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Energy and polarization of the telluric field in correlation with seismic activity in Greece

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Abstract
Many attempts have been made to disclose anomalous changes of the electromagnetic field in relation with tectonic earthquakes. We tentatively develop a new approach based on the energy and polarity of the electric field, and apply this method to the seismicity in Greece. The study of the parameters of the horizontal electric field is realized in a time interval of five years. The data set allows the study of long-term variations of the field. Further, we examined the possible relation of the geoelectric activity with long distance seismicity (up to 500 km). The energy of the electric signal was estimated and correlated with the logarithm of the seismic moment (M_0). The values of the seismic moment estimated for each earthquake were summed for daily intervals, and the logarithm of the sum was computed. The same process was applied to the energy of the geoelectric field. Then, a correlation was attempted between the energy of the geoelectric field and the seismic moment referring to daily intervals. In two cases, changes in the energy of the horizontal geoelectric field were observed before the burst of the seismic activity. The energy of the telluric field increased several months before the burst of seismic activity and recovered right after the occurrence of the mainshocks. The hodograms of the horizontal geoelectric field show polarization changes regardless of the magnetic field. This is possibly attributed to the process of generation of electric currents before major earthquakes. Due to high and continuous regional seismicity in Greece, it was impossible to attribute the response of the polarization to the activation of specific seismic areas. It seems that the long-term energy variations of the horizontal geoelectric field as well as the polarization are related to forthcoming seismic activity. Therefore, long-term energy variations of the horizontal geoelectric field as well as the polarization could be used in tandem with other possible precursors in order to contribute to earthquake prediction studies.

Key words *earthquake precursors – telluric field – electric field – polarization*

1. Introduction

A significant amount of research work on earthquake prediction has been carried out during the last century.

In recent decades, long period changes of the geoelectric field have been observed and attributed to forthcoming earthquakes (Fedotov *et al.*, 1970; Sobolev, 1975; Yamazaki, 1977; Raleigh *et al.*, 1977; Di Bello *et al.*, 1994). Short period changes considered as pre-seismic signals have also been reported (Varotsos and Alexopoulos, 1984a,b; Ralchovsky and Komarov, 1988, 1989; Tate and Daily, 1989; Nomikos *et al.*, 1997; Varotsos *et al.*, 1999). However, the form of these signals varies widely. Several techniques have been suggested on the identification and discrimination of the precursory signals (Tzanis and Gruszow, 1998; Vallianatos

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and Tzanis, 1998; Cuomo *et al.*, 1998; Pham *et al.*, 1999, among others). Discussion on the efficiency of various precursors tends to conclude that short-term prediction is still impossible (Geller, 1997).

The attempted correlations to date refer to abnormal changes of the telluric field in relation to the seismic activity (origin time and magnitude). A seismic burst can occur as a mainshock (seismic sequence) or as a swarm. It can even appear in different regions, and Greece is a typical example of such behavior. In such a case, the correlation could not be effective if we consider that geoelectric disturbances could be generated from a gradual release of energy. In this paper, we propose a new approach to the geoelectric disturbances possibly associated with seismic activity. Energy and polarization of the horizontal electric field (called hereafter *H*-field) have been compared with seismic moment of the earthquakes.

The polarization of the *H*-telluric field in relation to the epicenter and the focal mechanism of the earthquakes is also studied to find a possible relation between these parameters.

The telluric and magnetic fields were recorded from January 1993 until December 1997, at two stations installed in the southeastern margins of the Thessaly basin, in Central Greece (fig. 1). These magnetotelluric stations, Neraida (called here after NER) and Mavrolofos (MAV), were located along the active east-west «Anchialos» fault (Papazachos *et al.*, 1993). The Geophysical Laboratory of Aristotle University, Thessaloniki carried out the monitoring of the two perpendicular horizontal components of the electric field in the station of NER. The second station, MAV, 11 km to the east of the first one, installed by the Geophysical Laboratory of Orléans (LGO-CNRS, France), recorded both the horizontal components of the electric and magnetic fields.

2. Data collection

The southern part of Thessaly is one of the most seismically active regions in Greece (Papazachos and Papazachou, 1989). For this reason, the two magnetotelluric stations, NER and MAV, were installed along the active east-west «Anchialos» fault (Papazachos *et al.*, 1993).

The instrumentation at Neraida station consists of a triaxial magnetometer (Bartington type), the telluric lines and the recording units. At first, two pairs of non-polarized electrodes Cu-CuSO$_4$ had been used to measure the horizontal telluric components. On May 1995 these electrodes were replaced by solid solution Pb-PbCl$_2$ (Petiau and Dupis, 1980). Telluric lines were organized along the north-south and east-west directions. Each line was 50 m in long. Data were sampled every 30 s and the recordings were stored on a local PC.

At MAV station, the horizontal components of the magnetic field as well as those of the telluric field were recorded with a 20 s sampling on an autonomous data logger (20 Mb flash

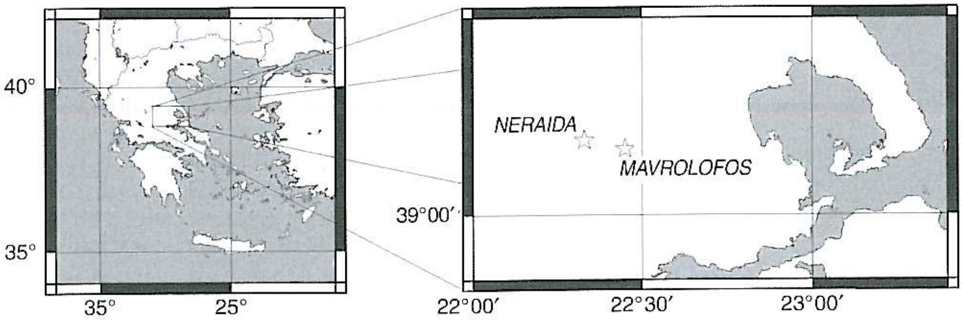


Fig. 1. Location of the MT stations.

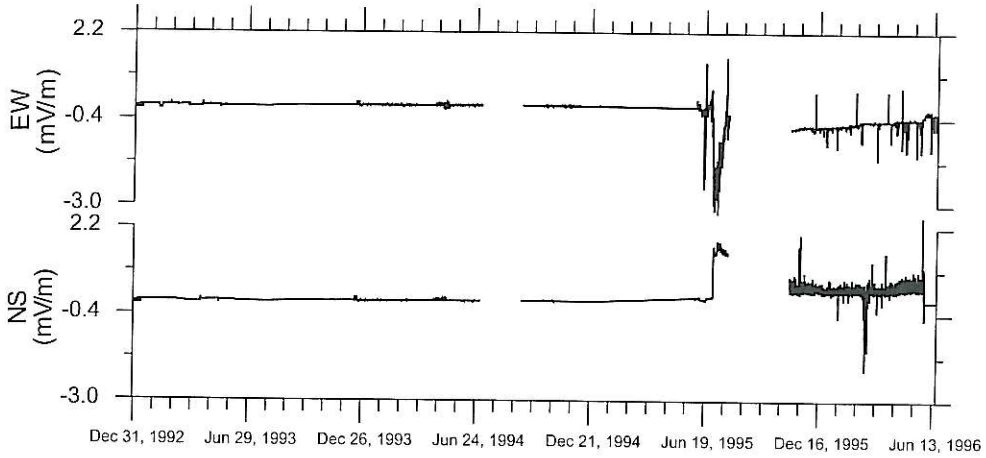


Fig. 2. Telluric recordings at NER station from February 1993 to June 1996.

