Tectonophysics, 224 (1993) 103–111
Elsevier Science Publishers B.V., Amsterdam

Periodic variations in the Earth's electric field as earthquake precursors: results from recent experiments in Greece

C. Thanassoulas [a] and G. Tselentis [b]

[a] *Institute of Geology and Mineral Exploration, Department of Geophysical Research, 70 Messoghion Avenue, 115-26 Athens, Greece*
[b] *University of Patras, Department of Geology, Section of Applied Geology and Geophysics, 261-10 Patras, Greece*

(Received October 20, 1990; revised version accepted June 15, 1991)

ABSTRACT

Thanassoulas, C. and Tselentis, G., 1993. Periodic variations in the Earth's electric field as earthquake precursors: results from some recent experiments in Greece. In: P. Varotsos and O. Kulhánek (Editors), Measurement and Theoretical Models of the Earth's Electric Field Variations Related to Earthquakes. *Tectonophysics*, 224: 103–111.

The results obtained during an extensive investigation of the variations in the Earth's electric field at three tectonically active areas in Greece, and their relation to the occurrence of earthquakes are described. In all three cases, a 24 h periodic oscillation of the Earth's electric field was observed prior to large imminent earthquakes, one of which was the September 13th, 1986 (measuring $M_s = 6.2$ R) earthquake which devastated the city of Kalamata. Finally, two physical processes, which could explain the above phenomenon are proposed.

1. Introduction

The development of methods of earthquake prediction proceed from the assumption that variations in a great number of geophysical and geochemical fields occur before the onset of any strong earthquake, due to the accumulation of geotectonic stresses in its focal area. The summarized data of precursors (Rikitake, 1976; Mogi, 1986) show the presence of a wide range of precursor times (from several minutes to several years) for various geophysical fields; indicating the existence of an almost uninterrupted frequency spectrum of precursors. These probably, reflect the fracturing of blocks of rock of various sizes.

Recordings of changes in the natural electric field of the Earth, in search of precursors of strong earthquakes, have been reported by many researchers. In the USSR, extensive experiments in the tectonically active area of Kamchatka (Mjachkin et al., 1971; Mjachkin et al., 1975; Sobolev, 1975; Fedotov et al., 1977) have revealed the existence of some characteristic bay-like anomalous changes in the Earth's electric field 3–16 d prior to the main shock and at epicentral distances of up to 150 km.

In China (Coe, 1971), these anomalies are expressed by an abrupt drop in the electric field, a few hours prior to the earthquake, which recovers after the occurrence of the shock. For example, the successfully predicted Haicheng earthquake of 1975, was preceded by an abrupt drop in the electric field at a station located at a distance of 25 km from the epicentre (Raleigh et al., 1977). Similar phenomena have also been reported in Japan (Koyama and Honkura, 1978).

In Greece, systematic observation of changes in the Earth's electric field prior to earthquakes began in 1981, using a network of 18 stations (Varotsos and Alexopoulos, 1984a,b; Meyer et al., 1985) telemetrically connected to a central station in Athens. Systematic analysis of the data obtained revealed that, in many cases, a transient change in the Earth's electric field of the order of several millivolts, for a 50 m dipole, and lasting between 1 and 60 min occurred several hours (and in some cases a few days) prior to the shock.

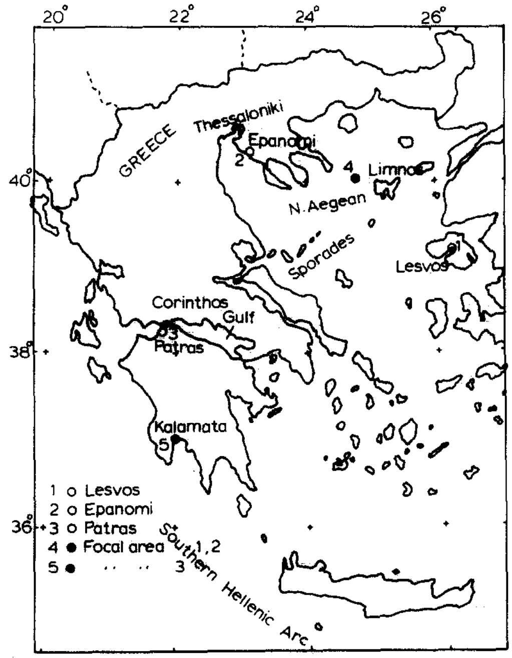

Fig. 1. Location of the three recording sites and the focal areas.

