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PHYSICAL PROPERTIES OF THE VARIATIONS OF THE ELECTRIC FIELD OF THE EARTH PRECEDING EARTHQUAKES. II. DETERMINATION OF EPICENTER AND MAGNITUDE

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ABSTRACT

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As reported in the preceding paper, a transient change of the electric field of the earth (seismic electric signal), hereafter called SES, appears many hours before an earthquake (EQ). By measuring this change in a given direction and dividing it with a suitable relative effective resistivity one obtains a quantity that reflects the current density in this direction. Measurements in two directions (E–W and N–S) give the relative signal intensity J_{rel} at the station under consideration. By measuring J_{rel} at a number of stations and considering that it attenuates according to a $1/r$-law, the epicenter can be determined with an accuracy usually around 100 km. Once the epicenter has been determined, the product $J_{rel} \cdot r$ can be evaluated so that the magnitude M can be estimated by resorting to an empirical $\log(J_{rel} \cdot r)$ versus M plot. The uncertainty of M is around 0.5 units. Following Sobolev (1975) and for the statistics to be beyond any doubt, predictions were officially documented before the EQ-occurrence. For 23 earthquakes with a magnitude equal or greater than $M_s = 5.0$ two events were missed.

The present method is compared to other electrical methods used in China, Japan and Soviet Union. A number of problems concerning the origin of the effect, its directivity and the attenuation with distance remain open for further studies.

INTRODUCTION

The preceding paper (Varotsos and Alexopoulos, 1984, hereafter referred to as Part I) was concerned with the physical properties of the variation of the electric field of the earth and their connections with subsequent earthquakes (EQ). This was the result of continuous monitoring of the electric field at eighteen stations sited throughout Greece (see fig. 1 of Part I).

A first step towards the confirmation that these electric seismic signals (SES) are actually correlated to earthquakes is the construction of time charts of SES and EQ,

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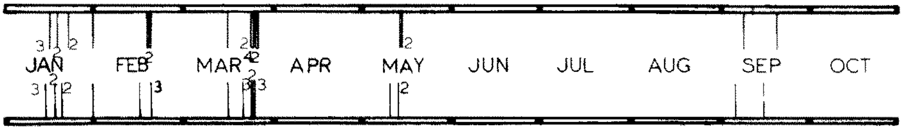


Fig. 1. Time charts of EQ and SES from Jan. to Oct. 1983. Lines above: *all EQ* with a magnitude greater or equal to 5 that occurred within a radius of 150 km from PIR. Further an $M = 4.8$ event on Febr. 20, 1983 at a small distance (10 ± 5 km) from PIR has been included. Lines below: *all SES* recorded at PIR with $\Delta V > 0.5$ mV. The numerals give the number of events. The data since Jan. 19 are given in Table 3 (p. 117).

for a given period of time, and the calculation of their correlation curve. This procedure has been repeatedly followed (Varotsos et al., 1981a, b, 1982a,b,c; Varotsos et al., 1983); however, the construction of a correlation curve becomes more convincing in cases where the following conditions are fulfilled.

A limited seismic area that has been active for a period of months and has given a number of significant events (e.g. with $M \gtrsim 5$ R) is selected. In addition, these events should be non-uniformly distributed in time, e.g., some events within a few days of each other followed by a period of quiescence of a few months and then again some events in a period of a few days and so on. As the lead time is relatively short (6–115 h) the timeseries of SES collected at a nearby station should show an array similar to the seismic events. In order to draw the time chart of SES one should choose a threshold for the strength of the transient electric variations. If the threshold is arbitrary, the number of SES and EQ will not be equal, although the correlation curve will show a feature indicating that the two kinds of events are correlated (i.e., it will show maxima well above the statistical noise for positive values of $\Delta t = t_{EQ} - t_{SES}$). However, if one selects appropriate thresholds for the magnitude of EQ and the ΔV-value of SES, an excellent one to one correlation emerges. An example is given in Fig. 1.

The fact that the two time-series of SES and EQ give an excellent correlation does not yet provide convincing evidence that the SES can be used for the prediction of EQ; this can be achieved only if they bear inherent properties which provide a tool for the determination of the magnitude and the epicenter. Only in such cases can a full one to one correspondence of SES and EQ be considered established. As will be seen below, an appropriate treatment of the ΔV-values (for a given EQ), simultaneously recorded at various stations, does actually lead to the determination of the epicenter; after the epicentral distances have been determined, the magnitude can be estimated either by resorting to the log $(\Delta V \cdot r)$ vs M plot of each station or to the log $(J_{rel} \cdot r)$ vs M plot which—as mentioned in Part I—is valid for all stations.

SIMULTANEOUS SEISMIC SIGNALS

The SES are changes of the electric field and therefore propagate with a velocity in the order of the velocity of the light. Therefore, an SES should occur simultaneously at the stations observed. This fact is of importance in recognizing an SES especially when imbedded in noise. Here we give two examples of a weak and a strong signal.

In Fig. 2 we see an electric disturbance recorded on the E–W line of HAL-station (for the abbreviations see Part I) at 21 : 38, June 7, 1983, whereas it does not appear on any line at the THI and IOA stations, the simultaneous recordings of which are depicted in the same figure. (The two components of these three stations are recorded on the same six-pen recorder.) In Fig. 3 we give an electric signal of magnetic origin that appears simultaneously at 12 : 25 on June 9, 1983, at the same three stations of Fig. 2. A comparison of these two figures indicates that if the electrical disturbance depicted in Fig. 2 were of magnetic origin, it should also have been recorded on the lines of the other two stations THI and IOA. In Fig. 4 we see clearly that this electrical disturbance has been recorded simultaneously on the N–S line of VER whereas on the E–W line of the same station it can only be detected with difficulty. (Note that the distance VER–HAL is 240 km.) In Fig. 5 we see that the signal has also been recorded on the N–S-line of NAF-station. This SES, recorded simultaneously at three stations, is a precursor of an $M = 4.5$ event that

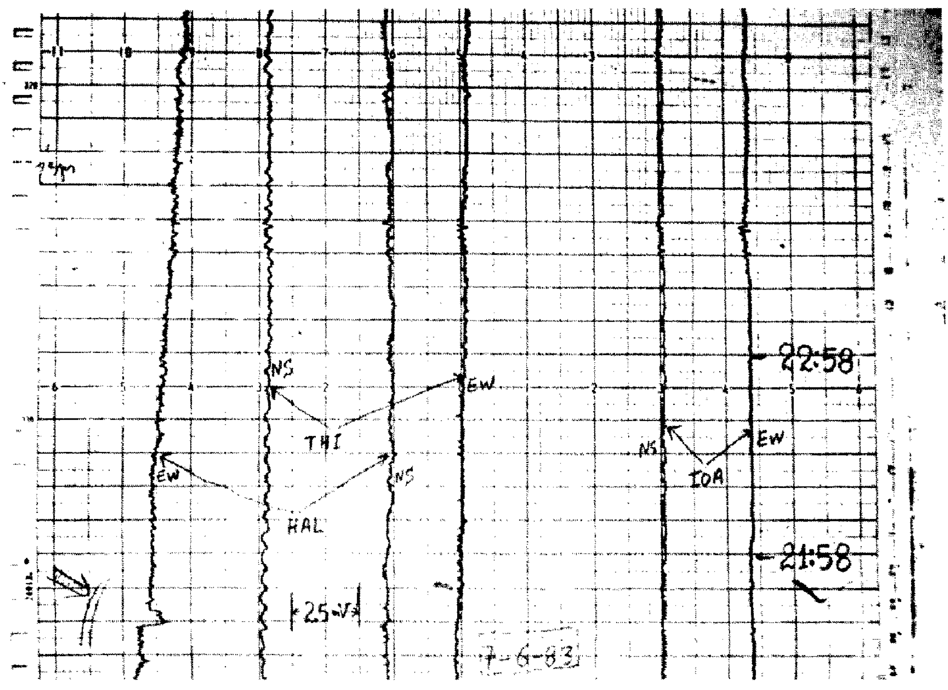


Fig. 2. An SES recorded on a multipen recorder at 21 : 38 GMT, June 7, 1983, on the E–W line ($L = 200$ m) at HAL. It is the precursor of the $M = 4.5$ EQ that occurred at 02 : 39, June 9, 1983, with an epicenter at (37.8 ° N, 27.7 ° E). Simultaneous signals are given in Figs. 4 and 5. Note that the SES has not been recorded at all at THI ($L = 100$ m).