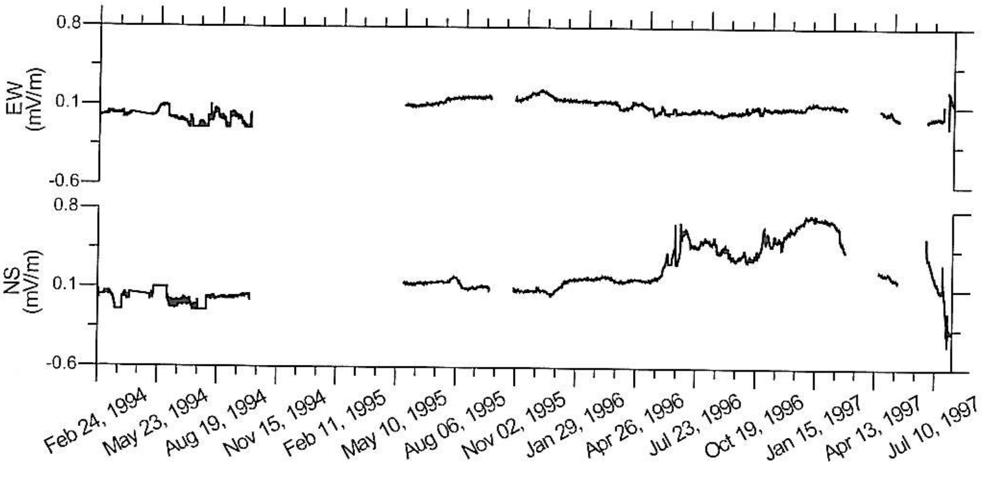


Fig. 3. Telluric recordings at MAV station from February 1994 to August 1997.

card). The magnetometer was a static one (Mosnier and Yvetot, 1977). Telluric lines were both 100 m long and Pb-$PbCl_2$ electrodes were buried at several tens of centimeters depth.

Better and longer records were obtained at MAV.

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

3. Data processing

In this study, two parameters are computed and correlated with the seismic activity. The first one is the energy of the *H*-geoelectric field and the second is the polarization.

The idea of correlating «energy to seismic activity» is based on the generation of geoelectric currents into faulting areas during the preparation of a seismic event. These currents are supposed to be propagated within the geological formations, even far away from the future epicenter, due to stress-build changes. The geoelectric disturbances measured at the surface could appear either as a sudden change in the form of a transient signal or as gradual changes in the long-term variations. In both cases, these changes should reflect variations in the energy of the telluric field.

The energy of a sequence as the waveform of the geoelectric recordings, is given by (Oppenheim and Schafer, 1975)

$$\varepsilon = \sum_{n=-\infty}^{\infty} \left| E(n) \right|^2 . \tag{3.1}$$

Initially, the horizontal field is calculated from the two recorded horizontal components using the following formula:

$$E = \sqrt{E_x^2 + E_y^2} \tag{3.2}$$

where E_x and E_y are the north-south and east-west components, respectively.

According to Vallianatos and Tzanis (1998), only very long periods may be detectable at long distances from the source. The waveform of the telluric field recorded far away from the source will exhibit a slow variation with time. The model they suggest refers to signals of bay-like shapes. Their conclusion is in agreement with changes of several hours' duration already reported in the literature (Vargemezis *et al.*, 1997; Nomikos *et al.*, 1997).

The energy of the telluric field was calculated for time intervals of one day and plotted *versus* time.

The polarization of the geoelectric field was studied by hourly averages and is depicted using hodograms of the horizontal components. The basic concept is that the polarization of the geoelectric signal for a homogeneous medium should be stable and perpendicular to the magnetic field. In the case of an area where a two-dimensional conductive structure exists, the geoelectric field could be polarized along its horizontal direction. In the case of a faulted area where preseismic telluric activity might be observed, this direction should reflect the strike of the fault.

The change in the polarization of the horizontal geoelectric field could therefore become a precursory attribute of the geoelectric activity. In case the station is sited near a seismic fault, geoelectric activity having the same polarization as the strike of the fault, could probably show an imbedding earthquake from the same area. Another concept of this survey is that the possible precursory signal could indicate a probable forthcoming seismic area.

4. Earthquakes occurring during the monitoring period

Greece and the surrounding area is well known as a high seismic area. Many events occurred during the monitoring period (January 1993 - September 1997). 18054 seismic events were recorded within a distance of 500 km from the stations. 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 or they had epicenters at a relatively long distance from the stations. In both cases, the shocks are assumed not to produce detectable signals. The earthquakes considered in the present study were those which fell into one of the following categories:

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 NER.

Since in the literature there are no criteria for this choice, we applied arbitrary criteria connecting magnitude and distance.

A total number of 936 earthquakes which occurred during the study period were found to meet the above mentioned criteria. Figure 4 shows the location of the epicenters of these earthquakes (categories A, B and C). Symbols

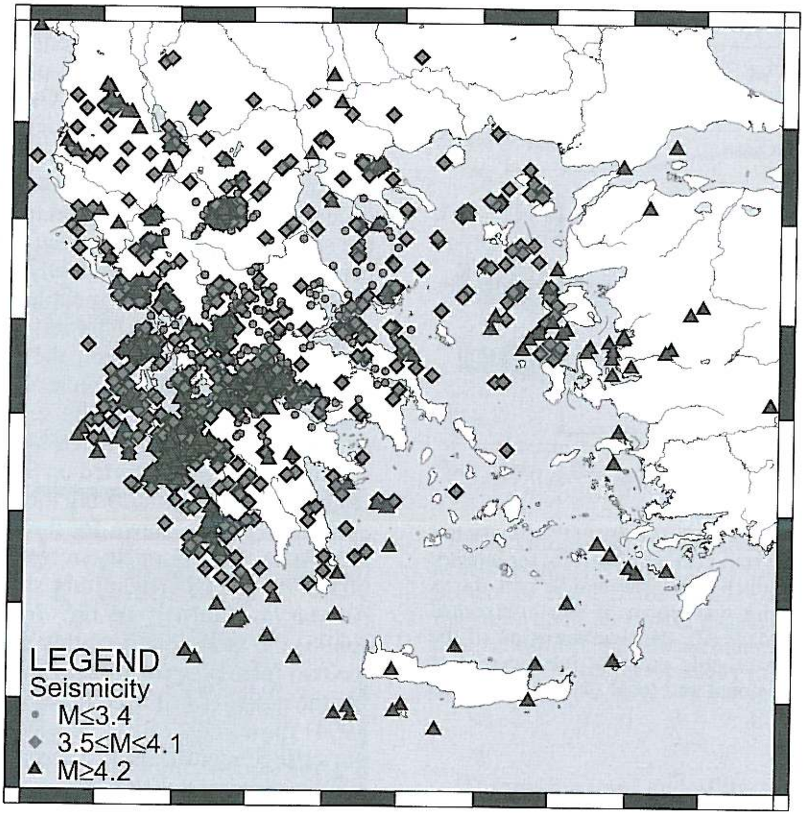


Fig. 4. Location of selected earthquakes epicenters to be associated with telluric activity.