Meyer and Pirjola (1986), working on some recordings of the Greek geoelectric network, observed periodic anomalies in the Earth's electric field, with a 24 h period, prior to an earthquake sequence in western Greece. These anomalies, occurring as a periodic component superimposed upon the larger variations in the electric field, started a few days prior to the shock. The periodic variations in the electric field appear to built up about 4–5 days prior to the main shock, with the successive peaks increasing towards the time of the impending earthquake and a successively decreasing after it.

The purpose of this paper is to discuss the results of some similar investigations which were carried out in three experimental sites in Greece (Fig. 1).

2. Collection of data

The collection of the experimental data was performed during three different periods, employing the following equipment: a 50 m dipole; a self potential back-up system; a low-pass filter with a 5 min. time constant; an analog recording device equipped with an A/D converter and an RS232 port for direct communication with a microcomputer.

2.1 First recording period: the Lesbos Island experiment

During the period January 29th, 1982, to March 3rd, 1982, continuous measurements of the Earth's natural electric field were carried out (Thanassoulas, 1982) on the island of Lesbos (Fig. 1). The North Aegean is an area with relatively high seismic activity (Drakopoulos and Makropoulos, 1983). During the period 1978–1982, a considerable increase in this activity was observed. A main shock of $M_s = 7$ occurred in the northeastern area of the Sporades trough (Fig. 1), to the west of the Island of Limnos.

Statistical analysis of the existing data in the area suggested that a second earthquake with a magnitude of not less than 4 was to be expected from the same focal area (Papazachos et al., 1984). Hence, it was decided to install an experimental device for monitoring the Earth's electric field on Lesbos Island. The dipole was installed on the southern part of the island and was directed in such a way as to bisect orthogonally the expected equipotential surfaces of the anomalous SP (self potential) field, originating from the hypothetical focal area in the North Aegean. The expected earthquake occurred on February 9th, 1982, and was of magnitude $M_s = 4.8$ R.

2.2 Second recording period: the Epanomi experiment

During the summer of the next year (1983), the experiment was repeated (Thanassoulas and Tselentis, 1986), installing the dipole in the Epanomi area, which is located a few kilometres eastward of the city of Thessaloniki (Fig. 1). The aim of the experiment was to examine the behaviour of the Earth's electric field in a seismically inactive period in the same area. The recording period lasted from July 24th, 1983, to August 22nd, 1983. On August 6th, 1983, an unexpected, strong earthquake ($M_s = 6.6$) occurred and was followed by a sequence of five aftershocks, all with magnitudes greater than 4.1 R.

2.3 Third recording period: the Patras experiment

The Gulf of Corinth and the Southern Hellenic Arc are two regions of pronounced seismic activity. During the summer of 1986, a micro-earthquake network was installed around the western part of the Gulf of Corinth, in order to record the seismic activity of the area. Thus, it was decided, in addition to the observation of the earthquake activity, to perform a continuous monitoring of the variations in the Earth's electric field as well. The dipole was installed on the outskirts of the city of Patras. The experiment lasted from August 24th, 1986, to September 17th, 1986. On September 13th, 1986, a strong earthquake with magnitude $M_s = 6.2$ occurred, devastating the city of Kalamata; 21 people were killed and many hundreds were injured.

3. Analysis of the experimental results

3.1 The Lesbos experiment

The data obtained for the entire recording period are shown in Figure 2a. Two different types of variations in the Earth's electric field are revealed in the data. The first is a strong variation, having the form of a step. This starts about 50 h prior to the main shock. This anomaly is more clearly shown in Figure 2b, where the original data have been low-pass filtered by a moving average technique. The rate of variation in the electric field obtained is of the order of 0.2 mV/h for a 50 m dipole. At the time the earthquake occurred, a drastic drop in the field, of the order

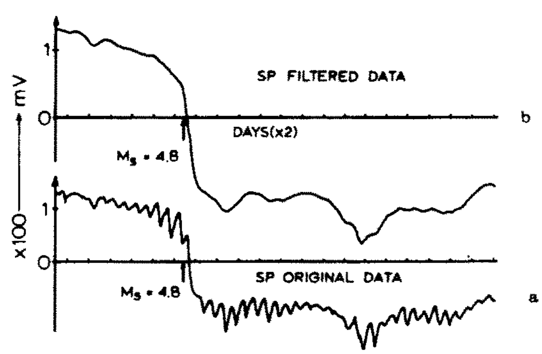

Fig. 2. Original and low-pass filtered data.

