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The application of the magnetotelluric impedance tensor to earthquake prediction research in Greece

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Abstract

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Continuous short period (0.1–3600 s) measurements of the magnetotelluric field components were conducted simultaneously at two sites in Greece for a period of 5 weeks. The estimation of the impedance tensor elements from 8-hr windows of recorded data, at each station, is found to describe the local electromagnetic induction with great accuracy. The computation of the residual electric field, obtained as the difference between the observed and estimated inductive part of the electric fields, clearly improves the detection of any local electric field anomaly. This method was used in an attempt to detect precursory seismic electrical signals (SES) that have been reported to precede earthquakes in Greece. The results indicate the success of this method in resolving ambiguities about the nature of the reported SES, i.e. whether it has an external or internal source.

Although during the recording period no large earthquake occurred, five with a magnitude of between $M_L = 4.0$ and $M_L = 4.3$ occurred within a radius of 150 km from one of the stations. The magnetotelluric recordings and the computed residual electric fields for the time intervals reported to contain the SES precursors to these events were analysed in some detail. In two of the cases it was found that the sources could not be related to earthquake processes. In the other three cases the nature of the source of the suspected SES, although electric, could not be established with certainty. These results indicate that for earthquakes of small magnitude ($M_L \leq 4.3$) or of large epicentral distance ($r \geq 100$ km), the detection of a SES is extremely difficult.

Introduction

Local variations in the earth's electric field prior to earthquakes in Greece have recently been reported by Varotsos and Alexopoulos (1984a, b). They claim that every sizable earthquake is preceded by a transient change in the electric field, the so-called seismic electric signal (SES). The amplitude of the SES, as observed by measuring the potential difference (ΔV) between a pair of electrodes placed in the ground, is supposed to contain information on the time of occurrence, epicentral distance and magnitude of an impending earthquake.

From results obtained thus far by the 18-station telluric network in Greece, the following rules have been established:

(1) The SES occur 6–115 hrs before the earthquake and have a duration of 1 minute to 1.5 hrs. The duration and lead time do not depend on earthquake magnitude (M_L).

(2) The SES appear as a transient change in the potential difference (ΔV) between two electrodes (up to a few millivolts for an electrode spacing $L = 50$ m) depending on M_L, epicentral distance, r, and local structural inhomogeneities.

(3) The SES recorded on a single line (east–west or north–south) of a given station and emitted

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from various seismic regions show ΔV values that decrease with increasing epicentral distance r roughly according to a $1/r$-law (for $r > 50$ km).

(4) For a given line at a given station, the SES's emitted from a given seismic region ($r =$ constant) have ΔV values that increase with increasing earthquake magnitude M_L.

(5) The SES of an impending earthquake appears simultaneously at a number of stations without being accompanied by any significant change in the magnetic field.

Varotsos and Alexopoulos (1984b) claim an outstanding success rate in predicting sizable earthquakes located within the network of telluric stations. As has been mentioned, magnetotelluric disturbances are a very serious shortcoming in the identification of the SES, especially for an impending earthquake of small magnitude or of large epicentral distance. The removal of magnetically induced effects from the telluric measurements should improve the detectability of the SES and thus make predictions for distant or small earthquakes more reliable. It is well known that the application of the tensor impedance concept to the analysis of magnetotelluric data as published by Sims et al. (1971) makes it possible to obtain estimates of the tensor elements which describe the local induction effect. This standard magnetotelluric analysis is employed to remove induction effects from the electrical measurements and thus we may observe what is henceforth termed the "residual" electric field.

Rikitake (1947) suggested that the method of computing the difference between observed earth potentials and those predicted from measurements of the magnetic field should be applied to monitor any anomalous changes in earth currents related to earthquakes. The transfer function relating the magnetic field to the electric field from a galvanic source will in general be different from the one describing the induction process analysed by the standard magnetotelluric method. Thus, for noise-free data, the calculated residual electric field should show if an electric potential is generated within the earthquake volume. In general, magnetotelluric data are noise contaminated, which can cause severe problems in the interpretation of the nature of an observed anomaly in the residual field. Noise related to the actual measuring technique is mostly related to the measurements of the electric field. This type of noise can easily be identified by using double coverage of the electrode setup. Another type of noise is related to artificial galvanic and inductive sources in the vicinity of the measuring station. Changes in the residual electric field showing a step-like rise of the anomaly can probably be referred to this type of noise, since electric field changes from suspected earthquake-related sources with well defined hypocenters should show a smooth rise in the signal because of stronger attenuation of the higher frequency components at some distance from the hypocentre. To safely distinguish between anomalous residual electric fields related to artificial sources and anomalous electric fields related to earthquake processes, it is necessary to observe the anomalous field at a minimum of two stations, separated by a distance large enough to ensure that artificial sources cannot affect both stations.

In order to test the feasibility of the above mentioned methodology, the Seismological and Solid Earth Physics Departments of Uppsala University, in cooperation with P. Varotsos, K. Alexopoulos and K. Nomicos from the Department of Physics of Athens University, installed and operated two magnetotelluric stations in Greece. The two magnetotelluric stations were near two of the telluric stations of the Greek network and monitored the five components of the magnetotelluric field for a 5-week period.

The analysis of the magnetotelluric data provides an accurate estimate of the local induction effect. The subsequent removal of such induction effects from the electric field measurements is shown to drastically improve the detection of any local variation in the earth's electric field caused by galvanic sources.

Instrumentation

Two pairs of non-polarizing electrodes of the copper-coppersulphate type were used for detecting the two horizontal components of the electric field in an east–west and north–south direction. The distance between the electrodes was 100 m for each pair. Three induction coil magnetometers

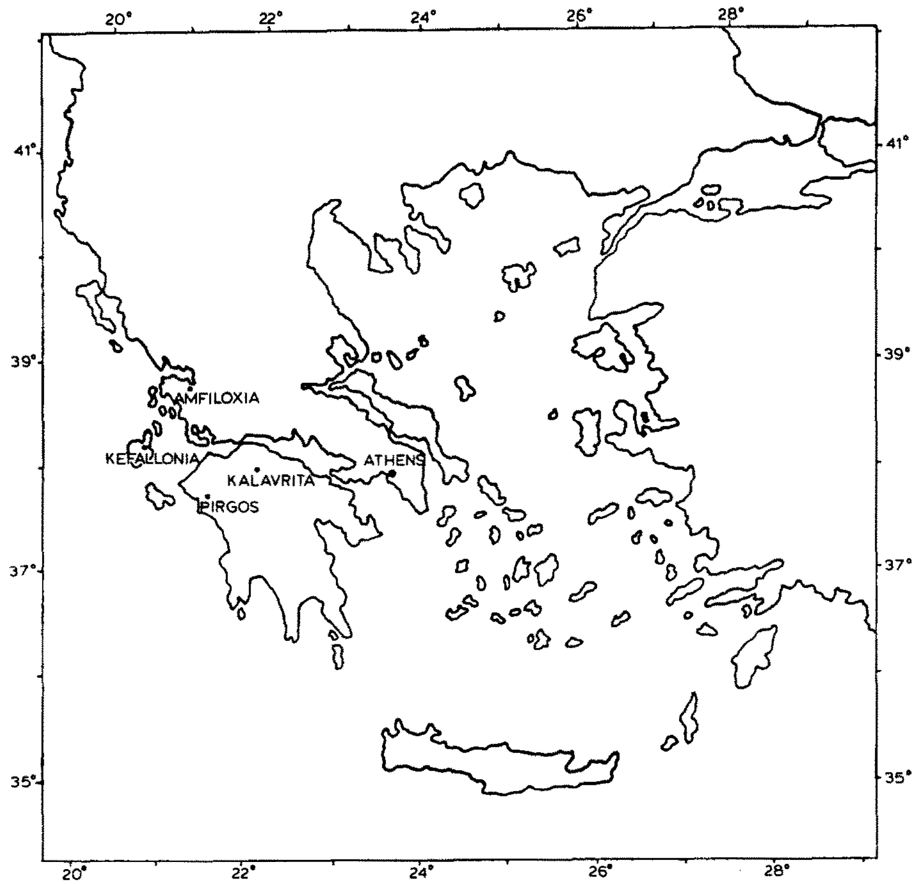


Fig. 1. Map of Greece showing the locations of the magnetotelluric stations in Pirgos and Amfiloxia.

were used to measure the time derivatives of the three orthogonal components of the magnetic field in north–south, east–west and vertical directions.

