The latest aspects of telluric and electromagnetic variations associated with shallow and intermediate depth earthquakes in the South Aegean

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Abstract
Recent observations of telluric and electromagnetic field variations (radioemissions) associated with shallow and intermediate depth earthquakes in the South Aegean are presented. A telemetric system, installed on Crete Island, which continuously records the telluric and electromagnetic field variations is described. In the field stations of the system we measure both the telluric variations (using an appropriate electric dipole configuration) and the horizontal electric component of the electromagnetic field in 3 kHz, 10 kHz, 41 MHz and 53 MHz (using tuned and $\lambda/2$ antennas, respectively). Furthermore, a theoretical model is given on the generation and the form of preseismic telluric variations based on the charge dislocation model.

Key words *earthquake precursors – Aegean – Greece*

1. Introduction

Recent observations suggest that wide-band electromagnetic emission occurs just prior to earthquakes (Gokhberg *et al.*, 1982; Oike and Ogawa, 1982; Fujinawa and Takahashi, 1990; Fraser-Smith *et al.*, 1990; Parrot, 1990; Yoshino, 1991; Nomikos *et al.*, 1995). A large amount of experimental data has been collected in differen areas of the world (see Parrot *et al.*, 1993; Park *et al.*, 1993). Furthermore, a series of papers (Varotsos and Alexopoulos, 1984a,b; Varotsos *et al.*, 1988; Varotsos *et al.*, 1993) suggested that telluric variations can be used as practical tools for the short-term prediction of earthquakes.

In order to investigate the above ideas and to study the coexistence of electromagnetic and telluric variations observed prior to shallow and intermediate depth earthquakes, a telemetric network was installed on Crete (South Aegean, Greece) (fig. 1). The South Aegean is an appropriate place for such experimentation because of the well known shallow and intermediate depth seismicity (Galanopoulos, 1953; Papazachos and Comninakis, 1971; Makropoulos and Burton, 1984; Papadopoulos, 1989; Papazachos, 1990; Hatzfeld and Martin, 1992).

The network records the Earth's electromagnetic field variations in four field stations installed along Crete. The central station is installed in Chania (see fig. 1). At each field sta-

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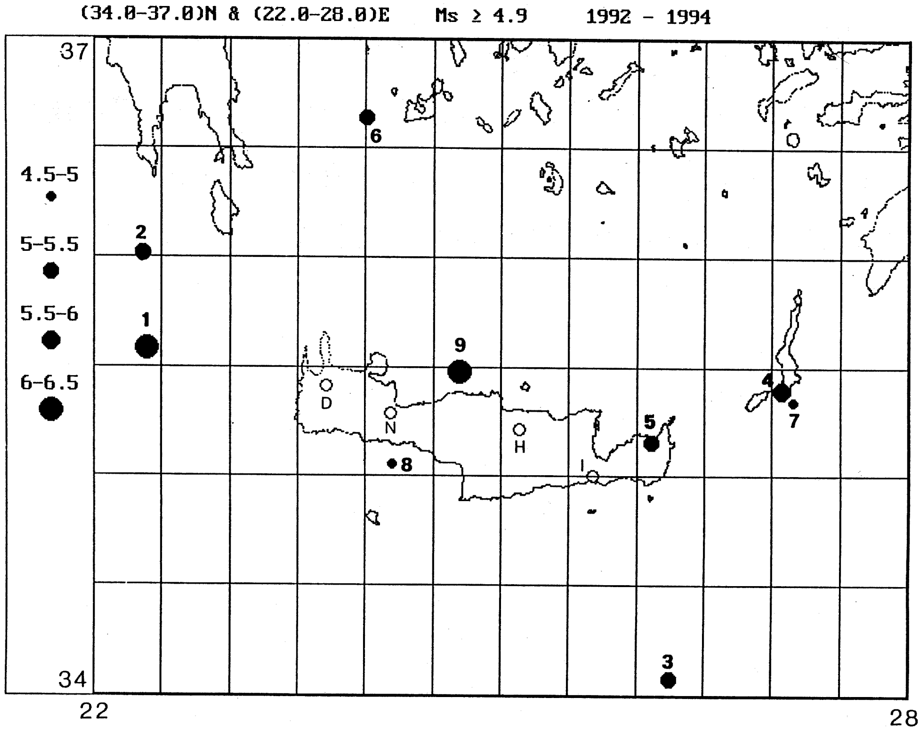

Fig. 1. Map showing the sites of the stations of the telemetric network and the distribution of the epicentres of earthquakes with $M_s > 4.9$ in the vicinity of Crete, from October, 1992 to December, 1994 (see table I).

tion, we measure the two horizontal components of the electromagnetic field variations, in Low Frequencies (LF), *i.e.*, 3 and 10 kHz using tuned loop antennas. Using $\lambda/2$ dipoles we measure High Frequencies (HF), *i.e.*, 41 and 53 MHz. Furthermore, in one of the field stations (in the area of Heraklion) are also recorded telluric field variations. The out stations of the network are based on a datalogger, which digitizes and stores information. The central station uses a computer that communicates with the datalogger and collects the data through a standard dial-up telephone line and finally plots the recordings. The telemetric system has been designed to work unattended. Data recorded from the telemetric system for a time period of almost one and a half years are shown, along with a theoretical model on the generation of preseismic telluric variation.

