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ΦΥΣΙΚΗ.— **Physical properties of the variations of the electric field of the earth preceding earthquakes,** by *P. Varotsos - K. Alexopoulos**, ὑπὸ τοῦ Ἀκαδημαϊκοῦ κ. Καίσαρος Ἀλεξοπούλου.

ABSTRACT

The electric field variations of the earth, that occur before earthquakes, have been studied in a network of 18 stations in Greece. These precursor seismic electric signals (SES) occur 6 to 115 hours before each earthquake (EQ) and have a duration of 1 to 70 minutes. The duration and the lead-time in contrast to other precursors, do not depend on EQ-magnitude (M). These signals appear as transient changes of the potential difference measured between two electrodes at a distance L; their strength depends on M, the epicentral distance r and the local inhomogeneities. The components of the electric field are measured in two directions (EW and NS). The totality of experiments showed that the interesting quantity of each SES is the maximum value ΔV of the potential change. The SES of an impending EQ appears simultaneously at a number of stations without being accompanied by any significant change of the magnetic field.

The following rules have been established:

1. Seismic electric signals registered on a single line of a given station and emitted from various seismic regions have ΔV—values that decrease with the epicentral distance according to a r^{-1}—law (for $r \geqslant 50$ km).

2. For a given line of a given station the SES emitted from a given seismic region ($r \approx$ const) have ΔV—values that increase with the magnitude; to a good approximation $\log \Delta V$ vs. M gives a straight line with a slope between 0.3 and 0.4. If another seismic region is considered for the same station and line the straight line is parallel to the previous one but shifted by a constant amount that depends purely on the ratio of the epicentral

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distances. Therefore if the quantity log ($\Delta V \cdot r$) is plotted versus M for the same station but for SES emitted from various seismic regions a unique line appears.

3. The simultaneous ΔV—values of a given EQ recorded at various stations do not follow an r^{-1}—dependence. The value $\Delta V/L$ of the electric field in each direction, divided by a suitable factor—an empirically determined effective resistivity—gives a quantity characteristic of the variation of the component of the current density in the earth. By combining the values of the two directions the relative signal strength J_{rel} of the SES results. This quantity is found to attenuate with the distances of the stations according to a r^{-1}—law so that log ($J_{rel} \cdot r$) is a unique linear function of M for all stations and seismic regions. 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 $J_{rel} \cdot r$ is evaluated so that the magnitude M can be estimated by resorting to an empirical log ($J_{rel} \cdot r$) vs M plot. The accuracy of M is around ± 0.5 R.

Since the completion of the network 170 successful predictions have been made. For the unbiased statistics of the reliability each prediction was issued in the form of a telegram expedited before the occurrence of the EQ. For 23 earthquakes that occurred within the network with magnitude larger or equal to $M = 5$ twenty one telegrams were expedited with errors less than 120 km and 0.8. The probabilty of the parameters having been predicted by chance is between 10^{-3} and 10^{-4}.

The present method is compared to other electrical methods invented in China, Japan and Soviet Union. In spite of the fact that the SES method seems to be of practical importance for EQ-prediction a number of problems concerning the origin of the effect, its directivity and the attenuation with the distance remain open.

1. INTRODUCTION

Variations of the electric field in the earth occur 6 to 115 hours before each earthquake. They shall be called seismic electric signals (SES). Initially their monitoring was carried out at a small number of stations that could collect signals only from a restricted region of Greece. Lead times between $6^1/_2$ and 13 hours were clearly established [**1**] although in some cases suspicion arose about larger values. Comparing the strength of signals collected simultaneously at various stations the epicenter of an impending earthquake (EQ) could be determined [**2, 3**] by accepting a 1/r decrease of the signal-strength with epicentral distance r. Once the epicenter had been determined the magnitude could be predicted by using an empirical connection between the signalstrength, the epicentral distance of the station and the magnitude M.* A

*Magnitudes throughout this paper equal to Ms taken from the officially certified series of EQ that occurred during the first months of 1983 showed lead times that reach up to 115 hours [**4**]. Since September 1982 a telemetric network of 16 stations* has gradually been set in operation [**5**] at sites shown in Fig. 1. The increased flow of data allowed new facets on the SES to be found mainly about the strength with which they appear at each station. They are described in the present paper together with a brief mention about the reliability of the predictions.

2. FEATURES OF THE SES

Seismic signals of various forms have been published in former papers [**1, 2, 6**]. They were described as transient variations of the telluric field with a duration between 1 and 70 minutes.