The output voltages were suitably amplified and filtered with a passband of 0.00027–10 Hz. The five channels were sampled at 48 Hz and recorded digitally on magnetic tapes. Each tape contained 8 hrs of simultaneous recordings of the five magnetotelluric components. 12-V batteries were used for power supply. Tapes were replaced three times a day and during these breaks in the recording the station functions (gains, self-potential compensation etc.) were checked and when necessary adjusted.

Two such magnetotelluric stations were installed at the locations shown in Fig. 1. Both stations were situated well away from industry and man-made sources of noise. Nevertheless, the station in Amfiloxia showed random transient disturbances from an unidentified source. These disturbances did not occur at night time.

The separation between the telluric and magnetotelluric station was about 8 km for the station at Pirgos and a few hundred metres for the station in Amfiloxia. The recording of data began on April 3 and was continuous until May 8, 1983.

Data analysis

Maxwell's equations imply a linear dependance between electric and magnetic fields at a particular frequency and spatial wave number. In the frequency domain this relationship may be written as:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \qquad (1)$$

where Z_{xx}, Z_{xy}, Z_{yx}, Z_{yy} are elements of the impedance tensor $\boldsymbol{Z}$, and depend on the conductivity structure beneath the measuring point. E_x and E_y are the horizontal electric field components and H_x, H_y the horizontal magnetic field components. The indices x and y refer to the measuring axis in the north–south and east–west direction, respectively.

A relationship similar to eqn. (1) relating the vertical magnetic field component H_z and the magnetic field components H_x and H_y in the frequency domain, may be written as:

$$H_z = AH_x + BH_y \quad (2)$$

where A and B are unknown complex coefficients. The pair (A, B) can be thought of as operating on the horizontal magnetic field and tipping a part of it into the vertical. For this reason (A, B) is often referred to as the "tipper"; its application to the interpretation of conductivity structures is described by Vozoff (1972).

The estimation of the impedance tensor elements from measured data as performed by Sims et al. (1971), is obtained as a least squares solution in narrow bands of frequencies so that the noise power in two of the channels is minimized while assuming the remaining two to be noise free. Recently, Jepsen and Pedersen (1981) developed a computer program which provides solutions for the impedance tensor elements and their random errors, given the recorded time series of the horizontal magnetotelluric components as input. The solutions are in terms of auto and cross spectral estimates in a given frequency band. The following model is considered in the frequency domain ($\_$ indicates vector quantity consisting of field values at discrete frequencies within the frequency band):

$$\underline{E}_x = Z_{xx}\underline{H}_x + Z_{xy}\underline{H}_y + \underline{N}_x \quad (3)$$

where $\underline{N}_x$ denotes the noise of that part of the electrical field which is not related to the induction process. Assuming $\underline{H}_x$ and $\underline{H}_y$ to be noise free and Z_{xx} and Z_{yy} to be constant within the frequency range of interest, through the minimization of $|\underline{N}_x|^2$, a least squares solution $\hat{Z}_{xx}$ and $\hat{Z}_{xy}$ for the tensor elements is found ($\tilde{}$ indicates vector transposition and conjugation and $\hat{}$ indicates estimated quantities):

$$\hat{Z}_{xx} = \frac{(\tilde{\underline{H}}_x\underline{E}_x)(\hat{\underline{H}}_y\underline{H}_y) - (\tilde{\underline{H}}_y\underline{E}_x)(\tilde{\underline{H}}_x\underline{H}_y)}{(\tilde{\underline{H}}_x\underline{H}_x)(\tilde{\underline{H}}_y\underline{H}_y) - (\tilde{\underline{H}}_x\underline{H}_y)(\tilde{\underline{H}}_y\underline{H}_x)} \quad (4a)$$

$$\hat{Z}_{xy} = \frac{(\tilde{\underline{H}}_y\underline{E}_x)(\tilde{\underline{H}}_x\underline{H}_x) - (\tilde{\underline{H}}_x\underline{E}_x)(\tilde{\underline{H}}_y\underline{H}_x)}{(\tilde{\underline{H}}_x\underline{H}_x)(\tilde{\underline{H}}_y\underline{H}_y) - (\tilde{\underline{H}}_x\underline{H}_y)(\tilde{\underline{H}}_y\underline{H}_x)} \quad (4b)$$

Similarly, $\hat{Z}_{yy}$, $\hat{Z}_{yx}$, $\hat{A}$ and $\hat{B}$ are found. This program, with minor modifications to handle longer time series and estimate the tipper (A, B), was used in the analysis of the magnetotelluric data collected in Greece.

The main steps in the analysis of each field tape containing 8 hours of simultaneous recording of the time series are:

(1) Each of the five time series is low pass filtered at 0.5 Hz with a Gaussian filter and resampled to provide for a total window length of 32,768 samples.

(2) Linear trends are removed and the time series are subsequently multiplied by a cosine window, at both ends, of 400 samples width. This reduces the effects of discontinuities on the computed spectra.

(3) The time series are Fourier transformed.

(4) Cross and auto spectra are calculated within each band of frequencies. The first nine frequency bands were chosen to be discrete and centred at the corresponding first nine harmonics. The subsequent bands were chosen so that we had ten frequency bands per decade. In total we used forty bands.

(5) Average impedance tensor elements and their standard errors are calculated from band ten onwards. The first nine bands are excluded from further computation since they involve periods above the 1/3600 Hz instrumental filter.

(6) Apparent resistivities and phases are calculated for the average.

(7) The estimated impedance tensor elements and the tipper estimates along with the spectra of the time series are inputs to a subroutine which computes the differences ΔE_x, ΔE_y and ΔH_z between the observed electric and vertical magnetic components and those predicted by the horizontal magnetic field components:

$$\Delta E_x = E_x - \hat{Z}_{xx}H_x - \hat{Z}_{xy}H_y \quad (5a)$$

$$\Delta E_y = E_y - \hat{Z}_{xx}H_x - \hat{Z}_{xy}H_y \quad (5b)$$

$$\Delta H_z = H_z - \hat{A}H_x - \hat{B}H_y \quad (5c)$$

These residuals and the recorded time series are finally transformed into the time domain and plotted.

In this mode of analysis we use the single station technique rather than the remote reference station technique (Clarke et al., 1983) in determining the impedance tensor elements. This is primarily justified by the noise-free nature of the input data, which can be achieved by careful selection of the station sites and by making preliminary site noise measurements. However, as indicated above, the magnetotelluric station in Amfiloxia did show random transient disturbances; in this case the tensor estimates were obtained by rejecting noise contaminated segments or by analysing data sets with a high signal-to-noise ratio. The random errors of the estimated elements in each analysis were calculated with the method described by Pedersen (1982).

Results

Impedance tensor estimates and tensor analysis

The magnetotelluric data collected during the 5-week recording period at the two stations consisted of a total of 210 field tapes. Upon analysis of the data it was found that about 15% of the field tapes could not be analysed, mainly due to earth-electrode coupling problems. Furthermore, it was found that the magnetotelluric station in Amfiloxia was situated near some unidentified source of transient electric disturbances during the daytime. The presence of such disturbances clearly affects to some degree the accuracy in estimating the impedance tensor elements, depending on how frequently they appeared during the recording interval and how strong the signal was.

Figs. 2–5 show typical results obtained by the standard analysis of an 8-hr recording window of noise-free data, at each of the two stations for the same recording interval. Figs. 2 and 3 show the normalized impedance tensor $\hat{\boldsymbol{T}}$ and the tipper $\hat{A}$ and $\hat{B}$, for each station. The impedance tensor $\boldsymbol{Z}$ is normalized using the following relationship:

$$\boldsymbol{T} = \begin{bmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yx} \end{bmatrix} = \frac{1}{\sqrt{\omega\mu_0}} \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \qquad (6)$$

where ω is the angular frequency and μ_0 the magnetic permeability in a vacuum.