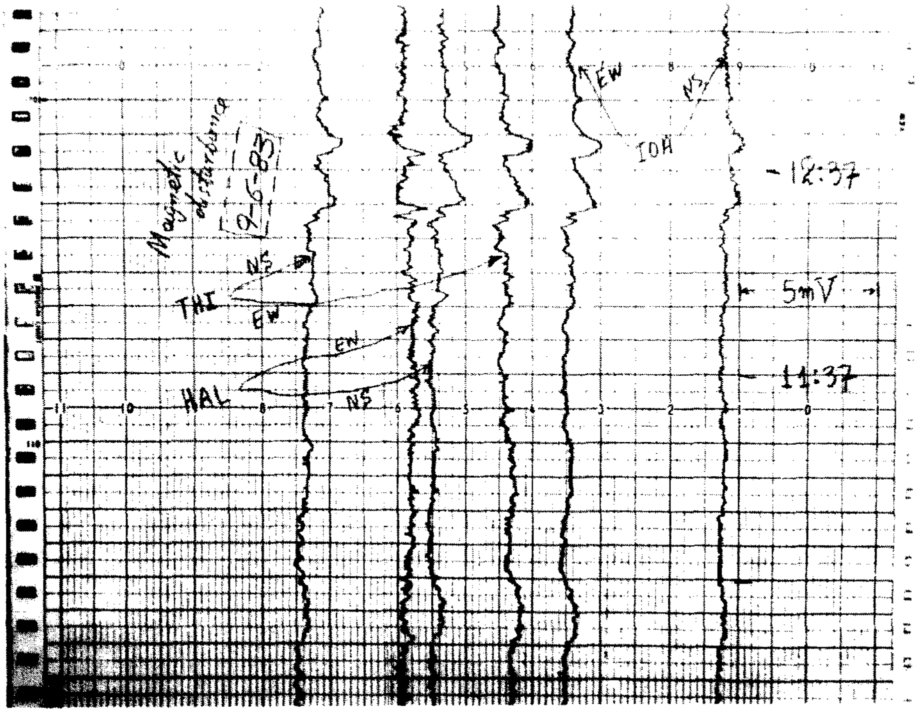


Fig. 3. Simultaneous recordings at IOA, THI and HAL during a magnetic disturbance.

occurred at 02:39 on June 9, 1983, with the epicenter at (37.8° N, 27.7° E). The combination of these SES with the above EQ is not arbitrary because, as we shall see in the next section, the employment of the ΔV-values of Figs. 2, 4 and 5, can, after a proper reduction, lead to a good estimation of the epicenter and the magnitude of the impending EQ.

In Figs. 6–8 we show simultaneous signals collected on both lines of the following four stations installed far apart: VER, ZAK, REN, and PIR. Furthermore in Fig. 9 we show the SES in the E–W direction of VER-station using a line one third of the length of that used in Fig. 6. In Fig. 10 we give the SES recorded at PIR-station but with unpolarized $CuSO_4$ electrodes, for the sake of comparison with Fig. 8, in which the SES has been collected with brass electrodes. This strong SES is the precursor of the $M = 6.5$ event that occurred in the Dardanelles (40.2° N, 27.2° E) on July 5, 1983.

DETERMINATION OF THE EPICENTER

Certain combinations of seismic regions and stations give for some unexplained reason zero intensity for the SES. We are inclined to believe that this is a property due not only to the physical properties of the substratum of the station but also to an anomaly between the seismic region and the station. Apart from such an (anomalous) absence of a signal the determination of the epicenter is, in practice, straightforward.

Consider that an SES has been recorded simultaneously, at a number of stations. From the recorded ΔV-values (those with an amplitude 2–3 times larger than the background noise) and the known effective relative resistivities of each line of each station we find the intensities J_{rel}, and then by taking into account that J_{rel} attenuates according to a $1/r$-law we apply a minimization procedure:

$$\sum_{k} \left(J_{\text{rel}_i} r_j - J_{\text{rel}_j} r_i \right)^2 = \min$$

where k denotes pairs of stations (i, j) and r_i, r_j are the corresponding epicentral distances, the joint solution of which gives the epicentral coordinates. We should stress that in this minimization procedure we must not include a station which has not recorded the SES (i.e. $J_i = 0$) because then we would have the following possibilities: either the station is so far from the epicenter that due to the attenuation

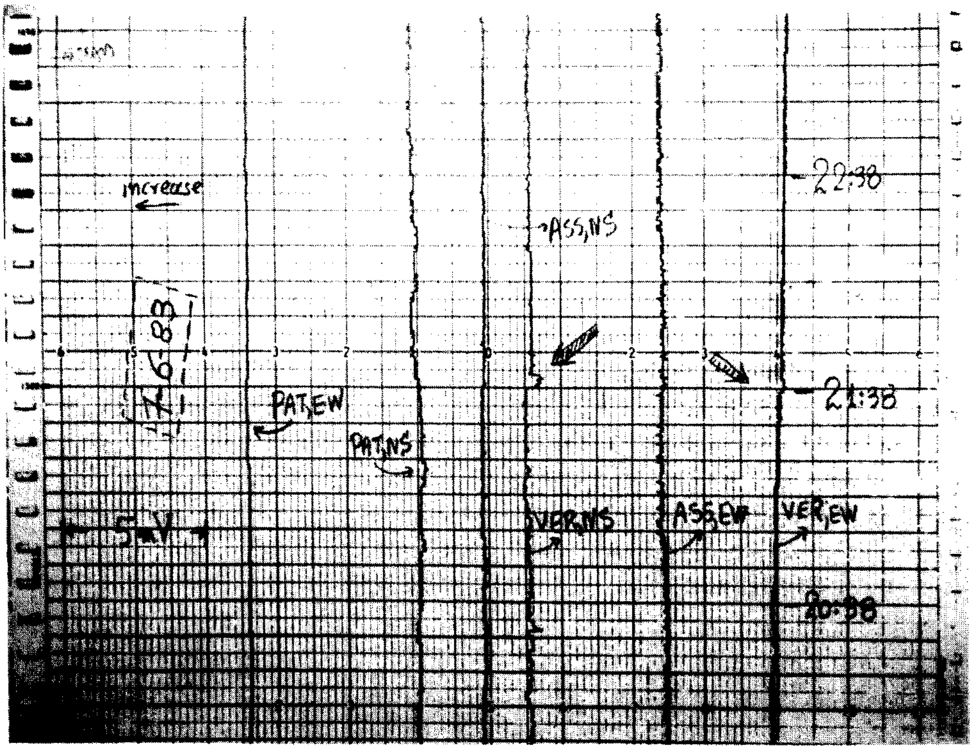


Fig 4. The simultaneous SES of Fig. 2 clearly recorded on the N–S line ($L = 50$ m) of VER. The SES can be also seen on the E–W line but much less clearly. Note the absence of the SES from PAT and ASS.

with distance the signal is so weak that it is hidden in the noise, or the intensity of the SES is zero although the station is close to the epicenter, due to "directivity" effect. Alternately the epicenter can be determined graphically with the method of Apollonian circles as will become clear below with some examples; this method gives more insight to the expected accuracy.

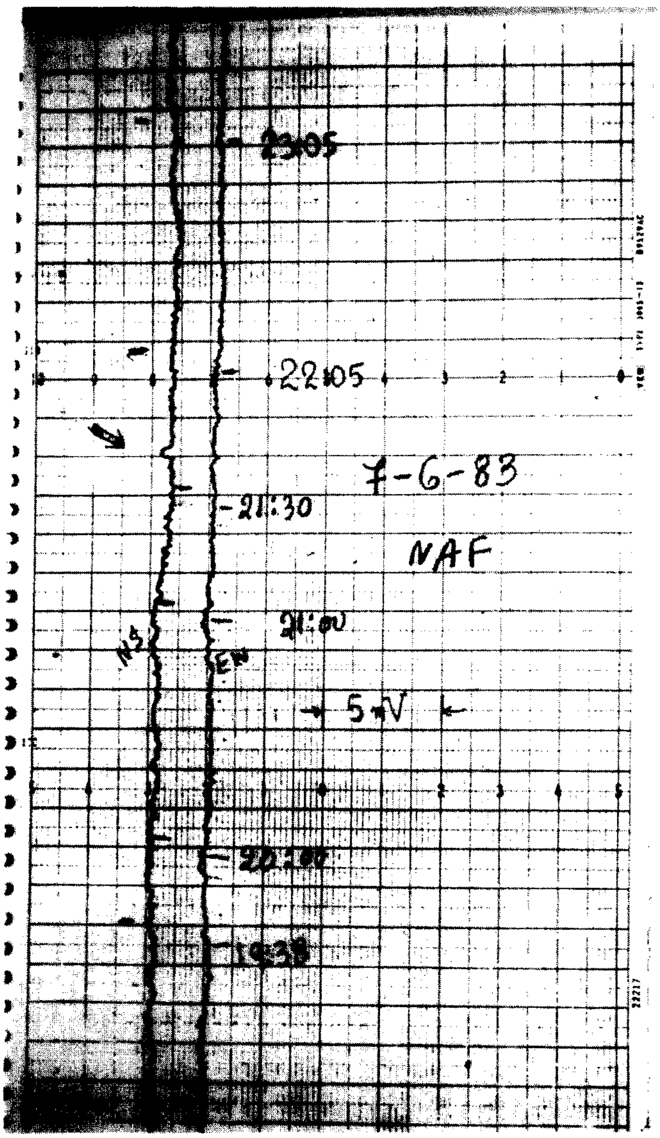


Fig. 5. The simultaneous SES of Figs. 2 and 4 recorded in the N–S-line ($L = 100$ m) of NAF. It would have not been recognized if the SES had not been detected simultaneously at HAL (Fig. 2) and VER (Fig. 4).