The SES usually starts gradually although in some cases instantaneous onsets (rise-time one minute or smaller) have been noticed. In the majority of cases the end of the signal decays gradually. Only in cases where an SES shows an abrupt onset and lasts not more than a few minutes is the end also abrupt. Such an example is shown in Fig. 2. It refers to a SES collected on the EW line (L = 200 m) at KAL at 15:15 July 11, 1983; it was followed by a 5.8 EQ that occurred at 02:55 of July 14, 1983 with an epicenter 150 km south of the station. Fig. 3 was simultaneously recorded at the same station on a parallel line with half the length (100 m) and shows a strict verification of the constancy of $\Delta V/L$. The inverse case i.e. gradual onset and abrupt end has never been observed. A smooth curve of small duration (<5 min) has also never been observed. In rare cases the recording shows a very strong overshoot at the start and the end. Further in a few cases the duration is appreciably larger and then the SES appear to be like a permanent deviation of the telluric field (however the amplitudes of these cases obey the same rule as the transient ones so that to consider them as being due to the same effect).

When comparing SES for earthquakes from the same seismic region or for aftershocks of a given strong event we find that they usually do not have the same form. We can visualise this in the following figures. Fig. 4 is the SES of the main shock M = 6.5 of Jan. 17, 1983 that occurred close to Kefal-

edition of the preliminary seismological bulletin of the National Observatory of Athens; when M_S not given we estimate $M_S = M_L + 0.4$.

* At the moment only 12 in operation.