Figures 4 and 5 show the apparent resistivities:

$$\rho_{ax} = |T_{xy}|^2 \qquad (7a)$$

$$\rho_{ay} = |T_{yx}|^2 \qquad (7b)$$

and corresponding phases:

$$\phi_x = \arg(-iT_{xy}) \qquad i = \sqrt{-1} \qquad (8a)$$

$$\phi_y = \arg(+iT_{yx}) \qquad (8b)$$

resulting from the analysis of each station.

Routine determination of impedance tensor elements, from data having high multiple coherence values, shows only minor changes in the tensor estimates during the recording period.

The interpretation of these results leads to the following conclusions: both stations exhibit lateral anisotropies regarding the electrical conductivity distribution; the impedance tensor elements are numerically larger for the x-measuring direction; this anisotropy is more pronounced in the Amfiloxia station; the transfer functions indicate three-dimensional earth structures below both stations.

Residual field analysis

Using the estimated impedance tensor and tipper elements shown earlier and the spectra of the recorded time series, from which they were derived, the residual horizontal electric and vertical magnetic fields were computed. An example is displayed for a 2-hr segment of data, recorded simultaneously at both magnetotelluric stations, in Fig. 6a, b. By using sufficiently long time series, compared to the duration of the suspected SES, the presence of such anomalous signals can be expected to be of minor importance for the determination of the transfer functions. The residual electric fields, ΔE_x and ΔE_y, for both stations show a good prediction of the horizontal electric fields from the corresponding magnetic fields. The same may be said about the prediction of the vertical magnetic field from the two horizontal components as seen by the residual ΔH_z.

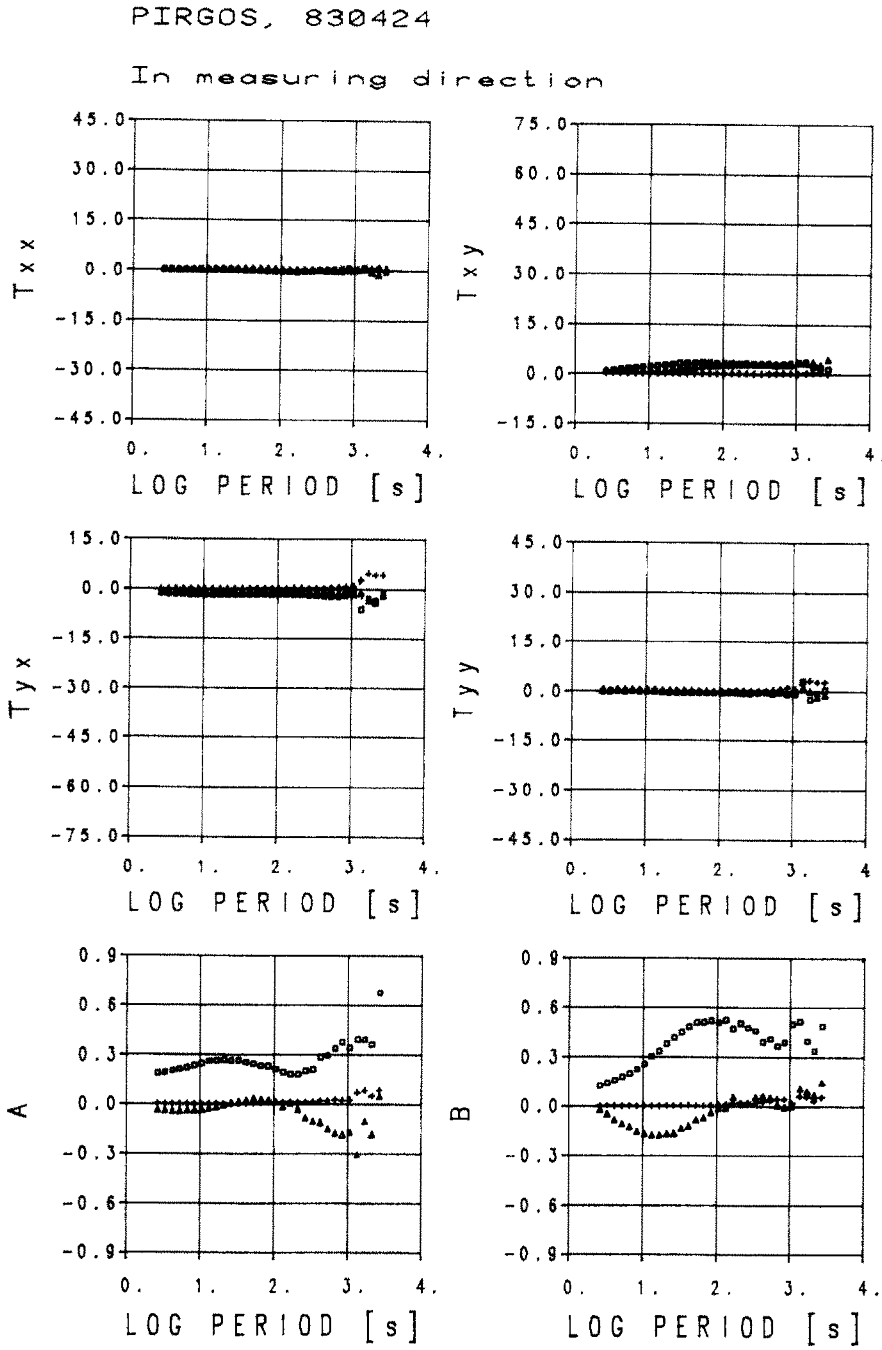


Fig. 2. Normalized impedance tensor $\hat{\underline{T}}$ and tipper ($\hat{A}$, $\hat{B}$) for the station in Pirgos. Squares are the real components, triangles are the imaginary components and crosses are the standard errors. Units for the normalized tensor elements are $(\Omega \mathrm{m})^{1/2}$.

The simultaneous variation in the electric field, indicated by an arrow, at both stations is of magnetic origin. This variation does not exist on the computed residuals. It is such simultaneous variations in the magnetotelluric field that make it difficult to identify local variations in the electric field, such as the SES, from the telluric recordings. Thus, knowledge of the source field is required and this is where the magnetotelluric method can be helpful in resolving such ambiguities.