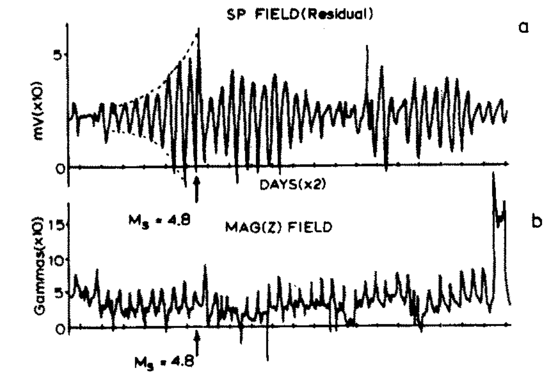

Fig. 3. Variations in the Earth's residual electric and magnetic field between 29/1/1982 and 10/3/1982.

of 150 mV, was observed. It is interesting to mention that the same type of anomaly was reported by Meyer and Pirjola (1986), prior to an earthquake in western Greece and prior to the Haicheng earthquake (Raleigh et al., 1977).

Figure 2a suggests that there is a 24 h periodic anomaly, modulating the above long period anomaly, which starts to built up almost 4 d prior to the shock. This second type of variation in the electric field is more obvious in Figure 3a, where the superimposed periodic signal has been separated. Judging from this figure, it is evident that no significant oscillation of the electric field is observed prior to January 30th. However, successive peaks appear to increase exponentially towards the time of the impending earthquake. After the main shock, this periodic oscillation is still observed in the recording with progressively decreasing amplitudes. We studied only the first segment of the graph, which is related to the main shock. A series of aftershocks produced similar effects on the electric field recorded, as can be seen in Fig. 3a.

In order to reveal any possible correlation between the variation in the Earth's magnetic and electric fields, geomagnetic records were obtained from the Penteli observatory (close to Athens). We used the most prominent component of the magnetic records (z component). Figure 3b shows the Earth's magnetic field for the entire recording period.

Next, the recording period was divided into sub-periods, the first lasting from January 29th to February 3rd, 1982, which is long before the

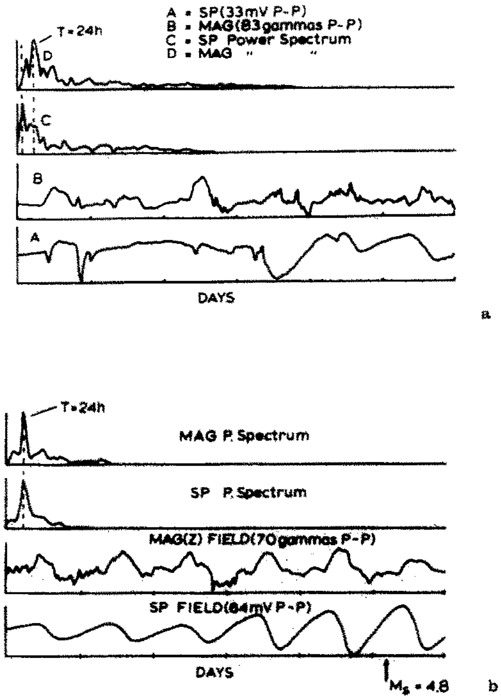

Fig. 4. Comparison between the variations in the Earth's electric and magnetic field and their power spectra for the periods 29/1/1982–3/2/1982 and 4/2/1982–9/2/1982.

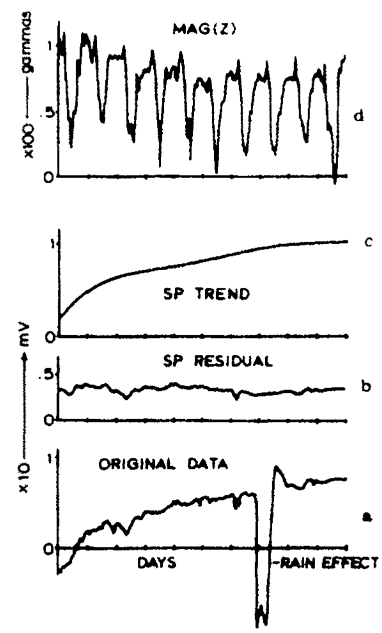

Fig. 5. Variation in the Earth's electric (raw data, residual and trend) and magnetic field, for the period 24/7/1983–2/8/1983.