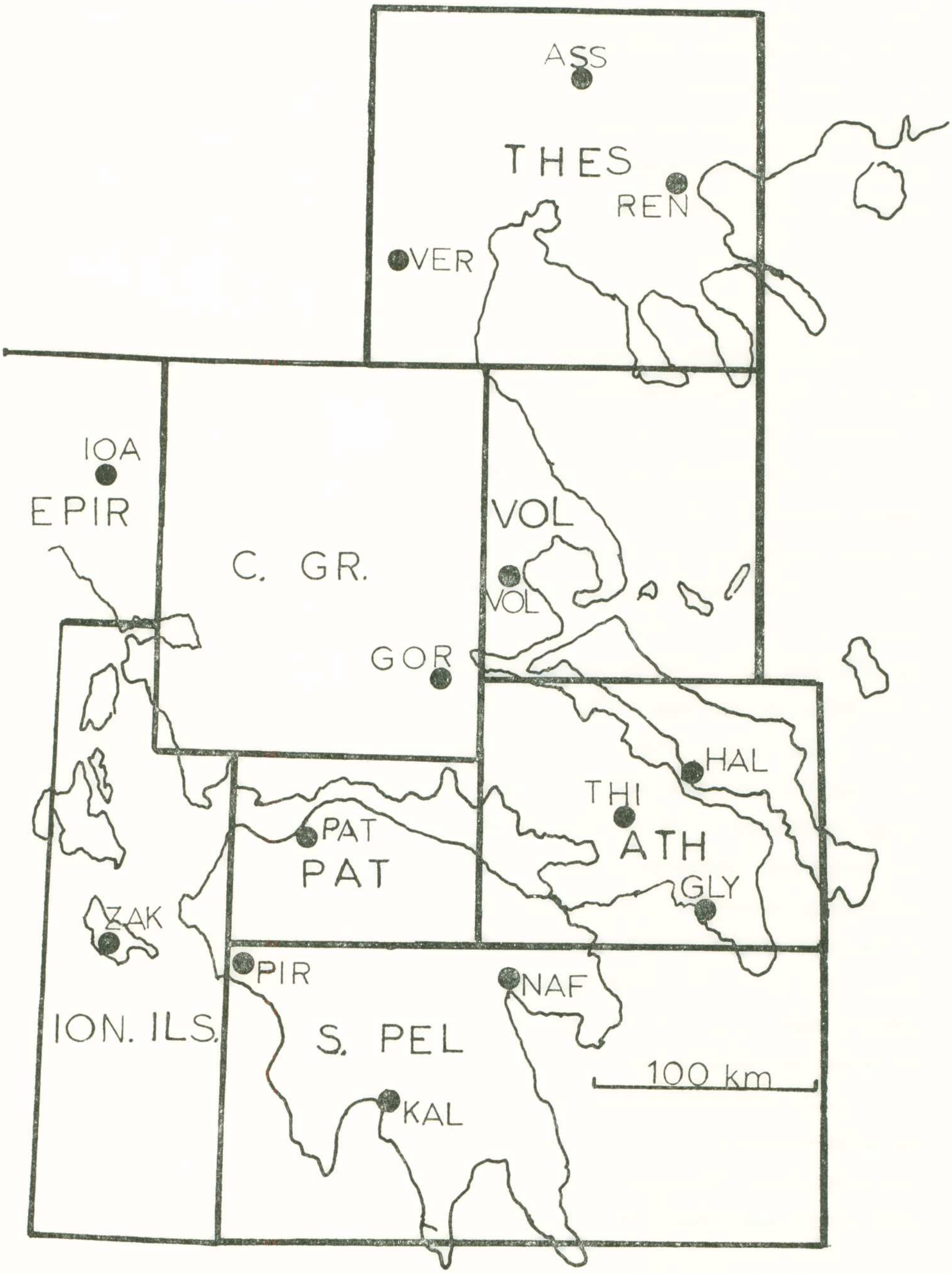


Fig. 1. Map or Greece showing the sites of the stations. For the regions see Paragraph 11.

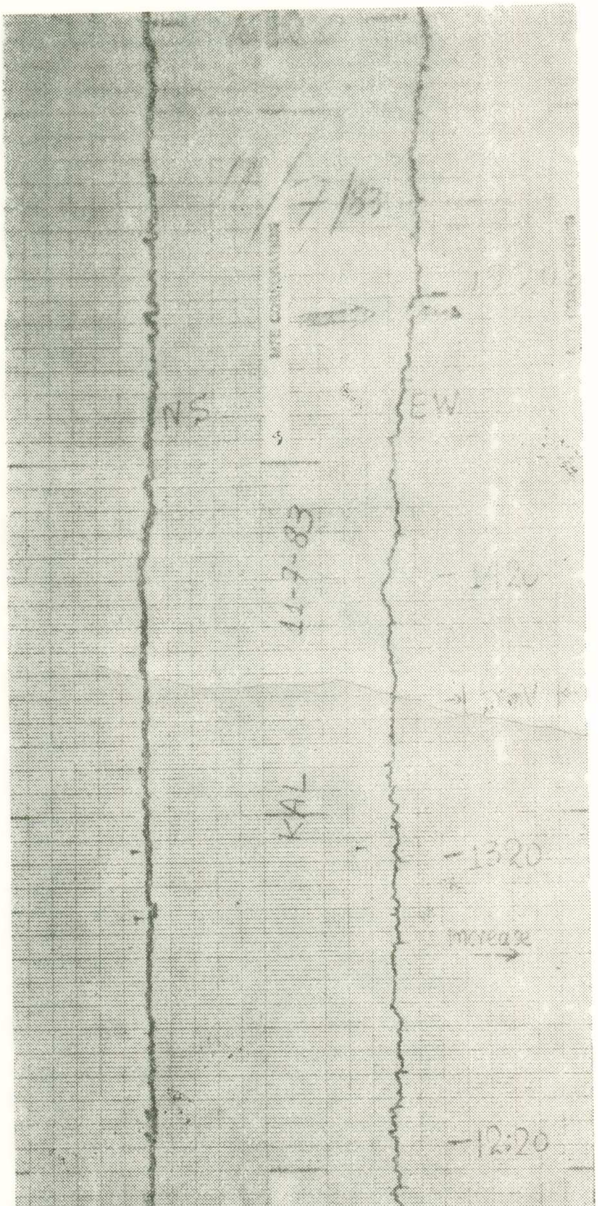


Fig. 2. A SES with abrupt edges and with a small duration. The arrow shows the SES.