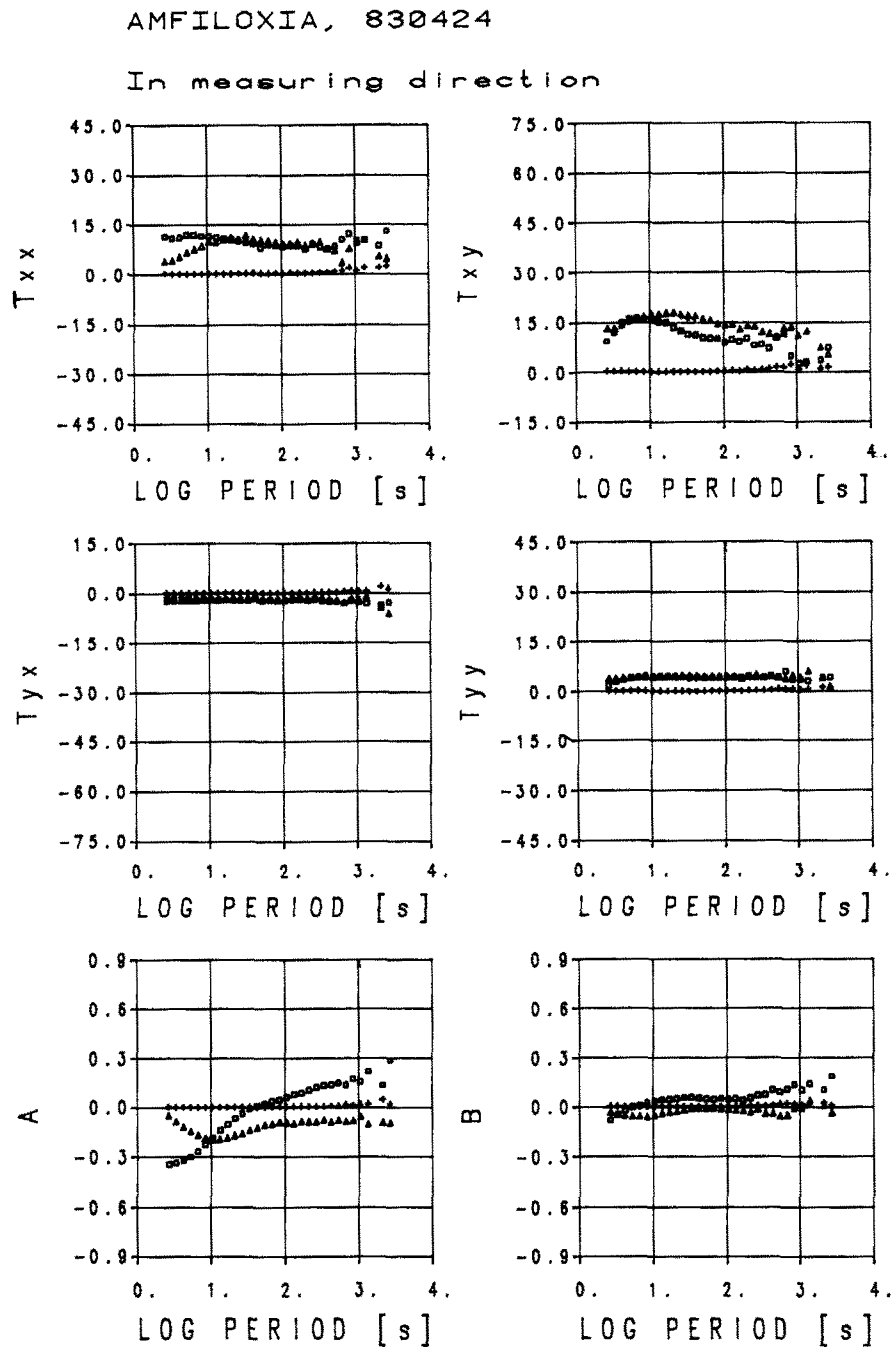
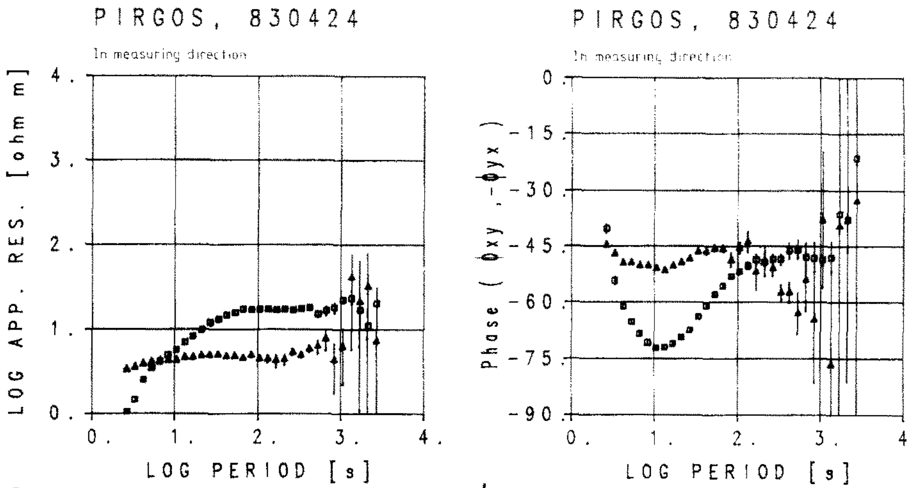


Fig. 3. Normalized impedance tensor $\hat{\underline{T}}$ and tipper ($\hat{A}$, $\hat{B}$) for the station in Amfiloxia. Squares are the real components, triangles are the imaginary compenents and crosses are the standard errors. Units for the normalized tensor elements are $(\Omega m)^{1/2}$.

Detection of the SES

During the recording period at the magnetotelluric stations, Varotsos (pers. cummun., 1983) issued 14 telegrams predicting the occurrence of 14 earthquakes in Greece. Of the 14 telegrams 5 were issued on the basis of the appearance of a SES at the Pirgos telluric station, which was simultaneously observed at other stations in the Greek telluric network.

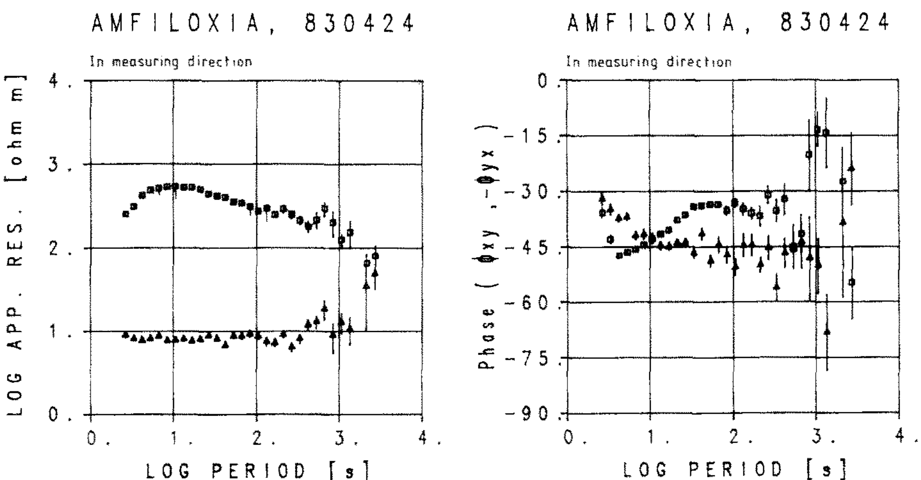


a b

Fig. 4. a. Logarithm of apparent resistivity ρ_{ax} and ρ_{ay} (Ωm) versus logarithm of period T(s) for the magnetotelluric station in Pirgos. Squares are the north–south direction and triangles are the east–west direction. Error bars are standard errors. b. Phases ϕ_x and ϕ_y (degrees) versus logarithm of period T (s) for the magnetotelluric station in Pirgos. Squares are the north–south direction and triangles are the east–west direction. Error bars are standard errors.

As described by Varotsos and Alexopoulos (1984b), every telegram issued is based on the appearance of a SES in the network of 18 telluric stations operating in Greece. Each telegram states the predicted epicentral distance and direction from Athens, the predicted magnitude and the time of appearance of the SES. The impending earthquake is expected to occur within a time window of 6–115 hours from the time of appearance of the SES.

It is clearly of interest at this point to analyse the magnetotelluric recordings from the stations in Pirgos and Amfiloxia at the time of appearance of the reported SES, in each of the five cases. It is expected that the residual field analysis of the magnetotelluric data should resolve ambiguities



a b

Fig. 5. a. Logarithm of apparent resistivity ρ_{ax} and ρ_{ay} (Ωm) versus logarithm of period T (s) for the magnetotelluric station in Amfiloxia. Squares are the north–south direction and triangles are the east–west direction. Error bars are standard errors. b. Phases ϕ_x and ϕ_y (degrees) versus logarithm of period T (s) for the magnetotelluric station in Amfiloxia. Squares are the north–south direction and triangles are the east–west direction. Error bars are standard errors.