2. Instrumentation

One of the most important problems for the detection of electromagnetic anomalies as earthquake precursors is to select an appropriate point of observation. It is desirable to set up the instruments of the out station far from industrial areas. For the observation of electromagnetic variation in each station, the following instruments are used:

1) Four receivers appropriate for measuring the electromagnetic field variations at 3 and 10 kHz in EW and NS directions. These are constructed using wide band and low noise amplifiers and switching band-pass filters that are tuned by crystal oscillators. The final stage is an RMS to DC converter. Thus, the output of the receiver is a DC voltage which is proportional to the input amplitude of the magnetic

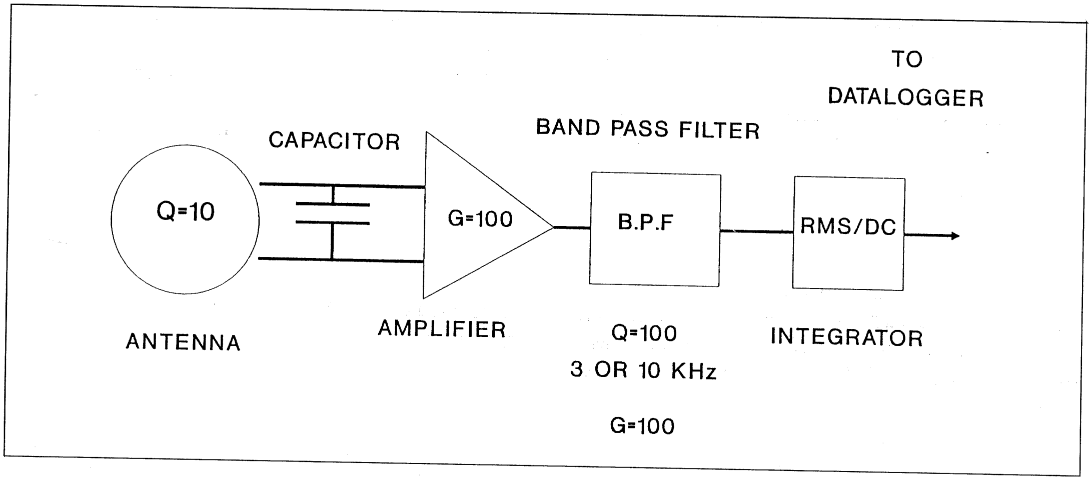

Fig. 2. Block diagram of the system for measuring electromagnetic field variations at 3 and 10 kHz.

field which excites the antenna (Collin, 1985). The block diagram of the system is shown in fig. 2. For observations in the low frequency region (*i.e.*, 3 and 10 kHz) tuned antennas are constructed. In order to maximize gain and signal to noise ratio, we choose a wire diameter of 0.3 mm and an antenna diameter of 1 m, giving us 165 and 56 turns for the 3 and 10 kHz tuned antenna, respectively (Nomikos *et al.*, 1995).

2) Two receivers for measuring the electric field variations at 41 MHz and 53 MHz. The receivers are constructed using double supper heterodyne technology and the output in each of them is a DC voltage which is proportional to the input amplitude of the electric field appearing in the antenna.The antennas used for these very high frequencies are horizontal $\lambda/2$ dipoles tuned at the above frequencies.

3) In the field station of Heraklion, for a limited time period, we measured the telluric field variations (*i.e.*, from 0.1 Hz to DC) in EW and NS directions.

4) A Campbell Scientific (model 21X) datalogger is used in the out station. The sampling rate was set to 1 sps for all channels and the average value of 60 samples per channel was saved in solid state memory (Nomikos and Chatzidiakos, 1993; Vallianatos and Nomikos, 1995; Nomikos *et. al.*, 1995). Thereafter, the signal from the field station is transmitted through the telephone line to the central station. The central station is equipped with a personal computer PC, a fast plotter, a switched telephone line, a digital timer which switches on the computer every night for a time period of 30 min in order to communicate with the field stations and a standard CCITT smartmodem V21/V22. Figure 3 presents the instru-

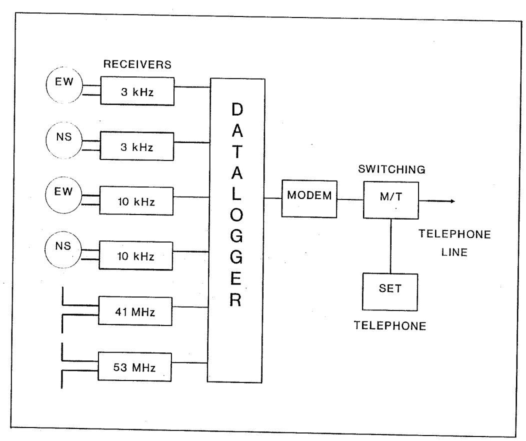

Fig. 3. Instrumentation arrangement of the telemetric system.

mentation arrangement of the telemetric system. Using telecommunication software we interrogate the out station for data in a similar way as described by Nomikos and Chatzidiakos (1993).

3. Observation results

Recording of the electromagnetic variations started in October 1992. Electrotelluric data collected during two different time windows; the first lasted from October 1 to December 30, 1992 and the second from July 10 to September 10, 1993. The most important point in our experiment was to determine noise-free observation frequencies. A number of transmitting stations radiate electromagnetic signals at almost all frequencies over and around the island of Crete. To make sure that the observation frequencies were silent, they were checked using a radio receiver for several months. A strong criterion for a preseismic electromagnetic signal should be its existence in both components and both frequencies of each observation band, simultaneously, otherwise they could be artificial interference. Any interference from mobile transmitters obviously will produce spikes on the recordings for a period of a few minutes at worst and only in the specific frequency of the transmitter. Furthermore, in order to localize the anomalous pattern, artificial intelligence techniques are applied (Yialouris *et al.*, 1996). Among other criteria the latter technique checks the change with time of the mean level and the sampling variance of the background noise.

We procede now to the presentation of the recordings obtained from October 1992 to December 1994. Table I shows all the earthquakes with M_s magnitude greater than 4.9 in the vicinity of Crete (Latitude: 34-37; Longitude: 22-28) during the above time window. A detailed analysis using a lower magnitude cutoff is given elsewhere (Nomikos and Vallianatos, 1996). The stations of our network and the frequencies at which electromagnetic emission was observed prior to earthquakes are shown in table I. Figure 1 shows the earthquakes during this period and the numbering of the position refers to their order in table I. The same figure shows the position of the out stations, indicated by their initials (*i.e.*, N = Nipos, I = Ierapetra, H = Heraklion and D = Drapania).

Figures 4a-d and 5a-d show typical recordings of an electromagnetic variation prior to an earthquake. In order to study the time sequence

Table I. List of the earthquakes with electromagnetic variations collected at the stations of the network. The position of the observation station is indicated by its initial (*i.e.*, N = Nipos, I = Ierapetra, H = Heraklion and D = Drapania).