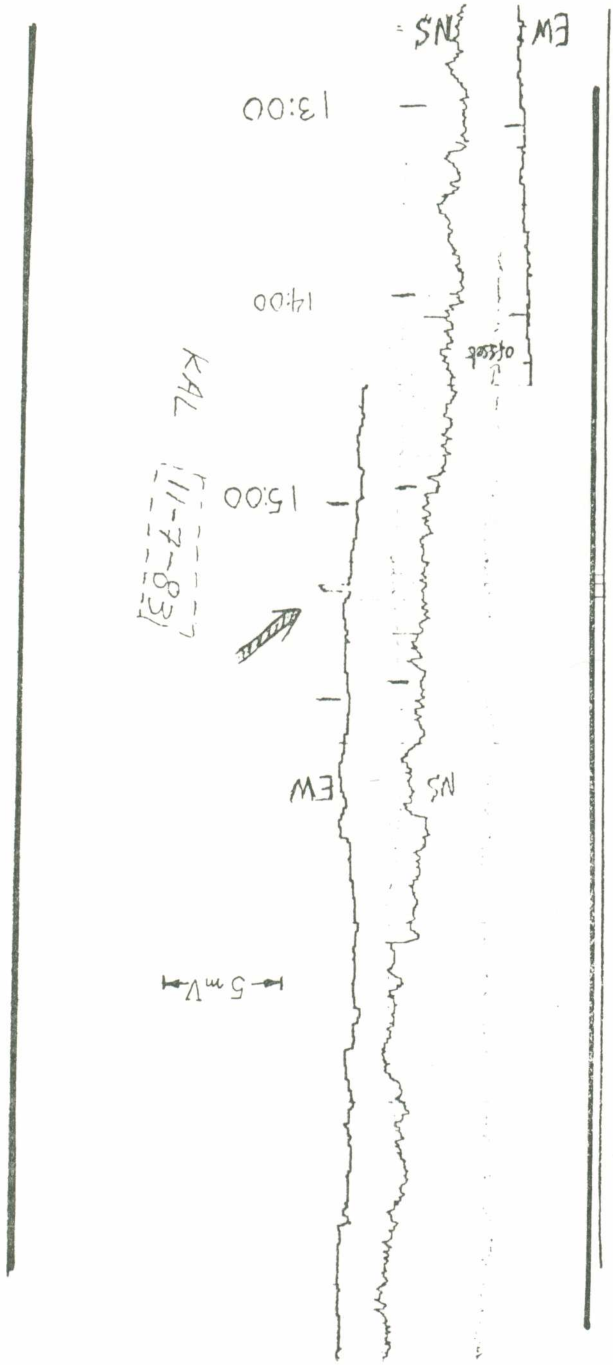


Fig. 3. The same SES as in Fig. 2 recorded at the same station on a parallel line with half the length (100 m); it shows a strict verification of the ΔV/L-test.