event, and the second sub-period lasting from February 4th to the 9th, 1982, within which period the earthquake occurred. Figure 4 shows the variations in the electric and magnetic fields obtained for the two sub-periods. The corresponding power spectra of the two fields are also shown. The calculated power spectra reveal that, during the first sub-period, only a very small coupling between the two fields is evident. However, a very high degree of correlation between the two spectra is revealed for the second sub-period. It is interesting to note that the dominant oscillation in the power spectrum has a 24 h period.

3.2 The Epanomi experiment

The experimental data are subdivided in three different periods. Figure 5a, shows the variations obtained in the electric field for the first period, which lasted from July 24th to August 2nd, 1983, while Figure 5b shows the residual electric field after the regional trend (shown in Figure 5c) has been removed. The variations in the magnetic field for the same period are shown in Figure 5d.

Following the same approach as before, the power spectra of the electric and magnetic fields were calculated for the above period (Fig. 6). Judging from this figure it would appear that the power spectrum of the magnetic field, as would be expected, is concentrated in the 24 h band. The power spectrum of the electric field, however, is characterized by periods greater than 24 h and a significant difference between the maximum peaks of the two spectra can be seen.

During the second sub-period, which lasted from August 3rd to August 11th, 1983, a signifi-

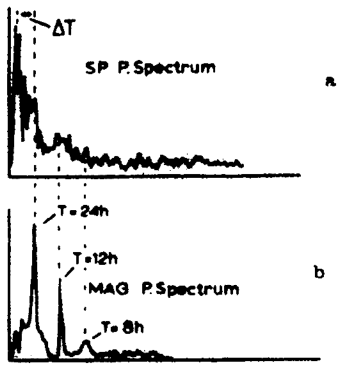

Fig. 6. Power spectra of the Earth's electric (residual) and magnetic field, for the period 24/7/1983–2/8/1983.

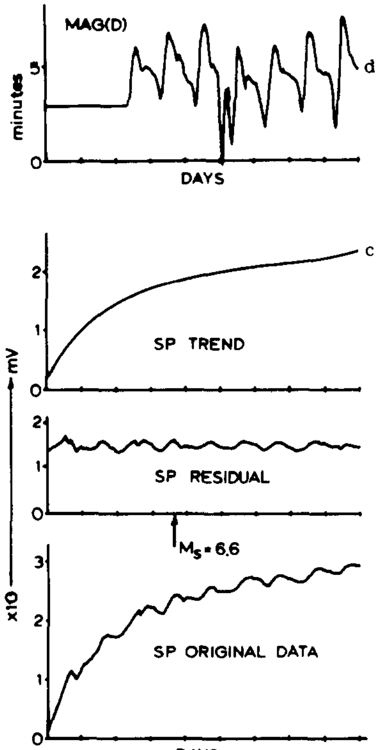

Fig. 7. Variation in the Earth's electric field (raw data, residual and trend) and magnetic field, for the period 3/8/1983–11/8/1983.

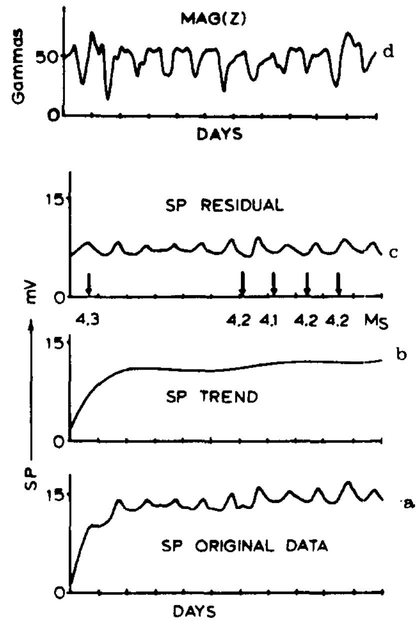

Fig. 9. Variation in the Earth's electric (raw data, residual and trend) and magnetic field, for the period 12/8/1983–22/8/1983.

cant increase in the seismic activity of the area was observed (Rocca et al., 1985). The data obtained are shown in Figure 7, while the corresponding power spectra are shown in Figure 8.