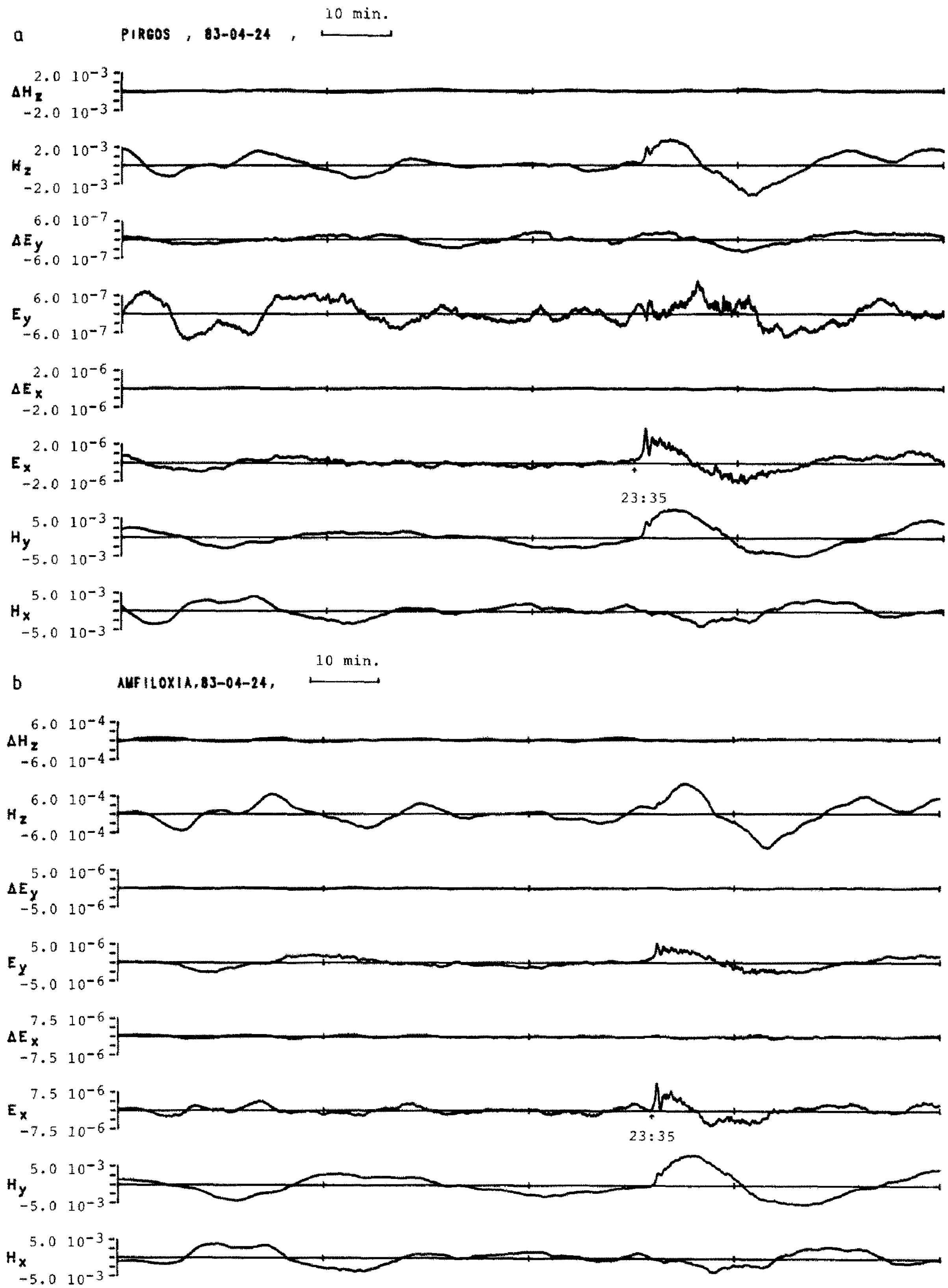


Fig. 6. Simultaneous recording of the five magnetotelluric components and the computed residuals from the magnetotelluric stations in Pirgos (a) and Amfiloxia (b). Index x refers to the north–south direction, y to the east–west direction and z to the vertical direction. H is the magnetic field component and E is the electric field component. ΔE and ΔH are the computed residuals. Units are A m^{-1} for the magnetic field and V m^{-1} for the electric field. Time indicated is G.M.T.

TABLE 1

Listing of telegram number, date and time of issue along with the suspected SES onset for each of the five cases, and the corresponding prediction of position (epicentral distance in kilometres and direction from Athens) and magnitude M_1 (Varotsos, pers. commun., 1983)

Case	Tel. no.	Date	Tel. time (G.M.T)	SES time (G.M.T.)	Prediction	
					position	M_L
I	79	06/04/83	20:12	17:55	W 170	3.6
II	81	15/04/83	13:15	12:16	W 160–200	–
III	83 *	17/04/83	16:14	12:53	WSW 230	3.6–4.0
IV	84 *	18/04/83	09:00	04:41	W300	–
V	91	05/05/83	18:27	13:53	W160	3.8

* Uncertain predictions.

regarding the nature of the SES, i.e. whether it has an external or internal source.

Table 1 shows details regarding the predictions issued in each of the five cases. Figures 7, 9a, 10a and 11 show the recordings and the computed residuals from the magnetotelluric station in Pirgos that include the time of appearance of the SES at the telluric station network corresponding to cases I, III, IV and V, respectively. Similarly, Figs. 8, 9b and 10b show the recordings and the computed residuals from the magnetotelluric station in Amfiloxia that include the time of appearance of

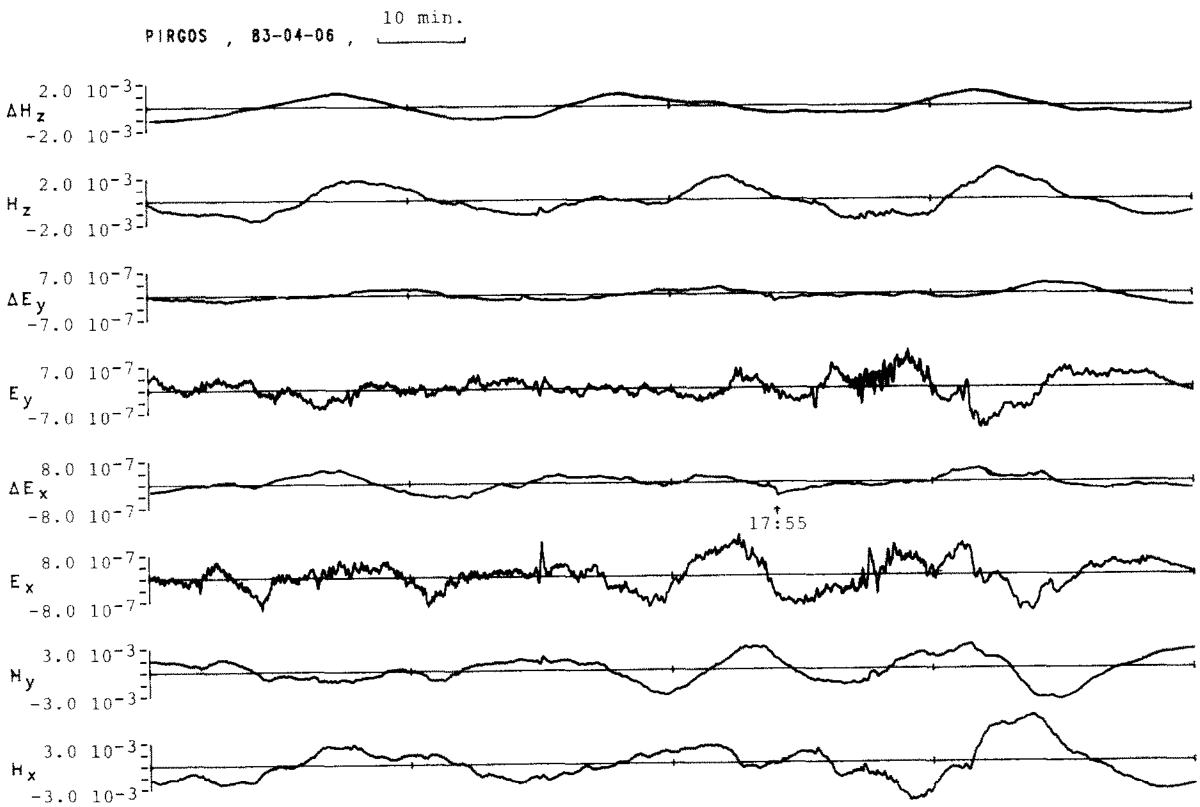


Fig. 7. Simultaneous recording of the magnetotelluric components and the computed residuals from the magnetotelluric station in Pirgos for case I. Index x refers to the north–south direction, y to the east–west direction and z to the vertical direction. H is the magnetic field component and E is the electric field component. ΔE and ΔH are the computed residuals. Units are A m^{-1} for the magnetic field and V m^{-1} for the electric field. The time indicated is G.M.T.

the SES at the telluric station network corresponding to cases II, III and IV, respectively.

No recordings are available from the magnetotelluric station in Amfiloxia corresponding to the time interval in cases I and V, nor for the Pirgos magnetotelluric station in case II. This is because station maintenance was being carried out during the specified intervals.

Case I

The computed residuals from the magnetotelluric recordings in Pirgos (Fig. 7) show a low-frequency periodic background "noise" due to errors in estimating the impedance tensor around that frequency. A transient signal is clearly superimposed on this background, in both electric residuals, at the same time as the reported SES appearance. The amplitude of the transient is larger in the x-direction (north–south) and it is of the order of 4.0×10^{-7} V m^{-1}. The transient signal has a duration of about 5 min.