of three sizes are used to denote the three magnitude windows (3.5-3.9, 4.0-4.6 and 4.7-5.7). It must be noted that recording of magnetotelluric data was interrupted for some time periods because of technical problems. For these periods, the seismic events of the following months were considered.

5. Correlation between signal energy and seismic activity

Figure 5, presents all associated parameters for the whole recording period.

Regional earthquakes also include the local ones, but the Long Distance (LD) earthquakes are examined as a separate group.

The following remarks can be made:

– The energy of the electric field at MAV shows a step anomaly after May 1996. This anomaly lasts for one year and its largest amplitude is 14 $(mV/m)^2$. It contains two peaks, the first between May and mid-September 1996 and the second between October 1996 and May 1997.

– The second interesting variation (according to amplitude and duration) at MAV, starts in September 1994 and lasts until the middle of May 1995. The amplitude of this change is much smaller (2 $(mV/m)^2$) than the previous one.

– In the lower part of fig. 5, a dominant change at NER can be seen in June 1995. Unfortunately, the station was not operating for sever-

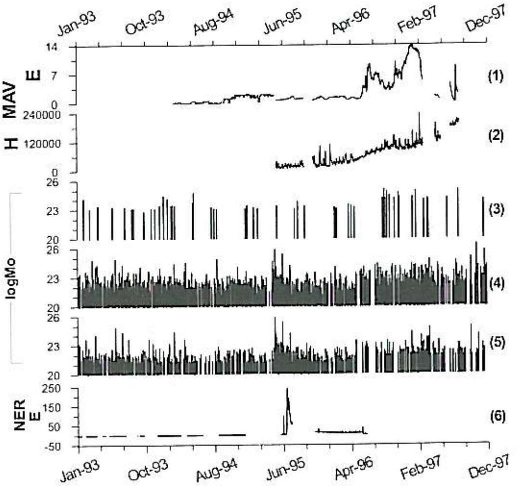


Fig. 5. Time changes of the energy of the geoelectric signal (E) at MAV station (1) and NER (6) for January 1993 until September 1997. The middle part shows the energy of the waveform of the horizontal geomagnetic field, H (2), the time variation of the logarithm of the seismic moment for the remote seismicity (3), regional and local (4) as well as the local seismicity (5).

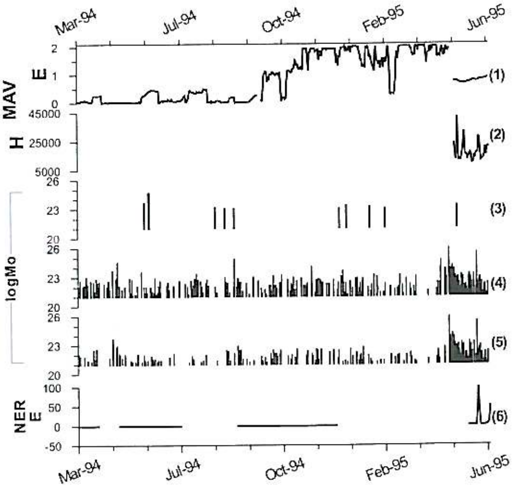


Fig. 6. Time changes of the energy of the geoelectric signal for MAV station (1) and NER (6) from March 1994 until June 1995 (same symbols as in fig. 5).

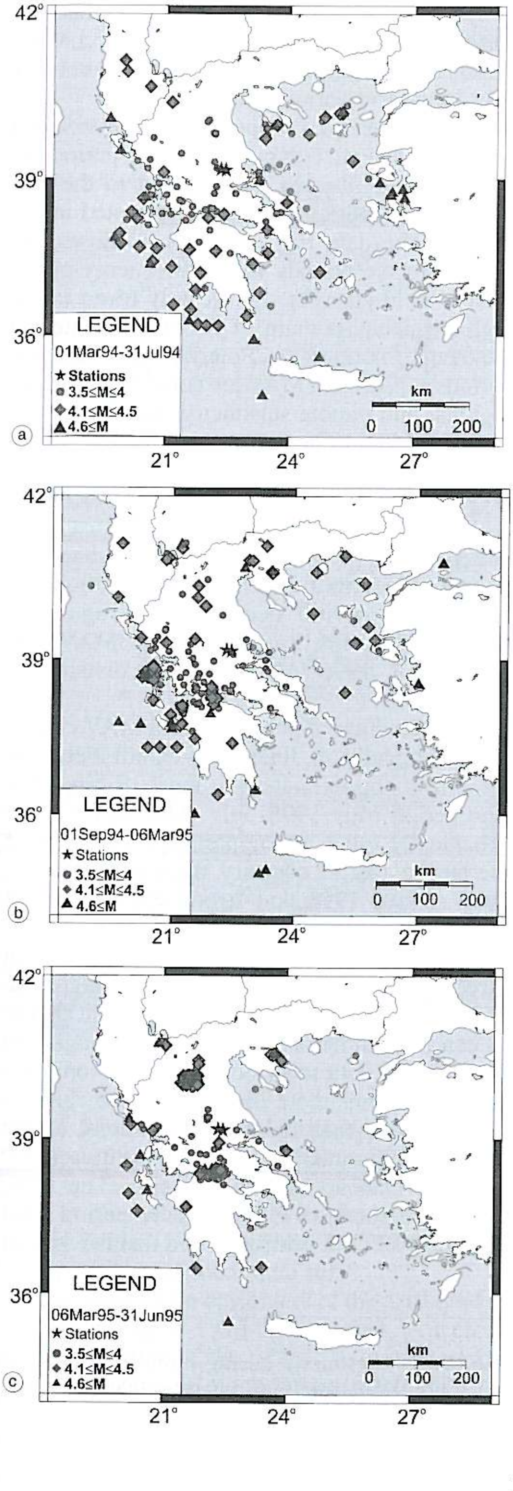
al months before June, so the beginning of the signal was not recorded. Nevertheless, it can be noticed that the specific time period coincides with a burst of seismicity in Greece. On May, 13, 1995 an earthquake of $M_w = 6.6$ hit the area of Kozani (126 km north from Neraida station) and on June 15 an earthquake of $M_w = 6.3$ occurred at the area of Aeyion (82 km south of the station). Figure 6 shows the records for the period of March 1994 until July 1995.