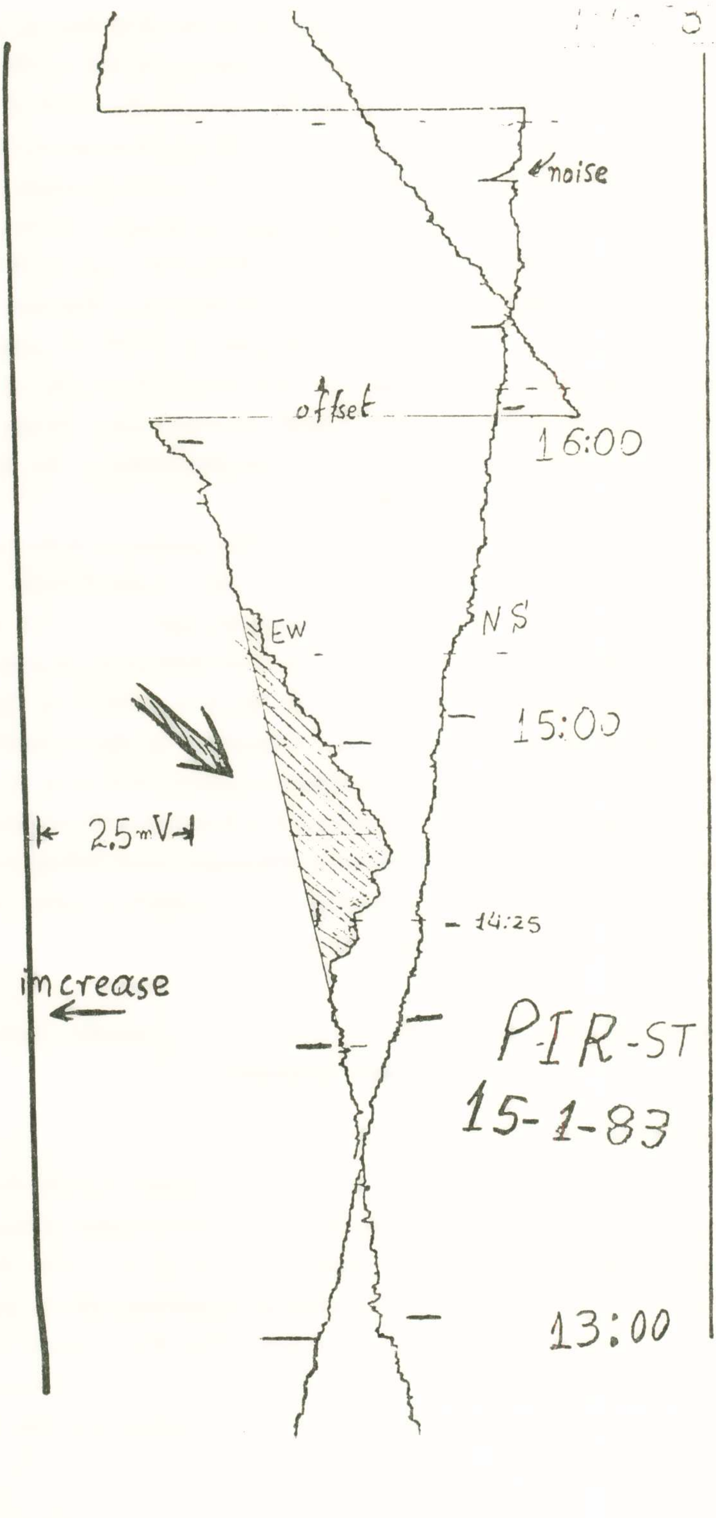


Fig. 4. The SES of a 6.5 R main shock. Note the strong variation of the background (Sobolev effect).

linia Island in the Ionian Sea. It was collected on the EW line (L = 50 m) of PIR 14:22 of Jan. 15, 1983 i.e. at a distance of 120 km WNW of the epicenter. Fig. 5, 6 are precursors of the two largest aftershocks of 6 R (Jan. 19) and 5.8 R (Jan. 31) recorded on the same line. No obvious similarity emerges from the comparison of these last three figures; however in some other cases earthquakes from the same seismic region give strikingly similar SES. We give as an example SES collected from the Kalavrita region (38°N, 20°E) collected on the same EW line of PIR (L = 50 km) at a distance of 60 km. Fig. 7 is a precursor to a 4.7 event that occurred at 17:06 of Jan. 30, 1983. Fig. 8 is a precursor of the 05:33 Jan. 31, 1983 event (M = 3.4) at the same epicenter. The event of Fig. 9 is a EQ that occurred only 10 km from the station of the preceding figures. We note the similarity of the signals and the same polarity (see Paragraph 9).

A SES, as mentioned, is a change ΔV of the potential difference V that recovers its normal value long before the earthquake occurs. Except the occurrence of these SES gradual changes of the whole background appear sometimes before an EQ with a duration of a few days. This drift of the background has been reported by Sobolev and coworkers [**7, 8**]. It is evident in Figs 4 and 5 and, when appreciably strong, may cause difficulties in the extraction of the true value ΔV of SES since the latter signal is superposed on a continuously varying background. We have never detected a Sobolev-drift without an SES also appearing. The two types of potential difference must belong to different mechanisms because ΔV occurs with the same expected value (see § 5.4) irrespective of the presence of a Sobolev-drift.

3. DISCRIMINATION OF THE SEISMIC SIGNALS FROM ELECTRIC DISTURBANCES OF OTHER SOURCES

3.1. Magnetic disturbances.

As already mentioned disturbances of the telluric electric field can be induced by usual magnetic variations. They can be excluded if the magnetic field is continuously monitored. It should be noticed however that during magnetic storms the corresponding electrical variations are so strong that the SES cannot be recognized when the impending EQ is weak or the epicentral distance large. The SES can usually be collected at a small number of stations depending on the distance from the epicenter and the magnitude