Date			Time	Lat.	Long.	M_s	H km	Frequencies (Stations) 3 kHz	10 kHz	41 MHz	53 MHz
1992	Nov.	21	05:07:19.4	35.58	22.39	6.0	70	NDH	NDH	NDH	NDH
1993	Jan.	27	23:41: 1.0	36.02	22.36	5.4	120	N	N	ND	ND
1993	Jun.	1	09:45:25.2	34.07	26.25	5.2	1	–	–	–	–
1993	Jun.	29	04:37:12.5	35.39	27.07	5.5	1	I	I	ND	ND
1993	Aug.	18	12:09:26.1	35.15	26.11	5.2	72	NDI	NDI	NDH	NDH
1993	Oct.	1	03:59:34.3	36.64	24.01	5.4	109	NHI	NHI	NDI	NDI
1993	Oct.	16	21:23:13.7	35.34	27.16	4.9	24	HI	HI	–	–
1993	Dec.	25	10:15:30.2	35.05	24.20	4.9	26	ND	ND	ND	ND
1994	May.	23	06:46:17.3	35.48	24.70	6.0	66	NDI	NDI	ND	ND

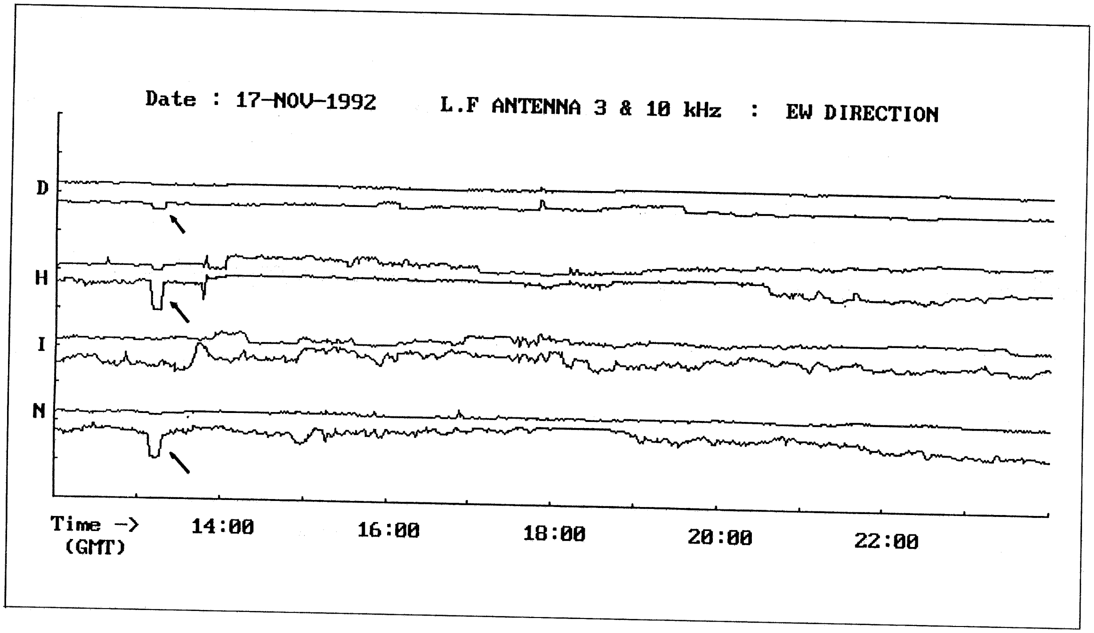

Fig. 4a. Electromagnetic variation at 3 and 10 kHz in EW direction, recorded prior to the November 21, 1992 earthquake.

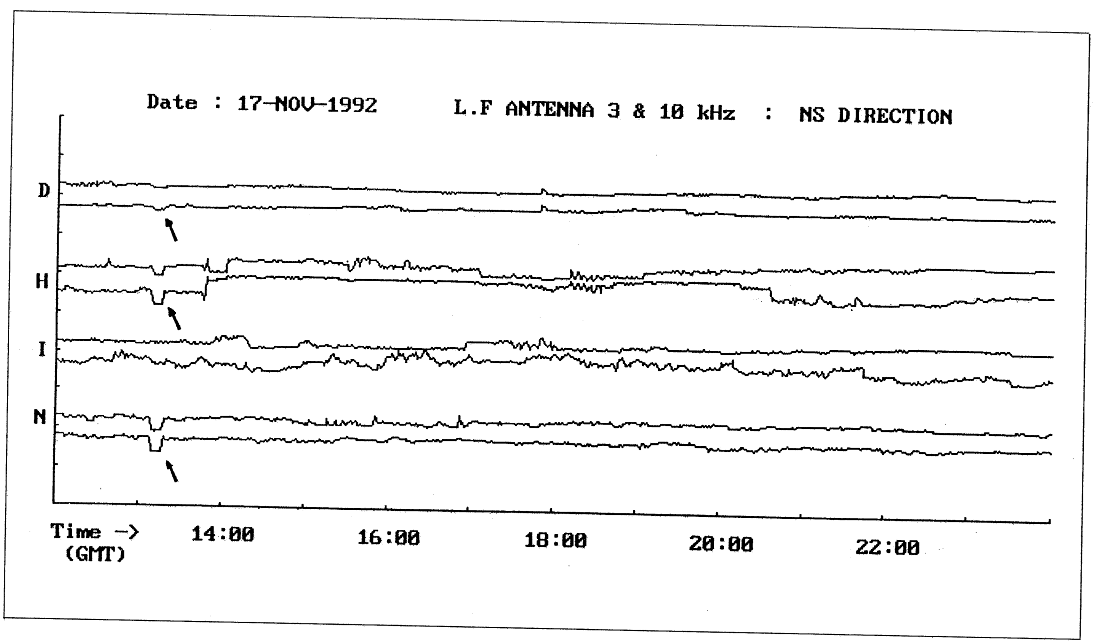

Fig. 4b. Electromagnetic variation at 3 and 10 kHz in NS direction, recorded prior to the November 21, 1992 earthquake.