It is very difficult in this case to draw any conclusions regarding the source of this transient from the recordings of only one station. However the amplitude of the transient as recorded by the magnetotelluric station in Pirgos appears to be one order of magnitude lower than that of the SES reported by Varotsos and Alexopoulos (1984a). This difference is most likely due to the different surface resistivities of the two sites at Pirgos.

Case II

The computed residuals from the magnetotelluric recordings in Amfiloxia (Fig. 8) show a transient signal superimposed on the background noise of the computed residual in the x-direction, at the same time as the reported SES appearance. The duration of the transient signal is about 3 min and it has an amplitude of the order of 6.0×10^{-6} V m^{-1}, which is compatible with the amplitudes reported by Varotsos and Alexopoulos (1984a).

Also displayed at the beginning of the same

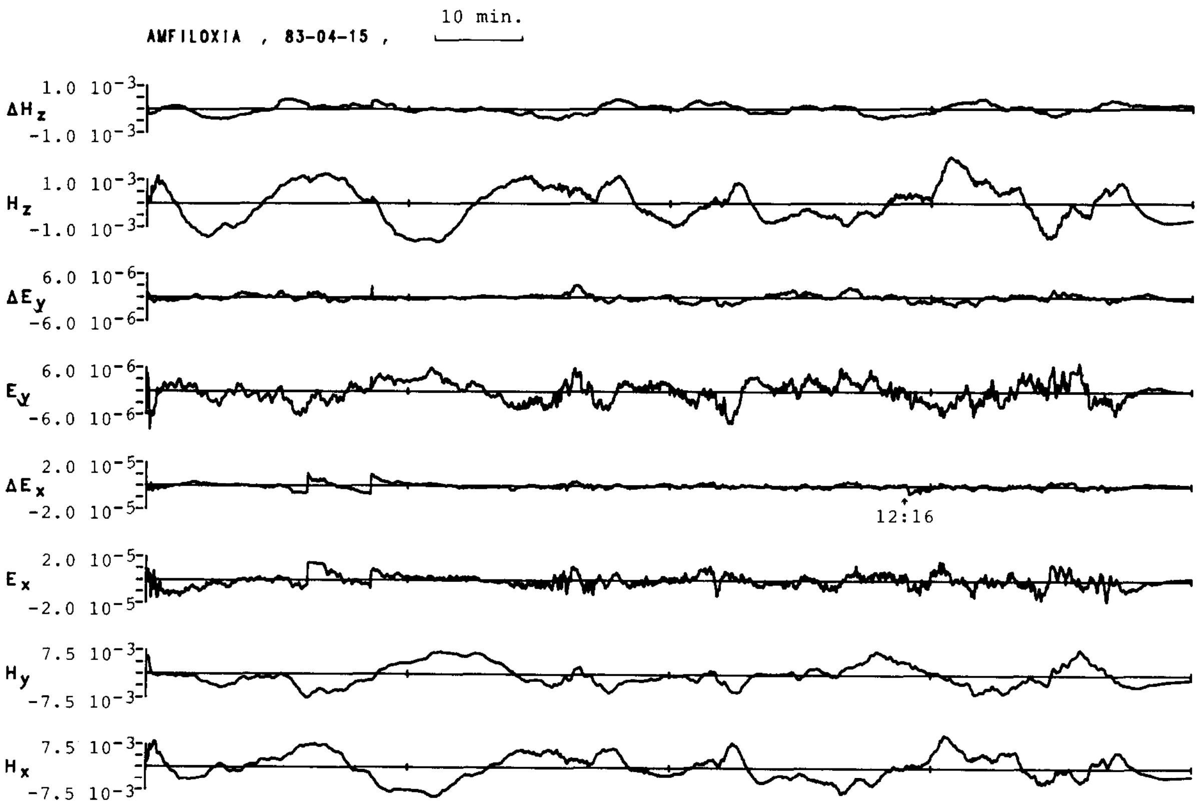


Fig. 8. Simultaneous recording of the magnetotelluric components and the computed residuals from the magnetotelluric station in Amfiloxia for case II. Index x refers to the north–south direction, y to the east–west direction and z to the vertical direction. H is the magnetic field component and E the electric field component. ΔE and ΔH are the computed residuals. Units are A m^{-1} for the magnetic field and V m^{-1} for the electric field. The time indicated is G.M.T.

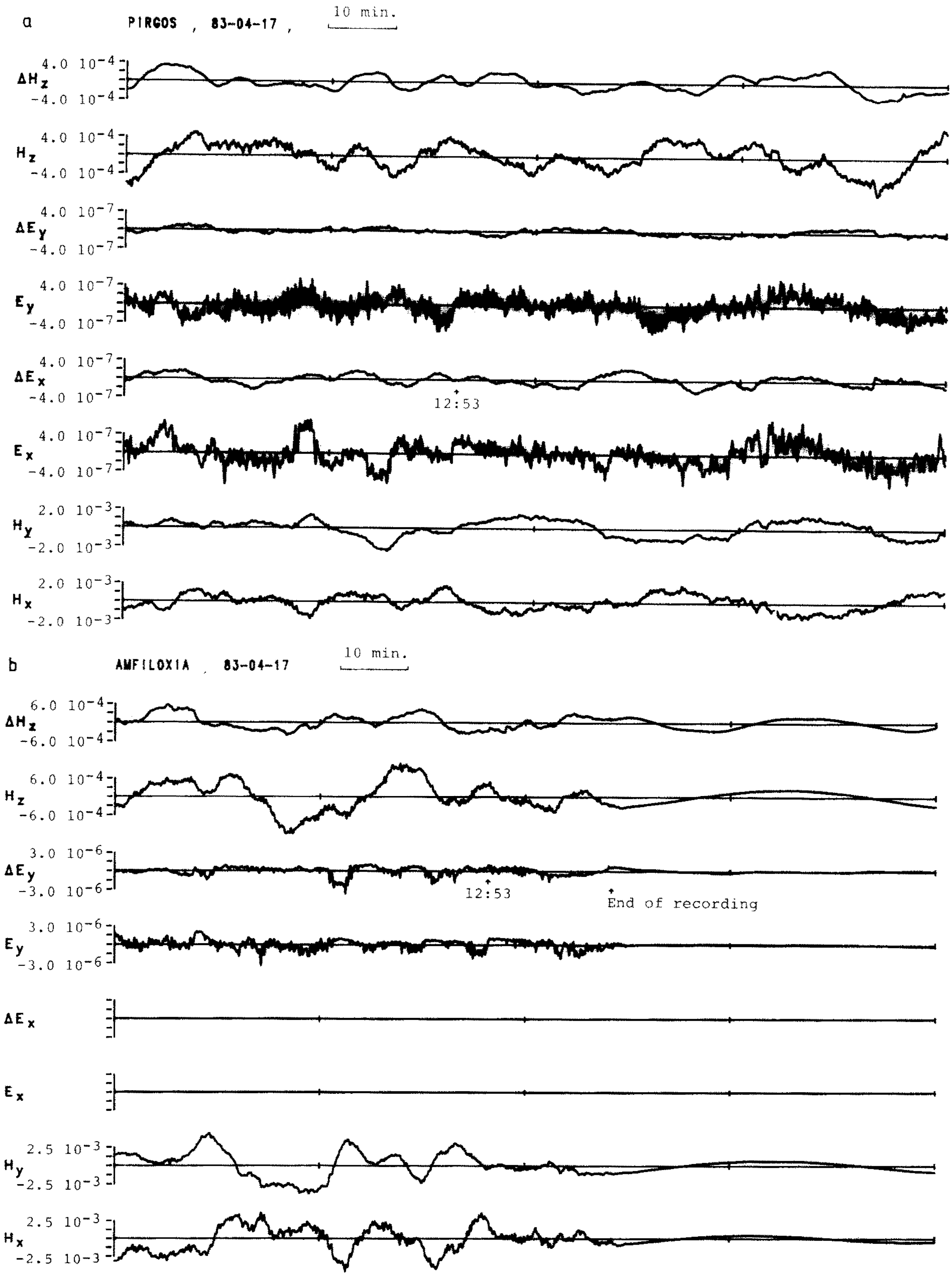


Fig. 9. Simultaneous recording of the magnetotelluric components and the computed residuals from the magnetotelluric stations in Pirgos (a) and Amfiloxia (b) for case III. Index x refers to the north–south direction, y to the east–west direction and z to the vertical direction. H is the magnetic field component and E is the electric field component. ΔE and ΔH are the computed residuals. Units are A m^{-1} for the magnetic field and V m^{-1} for the electric field. The time indicated is G.M.T.