In contrast to the first period, a periodic oscillation of the electric field built up and on August 6th an earthquake of $M_s = 6.6$ occurred, expressed by a sudden decrease in the amplitude of the periodic oscillations. For the same period, it is deduced from the power spectra, that there was a concentration of the energy in the 24 h and 12 h period band for both the magnetic and the electric fields.

Finally, there was a great increase in the seismicity of the area during the third period, where an aftershock sequence occurred. This is expressed by a continuous increase in the amplitude oscillations (Fig. 9). The corresponding power spectra are shown in Figure 10, which reveals a characteristic coupling between the two fields.

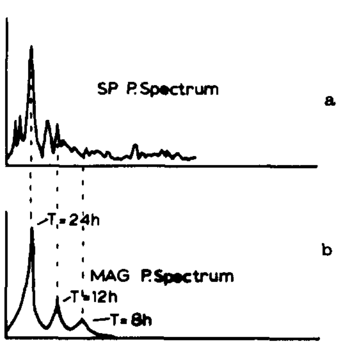

Fig. 8. Power spectra of the Earth's electric (residual) and magnetic field, for the period 3/8/1983–11/8/1983.

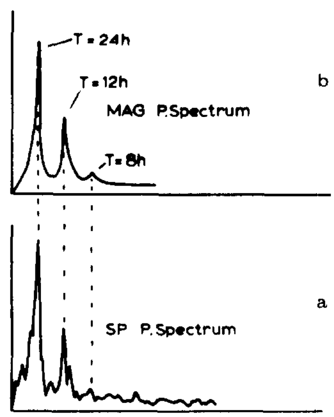

Fig. 10. Power spectra of the Earth's electric (residual) and magnetic field, for the period 12/8/1983–22/8/1983.

3.3 The Patras experiment

Data for this experiment were obtained from August 24th to September 17th, 1986. Due to some malfunction of the recording system, this period was divided (for processing purposes) into three sub-periods, which contain the actual data recorded.

Figure 11a, depicts the data recorded within the first sub-period (24/8/1986–2/9/1986), while Figure 11b shows the residual data for the same time interval, after some long wavelength trends have been removed. Figure 11c shows the corresponding power spectrum of the residual data. From this figure, it is obvious that there is no energy concentration in the 24h period band, while the greatest energy peak occurs at a wavelength greater than 24 h (almost 3 d).

After the above recording interval, there is a gap in the recording sequence of 1 d (3/9/1986). Data acquisition was resumed from September 4th to the 10th, 1986, and the data obtained are shown in Figure 12a. Figure 12b shows the residual detrended data for very long periods, while Figure 12c shows their power spectrum. In Figure 12 a change in the appearance of the power spectrum for this time period, as compared to the previous one, can be seen: the energies are concentrated towards the 1 d period and its higher harmonics (12 h, 8 h).

On September 11th, 1986, another technical problem disturbed the recording. This meant that, in fact, the last recording sub-interval started on September 12th 1986 (18 h) and lasted until September 17th (24 h). The data obtained are

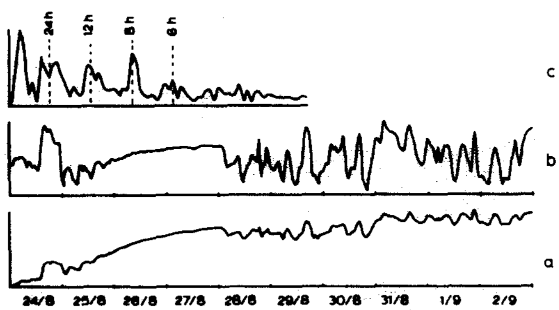

Fig. 11. Variation in the Earth's electric field (raw data and residual) and the corresponding power spectrum, for the period 24/8/1986–2/9/1986.