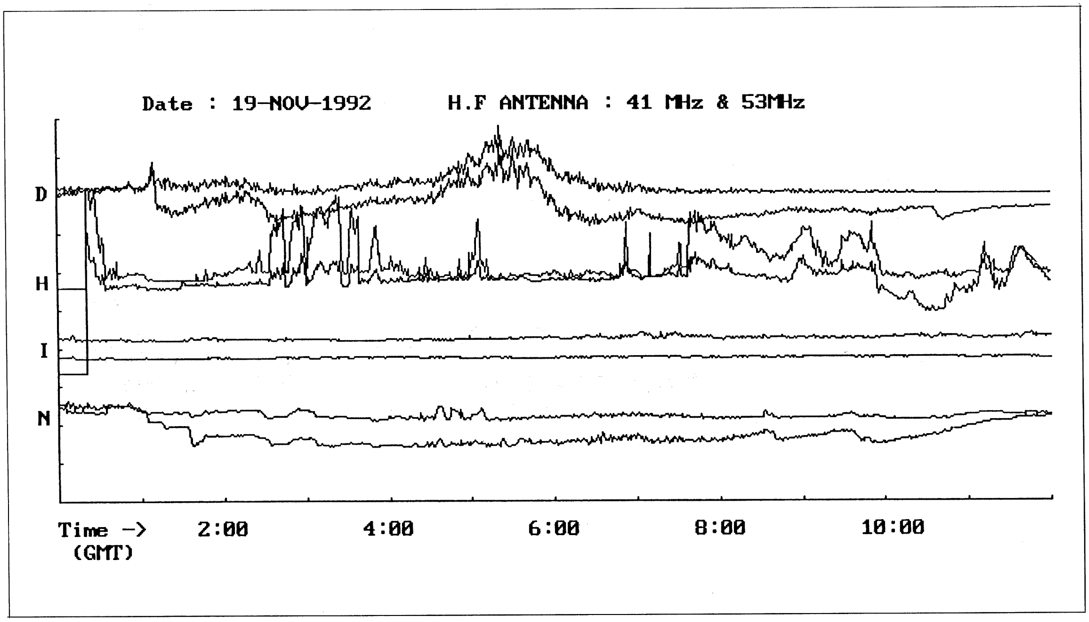

Fig. 4c. Electromagnetic variation at 41 and 53 MHz, recorded prior to the November 21, 1992 earthquake.

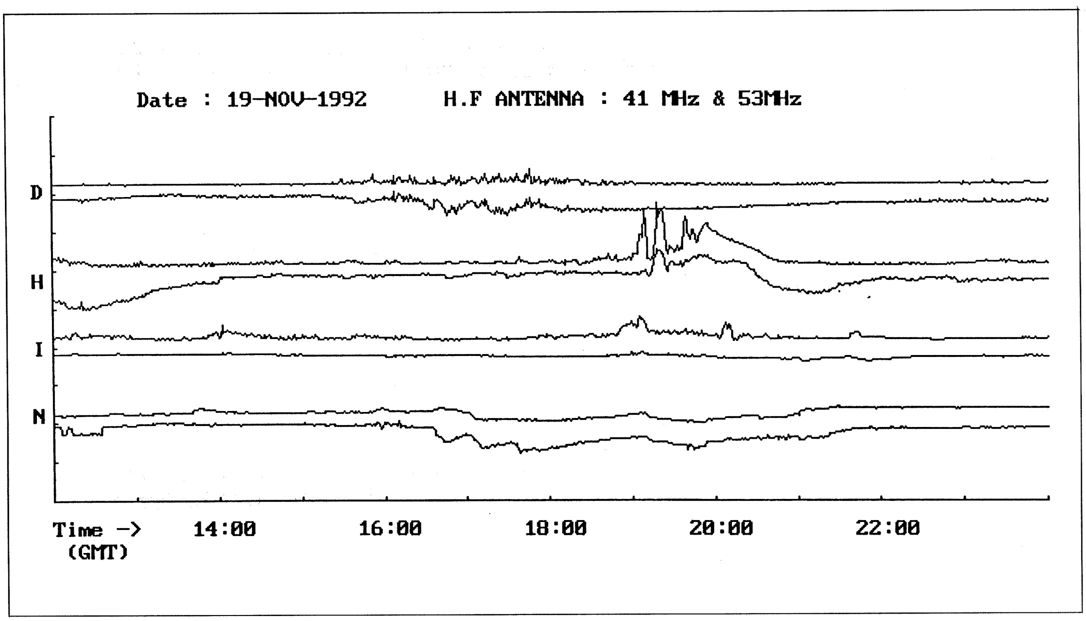

Fig. 4d. Electromagnetic variation at 41 and 53 MHz, recorded prior to the November 21, 1992 earthquake.

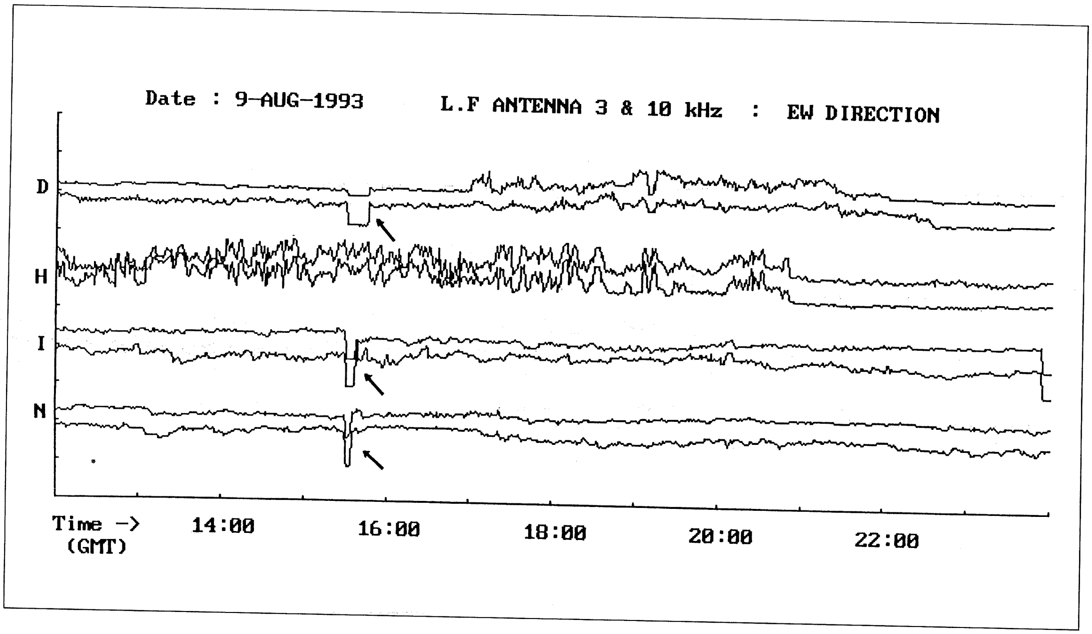

Fig. 5a. Electromagnetic variation at 3 and 10 kHz in EW direction, recorded prior to the August 18, 1993 earthquake.

