 36 (19.5%)

Correlation of seismicity and correlated telluric anomalies

Duration (h)		Amplitude (mV/km)		Lag time (h)		M_w		Distance from Neraida station (km)	
From	To	From	To	From	To	From	To	From	To
1	576	2	400	0.006	788	3.0	5.8	0	490

correlation by the use of this catalogue is that the number of the uncorrelated telluric anomalies is enormous compare to the number of earthquakes.

6. Conclusions and discussion

The main conclusions inferred from the study of the precursory behavior of the telluric changes and their correlation with the seismic activity as deduced from the data here analyzed, are the following:

– The recognition of telluric anomalies of a preseismic nature is very difficult and uncertain. Mathematical procedures for «cleaning» the telluric field by removing the magnetotelluric signal and noise from other sources except the probable precursory signal are very difficult. That is because the elements of the impedance tensor can be estimated only if the noise (including a probable precursory signal) could be eliminated from the data. This looks like an unresolved problem since the noise may come from various sources including the preseismic activity.

– The form of the telluric abnormal changes – even those not associated with earthquakes – varies widely. Following the concept that the form of an abnormal change is related to the seismic focus, different forms of abnormal changes have been correlated with earthquakes which originated at certain areas but no relation has been found.

– The seismicity in Greece is very high, scattered all over the area. That makes any correlation very difficult since seismic activity can be expressed simultaneously in different areas. Considering that a telluric anomaly might be precursory, co-seismic or even post-seismic, and also that it might have a long duration, it is practically impossible to make any positive correlation between an anomaly and an earthquake.

In many cases of strong seismic activity, telluric anomalous disturbances have been observed. These anomalies have been recorded several hours or even weeks before. Since these disturbances cannot be related to any other natural causes, they have been examined as the result of preseismic occurrences. Quantitative correlation of the characteristics of these anomalies does not provide clean and district relations, which could constitute the base of an applicable prediction method.

Natural systems possess a very large number of degrees of freedom, and they are not as repetitive as scientists would wish. This implies that a «one to one» correlation analysis could often be negative and/or misleading. Non-linearity can also play an important role among the involved physical quantities, so as to prove any standard linear correlation analysis.

Nevertheless, it is the authors' opinion that the changes in the telluric and magnetic fields must be continuously studied and correlated with the seismic activity, together with a multiparametric correlation, because the solution to the problem of the prediction is in some places lacking, and seismotelluric precursory signals may contribute much to this achievement.

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