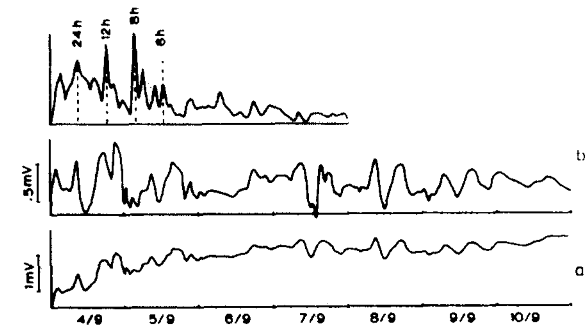

Fig. 12. Variation in the Earth's electric field (raw data and residual) and the corresponding power spectrum, for the period 4/9/1986–10/9/1986.

shown in Figure 13a, while Figure 13b depicts the detrended (residual) data for long periods. The corresponding power spectrum is shown in Figure 13c. It is worth noting the distinct 24 h peak in this spectrum, as well as its second harmonic (12 h). The corresponding oscillation of the Earth's electric field (24 h period), is also obvious in the residual data plot (Fig. 13b), and lasts for the whole of September 13th. The same day, an earthquake of $M_s = 6.2$ occurred just below the city of Kalamata, about 200 km south of the site of the installed dipole (Fig. 1). As it is evident from Figure 13b, after the above event, the 24 h period oscillation of the Earth's electric field disappears. This is clearer in Figure 13d, where all the high frequencies have been removed from

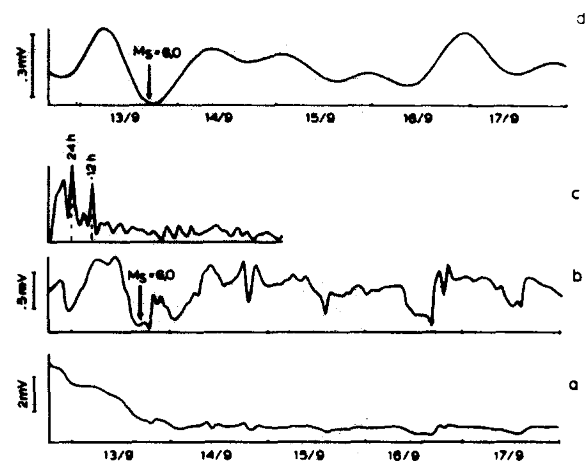

Fig. 13. (a–c) Variation in the Earth's electric field (raw data and residual) and the corresponding power spectrum, for the period 13/9/1986–17/9/1986. (d) Low-pass filtered data (residual) of the Earth's electric field for the period 13/9/1986–17/9/1986.

the residual data so that the 24 h period oscillation is highlighted. A decrease in its amplitude after the occurrence of the earthquake can be seen.

4. Discussion

From all the three experiments mentioned above, we can make the following observations:

(1) Long before the occurrence of a shock, the Earth's electric field is dominated by long wavelengths, with periods greater than 24 h, superimposed on random, high frequency noise.

(2) As we move towards the time of occurrence of the event, a characteristic oscillation of the electric field with a 24 h period builds up and is superimposed on the previous long wavelengths.

(3) A few days prior to the occurrence of the earthquake, this 24 h period oscillation increases in amplitude, nearly exponentially, until the earthquake begins, when a decrease in the amplitude of the oscillation is observed.

Similar observations have been also reported by Meyer and Pirjola (1986). These authors studied recordings obtained from the VAN network and the same kind of oscillation was revealed (Fig. 14), some days prior to an earthquake measuring $M_l = 6.2$.

From the above, it can be concluded that the 24 h period oscillation of the Earth's electric field observed is associated to a high degree with the dynamic conditions in the focal area prior to the occurrence of the shock.

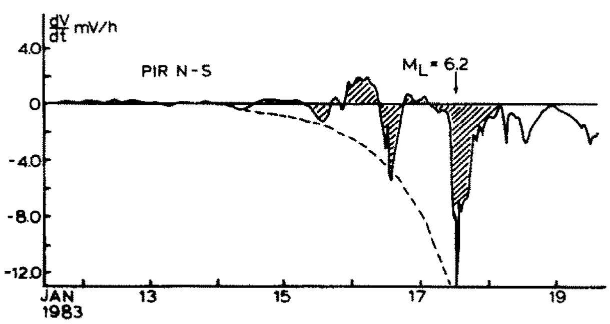

Fig. 14. Time derivative of the Earth's electric field, for the period 12/1/1983–19/1/1983, recorded at Pirgos site, Greece (after Meyer, 1986).

Varotsos and Alexopoulos (1984a,b), proposed the "piezostimulated" model to explain the electric signals generated in the focal area. This model does not account for the observed 24 h period observed in the oscillations of the Earth's electric field.