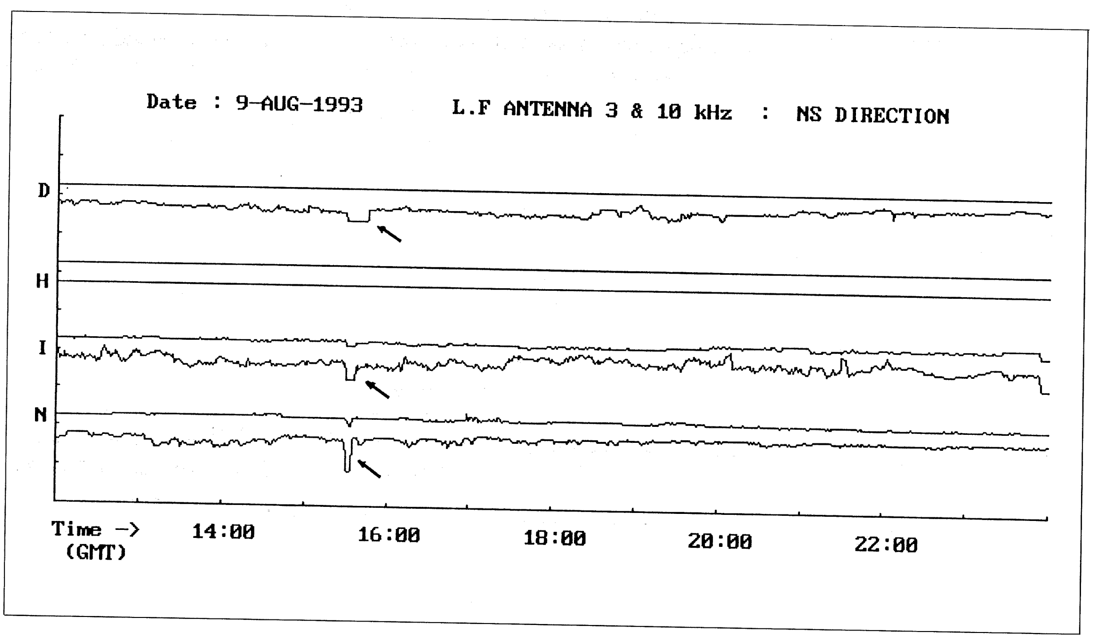

Fig. 5b. Electromagnetic variation at 3 and 10 kHz in NS direction, recorded prior to the August 18, 1993 earthquake.

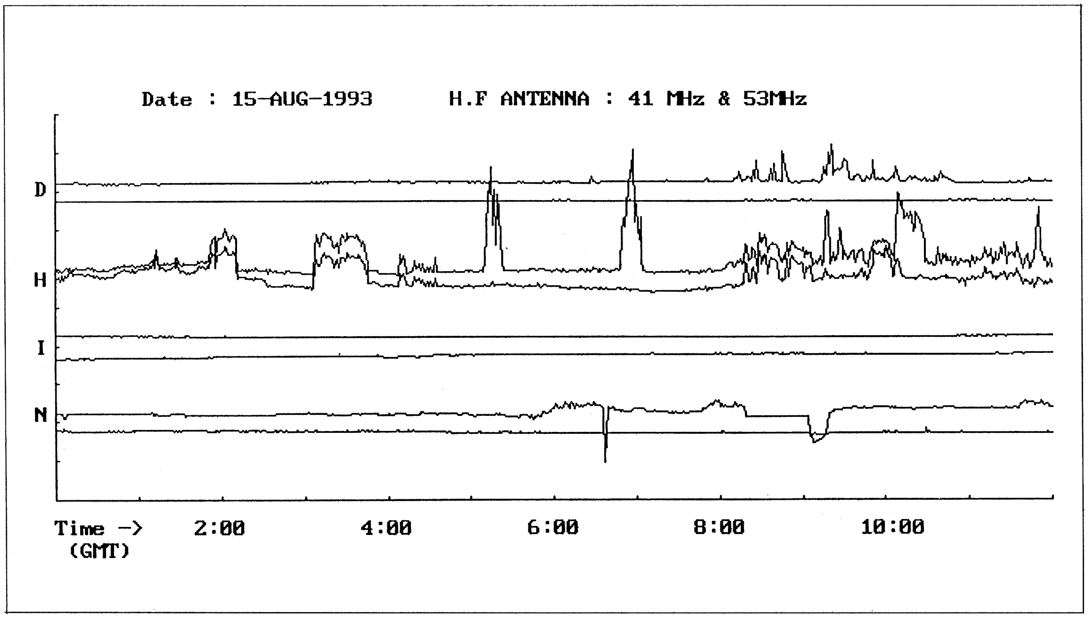

Fig. 5c. Electromagnetic variation at 41 and 53 MHz, recorded prior to the August 18, 1993 earthquake.