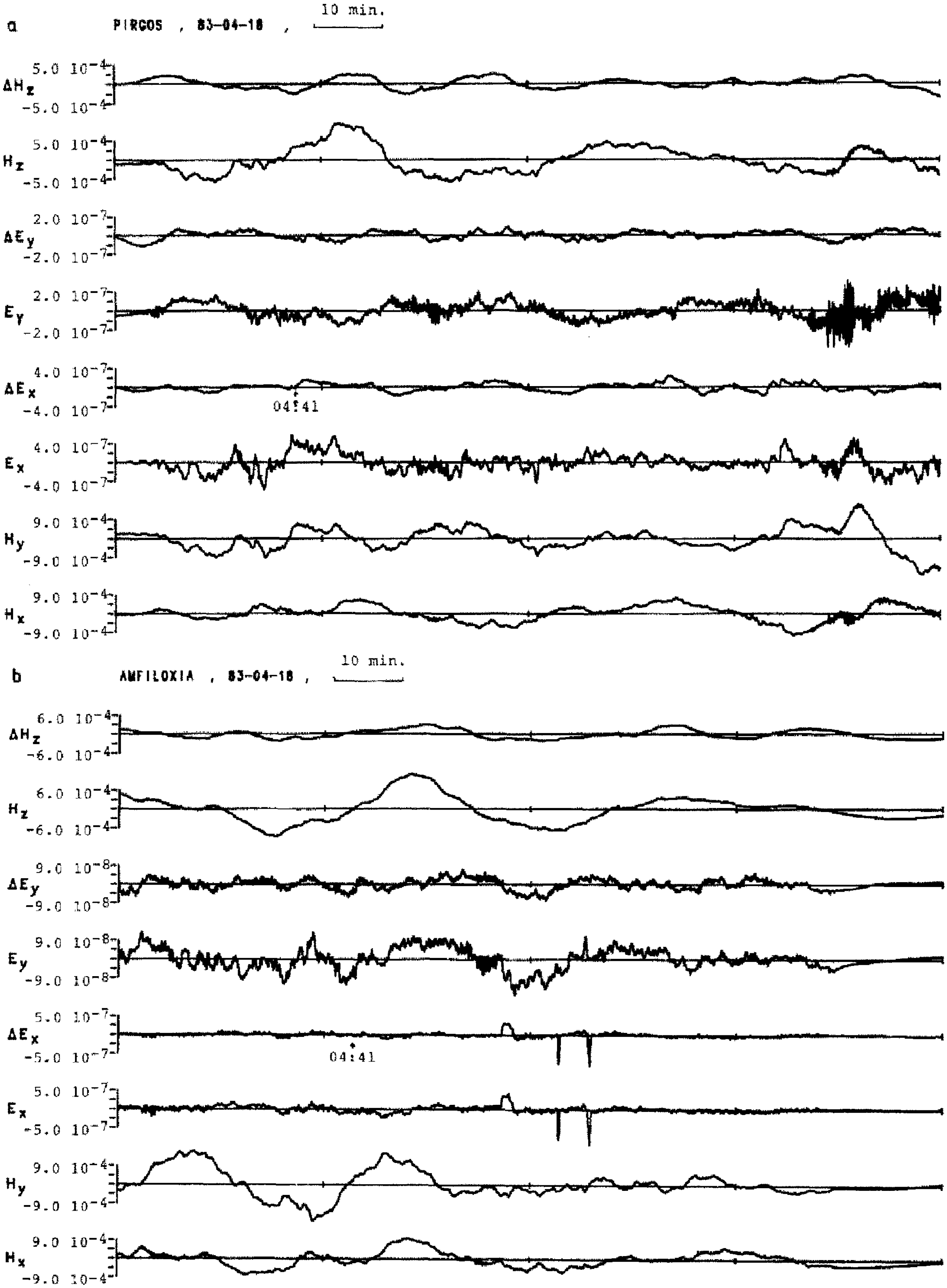


Fig. 10. Simultaneous recording of the magnetotelluric components and the computed residuals from the magnetotelluric stations in Pirgos (a) and Amfiloxia (b) for case IV. Index x refers to the north–south direction, y to the east–west direction and z to the vertical direction. H is the magnetic field component and E is the electric field component. ΔE and ΔH are the computed residuals. Units are A m^{-1} for the magnetic field and V m^{-1} for the electric field. The time indicated is G.M.T.

segment are two transient signals which can be related to an artificial source due to their sharp rise time. A residual field anomaly similar to the one at 12 : 16 may be found about 20 min later in the same measuring direction.

In view of this and given the presence of an artificial source at Amfiloxia, it becomes rather difficult to draw any conclusion regarding the source of this transient, which nevertheless appears on the electric residual' in the x-direction at Amfiloxia simultaneously with the reported SES appearance at the Pirgos telluric station.

Case III

A direct comparison of Figs. 9a and 9b, displaying the recordings and the computed residuals for the magnetotelluric stations in Pirgos and Amfiloxia, at the time of the reported SES, reveals no transient signals superimposed on the low background "noise" of the residual electric fields.

One of the directions of the electric field (E_x) in Amfiloxia was not monitored due to bad earth-electrode coupling. The other (E_y) shows a transient variation at the same time as the reported SES, but this is clearly accompanied by a magnetic field variation as seen on the H_x recording. The same observation is made from Pirgos where the same transient variation is seen simultaneously on the E_x and H_y components of the electric and magnetic fields, respectively.

It should be pointed out that the telegram corresponding to the SES in this case issued an "uncertain prediction" and the suspicion that the signal was induced by the external magnetic field is confirmed clearly by applying the residual methodology to the magnetotelluric data.

Case IV

As in the previous case, a direct comparison of the recordings and the computed residuals in Figs.