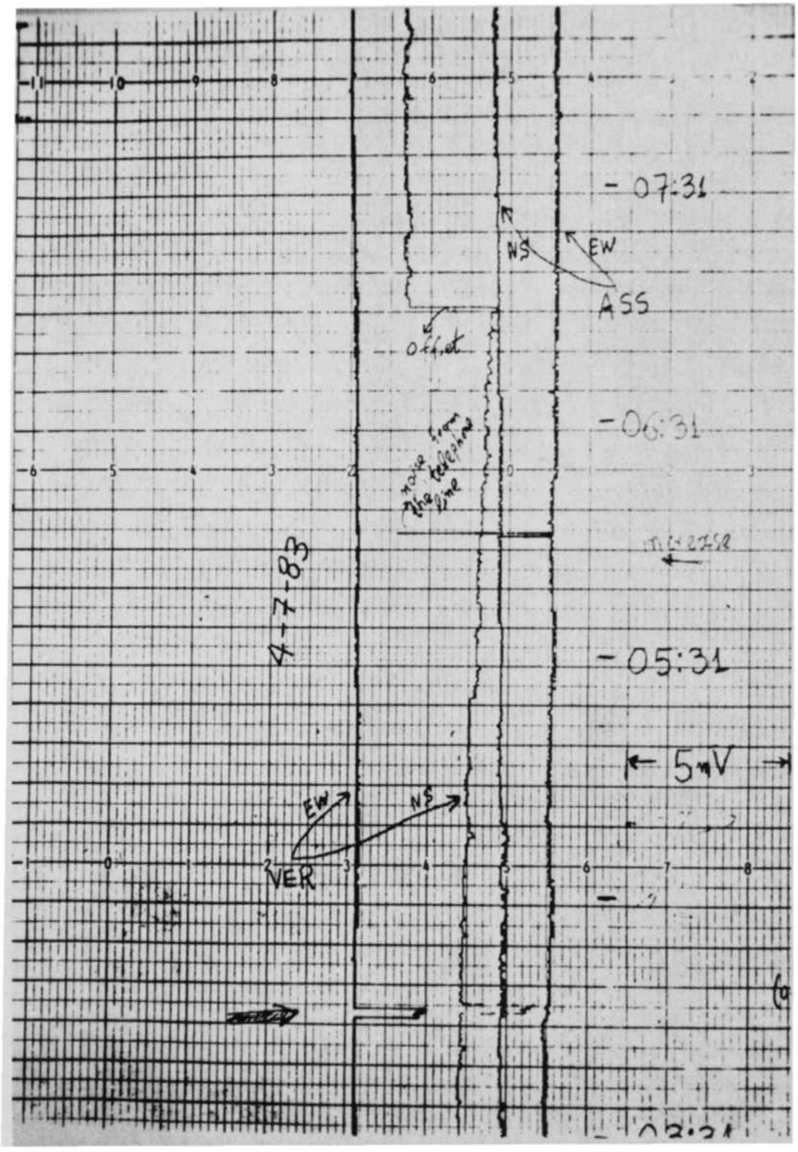


Fig. 6. An SES recorded at ~ 04:00 on July 4, 1983, on both lines ($L_{E-W} = 50$ m, $L_{N-S} = 100$ m) of VER. Note the sharp initiation and sharp end and that the E–W line is a "magnetically insensitive line". The relative effective resistivities of the two lines are $\rho_{E-W} \approx 1$ and $\rho_{N-S} \approx 3$. This SES is a precursor of an $M = 6.5$ event that occurred in the Dardanelles (40.2° N, 27.2° E) on July 5, 1983, i.e. at an epicentral distance of about 400 km. The directivity of the effect is evident: the SES do not appear at all at ASS although they were detected simultaneously at ZAK, PIR and REN (see the next figures).

Let us consider first a case for a weak EQ the SES of which can be recorded only at two stations installed at a distance around 50–100 km. If the ratio of the two intensities is considerably different from unity, e.g. 2–5, the epicenter can be directly determined with an accuracy of a few tens of kilometers because it will be

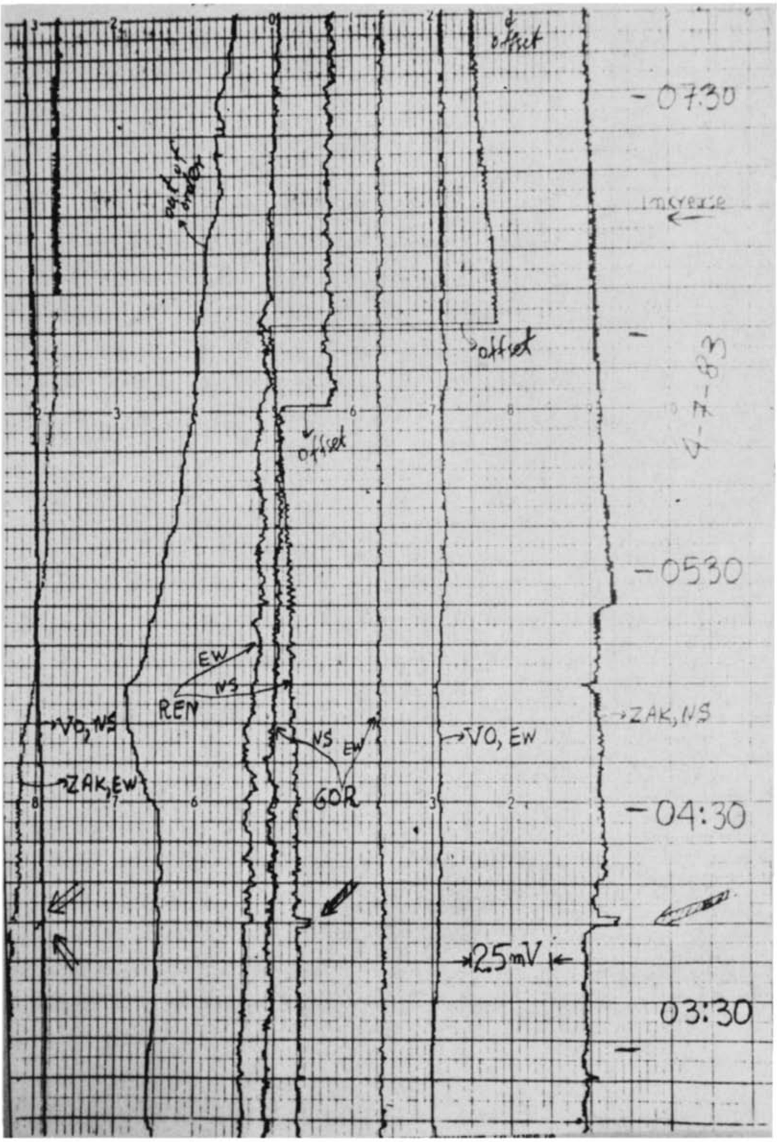


Fig. 7. The simultaneous SES of Fig. 6 recorded at ZAK ($L_{E-W} = L_{N-S} = 150$ m) and REN ($L_{E-W} = L_{N-S} = 30$ m). As expected the form of the signal is similar to that of Fig. 6 (the SES on the E–W line of ZAK is seen with some difficulty due to the bad quality of the pen of the recorder). The epicentral distances of ZAK and REN are 610 and 300 km respectively.

appreciably closer to the station at which the intensity is larger. We give the following example: at 10 : 50 on May 28, 1983, a signal $\Delta V = 1$ mV is recorded on the E–W line of HAL-station. At the same time the SES is also recorded on N–S-line of NAF-station ($\Delta V \simeq 0.4$ mV) while no signal was detected at THI

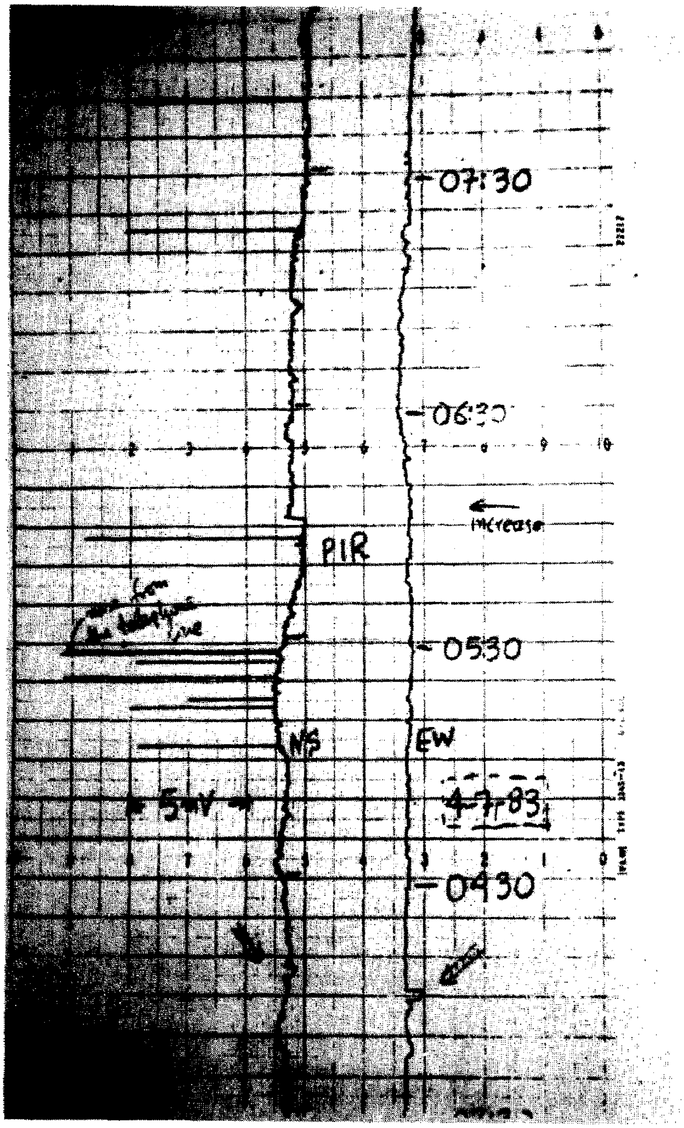


Fig. 8. The simultaneous SES of Figs. 6 and 7 recorded on both lines with brass electrodes at PIR ($L_{E-W} = L_{N-S} = 50$ m). Note that due to the noise it would not have been easily recognised if the SES had not appeared simultaneously at the pairs of unpolarized electrodes (see Fig. 10). Epicentral distance 570 km.