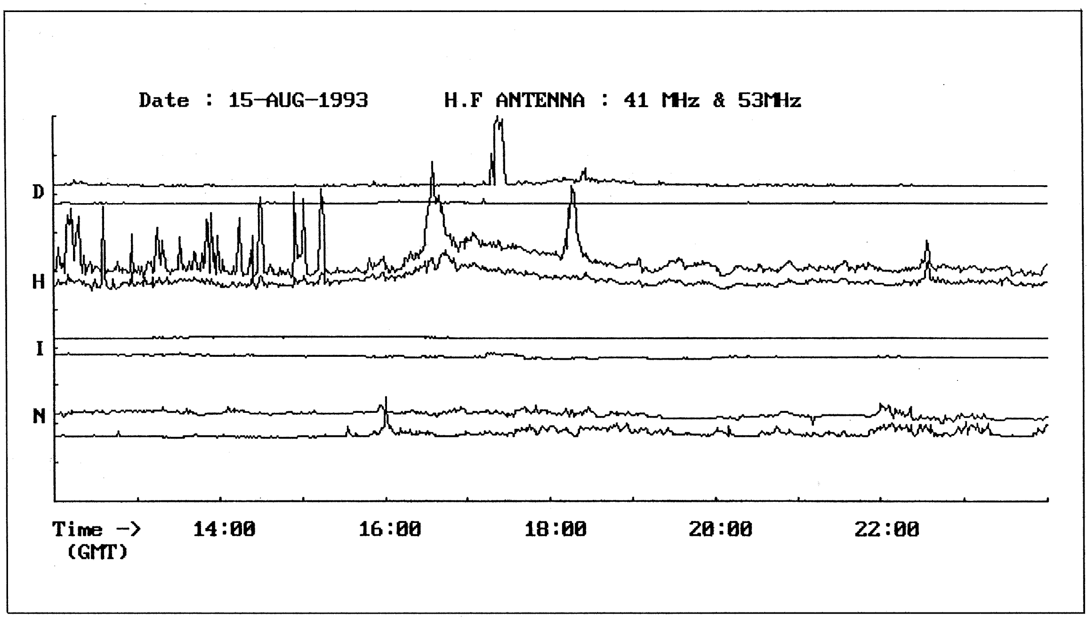

Fig. 5d. Electromagnetic variation at 41 and 53 MHz, recorded prior to the August 18, 1993 earthquake.

of seismoelectromagnetic events time charts are constructed. The time chart of fig. 6 shows schematically the sequence of electromagnetic events that precede the earthquakes in the time window under investigation. An inspection in fig. 6 indicates that the LF variations (*i.e.*, in 3 and 10 kHz) always precede the HF variations (*i.e.*, in 41 and 53 MHz).

Let us now discuss the electromagnetic variations that preceded the November 21, 1992 and August 18, 1993 intermediate depth earthquakes. The first one on November 21st, 1992 with M_s 6, epicenter at 35.9°N, 22.5°E and focal depth 70 km belongs to the seismogenic source zone 1A, as identified by Papazachos (1990); this source region lies under the eastern part of Peloponnese but extents to the north up to 39° latitude and to the south to the western corner of the island of Crete. The second earthquake, on August 18, 1993 with M_s 5.2, with an epicenter at 35.16°N, 26.13°E and focal depth 72 km, belongs to source volume 1B, which lies under the island of Crete and is located near the boundary with zone 1C, under Dodecanese (see fig. 1 of Kiratzi and Papazachos, 1995).

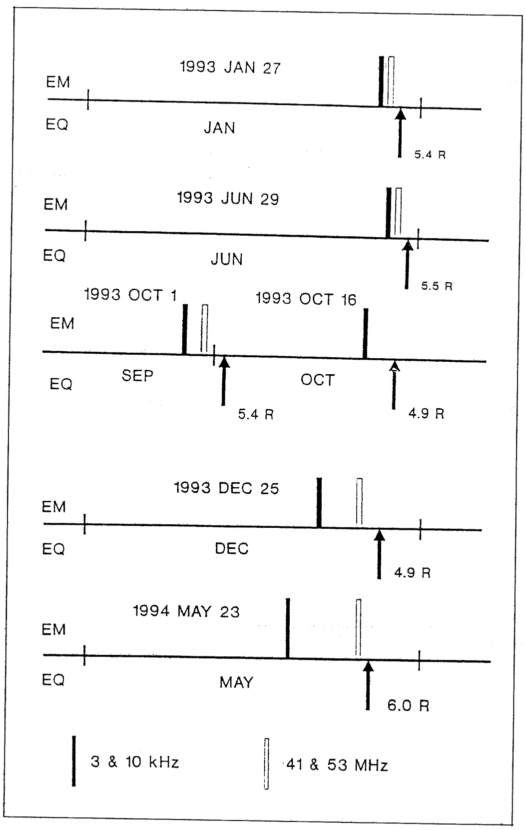

Fig. 6. Time chart depicting all the electromagnetic variations along with all earthquakes with $M_s > 4.9$ and epicenter in the vicinity of Crete from October, 1992 to December, 1994.

3.1. *Electromagnetic variations prior to the November 21, 1992 earthquake*

1) At the low frequencies 3 and 10 kHz on November 17, 1992 and at 13:15 GMT time, for a time period of 15 min a simultaneous electromagnetic variation was recorded, at Drapania, Nipos and Heraklion and in both measuring directions (figs. 4a,b). The strongest signal appeared in Heraklion and the weakest in Drapania. Ierapetra, being the furthest from the epicenter, did not record any signal.

2) At high frequencies the electromagnetic variations started mainly from 1:00 GMT of November 19, 1992 and continued until 22:00 GMT of the same day, even though slight variations did continue thereafter. It can be seen that the strongest signals were recorded at the nearest (to the epicenter) station of Drapania (figs. 4c,d).

3.2. *Electromagnetic variations prior to the August 18, 1993 earthquake*

This earthquake presents a great interest because it occurred near to the stations of Ierapetra and Heraklion.

1) On August 9 (15:30 GMT) at low frequencies of 3 and 10 kHz, electromagnetic variations lasting about 10 to 15 min were recorded simultaneously at Drapania, Nipos and Ierapetra, both in the EW and NS components (see figs. 5a,b).