It is pointed out that remarkable seismicity occurred in May and June 1995 (Kozani and Aeyion earthquakes) when the energy of the telluric field at MAV station recovered low values. A detailed study of the seismicity of the specific period is represented in fig. 7a-c.

Changes at MAV started on September 1994 (fig. 6). Three maps showing the location of the epicenters can be drawn for three time-periods (fig. 7a-c). The seismicity in fig. 7b (01Sept94-06Mar95) is higher than that shown in fig. 7a (01Mar94-31Jul94). In fig. 7c (06Mar95-31 Jun95) the seismicity is rather concentrated in the two focal areas of Kozani and Aeyion. During the normal seismic activity (until September 1994) the energy of the geoelectric field does not change significantly. Thereafter a simultaneous increase in the telluric signal energy and the number and magnitude of earthquakes are observed. On March 1996 a drop in the energy value was followed by a sudden increase, and that is why the 6th of March is the limit of the remaining two maps.

Between July 1995 and August 1997 three time periods can be distinguished (fig. 8). The first one from July 1995 until June 3, 1996 has no significant changes. The second period ends in October 1998 during which a maximum value of 9.5 $(\mathrm{mV/m})^2$ is observed on July 9. The last period lasts from October 27,1996 to May, 1997. The energy reaches a value of 14 $(\mathrm{mV/m})^2$ on January 5,1997. The corresponding seismicity for these periods is presented in fig. 9a-c.

Although the seismicity was considerably high during the first period (fig. 9a), no significant change in the energy of the telluric field is observed. On the other hand, the seismicity weakens during the second period (fig. 9b) and a significant change in the energy of the telluric field occurs.



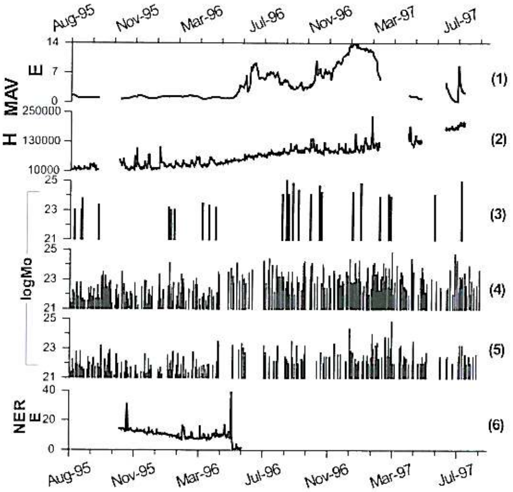


Fig. 8. Time changes in the geoelectric signal energy at MAV station (1) and NER (6) from July 1995 until September 1997. In the middle part, energy of the waveform of the horizontal geomagnetic field (2), the time variation of the seismic moment for remote (3), regional (4) and local seismicity (5).

During the third period the seismicity again becomes high and several earthquakes with M_w greater that 4.6 occur (fig. 9c).

6. Horizontal polarization of the telluric field

A basic feature of the telluric field is the horizontal polarization, which normally should be orthogonal to the magnetic one. If a conductive structure exists in the vicinity of the station, the polarization (telluric field) should be affected. In the case of a fault, which corresponds to a two-dimensional structure, the geoelectric field is expected to be polarized according to the strike of the fault.

Fig. 7a-c. Local seismicity (distance < 160 km) for three time periods: a) March-July 1994; b) September 1994-March 1995; c) March-June 1995.

In this section, the polarization and the time variation of the telluric field at NER and MAV stations is examined to detect any precursor over long-term variations.

Hourly averaged values of both horizontal components were computed for time periods of a month. No filtering was applied to the raw data, because although we are interested in examining the data for long time-windows, we need to locate periods where the energy of the telluric field changes significantly (even in the high frequency domain). Data are presented in the form of hodograms. Polarization by month-periods at NER and MAV are compared to local, regional and remote seismicity (fig. 10a-c).

Until May 1996 the mean direction of the polarization is approximately E-W corresponding to the main E-W direction of the Anchialos fault. Exceptions can be seen in August 1995 and January 1996 at MAV station where the polarization turns to N-S. The major earthquakes during this period occurred on August 22 ($M_w = 4.7$, at 486 km away from MAV and February 1, 1996 ($M_w = 4.9$, at a distance of 250 km)).

The direction of polarization at MAV changes dramatically in June 1996. Until February 1997 it is approximately in the N-S direction. The period May 1996 - July 1996 seems to be seismically quiet in comparison to the rest of the period. On the contrary, the seismicity rises after August 1996 and strong earthquakes of magnitude close to 5.0 occur.

In fig. 10a-c, earthquakes are presented in three different sets according to their magnitude and distance from the stations. Significant changes can be seen before earthquakes belonging to all the three data sets (local, regional, long distance). It seems more likely that these changes are related to earthquakes that belong to the regional data set having a magnitude around 5.0 or more (January and July 1996). The same picture is obtained for the whole period until February 1997. It is also noticed that for August

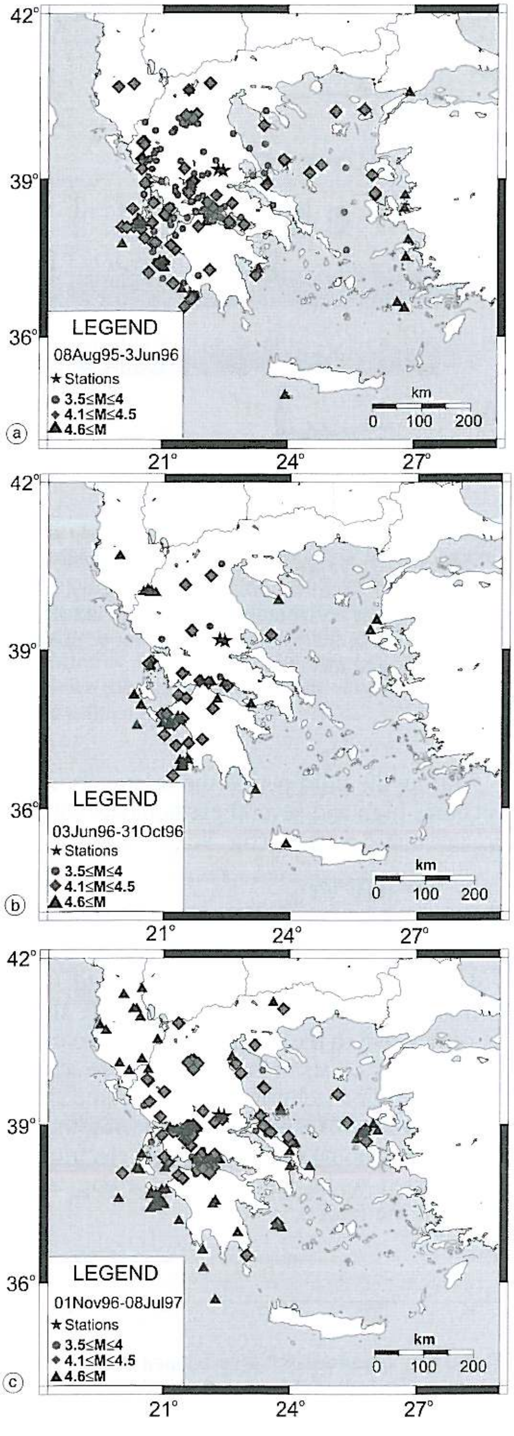


Fig. 9a-c. Seismicity during three time periods: a) 8 August 95-3 June 1996; b) 3 June 1996-31 October 1996; c) 1 November 1996-8 July 1997.