(located close to the epicenter, see Fig. 11). By taking the length of a line of 50 m as unity and considering that: (a) the relative resistivities of the above lines of HAL and NAF (in comparison to that of PIR) are around unity and (b) the above ΔV-values refer to lines with a length $L = 100$ m (and hence $L_{rel} = 2$) we have the following numbers:

for HAL:

$\Delta V = 1$ mV, $\quad L_{rel} = 2, \quad \rho_{E-W} \simeq 1 \quad J_{rel} = 0.5$

for NAF:

$\Delta V = 0.4$ mV, $\quad L_{rel} = 2, \quad \rho_{N-S} \simeq 1 \quad J_{rel} \simeq 0.2$

Therefore the epicenter should lie on an Apollonian circle the points of which have distances from the HAL and NAF-stations at a ratio 0.5/0.2 (Fig. 11). In the same figure we give, with an asterisk, the true epicenter of an $M = 3.9$-event that occurred almost 8 hrs. later (at 18:54 on May 28, 1983). In spite of the fact that in this case the exact epicenter cannot be determined as a single point, a guess on how to estimate the magnitude of the expected event is made as follows: The points of the

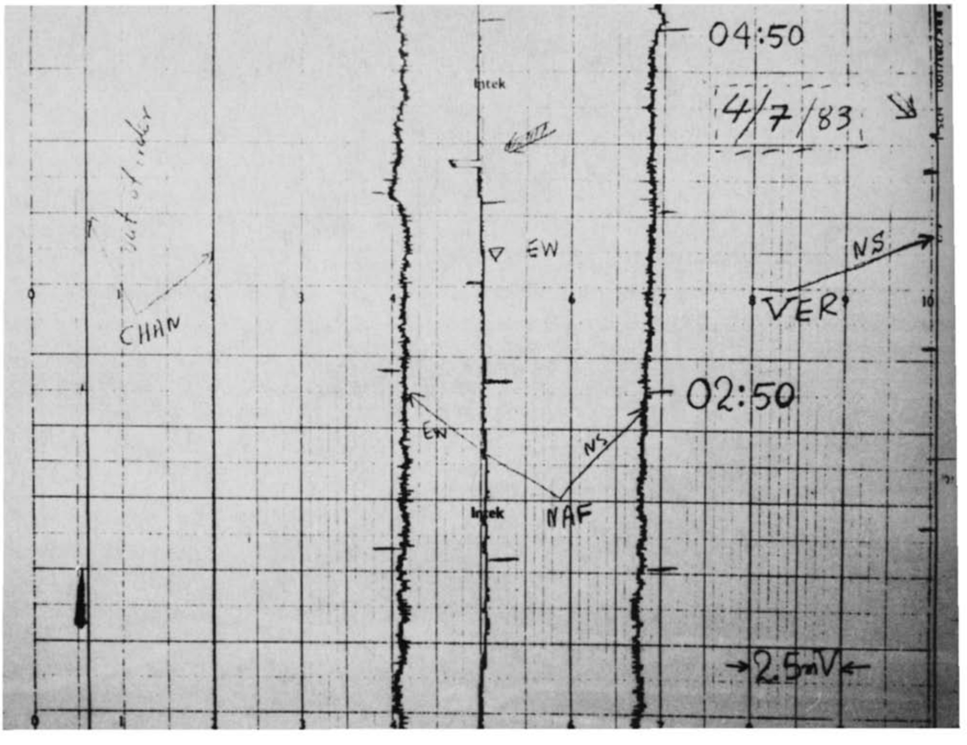


Fig. 9. The same SES as displayed in Figs. 6–8 recorded on the E–W line of VER with a length around 1/3 of that of the parallel line depicted in Fig. 6. A comparison of these two figures indicates that ΔV is proportional to L ($\Delta V/L$ = const.). The SES on the other line, N–S, was unfortunately not recorded since the pen was not working at the time. This multipen-recorder has no memory.

Apollonian circle have an average distance from HAL-station of about 40 km and hence we have $J_{rel} r \simeq 20$. This implies, according to fig. 19 in Part I, that $M = 3.7 \pm 0.5$ agreeing with the observed value. An anomalous "directivity effect" is evident in the above example. Although one would expect that the SES would have been recorded at THI-station, located closer to the epicenter than NAF-station, no signal was apparent at this station. This will be discussed later.

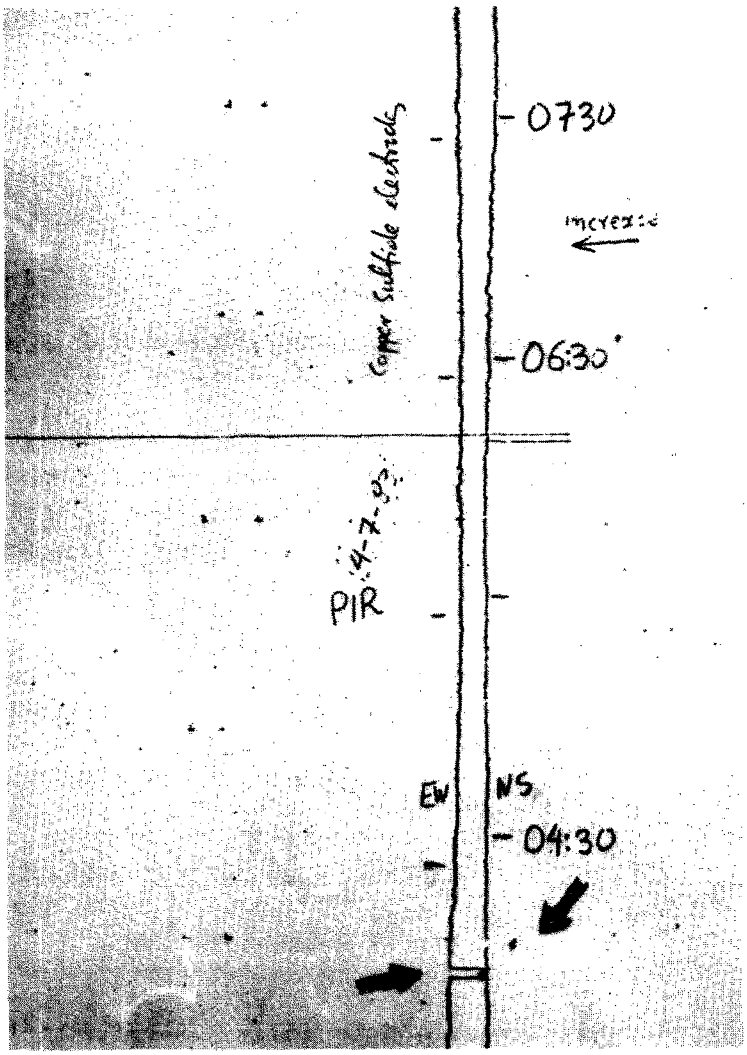


Fig. 10. The simultaneous SES of Figs. 6–9 collected at PIR with unpolarized $L = 50$ m electrodes, not clearly visible on the N–S line. Note that the scale is four times more sensitive than that of Fig. 8. During the SES one can note some "vibration" which is not a local effect because it can also be seen at VER (in Fig. 6) which is located at a distance of 300 km from PIR.

TABLE 1

Calculation of J_{rel} for simultaneous SES corresponding to the $M = 4.5$-event * at 02:39 on June 9, 1983

	HAL		NAF		VER	
	E–W	N–S	E–W	N–S	E–W	N–S
ΔV-values from Figs. 2, 4 and 5 (mV)	1 ($L = 200$ m)	–	–	0.4 ($L = 100$ m)	0.1 ($L = 150$ m)	0.45 ($L = 50$ m)
ΔV-values for $L = 50$ m (mV)	0.25			0.2	0	0.45
ρ_{rel}	1	2	1	1	1	3
J_{rel} (relative units)	0.25		0.2		0.15	

* This M_S-value has later been revised by -0.2 units.

We now proceed to the determination of the epicenter of an event recorded at three stations with an epicenter at a greater distance from the network.

We consider the SES which was recorded simultaneously at 21 : 38 on June 7, 1983 at the following stations: HAL, VER and NAF (see Figs. 2, 4 and 5). The ΔV-values extracted from these figure and J_{rel} for these stations are given in Table 1. In Fig. 12 we plot the two Apollonian circles that correspond to the J_{rel} of the following pairs of stations: HAL–VER (0.25 : 0.15) and NAF–VER (0.2 : 0.15). The

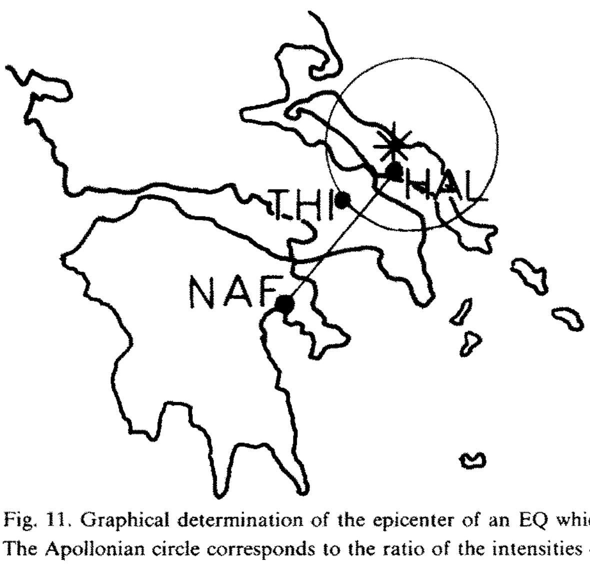


Fig. 11. Graphical determination of the epicenter of an EQ which occurred at 18:54 on May 28, 1983. The Apollonian circle corresponds to the ratio of the intensities of the signal recorded simultaneously at HAL and NAF. The asterisk marks the true epicenter.