Meyer and Pirjola (1986), pointed out that these oscillations could not be induced by variations in ionospheric currents generated from magnetic field variations. It was shown that induced currents should have very low amplitudes, that generate a voltage drop on the ground of the order of 1.5 mV, for a 50 m dipole. This contrasts with the signals observed in the Lesbos experiment, which were of the order of several decades of millivolts. In an attempt to explain the origin of these 24 h period oscillations, two models are proposed.

The *induction model* is based on induction currents in the ground from the ionosphere. According to this hypothesis, it is accepted that the amplitudes of the induced telluric currents at the focal area, are "stress dependant", that is, in the equation for the induced electric field (Meyer and Pirjola, 1986):

$$E(t) = F(B_0, \mu_0, a, \sigma, t) \quad (1)$$

An extra stress-dependant parameter $g(\phi)$, is included, so that the modifying the electric field $E(t)$ can be described by:

$$E(t) = F(B_0, \mu_0, a, \sigma, t) g(\phi) \quad (2)$$

where B_0, μ_0, a, σ and t are parameters described by Meyer and Pirjola (1986), and $g(\phi)$ is a functional stress load (ϕ) which is applied in the focal area. In order to explain the nearly exponential increase in the amplitudes of the oscillations observed, it is assumed that the function $g(\phi)$ can be described by the following analytical expression:

$$g(\phi) = Ae^{\phi(t)} \quad (3)$$

where $\phi(t)$ is the stress applied at the focal area and A is a constant.

As long as the stress is small, the term $g(\phi)$ in eqn. (2) is negligible and does not influences the Earth's electrical field significantly. As the stress starts to increases within the focal area, the fac-

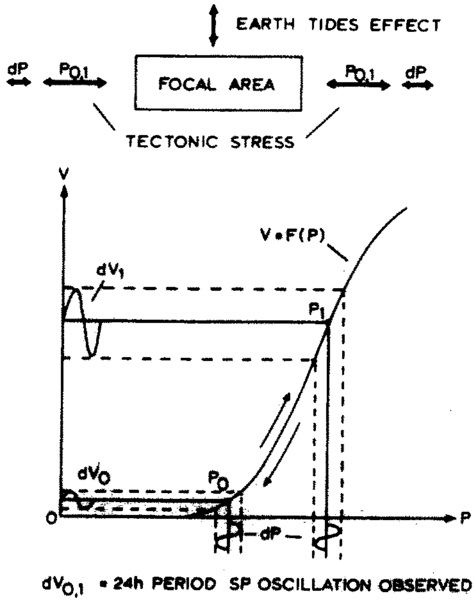

Fig. 15. Schematic representation of the proposed large-scale piezoelectric model mechanism.

tor $g(\phi)$ takes large values, thus it modifies the electric field of the Earth to a considerable degree, until the occurrence of the shock, when the decrease in the stress applied results in a drop in the observed variations in the Earth's electric field towards the previous, undisturbed levels.

Large-scale piezoelectric phenomena is the second model proposed for the explanation of the 24 h period oscillations. The generating mechanism proposed is explained in Figure 15. Under large stress levels the crystalline basement exhibits a piezoelectric behaviour. Figure 15 shows piezoelectric potential (V) as a function of the pressure (P), applied to a block of crystalline basement.

At low stress levels, the function $V = F(P)$ is either constant or has a very low gradient. Above a certain threshold the gradient increases, so that the pressure component, $\mathrm{d}P$, induced by the tidal components, $K1$ (23.93 h) and $P1$ (24.07 h) and, most probably, from the higher harmonics (12 h), modulates the piezoelectric potential generated in the focal area, with a period equal to the period of the tides (Knopoff, 1964).

It is obvious that the amplitude of the oscillations generated must depend upon the dynamic (stress) state of the focal area and can be described by the following equation:

$$V(t) = K(\partial V/\partial p)\mathrm{d}P \tag{4}$$

where K is a constant and $\mathrm{d}P$ is the oscillating tidal component.

In both the above models an electric potential is generated within the focal area and the electric field produced in this way can be detected at great distances from the earthquake's epicentre.

5. Conclusions

The systematic investigation of the Earth's electric field, in conjunction with earthquake activity, revealed the existence of a 24 h periodic oscillation in the monitored field, which starts to develop a few days prior to the occurrence of the earthquake. This phenomenon could be of use in short-term earthquake prediction. For this reason, extensive recordings of the Earth's electric field should be carried out using monitoring networks, comprising dipoles with various orientations, in tectonically active areas. The data obtained should be scrutinized to reveal possible periodicity in the oscillations of the electric field. More research should also be carried out on the estimation of the various earthquake parameters (e.g., focal area, origin time and magnitude).