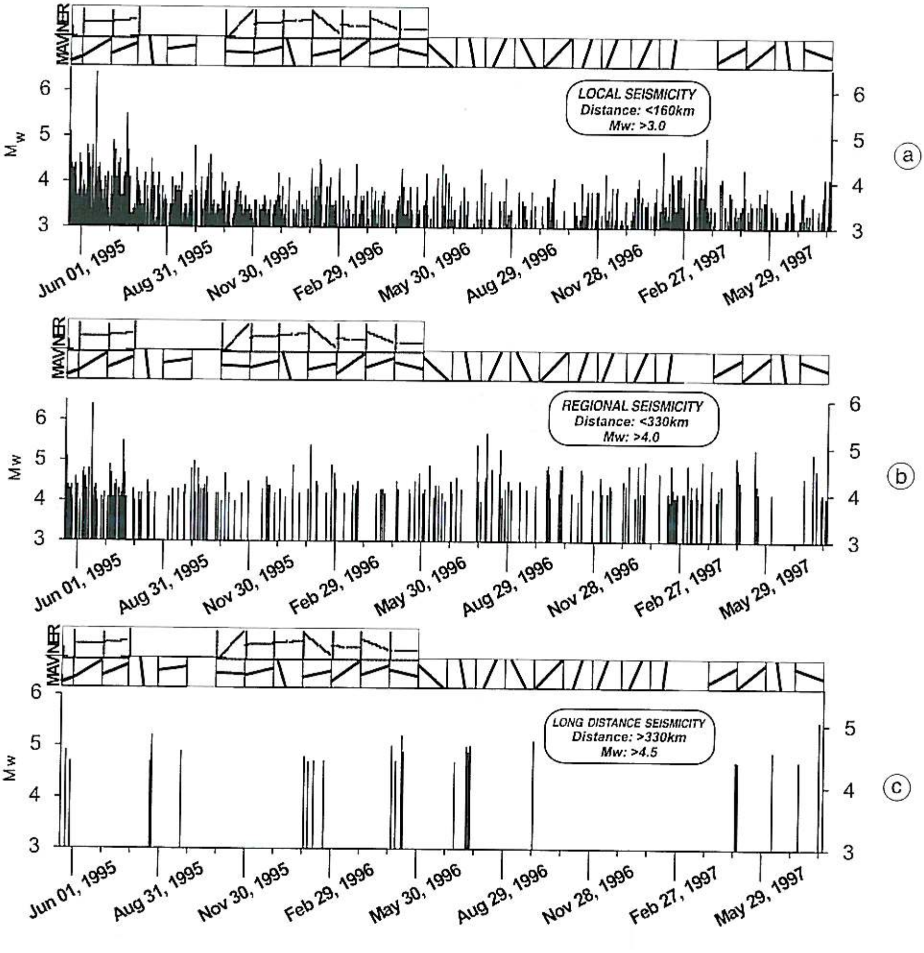


Fig. 10a-c. Polarization of the horizontal geoelectric field at NER and MAV stations and seismicity between June 1995 and July 1997. Seismicity: a) local; b) regional; c) long distance seismicity with time; the bar length corresponds to the magnitude M_w.

1995, January, July and September 1996, remote earthquakes occurred as well. However, with the exception of August 1995, the influence on the polarization of the horizontal geoelectric field is most probably due to the earthquakes of the regional data set.

Location of the epicenters of the earthquakes corresponding to 1993-1997 period, as well as the polarization of the telluric field is shown in fig. 11 which was plotted using the GMT software (Wessel and Smith, 1991).

The polarization of the geoelectric field changes with time, even if the behavior of the magnetic field does not change dramatically (fig. 12). Until June 1995, the telluric polarization seems to be perpendicular to the magnetic one but from July 1995 it changes to the E-W direction and then to the N-S one. The polarization of the geoelectric field changes regardless of the polarization of the magnetic field. It could be interpreted as a disturbance due to a preseismic activity.