TABLE 2

Calculation of J_{rel} for simultaneous SES corresponding to the $M = 6.5$-event at 12:01 on July 5, 1983

	VER		REN		PIR		ZAK	
	E–W	N–S	E–W	N–S	E–W	N–S	E–W	N–S
ΔV-values from Figs. 6–8 (mV)	2.25 $L = 200$ m	2.4 $L = 100$ m	0.35 $L = 30$ m	0.5 $L = 30$ m	0.4 $L = 50$ m	0.3 $L = 50$ m	0.9 $L = 150$ m	1 $L = 150$ m
ΔV-values for $L = 50$ m (mV)	0.56	1.2	0.58	0.83	0.4	0.3	0.3	0.33
ρ_{rel}	1	3	1	1	1	1	1	1
J_{rel}	0.69		1		0.5		0.45	

circles intersect at two points, one of which is about 80 km far from the true epicenter; the latter is indicated with a circle. By considering the distances of that point from the stations one finds that the product $J_{rel} \cdot r$ is around 80–90 and hence

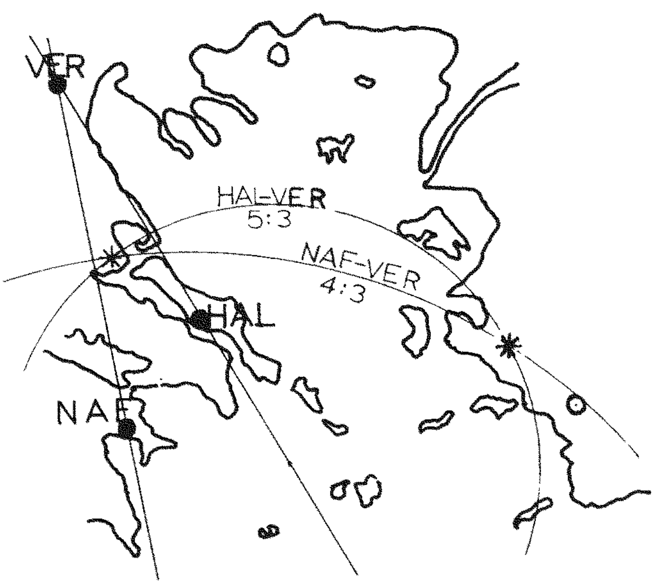


Fig. 12. Graphical determination of the epicenter of the $M = 4.5$ EQ that occurred at 02:39 on June 9, 1983. The precursor SES was recorded simultaneously at HAL, NAF and VER with relative intensities proportional to the numbers 5, 4 and 3. The Apollonian circles intersect at two points, denoted with asterisks, one of which lies some tens of km away from the true epicenter depicted as (○). Only the eastern intersection, in Turkey, was announced in advance (telegram 112) because of experience about the "directivity" of VER which also precluded a correlation of this SES to another EQ ($M = 4.3$) that occurred within the same time-window 35 km north of HAL. The latter EQ was independently announced in advance with an accuracy $\Delta r = 0$, $\Delta M = 0.3$ in telegram 113.

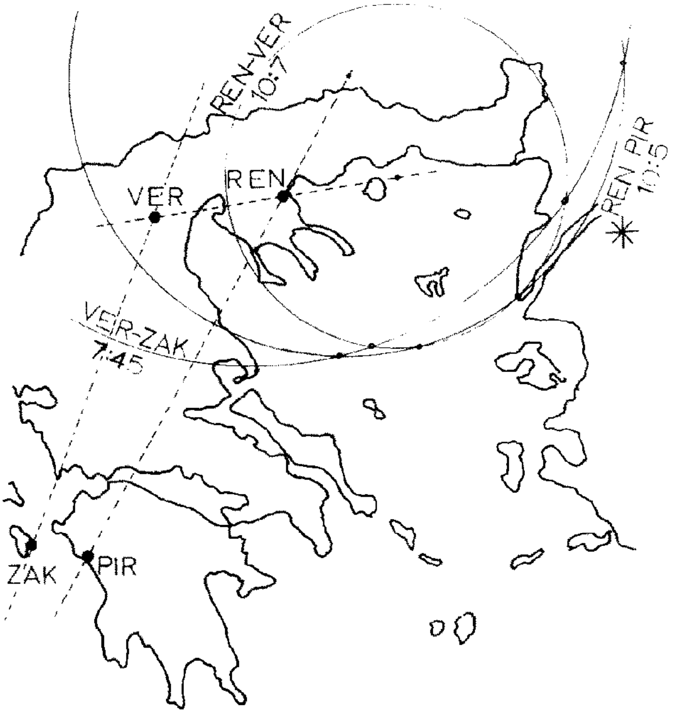


Fig. 13. Graphical determination of the epicenter of the $M = 6.5$ event that occurred at 12:01, July 5 in the Dardanelles. The SES was recorded at REN, VER, ZAK and PIR. The Apollonian circles correspond to the pairs of stations denoted in the figure. The star shows the true epicenter and solid circles the predicted epicenter from the intersection of the circles.

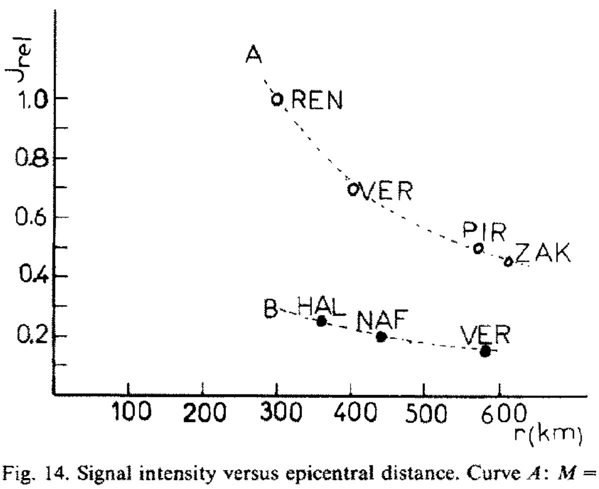


Fig. 14. Signal intensity versus epicentral distance. Curve A: $M = 6.5$ event in the Dardanelles; curve B: $M = 4.5$ event that occurred at 02:39 on June 9, 1983 at (37.8° N, 27.7° E). The lines have been drawn as a visual aid.

the expected magnitude (determined again from fig. 19 of Part I is about $M = 5.0$, to be compared with the observed magnitude $M = 4.5$).

As a last example we discuss the strong event $M = 6.5$, that occurred close to the Dardanelles at 12:01 on July 5, 1983. The simultaneous signals collected at four stations are given in Figs. 6–10 and the corresponding ΔV-values are shown in Table 2. In Fig. 13 we plot the Apollonian circles for the following pairs of stations REN–VER, REN–PIR and VER–ZAK according to the J_{rel} values given in Table 2. According to Fig. 13 the expected epicenter lies either 150–180 km NE of Athens or 350 km NE of Athens. The latter point is roughly 80 km from the true epicenter which is indicated with an asterisk. Note that the calculated four $J_{rel} \cdot r$-values actually indicated that the magnitude of the impending EQ would be large, i.e. $M \simeq 6.0$ to 6.8.

In order to visualize the degree of reliability of the $1/r$-law we plot in Fig. 14 the J_{rel}-values in function of the true epicentral distances for the last two examples discussed above.

DIRECTIVITY OF THE EFFECT

One would expect that stations located at equal distances from an epicenter would record the same signal intensity. The study of the totality of events shows that this does not always hold. The simultaneous SES of a given EQ do not appear at all the stations for which the $1/r$-law would require their detection. The signal, whenever detected, obeys the $1/r$-behaviour but at some stations the SES does not appear at all.

As a striking example we refer to earthquakes from the Kefallinia region (38.0° N, 20.0° E); corresponding SES are clearly recorded in PIR but they do not appear at all at PAT which has approximately the same epicentral distance; on the other hand they do appear at GOR and IOA although these stations have larger epicentral distances. As a second example we note the strong EQ that occurred in the Dardanelles. An inspection of Figs. 6, 7 and 8 shows that the SES has been clearly recorded at PIR and ZAK but did not appear at ASS or GOR which have smaller epicentral distances.

It is remarkable that this "directivity" effect is not reversible, in the sense that a current source at A can be detectable at B but not vice versa. Such cases have been observed for some pairs of stations in Greece, e.g. earthquakes having epicenters close to PIR, as mentioned, are never recorded at PAT although earthquakes that have their epicenters close to PAT (at Kalavrita, 38.0° N, 22.0° E) are always clearly recorded at PIR (see Figs. 10, 11 and 12 of Part I).

Another observational effect refers to the *polarity* of the SES. It is an empirical fact that the recorded direction of a signal at a given station is always the same for EQ coming from a given seismic area. For example the earthquakes from the Kefallinia region are always recorded on the E–W line of PIR as a negative onset of the measured voltage.

Directivity and polarity can, when known, as mentioned above give useful additional information for a correct prediction.

COMPARISON TO OTHER ELECTRIC ANOMALIES PRECEDING EARTHQUAKES

Attempts at predicting earthquakes by electrical measurements have been carried out mainly in eastern countries. A comparison of their studies with the SES method shows that in some cases they concern precursors of a different kind. We emphasize that with the use of the SES the determination of the epicenter and magnitude of the impending EQ is based on the "relative current density" J_{rel} (see Part I), a quantity which has not been considered until now by other authors. We will discuss the three research efforts of China, Japan and Soviet Union.