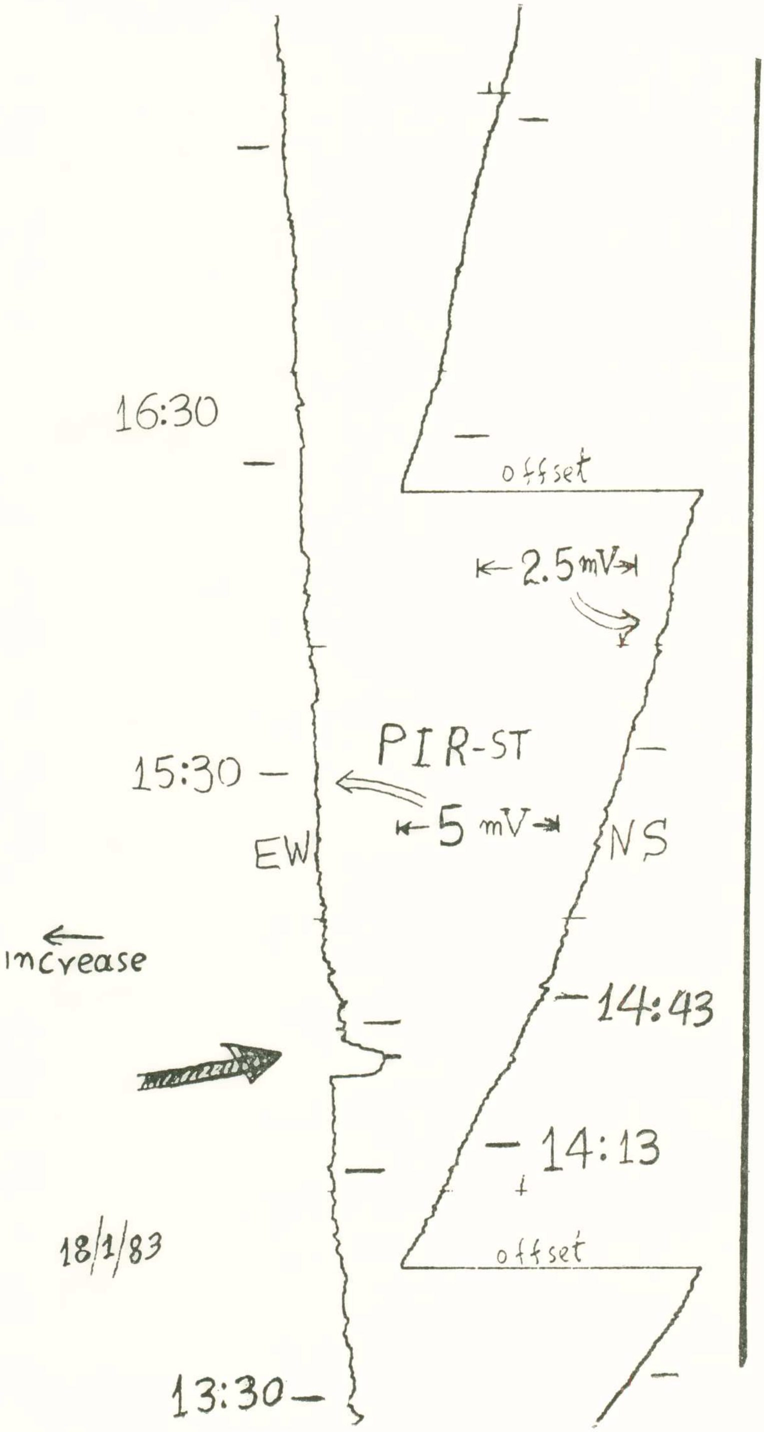


Fig. 5. Aftershock to Fig. 4. Note the smaller duration and a different form than that of the main shock.