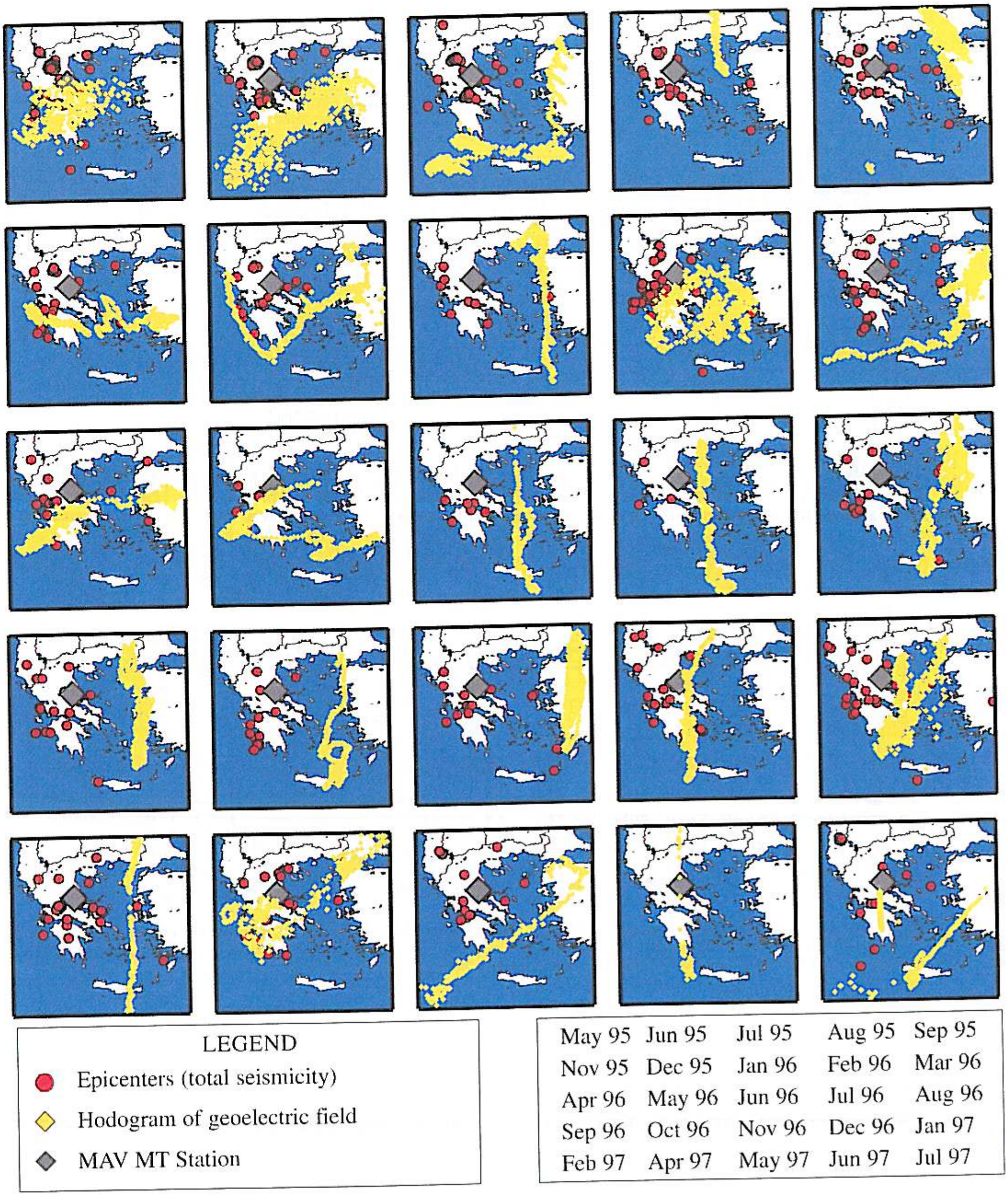
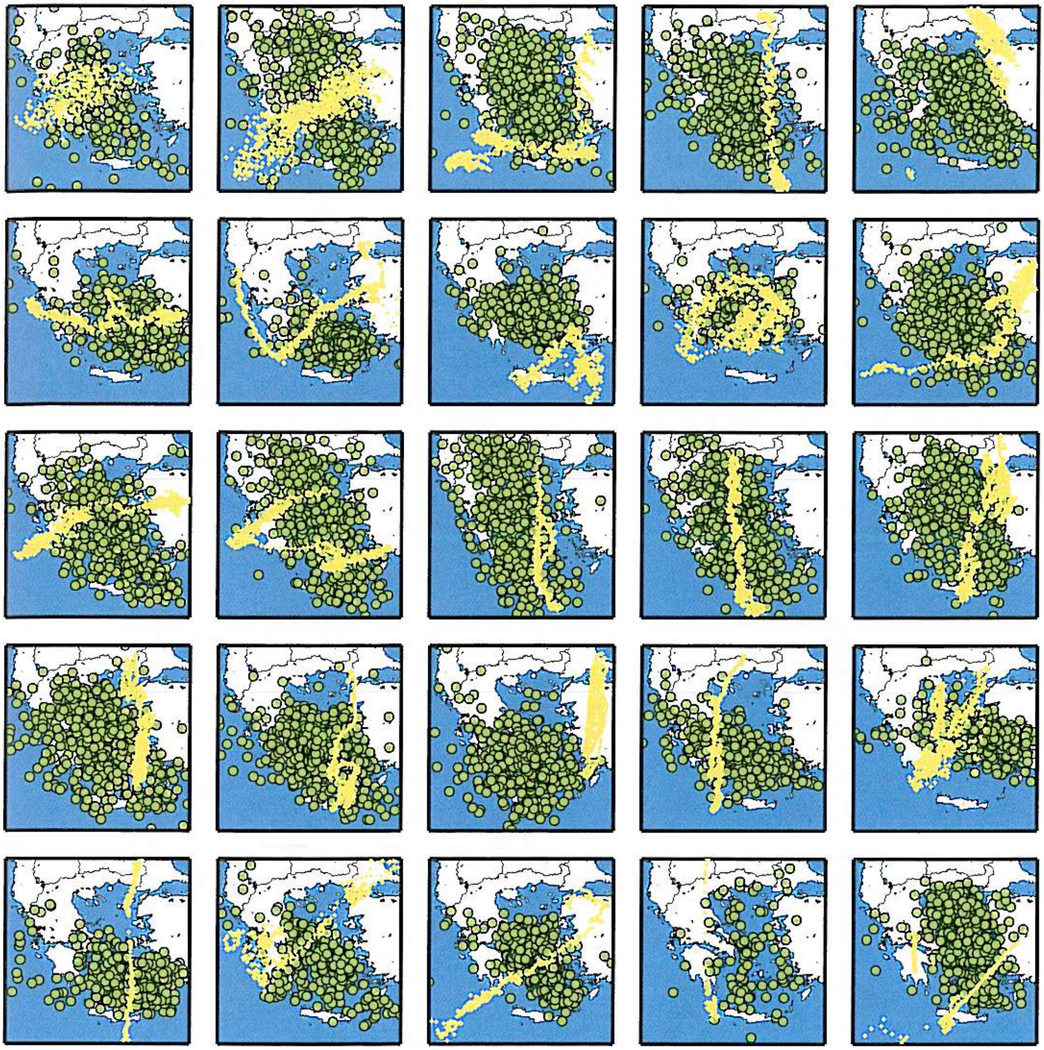


Fig. 11. Map of Greece showing the hodogram of the horizontal geoelectric field and the location of the epicenters of total seismicity per month, at MAV and NER stations.



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● Hodogram of magnetic components

◆ Hodogram of telluric components

May 95	Jun 95	Jul 95	Aug 95	Sep 95
Nov 95	Dec 95	Jan 96	Feb 96	Mar 96
Apr 96	May 96	Jun 96	Jul 96	Aug 96
Sep 96	Oct 96	Nov 96	Dec 96	Jan 97
Feb 97	Apr 97	May 97	Jun 97	Jul 97

Fig. 12. Maps of Greece showing the hodograms of the horizontal geoelectric and horizontal geomagnetic field.

No obvious relation between polarization and seismicity is observed in fig. 11. This is most probably due to the high seismicity of Greece, which does not allow the association of single isolated shocks with the telluric field as developed in this section.

A question arises as far as the expected horizontal polarization of the preseismic telluric signal is concerned. The preseismic telluric signal could be polarized (a) parallel to the strike of the seismic fault or (b) along the propagation direction. In this case, the polarization of the signal could be indicative of the direction of the epicenter of the forthcoming earthquake in relation to the location of the magnetotelluric station.