China

Telluric current anomalies associated with EQ have been observed in China. According to Coe (1971) the anomaly consists of a change in the electric field about 5 h before an EQ and it regains its initial value after the earthquake. (We will refer to this phenomenon as the Chinese effect). The fact that the SES is a transient change that recovers many hours before the EQ provides an indication that the phenomenon refers to a fundamentally different physical mechanism. The Chinese effect has been observed in Greece only in a few cases, namely in the case of the $M = 6.4$ event of Kefallinia on March 23, 1983, and of the $M = 4.3$-event of June 13, 1983, which occurred 40 km south of REN. For the latter EQ we see the SES between 20:36 and 21:06 (see figs. 13 and 14 of Part I) whereas the continuous decrease of the background (i.e. the Chinese effect) started one hour later and recovered after the shock.

There is evidence that the SES also occur in China; considering fig. 11 of the report of Wallace and Teng (1980) concerning the Sungpan–Pingwu earthquakes of August 1976 the graph of the telluric current exhibits a transient change of around 20 mV between 6 and 8 h before the EQ.

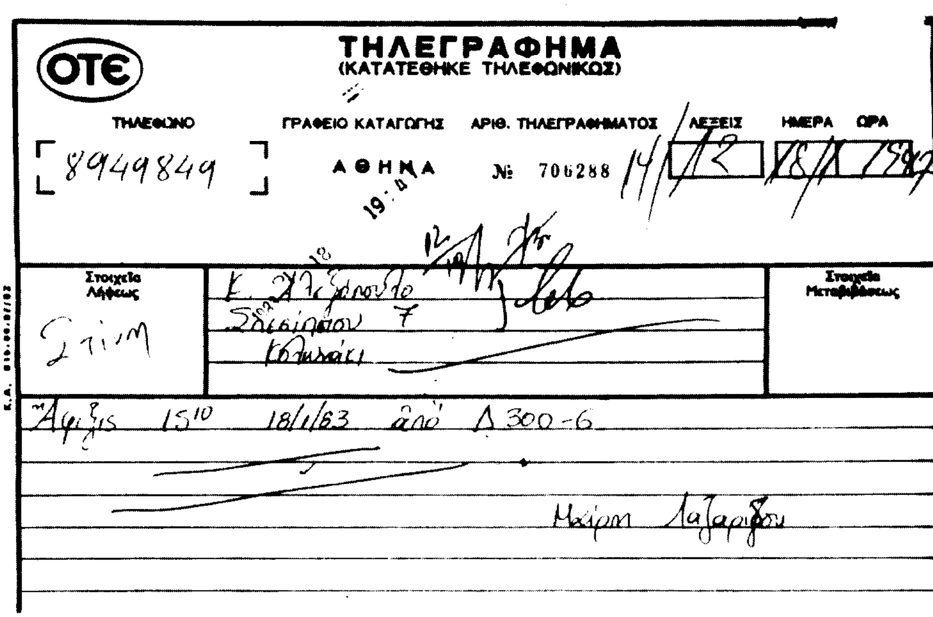
Japan

A resistivity variometer of high sensitivity has been in operation in a 4-electrode array about 60 km south of Tokyo since 1968. According to Rikitake and Yamazaki (1978) a 67 Hz alternating current of 100 mA is sent into the ground through the two outer electrodes placed at a distance of a few meters and the potential difference between the two inner electrodes is recorded. This is a tool to measure the resistivity of the upper stratum of the ground on which the station is based. In 21 cases among the 30 examples for which a coseismic resistivity step was recorded, a premonitory gradual decrease of the resistivity takes place a few hours before the main shock. This experimental technique, although it allows an accurate determination of the resistivity, cannot detect SES which are transient changes of electric current density. During the recording of the SES the resistivity under the station does not necessarily change. But even if it did, it would only affect the measured ΔV by around 5% which is the order of the resistivity changes measured and hence a corresponding change in the ΔV-value would be hidden anyway in the noise. The Japanese observations are analogous to the SES as regards the lead-time on one hand, (the premonitory resistivity changes start a few hours before the shock) and the large epicentral distances at which they can be observed on the other hand (of the order of some hundred kilometers for strong events).

Koyama and Honkura (1978) and later Rikitake et al. (1980) have reported some precursor "self-potential" anomalies but their form and the lead time, a few months before the EQ, has no similarity to the present SES. Further, as noticed by Honkura (1978), their self-potential anomaly was simultaneous and similar in shape to variation of the total intensity of the magnetic field, a fact which definitely does not occur with SES.

Soviet Union

Pioneering electric field measurements have been made in Kamchatka since 1966 by Sobolev and co-workers. They installed a network of coastal stations at distances



ΟΤΕ

ΤΗΛΕΓΡΑΦΗΜΑ
(ΚΑΤΑΤΕΘΗΚΕ ΤΗΛΕΦΩΝΙΚΩΣ)

ΤΗΛΕΦΩΝΟ	ΓΡΑΦΕΙΟ ΚΑΤΑΓΩΓΗΣ	ΑΡΙΘ. ΤΗΛΕΓΡΑΦΗΜΑΤΟΣ	ΛΕΞΕΙΣ	ΗΜΕΡΑ	ΩΡΑ
8949849	ΑΘΗΝΑ	№ 706288			

Στοιχεία Λήψεως

Στοιχεία Μεταβιβάσεως

18/1/83 Δ 300-6

Fig. 15. Telegram deposited at 19:47 (local time) on Jan. 18, 1983 stating that an SES had been recorded at 15:10 (L.T.) Jan. 18 and that an $M = 6$ event would occur with an epicenter 300 km west of Athens. Actually $6\frac{1}{2}$ h (i.e. 00:02 GMT, on Jan. 19) after the deposition of the telegram an $M = 6$ event occurred with an epicenter 330 km west of Athens. Telegram Nr. 32.

of 100–200 km and concluded that changes of telluric currents correlate with earthquakes. However, no attempt at the determination of the epicenter and the magnitude of the impending EQ has been reported. Although their study is the most comprehensive in the literature, as far as the telluric field anomalies are concerned, they are of the opinion that their forecasts (made for scientific purposes) have a too low probability for practical applications (Sobolev, 1975).

The most significant anomaly (100–300 mV/km) was reported by Myachkin et al. (1972); it started 3–16 days before the shock and had a bay form with a duration of a few days. We have also observed anomalies of this kind in a number of cases, mainly, prior to strong events.

RELIABILITY OF THE SEISMIC ELECTRICAL SIGNAL METHOD

In order to examine objectively the reliability of the SES-method for EQ-prediction we have used a method similar to that mentioned by Sobolev (1975). After the detection of an SES and having checked that it is not due to some other cause (e.g.,

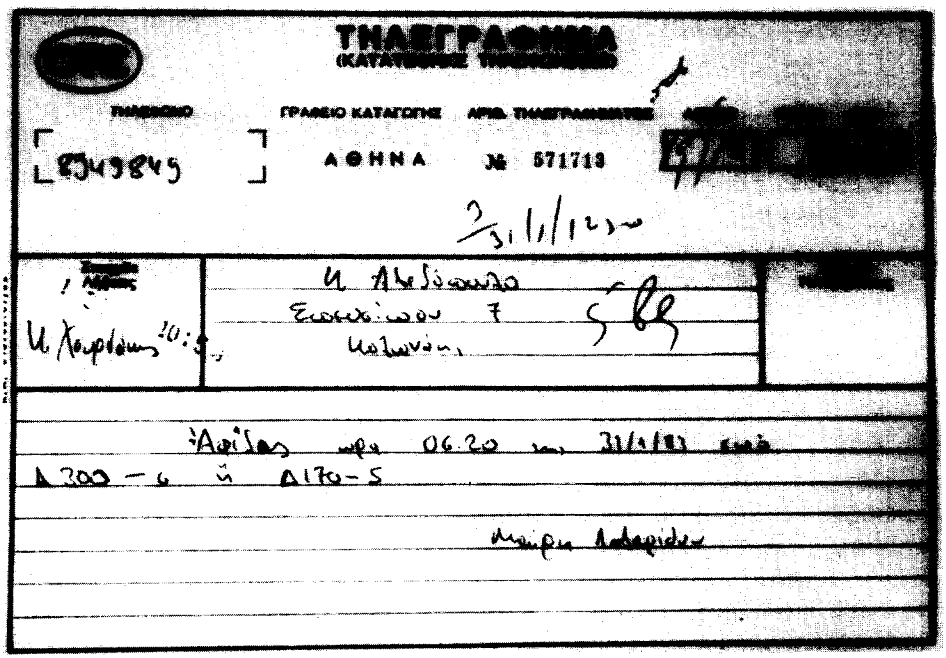


Fig. 16. Telegram deposited at 10:58 (local time) on Jan. 31, 1983, stating that an SES had been recorded at 06:20 (local time) Jan. 31, 1983, and predicting either an $M = 6$ event 300 km west of Athens, or an $M = 5.0$ event 170 km west of Athens. An $M = 5.7$ event actually occurred $7\frac{1}{2}$ h after the deposition of the telegram, i.e. at 15:27 GMT on Jan. 31, with an epicenter 300 km west of Athens. This case is similar to that of Fig. 12 where the Apollonian circles intersect at two points and hence two probable epicenters are indicated. Telegram No. 41.

magnetic variation, noise from electric power, etc.), we proceed to the determination of the epicenter and the magnitude of the impending earthquake. *The resulting values for each case are always officially documented before the EQ-occurrence.* They were mechanographically registered in the form of telegrams charged on a single telephone number (8949849) that was exclusively used for this purpose. Two photocopies of such documents (telegrams) are given as an example in Figs. 15 and 16. The telegrams were consecutively numbered according to the list of the Telephone Corporation.