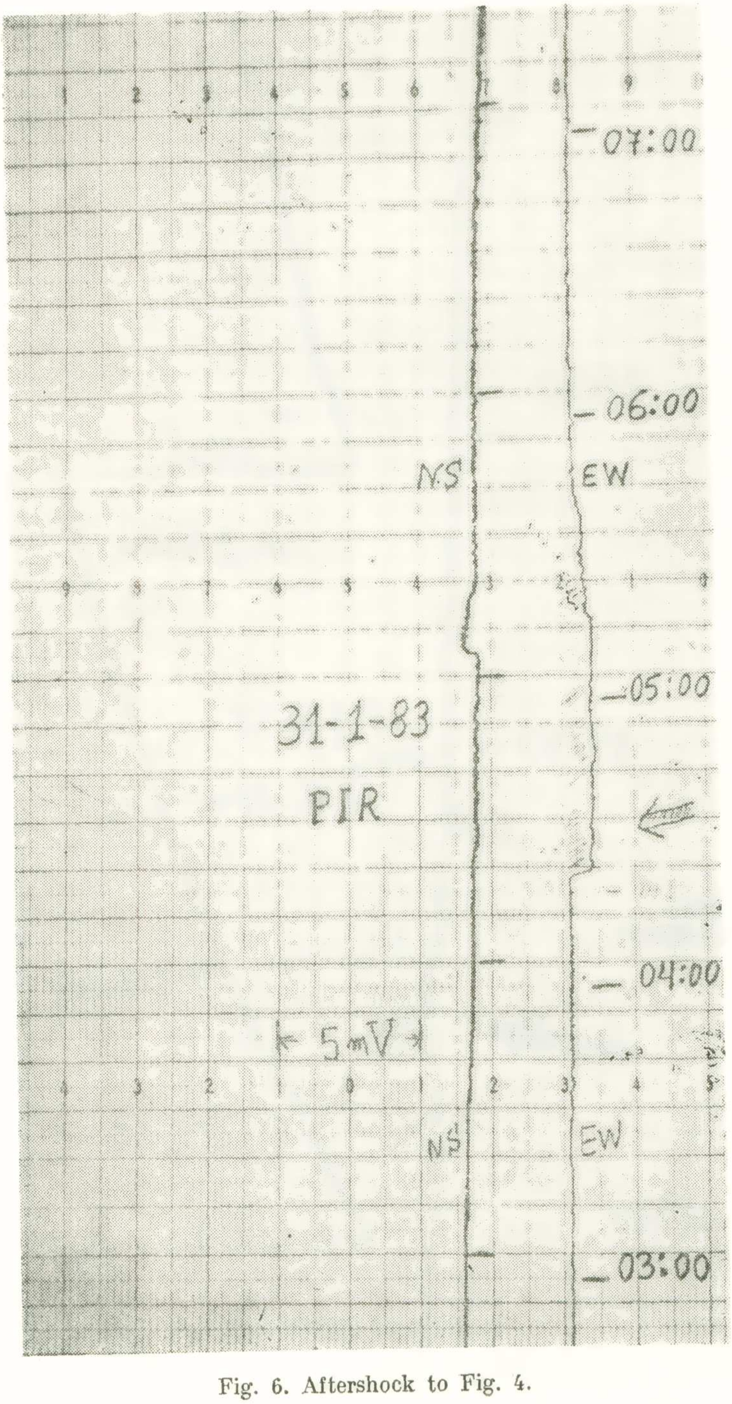


Fig. 6. Aftershock to Fig. 4.