The most common strikes of seismic faults in Greece are in the NE-SW and the NW-SE direction (fig. 13). Therefore, if case (a) holds, when a change in the polarization occurs, it should turn to be parallel to the faults of the stimulated seismic area. However, this consideration cannot explain why in most cases the polarization of the geoelectric signal turns to the NS direction. On the other hand, the assumption of case (b) cannot explain the fact that in some cases the polarization remains to the NS direction even if the azimuth of the epicentral area is in the EW direction.

From the results of the study, it seems that the only information, which could be extracted from the polarization of the geoelectric field, is the estimation of the time when the polarization changes occur.

During the period 1220-1230 in Julian Days (May 5-15, 1996), only two shocks occurred (day 1220, fig. 14a-d), with magnitude less than 4.5 (fig. 14a-d). Considering this period as a

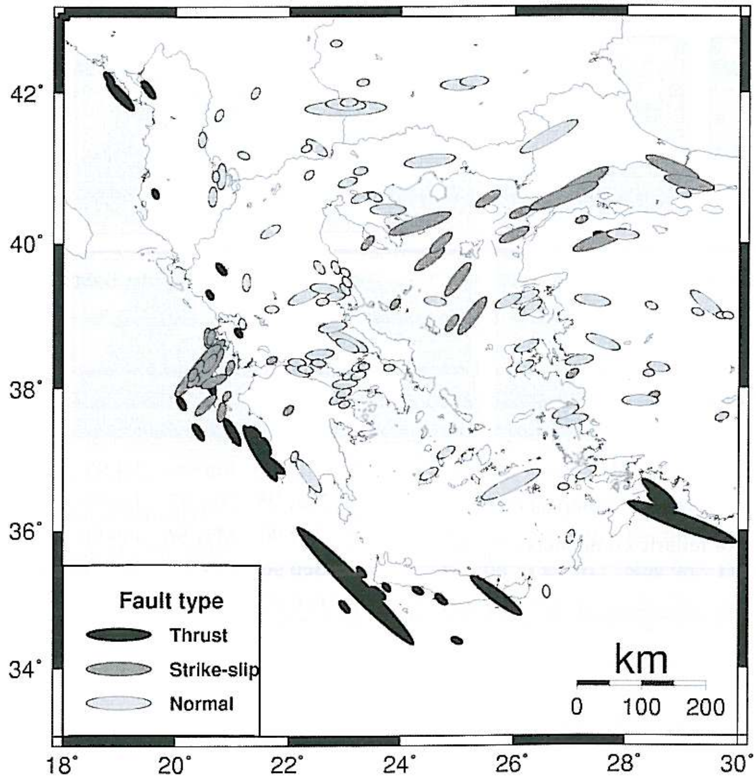

Fig. 13. Rupture zones of 150 shallow earthquakes (after Papazachos *et al.*, 1997).

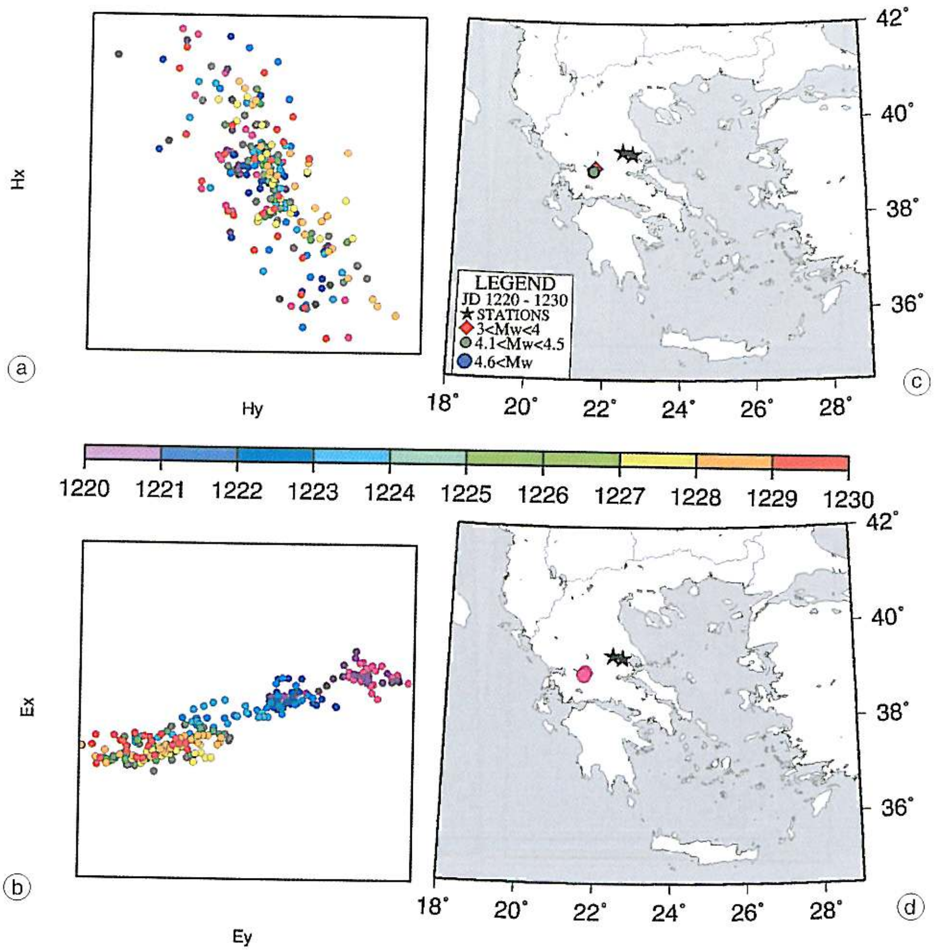

Fig. 14a-d. Hodogram of: a) geoelectric field; b) geomagnetic field; c,d) location of the epicenters with color magnitude scale. The earthquake occurrence and polarization have the same time color scale (time scale in Julian days, beginning the 1st January 1993).

quiet one, we can conclude that the geoelectric field is almost perpendicular to the magnetic field, as it is assumed to be.

Another time period of ten days is shown in fig. 15a-d where the relevant hodograms have been drawn. A seismic swarm started in Patras on day 1134 (February 8, 1996). Until the day before the geoelectric field has NE polarization. However, the polarization changes suddenly the next day (1134) to NW. This change could be related to the seismic activity in Patras Gulf.

Figure 16a-d presents a local earthquake. The geoelectric field has been plotted instead of the polarization of the magnetic field. No significant change in the geoelectric field or its polarization can be observed on Julian day 1466, when earthquakes with magnitude ranging between 3 and 4 occurred. On the contrary, at the end of Julian day 1468 (January 7, 1997) a sudden change in the geoelectric field occurred, followed by an earthquake (M_w = 3.9) which occurred only 16.6 km away from the station.