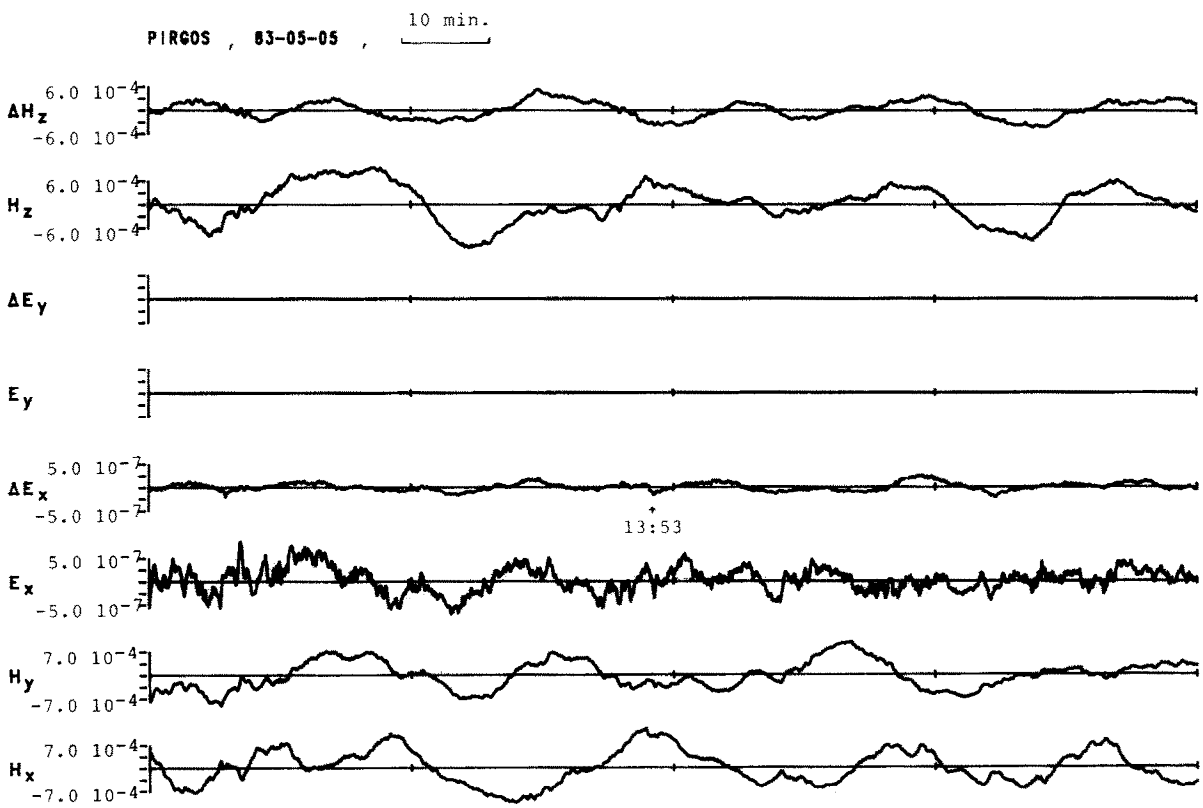


Fig. 11. Simultaneous recording of the magnetotelluric components and the computed residuals from the magnetotelluric station in Pirgos for case V. Index x refers to the north–south direction, y to the east–west direction and z to the vertical direction. H is the magnetic field component and E is the electric field component. ΔE and ΔH are the computed residuals. Units are A m^{-1} for the magnetic field and V m^{-1} for the electric field. The time indicated is G.M.T.

10a and 10b, from the magnetotelluric stations in Pirgos and Amfiloxia, respectively, at the time of the reported SES, leads to the following observations. No transient signal is seen on the residuals from the Amfiloxia recording. The Pirgos recording shows a transient variation of the electric field component E_x which is accompanied by a simultaneous transient variation of the magnetic field component H_y having a duration of about 13 min. The electric residual ΔE_x for Pirgos shows a small component of this transient variation within the background noise and this is due to errors in the estimation of the impedance tensor at these frequencies. Since the same variation appears on the magnetic recordings of Amfiloxia but not on the computed electric residuals it is considered an external magnetic field variation.

The telegram issued in this case, as in the previous case, spoke of an 'uncertain prediction'. The suspicion that the SES was induced by the external magnetic field is again confirmed with the methodology presented here.

Case V

Figure 11 displays the magnetotelluric recordings and the computed residuals from the station at Pirgos which includes the time of the reported SES. The E_y direction had earth-electrode coupling problems and is not displayed. However one can see a signal superimposed on the residual ΔE_x at the same time as the reported SES in this case. The amplitude of the signal at this station is again one order of magnitude less than that of the SES reported and as in case I, this is attributed to the different surface resistivities of the two sites at Pirgos.

As in cases I and II, it is extremely difficult to draw any conclusions on the source of this electric signal, solely on the basis of this data.

Seismicity and correlation with issued predictions

Seismological data from the Preliminary Seismological Bulletin of the National Observatory of Athens for the period April 3, 1983 to May 12, 1983 show no earthquakes of magnitude $M_L(\text{ATH}) > 4.3$ to have occurred within a radius of 150 km from Pirgos. However, there were roughly 20 seismic events ranging in magnitude from $M_L(\text{ATH}) = 3.7$ to $M_L(\text{ATH}) = 4.3$. Most of these took place in the Kefalonia region and are aftershocks to the January 1983 earthquake sequence. Three events during the recording period were of magnitude $M_L(\text{ATH}) = 4$ and occurred roughly 120 km to the west of Pirgos. The largest events during the recording period were two of magnitude $M_L(\text{ATH}) = 4.3$ which occured in the Kalavrita region roughly 55 km east-northeast of Pirgos. These data can be seen in Table 2.

Varotsos and Alexopoulos (1984b) claim that "every sizable earthquake is preceded by an SES". The term "sizable" refers to a limitation of the telluric method, which is unreliable for predicting earthquakes of small magnitude ($M_L(\text{ATH}) < 4.0$) and of large epicentral distance from the field stations ($r > 100$ km), due to difficulties in identifying the low amplitude SES in the presence of the background magnetotelluric noise.

In order to examine objectively the cross-correlation between SES and earthquake occurrence one should refer to Varotsos and Alexopoulos (1984b) where this task was performed using a

TABLE 2

Earthquakes with $M_L(\text{ATH}) \geq 4$ occurring within a radius of 150 km from the Pirgos station between April 3, 1983 and May 8, 1983 (epicentral coordinates are given by Strasbourg Monthly Bulletin and local magnitudes by the National Observatory of Athens Preliminary Monthly Bulletin)

Date	Time (G.M.T)	Epicentre (°N–°E)	Epicentral dist. from Athens (km)	Magnitude (M_L)
10/04/83	22:53	38.48–20.07	W340	4.0
11/04/83	17:23	37.95–21.99	W150	4.3
19/04/83	10:23	38.13–20.28	W300	4.0
22/04/83	02:46	38.07–20.25	W300	4.0
08/05/83	22:44	38.25–22.50	W130	4.3

significant number of sizable (M_L(ATH) $\geq$ 4.0) earthquakes well separated in time. In view of the few sizable earthquakes during the recording period we are concerned with here, and given the fact that four out of five occurred within a window of 6–115 hours from each other, one can hardly make an objective cross correlation here. Nevertheless, by directly comparing the issued predictions in Table 1 and the earthquakes in Table 2 we may note the following. The prediction issued by telegram 79 may correspond to either of the earthquakes on April 10 and April 11, regarding the time window between SES appearance and earthquake occurrence. However, it can be correlated better with the earthquake on April 11, regarding the location of this event.

The earthquake on April 19 occurred within the time window of the prediction issued by telegram 81.

Anomalies induced by the external magnetic field were present at the time of the reported SES for the predictions issued by telegrams 83 and 84. Telegrams 83 and 84 issued uncertain predictions.

The prediction of telegram 91 is compatible with the earthquake on May 8, regarding time, position and magnitude.

It should be noted that in cases I, II and V, corresponding to telegram numbers 79, 81 and 91, an electric signal was found to have been present in at least one of the residuals from the magnetotelluric recordings simultaneously with the appearance of the reported SES in the Greek telluric network. In the remaining two cases suspicions of artificial SES were further confirmed by the residual method presented earlier.

Discussion

Variations in the local electric field preceding earthquakes have long been reported in the literature and have been summarized by Rikitake (1976). However, their correlation with earthquake occurrences has been difficult to establish because background fluctuations in the electric field of external origin have not been completely eliminated.

It is obvious that measurements of only the telluric field can produce ambiguities in the results, and knowledge of the source field is required. In this paper, we have presented a method for removing magnetotelluric field variations of external origin from short period telluric data using magnetotelluric impedance tensor analysis. The results from continuous short period magnetotelluric measurements conducted in Greece indicate that impedance tensor analysis is successful in estimating the electromagnetic induction at the measuring point with great accuracy. The subsequent calculation of the residual electric field clearly improves the detection of any anomalous change in the telluric field. In this first step towards a more quantitative analysis of electromagnetic field variations prior to earthquakes, the information available from having simultaneous recordings at two sites was used only in a rather qualitative fashion. The measurements are clearly noise contaminated and this can lead to difficulties in interpreting the nature of the residual electrical variations observed. It would be of interest for future work to incorporate simultaneous measurements of the magnetic field from more than one station, whereby a better description of the noise terms involved in the residual calculations could be obtained.

The present method was applied to the detection of the suspected SES in five cases during the recording period. Of the five cases under study, in two it was found that an external transient magnetic disturbance was present simultaneous to the reported SES time. For these cases an uncertain prediction was actually issued. For the remaining three cases a transient electric signal was observed superimposed on the computed residual electric field of the magnetotelluric recordings, simultaneous to the SES reported by Varotsos (P. Varotsos, pers. commun. 1983).

In view of the absence of larger earthquakes during the time of recording, our limited data do not contribute to the establishment of the relation between reported anomalous changes of the geoelectrical field (SES) and earthquakes. It is obvious that recordings prior to small magnitude earthquakes, such as those presented here, are insufficient to establish such a relation. However, the magnetotelluric results presented here hardly contradict the observations from the ongoing research in the Greek telluric network. As a result, this paper may be considered to be of a preliminary nature, suggesting that the residual methodology described above may prove useful in future research into earthquake prediction by means of geoelectrical currents.

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