Earthquakes with $M \geqslant 5$

In Table 3 we give *all* earthquakes with $M_s \geqslant 5$ that occurred within or close to the perimeter of the telemetric network from Jan. 19, 1983 to Oct. 21, 1983. The

TABLE 3

All earthquakes with $M_s \geqslant 5$ occurring within or close to the telemetric network from Jan. 18, 1983, until Oct. 21, 1983

Earthquake					Telegram		
date	time	M_s	epicenter		Δr (km)	ΔM	No. of telegram
			(°N)	(°E)			
19-1-83	00:02	6.0	38.21	20.28	10	−0.0	32
19-1-83	05:41	5.5	37.97	19.97	20	−0.5	30
22-1-83 *	12:54	5.2	38.02	20.24	0	−0.3	33a
22-1-83 *	16:01	5.0	38.11	20.22	0	−0.5	33b
31-1-83	15:27	5.7	38.06	20.29	10	−0.3	41
19-2-83	15:55	5.0	36.90	21.50	–	–	missed
20-2-83	12:42	5.5	37.90	21.10	155	0	53
21-2-83	00:13	5.6	37.84	20.16	25	0.6	55
16-3-83	21:19	5.4	38.80	20.60	90	0.6	65
23-3-83	19:04	5.3	38.80	20.60	120	1.3	68
23-3-83	23:51	6.4	37.90	19.80	40	0.8	67
24-3-83	02:36	5.2	38.36	20.17	70	0.7	69
24-3-83	04:17	5.6	38.13	20.36	20	0.1	70
24-3-83	12:50	5.3	38.08	20.28	15	0.1	71
24-3-83	19:35	5.2	38.00	20.10	–	0.4	72
25-3-83	18:56	5.5	38.38	20.24	40	0.2	73
25-3-83	20:20	5.0	38.20	20.20	50	0.5	70
26-3-83	17:17	5.0	38.18	20.10	20	−0.7	74
13-5-83	23:50	5.3	38.50	20.50	70	0.8	96
14-5-83	23:13	5.5	38.40	20.20	65	0.5	97
14-5-83	23:26	5.3	38.40	20.30	–	–	missed
8-9-83	22:05	5.4	38.00	21.20	80	−0.1	146
19-9-83	01:18	5.0	38.70	22.40	40	0.7	148

* The magnitudes of the earthquake on Jan. 22, 1983 have been later slightly revised.

TABLE 4

All EQ since Oct. 1982 until Oct. 21, 1983 in the vicinity of large towns of Greece

Earthquake					Telegram			Region
date	time	epicenter		M_s	Δr (km)	ΔM	No. of telegram	
		(°N)	(°E)					
6-2-83	18:14	38.4	23.2	4.0	missed		48	ATH
18-5-83	16:48	38.6	24.1	4.2	40	0.4	99	
3-6-83	22:16	38.2	23.2	4.1	50	0.1	109	37.8°–38.8°N
10-6-83	22:56	38.7	23.6	4.3	0	0.3	113	22.6°–24.3°E
12-8-83	17:17	38.2	23.1	4.7	missed		*	$M \geqslant 4$
13-8-83	14:52	38.7	24.1	4.1	85	−0.5	135 a	
4-10-82	20:51	40.6	23.5	3.8	25	−0.2	3	THES
14-11-82	21:44	40.1	23.7	3.8	missed		*	
27-12-82 [a]	08:15	40.7	23.0	4.2	0	0.2	19	40.0°–41.4°N
6-4-83	04:55	40.8	23.0	4.3	missed		**	22.0°–24.0°E
25-4-83	06:05	40.6	23.9	3.8	130	−0.2	86	$M \geqslant 3.8$
31-5-83	22:15	40.2	22.2	3.8	50	0	107	
14-6-83	04:41	40.4	23.9	4.3	80	1.1	114	
26-8-83	12:52	40.3	24.0	4.8	50	0.4	140	
26-8-83	16:16	40.7	22.5	4.4	missed		**	
8-11-82	18:29	38.15	22.1	4.3	30	0.5	9	PAT
30-1-83	17:06	37.9	21.8	4.3	90	−0.5	39	
30-1-83	17:09	37.9	21.9	4.2	40	−0.6	38	
4-2-83	05:51	38.0	22.0	4.2	20	−0.1	42	
10-2-83	16:09	38.4	22.1	4.2	45	0.2	49	37.8°–38.5°N
15-3-83	15:41	38.1	21.5	4.3	0	0.3	63	21.4°–22.6°E
11-4-83	17:23	37.9	21.9	4.7	missed		*	$M \geqslant 4$
8-5-83	22:45	38.0	22.0	4.7	0	0.5	91	
14-5-83	03:42	38.2	22.0	4.0	20	0	95	

starting date was chosen because the ZAK-station was installed on Jan. 18, 1983 while the end-date refers to the last telegram sent to the Minister of Public Works. In Table 3 we also give the running number of the telegram issued for the prediction of each event, along with the deviations ΔM and Δr between the true and the predicted values of the magnitude and the epicentral coordinates. An inspection of this table shows the following results:

(a) From a total of 23 earthquakes, 21 predictions were issued. In other words for these 21 cases clear SES were recognized well in advance. The EQ missed on Febr. 19, 1983 gave a signal that has been recognized in retrospect. The case of the other EQ missed at 23:26 on May 14, 1983 occurred only 13 min after the previous event from the same area; nevertheless after reexamining the recordings we saw that two consecutive SES were present which were mistakenly taken as a single SES and hence only a single prediction was issued.

(b) By accepting as a successful prediction a case where $\Delta r \leqslant 100$ km and $|\Delta M| \leqslant 0.8$ the successful predictions amount to 18.

(c) Restricting ourselves to EQ relatively isolated in time we can calculate the probability of a prediction of time, epicenter and magnitude having been made by chance. For example for the last EQ of Table 3 with the epicenter in continental Greece, i.e. an area within which no event with magnitude greater or equal to 5 had occurred for nearly one year, the probability is 10^{-3} or less. The same holds for the event on Sep. 8, 1983, with $M = 5.4$ by considering that no event with $M \geqslant 5$ has occurred within the whole network since May 14, 1983. Two telegrams expedited within a period shorter than the time-window predicting earthquakes of comparable (but *large*) magnitude, e.g. $M = 6$, from the same epicenter constitute an excellent check of the reliability of the method when these events actually occur; in such cases, however, predictions and earthquakes cannot be uniquely cross-correlated, e.g., telegrams 30 and 32 of Table 3.

Earthquakes with $M < 5$

The telemetric stations in the vicinity of the three largest towns of Greece, i.e. Athens (ATH), Thessaloniki (THES) and Patras (PAT), were installed in October 1982. During the period of almost one year, i.e. until Oct. 21, 1983, a number of events with $M < 5$ occurred with epicenters at a distance of some tens of kilometers

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Note to Table 4

[a] By drawing a circle with radius of 100 km around the predicted point we find that for 9 months (i.e. since May 6, 1982) no EQ with $M_S \geqslant 4$ had occurred in that area; although $\Delta r = 0$, we accept $\Delta r = 10$ km and hence the probabilities for predicting separately the time (p_t) and the epicenter (p_e) are: $p_t = 5$ days/9 months $= 1.8 \times 10^{-2}$; $p_e = (10/100)^2 = 10^{-2}$. Therefore the probability $p_{t,e}$ for achieving the simultaneous prediction of these two parameters *by chance* is: $p_{t,e} = p_t \times p_e \simeq 10^{-4}$.

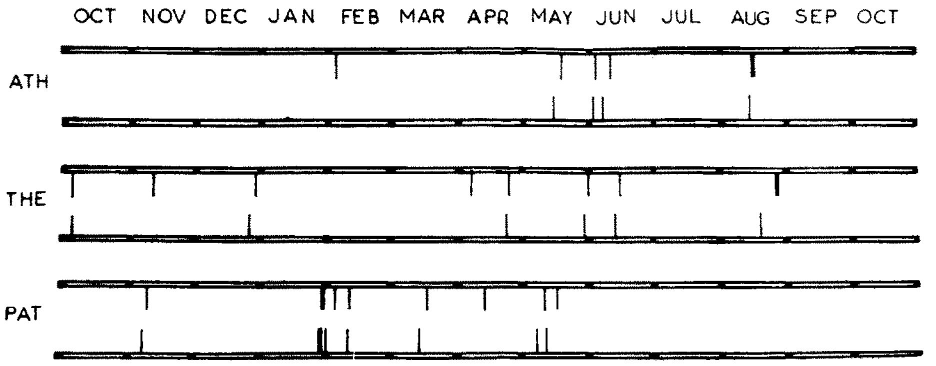

Fig. 17. Time charts of all events from Oct. 1982 to Oct. 1983 for regions around Athens, Thessaloniki and Patra. Thresholds and coordinates in Table 4. Lines mark EQ (above) and telegrams (below).

from these cities. We have studied the events within certain regions surrounding these towns. The corresponding data are given in Table 4 along with the deviations of the documented predictions issued for each event. We stress that in this table we give *all* shallow earthquakes that occurred in each area mentioned in the preliminary bulletin of the National Observatory of Athens with magnitudes down to a threshold (i.e. $M \geqslant 4$ for ATH and PAT, $M \geqslant 3.8$ for THES) selected for each region so as to contain a significant number of events. The corresponding time-charts of the earthquakes along with the telegrams issued are given in Fig. 17.

An inspection of Table 4 shows that for a total of 24 events 18 predictions were issued in advance (8 for PAT, 4 for ATH and 6 for THES). Concerning the six missed events the following remarks can be made: the three events marked with an asterisk refer to cases when the central system was not supervised due to the absence of the authors in the field or at a conference. In retrospect an examination of the charts shows that SES were present in all three cases and could have warranted a prediction. Events with a double asterisk refer to cases in which although SES were present they were not recognized before the EQ-occurrence. Finally in one case (Febr. 6, 1983) the central station was out of operation due to a blackout that started on Febr. 4, 1983 and finished on Febr. 7, 1983; telegram 48 announced the initiation of this blackout.