Since the focal area can be described as an electric potential source (electrically polarized fault plane), it is possible that some of its geometric and electrical parameters (length, strike direction, depth extent, dip angle and electrical charge) could be estimated using conventional potential inversion techniques on models simulating faults (like the "patch model" used in geothermal exploration with the self-potential method), provided that adequate data are available.

References

Coe, R.S., 1971. Earthquake prediction programme in the People's republic of China. EOS, Trans. Am. Geophys. Union, 52(12): 940–943.

Drakopoulos, J. and Makropoulos, K., 1983. Seismicity and hazard analysis studies in the area of Greece. Univ. Athens Seismol. Lab. Publ., 1: 1–184.

Fedotov, S.A., Sobolev, G.A., Boldyrev, S.A., Gusev, A.A., Kondratenko, A.M., Potapova, O.V., Slavina, L.B., Theophylaktov, V.D., Khramov, A.A. and Shirokov, V.A., 1977. Long and short term earthquake prediction in Kamchatka. Tectonophysics, 37: 305–321.

Knopoff, L., 1964. Earth tides as a triggering mechanism for earthquakes. Bull. Seismol. Soc. Am., 54: 1865–1877.

Koyama, S. and Honkura, Y., 1978. Observations of electric self potential at Nakaizu. Bull. Earthquake Res. Inst., 53: 939–942.

Meyer, K. and Pirjola, R., 1986. Anomalous electrotelluric residuals prior to a large imminent earthquake in Greece. Tectonophysics, 125: 371–378.

Meyer, K., Varotsos, P. and Alexopoulos, K., 1985. Efficiency test of earthquake prediction around Thessaloniki, from electrotelluric precursors. Tectonophysics, 120(1/2): 153–161.

Mjachkin, V., Sobolev, G., Dolbilkina, N., Morozow, V. and Preobrazensky, V., 1971. The study of variations in geophysical fields near focal zones of Kamchatka. Tectonophysics, 14(3/4): 287–293.

Mjachkin, V., Brace, W., Sobolev, G. and Dieterich, J., 1975. Two models for earthquake forerunners. Pure Appl. Geophys., 113: 169–180.

Mogi, K., 1986. Earthquake Prediction. Academic Press, New York, 367pp.

Papazachos, B.C., Kiratzi, A.A., Voidomatis, P. and Papaioannou, C., 1984. A study of the December 1981–January 1982 seismic activity in Northern Aegean sea. Boll. Geofis. Teor. Appl., 26 (101–102): 101–113.

Raleigh, B., Bennet, G., Craig, H., Hanks, T.. Molnar, P., Nur, A., Savage, J., Scholz, C., Turner, R. and Wu, F., 1977. Prediction of the Haicheng earthquake. Trans. Am. Geophys. Union, 58: 236–272.

Rikitake, T., 1976. Earthquake Prediction. Elsevier, Amsterdam, 357pp.

Rocca, A., Karakaisis, G., Karakostas, B., Kiratzi, A., Scordilis, E. and Papazachos, B., 1985. Further evidence on the strike-slip faulting in Northern Aegean trough, based on properties of the August–November 1983 seismic sequence. Boll. Geofis

Sobolev, G., 1975. Application of electric method to the tentative short term forecast of Kamchatka earthquakes. Pure Appl. Geophys., 113: 229–235.

Thanassoulas, C., 1982. Self potential variations measurements at Skala Kallonis area, Greece, for the period 29/1–10/3/82. Open File Rep. E3648, Inst. Geol. Miner. Explor., Athens. Greece, 16 pp.

Thanassoulas, C. and Tselentis, G.A., 1986. Observed periodic variations of the earth electric field prior to two earthquakes in N. Greece. In: Proc. 8th European Conf. Earthquake Engineering (Lisbon, Portugal), Vol. 1, pp. 41–48.

Varotsos, P. and Alexopoulos, K., 1984a. Physical properties of the variations of the electric field of the earth preceding earthquakes, I. Tectonophysics, 110: 73–98.

Varotsos, P. and Alexopoulos, K., 1984b. Physical properties of the variations of the electric field of the earth preceding earthquakes, II. Determination of epicenter and magnitude. Tectonophysics, 110: 99–125.