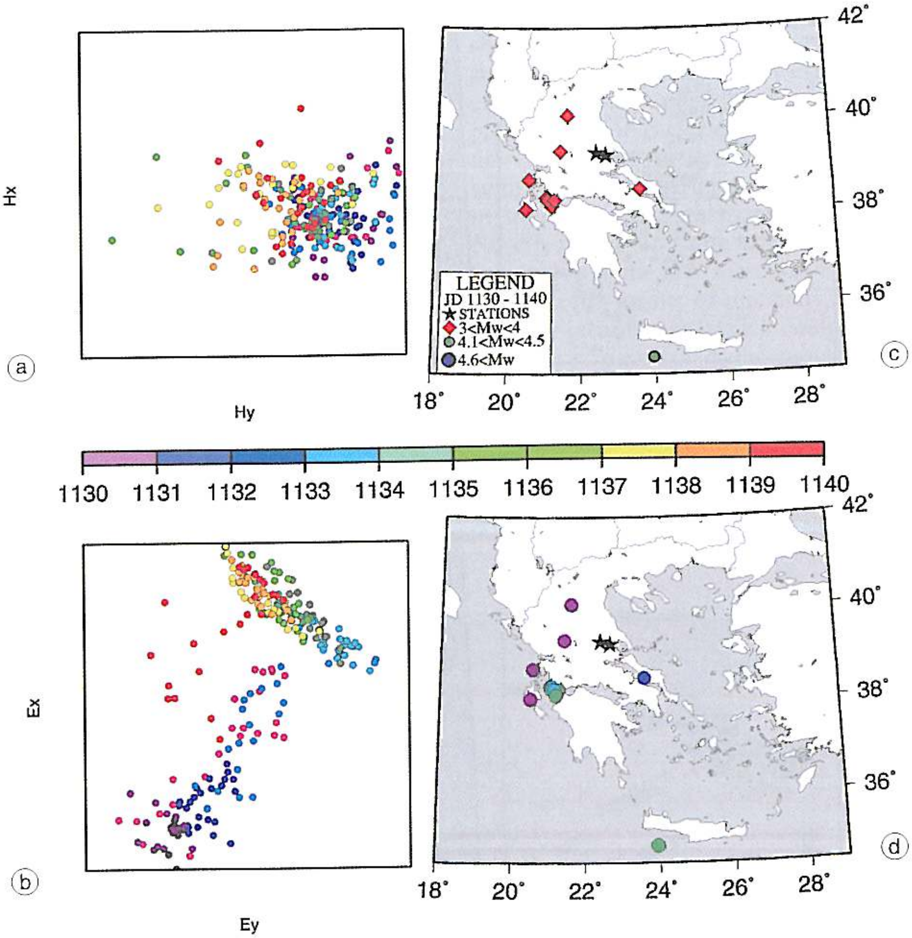

Fig. 15a-d. Seismic activity and polarization of the geoelectric and magnetic field during the time period 1130-1140 Julian days (February 4-14, 1996). Description of the figure same as fig. 14a-d.

7. Conclusions

The aim of the present work was to study the correlation between the energy and the polarization of the horizontal telluric field and the seismic activity. We focused on the long-term variations in order to examine any possible relation of the geoelectric activity with remote seismicity (up to 500 km).

In two cases, the energy of the *H*-geoelectric field seems to change some months before the burst of the seismic activity. The changes observed during the period September 1994 - May 1995, which was followed by seismic swarms in Aeyion and Kozani area, seem reliable.

The hodograms of the *H*-geoelectric field show that the polarization in monthly periods changes significantly regardless of the magnetic field. This could be the effect of the process of generation of electric currents prior to some major earthquakes. The polarization changes do not show any regular behavior according to the location of the future epicentral area. In general, because of the very high seismicity in Greece, it was not possible to define the response of the polarization to the activation of specific seismic areas.

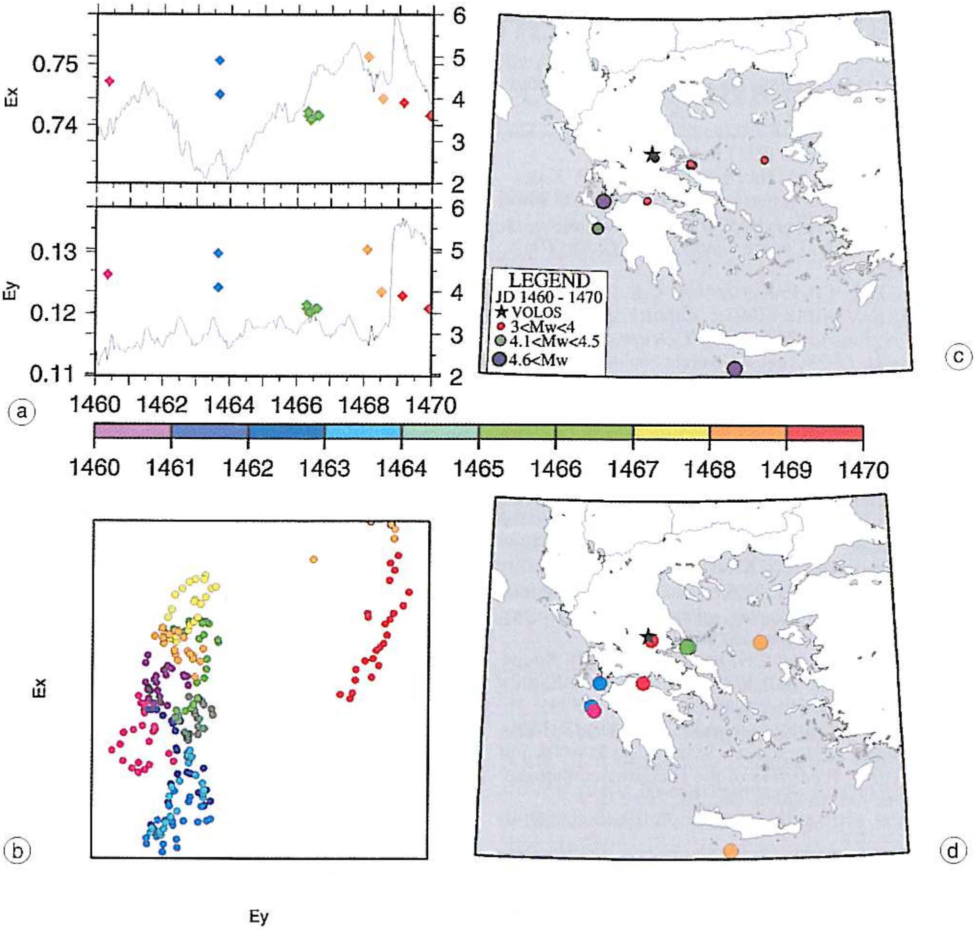

Fig. 16a-d. Case of a local earthquake: a) time variation; b) hodogram of geoelectric field; c) location and magnitude; d) location and occurrence of earthquakes.

In any case, it seems that both long term energy changes of the *H*-geoelectric field and its polarization could be used in tandem with other geophysical parameters in order to advance towards an earthquake prediction scheme.

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