By evaluating the 18 predictions given in Table 4 we see that in only one case (June 14, 1983) the inequality $|\Delta M| \leqslant 0.6$ was violated; furthermore the deviations * Δr between the predicted and the real epicenters were at most 90 km except the one case of April 25, 1983.

In summary, our present experience indicates that *every sizable EQ is preceded by an SES* and inversely *every SES is always followed by an EQ* the magnitude and the epicenter of which can be reliably predicted.

* As expected the efficiency of the predictions drastically decreases for earthquakes *outside* the network.

SUMMARY OF RESULTS

In the following we summarize the main results concerning the properties of SES as obtained from the present paper and part I.

(1) The SES is observed 6–115 h before the EQ and has a duration τ of 1 to 90 min, appearing as a transient variation of the telluric current.

(2) There is no correlation, either between the lead-time Δt and magnitude M or between the duration τ of the SES and M. There is also no connection between Δt and τ.

(3) The lead times can be classified into two main groups: one from 6–$13\frac{1}{2}$ h and another one from 43 to 60 h. Also two intermediate groups exist containing only rare cases with Δt from 24 to 36 h and 65 to 115 h.

(4) A given seismic region does not always emit signals of the same form, duration or lead-time; it is however always recorded on the same line of a given station and always with the same polarity. The SES is either observed on one line or on both lines of a station (E–W or N–S component).

(5) SES signals recorded on a single line of a given station, emitted from various seismic regions, have ΔV-values that decrease with the epicentral distance (for $r \gtrsim 50$ km) according to a $1/r$-law.

(6) SES appear simultaneously at different stations for a given EQ. However, due to different conditions of the resistivity at the stations (maybe also near the vicinity) the corresponding ΔV-values do not fit the $1/r$ attenuation law. In order to overcome this problem we relate all stations with each other to the same resistivity level by applying individual station corrections in comparison to one reference station. In this way we obtain "relative effective resistivity" correction factors.

(7) SES emitted from a given seismic region ($r =$ const., azimuth = const.) recorded on the same line (E–W or N–S) of a given station have ΔV-values which, with good approximation, are related to the magnitude M by the law: $\log \Delta V = \beta M + a$ where β has a positive value between 0.3 and 0.4 and a is the intercept.

(8) SES emitted from various regions $i = 1, 2, \ldots, n$ ($r \neq$ const., azimuth $\neq$ const.), recorded on the same line (E–W or N–S) of a given station have ΔV-values which are related to M by $\log \Delta V = \beta M + a_i$ where β is again the positive slope factor, 0.3–0.4. The intercept a_i however, is different for different seismic regions. Using the formulation $\log(\Delta V \cdot r)$ and plotting it vs. M, we get $\log(\Delta V \cdot r) = \beta M + c$. The parallel lines are now one single straight line, i.e. c is a certain constant.

(9) SES from various seismic regions $i = 1, 2, \ldots, n$, recorded on the same line (E–W or N–S) at k different stations $k = 1, 2, \ldots, j, \ldots, l, \ldots$ reveal a $\log(\Delta V \cdot r)$ vs M relation of the form: $\log(\Delta V \cdot r) = \beta M + a_k$ where β is again the same slope factor as above, but a_k differs for different stations. The ratio $(\Delta V \cdot r)_j / (\Delta V \cdot r)_l$ gives the effective resistivity of the jth station related to a reference (lth) station (for constant M).

(10) The intensity J of SES on a certain line (E–W or N–S) at a certain station is

defined as:

$$J = \frac{1}{L}\frac{\Delta V}{\rho}$$

Considering the two different lines we have:

$$J_{\mathrm{EW}} = \frac{1}{L}\frac{\Delta V_{\mathrm{E-W}}}{\rho_{\mathrm{E-W}}} \quad \text{and} \quad J_{\mathrm{NS}} = \frac{1}{L}\frac{\Delta V_{\mathrm{N-S}}}{\rho_{\mathrm{N-S}}}$$

where ρ is the effective resistivity. The intensities of the same SES recorded at a number of stations decrease according to a $1/r$-law.

(11) The intensity J of SES, reduced by the epicentral distance is given by log $(J \cdot r) = \beta M + a_1$ where β is again the common slope, 03.–0.4, and a_1 is the intercept which joins all seismic regions and all stations on a single straight line.

(12) Once an SES has been (simultaneously) recorded at a number of stations a reliable prediction of the epicenter and the magnitude can be made as follows: from the recorded ΔV-values of each station and the effective resistivities of the lines one finds the (relative) intensity $J_{\mathrm{rel,i}}$ for each station (i); by using the rule $J_{\mathrm{rel}} \propto r^{-1}$ the epicenter is determined either by a computer minimization procedure or graphically by drawing the Apollonian circle for each pair of stations. Once the epicenter has been determined the product $J_{\mathrm{rel}} \cdot r$ is known for each station and then from the empirical log $(J_{\mathrm{rel}} \cdot r)$ vs M plot the magnitude is determined. The present accuracies are 50–100 km for the determination of the epicenter and ± 0.5 for the magnitude.

PROBLEMS TO BE SOLVED

The present article is concerned with the fact that each EQ is preceded by a transient current emitted from the focal area and with the empirical rules it follows. The emission of a transient current under changing stress on a body is an effect that solid state physics describe as "pressure induced (de)polarization" (Varotsos et al., 1982b). The electric current comes from the orientation of the dipoles of the form "aliovalent impurity plus a vacancy" (or interstitial) which exist anyway in the volume close to the focus (Varotsos et al., 1982b); the relaxation time of these dipoles varies with pressure. Before an EQ the stress gradually increases and reaches a certain critical value σ_{cr} for which the relaxation time becomes short and a transient current is emitted; the earthquake occurs when the stress reaches the fracture stress σ_{f} and hence the time-lead is given by:

$$\Delta \mathrm{t} = \frac{\sigma_{\mathrm{f}} - \sigma_{\mathrm{cr}}}{b}$$

Our suggestion (Varotsos et al., 1982a, b) that a rock subjected to a gradually increasing stress emits a transient electric current well before its rupture has been recently confirmed experimentally in a large granite sample by Sobolev et al. (1983); as they note the high repeatability of the phenomenon (see Fig. 7 of their paper) indicates the reliability of their findings.

As the values of σ_f and σ_{cr} are more or less constants and Δt varies only from 6 to 115 h one has to accept that the stress-rate b varies only within one order of magnitude for earthquakes of the hellenic region.

The empirical rules mentioned in Part I cannot be explained so easily. For example the $1/r$-rule about the attenuation of the current density with distance cannot be theoretically derived for currents emitted from a polarizing or depolarizing body (i.e. the volume which is under stress at the focal area) irrespective of the extension of the current source (point dipoles, polarized ellipsoid) and of its surroundings (full space, half space or two-dimensional conduction from a source near the surface).

The linear connection between the logarithm of the signal intensity and the magnitude (and the small value 0.3–0.4 of the slope) is tentatively explained by assuming that the dimensions w, h of the volume under stress at the focal region do not increase in the same way with the magnitude as the length.

On the other hand the effect of "directivity" can be explained to some extent by suitable assumptions on local or extended anomalies of the conductivity. The "polarity" might be connected in some way to a regularity of all fault mechanisms of a seismic area.

The most puzzling problems are the duration of the signal and the time-lead, both of which are *not* connected to the magnitude.

A similar important problem arises for the duration τ of the signal (1 min to $1\frac{1}{2}$ h). If one assumes that current is emitted when $\sigma = \sigma_{cr}$ and the stress distribution in the earth is heterogeneous one does not expect the (de)polarization effect to occur at all points of a large volume simultaneously. If one considers that the condition $\sigma = \sigma_{cr}$ is sweeping through the volume under stress, its "velocity" for dimensions of the order of 1–10 km must be:

$$v = \frac{1 \text{ to } 10 \text{ km}}{\tau} = \frac{1 \text{ to } 10 \text{ km}}{1 \text{ min to } 1 \text{ h}}$$

i.e. of the order of 1 to 200 m/sec. Such values are not far from slip-velocities of EQ, but no conceivable connection can be envisaged between the slip-motion which is a declenching process and the current which is emitted during a practically tranquil period. Gokhberg (pers. commun., 1983) has indicated that the above velocity is comparable to the velocity of redistribution of stresses.

All the above empirical facts await a theoretical background; their explanation will constitute an important step towards understanding the physical situation of the focal area during the pre-seismic stage.

NOTE ADDED ON THE PROOF

During the recent period January 1, 1984 – May 20, 1984, five EQ with $M_L \geqq 4.3$ with epicenters inside the network occurred. These EQ occurred on: Febr. 9, Febr.

11, Febr. 19, March 12, May 8, 1984 with epicenters at: (40.6°N, 21.6°E), (38.3°N, 22.0°E), (40.6°N, 23.4°E), (39.3°N, 20.9°E), (40.4°N, 22.8°E) with $M_L = 4.5$, 5.1, 4.3, 4.4 and 4.3 respectively. For *all* of them predictions were issued in advance (telegrams nos.: 199, 201, 211, 232, 255) with the following deviations: $\Delta r = 60$, 110, 90, 90, 25 km in the epicenter, and $\Delta M = -0.4$, 0.4, 0.2, -0.2, 0.0-units in magnitude respectively. Details on these recent results will be shortly published.

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