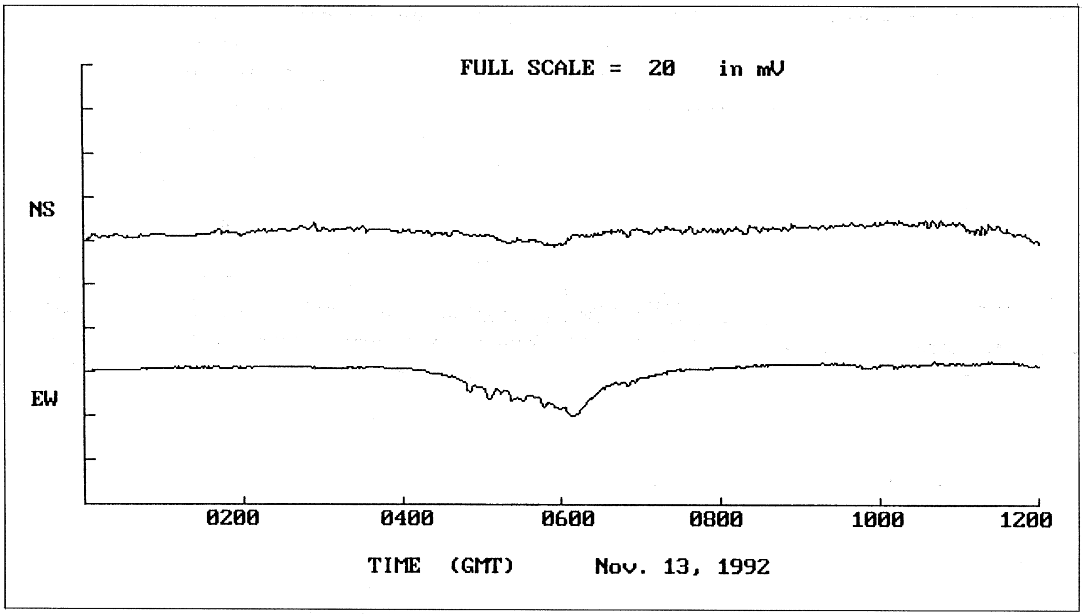

Fig. 7. Telluric variation recorded on both dipoles (*i.e.*, EW and NS) in Heraklion station almost 8 days before the M_s 6.0 intermediate-depth earthquake which occurred on November 21, 1992.

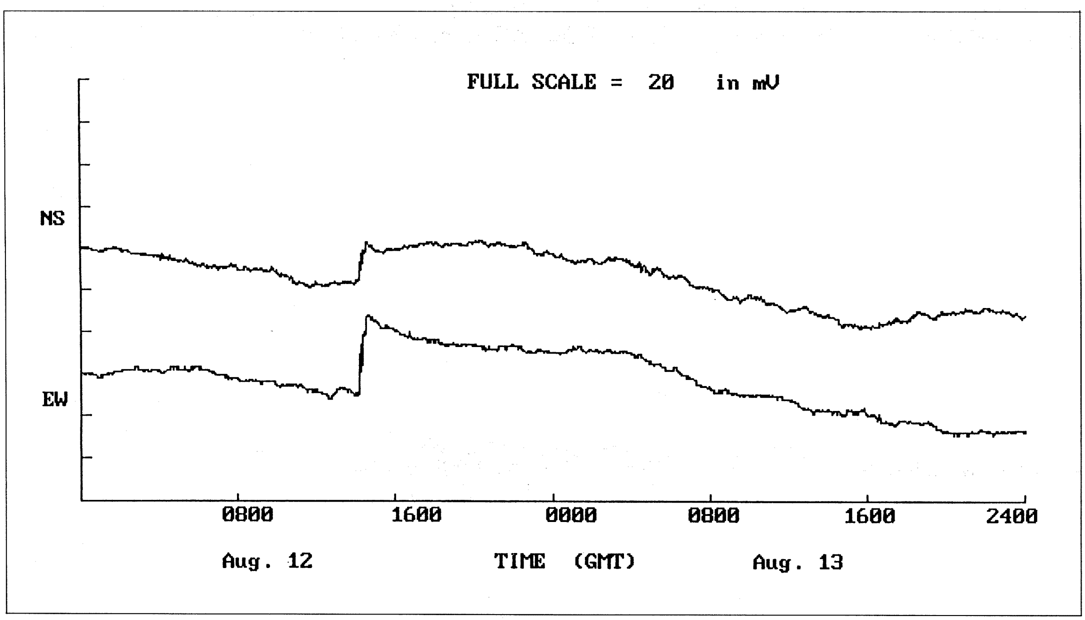

Fig. 8. Telluric variation recorded on both dipoles (*i.e.*, EW and NS) in Heraklion station almost 6 days before the M_s 5.2 intermediate-depth earthquake which occurred on August 18, 1993.

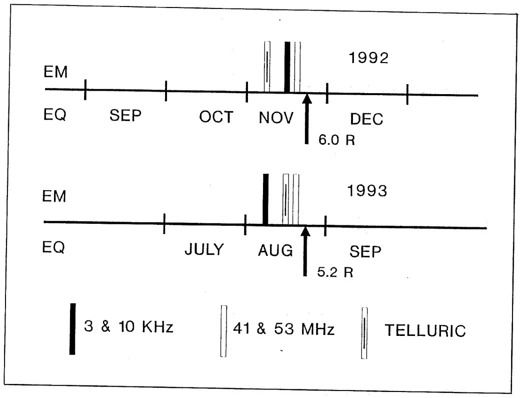

Fig. 9. Time chart of Heraklion station for the time windows from September 1, 1992 to December 30, 1992 and from July 10, 1993 to September 10, 1993, for which the telluric station was in operation. It depicts all electric and electromagnetic field variations along with all earthquakes with $M_s > 4.9$ and epicenter in the vicinity of Crete.

2) At high frequencies 41 and 53 MHz electromagnetic variations were observed on August 15, 1993 (from 2:00 GMT to 19:00 GMT) at Drapania, Heraklion and Nipos. The strongest variations were recorded at Heraklion (figs. 5c,d). We mention that Ierapetra did not pick up any high frequency signals.

Another very interesting feature of these events is that anomalous telluric variations were recorded in Heraklion electrotelluric station a few days (6 and 8 respectively) before each of the aforementioned earthquakes (figs. 7 and 8). In order to show the correlation between the observed electromagnetic and telluric variations and the earthquakes in the vicinity of Crete, we compiled time charts showing all the earthquakes ($M_s > 4.9$), (see table I), along with the observed electromagnetic and telluric variations (fig. 9). We see that there is a strong indication for a one-to-one correlation, due to the fact that in both cases the earthquakes were «isolated» in time. Furthermore, fig. 9 shows that the LF variations precede the HF ones. However, the telluric variations have different positions in the time sequence, in each of the time charts.

4. Generation mechanism and form of preseismic telluric variations

Different attempts have been made to explain the generation of electrotelluric variations before an earthquake that take place in an earthquake preparation zone (Varotsos and Alexopoulos, 1986; Slifkin, 1993; Utada, 1993; Lazarus, 1993; Teisseyre, 1997). It is worth mentioning the model of piezostimulated currents (PSPC) (Varotsos *et al.*, 1993). According to this model during the preparatory stage of an earthquake, as the stress in the focal area increases gradually, the relaxation time of the dipoles in the rock decreases and an electric current is emitted before the earthquake. It is assumed that the fracture stress is larger than the critical stress value at which the PSPC current is emitted and it is implicitly assumed that the so-called migration volume is negative. It is important to point out that the latter crucial negative parameter has not been experimentally reported for rocks to date.

We procede now to an analysis of the form of the observed variations based on the charge dislocation model (Whitworth, 1975; Petrenko and Whitworth, 1983; Slifkin, 1993). According to this all the rocks contain crystalline materials which already bear linear defects (*i.e.*, charged edge dislocations) due to some deformation they were previously subjected to. On the other hand, an earthquake zone is represented by cracks or, equivalently, by dislocation arrays *i.e.*, by a concentration of charged dislocations (Teisseyre, 1985a,b, 1987). Thus, the earthquake preparation (*i.e.*, the non-linear evolution of stress) and energy release processes are determined by the propagation of these defects and changes in their density as well.

The aforementioned representation of the earthquake source leads to the conclusion that an electric current is generated whose intensity is proportional to the velocity of the propagation of the charge dislocations and to their density. The current density vector at the source is parallel to the velocity vector. Then, the electric field horizontal component, measured at a given point in a horizontal distance Δx from the source and at time t_K, can be qualitatively presented by (Ernst *et al.*, 1993):

$$E_h\,(x,\,t_K) = g\,\rho\,\sum_i (a_i\,V_i)\,\frac{x - x_i\,(t_K)}{R_i^n\,(t_K)} \qquad (4.1)$$

where R_i is the distance of the observation point from the moving charge dislocation element located at x_i, $n = 2$ for a linear source; a_i is the (charged) dislocation density at point x_i; V_i is the dislocation velocity at x_i; ρ is the resistivity of the medium; g is an unknown proportionality factor depending on the geometry of the source and the anisotropy of the medium. We stress that expression (4.1) is based on the assumption that the time sequence of stress evolution is the same at each point on the source plane, only shifted by the time delay needed for crack propagation and thus on the evolution of stress. However, the macroscopic deformation rate, $\dot{\varepsilon}_i$ is related to the mobile charged dislocation density and velocity via Orowan's law $\dot{\varepsilon}(t_K) = \lambda\, b\, a_i\, V_i$ (Dekker, 1971; Nabarro, 1987) and thus eq. (4.1) becomes:

$$E_h\,(x,\,t_K) = \gamma\rho \sum \dot{\varepsilon}_i\,(\Delta x_i\,(t_K)/R_i^n\,(t_K)), \quad (4.2)$$

where $\gamma = g\,\lambda\, b$.

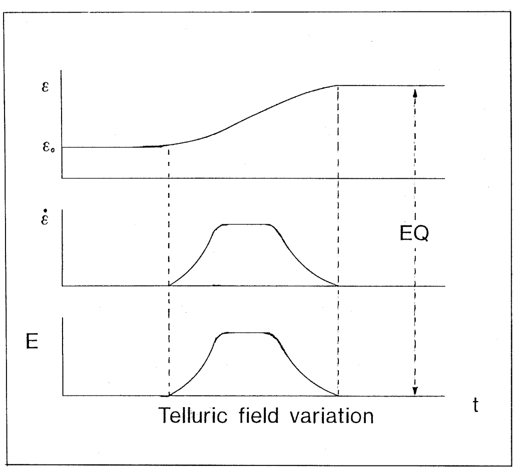

Fig. 10. Diagram depicting the deformation (upper), the deformation rate (middle) and the corresponding telluric variation (lower).

Equation (4.2) reveals that the observed transient electric variation is related to the non-stationary accumulation of deformation. Thus, with the help of a preseismic electric variation, recorded in a particular site, the deformation rate during the preparation stage of an earthquake could be observed qualitatively. Specifically, when the deformation rate increases with respect to a variable rate (*i.e.*, $\dot{\varepsilon} > 0$ and $\ddot{\varepsilon} \neq 0$), then two cases are distinguished: if $\ddot{\varepsilon} > 0$ $\ddot{\varepsilon} < 0$) then $\dot{E} > 0$ ($\dot{E} < 0$); the latter means an increase (decrease) in the observed electric field variation. If $\dot{\varepsilon} > 0$ and $\ddot{\varepsilon} = 0$ (*i.e.*, $\dot{\varepsilon}$ is constant with time) then E is also a constant (see fig. 10).

Thus, the charge dislocation model could explain the form of a preseismic electric signal and lead to the conclusion that the preseismic electric variation is controlled by the evolution of the deformation rate during the preparation stage of an earthquake.

5. Concluding remarks

The present paper describes a telemetric network appropriate for the measurement of electromagnetic emission and telluric variation prior to earthquakes.

The experimental observations concern telluric and electromagnetic variations in the frequencies of 3 and 10 kHz, 41 and 53 MHz, associated with shallow and intermediate depth earthquakes in the vicinity of Crete Island (South Aegean - Greece). The experiment indicates the appearence of both telluric and electromagnetic variations prior to earthquakes. Furthermore the electromagnetic variations appear to follow an invariant time pattern *i.e.*, LF variations – HF variations – earthquake event.

An attempt is made to explain the generation and the form of the transient electric variation before an earthquake.

Our approach is based on the charge dislocation model and it is concluded that the transient electric variation could be a measure of the rate of deformation during the preparation stage of an earthquake.

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