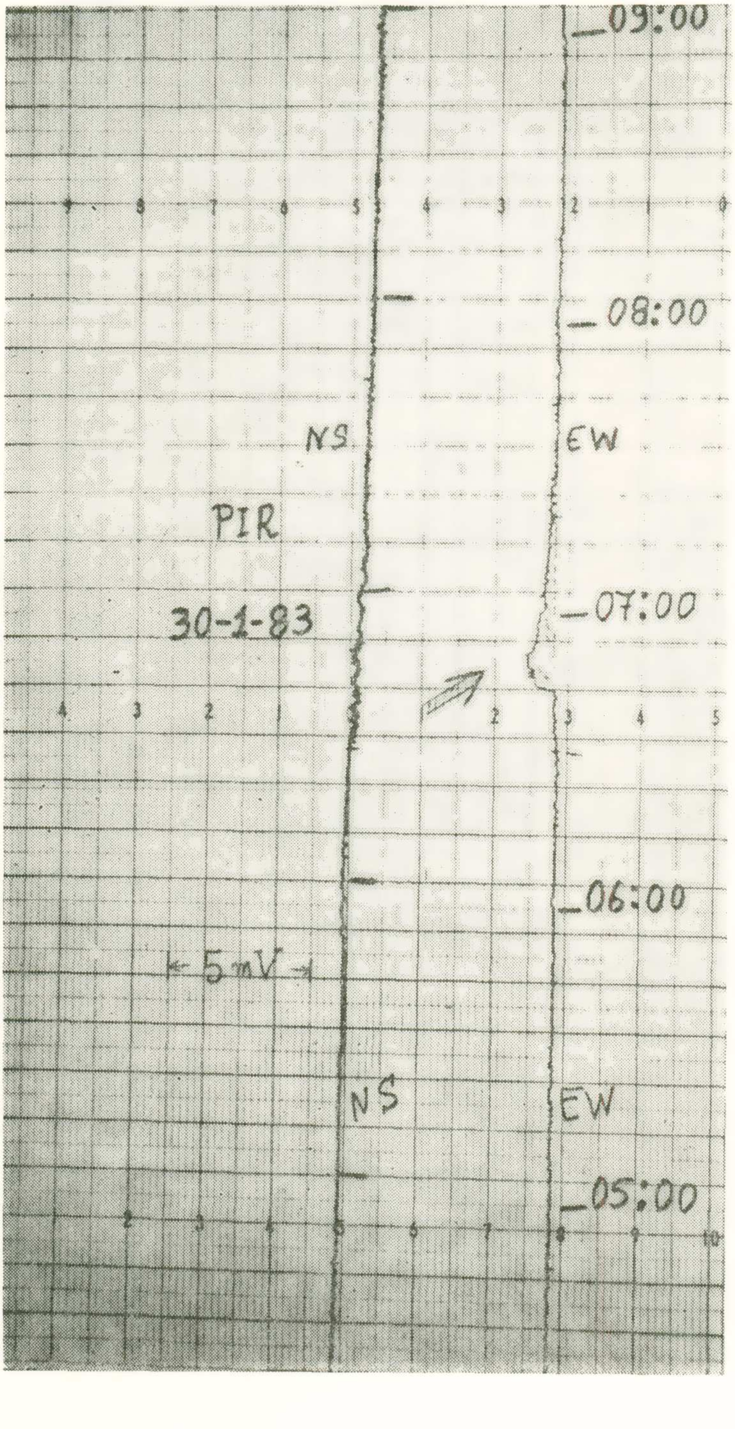


Fig. 7. The SES collected at PIR is a precurser to a 4.7 R event that occured at a distance of 60 km from the station.

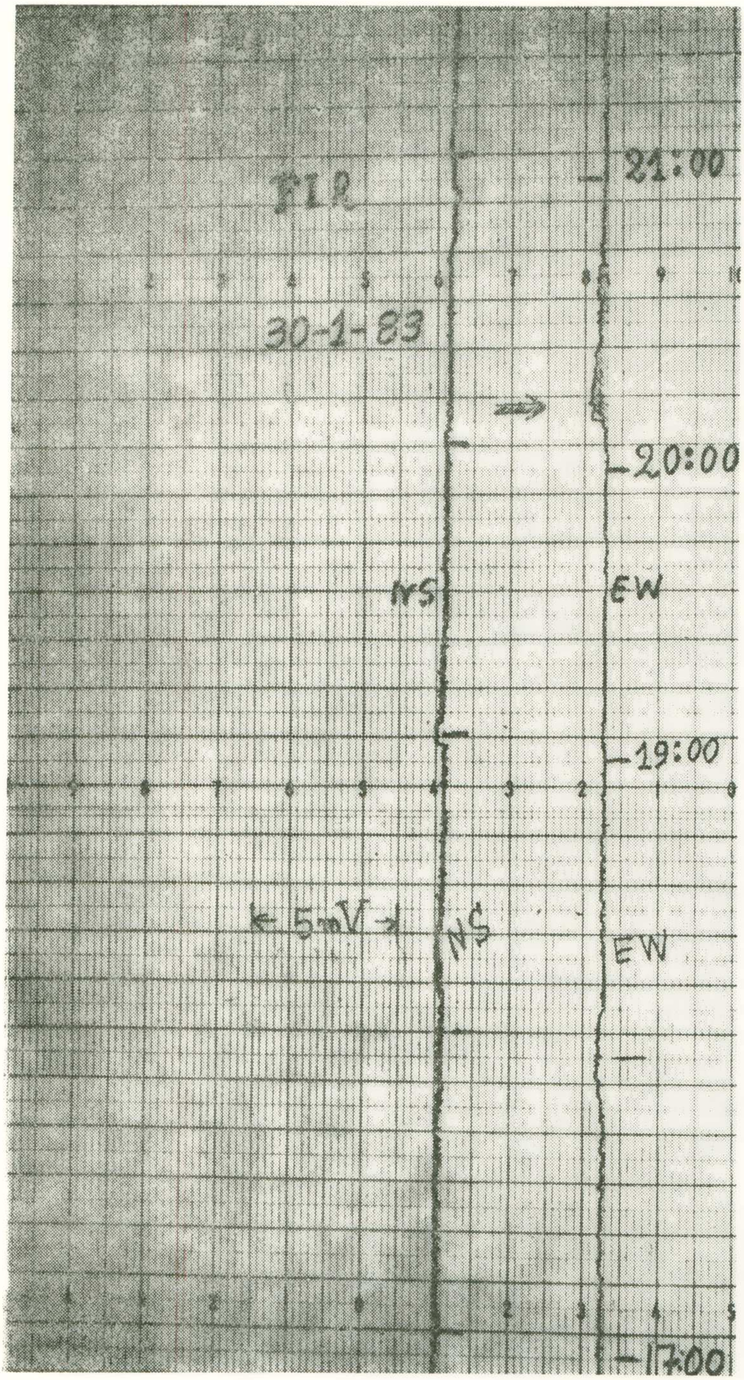


Fig. 8. The SES collected at PIR is a precursor to 3.4 R event with the same epicenter as Fig. 7. Note the similarity of the form and the polarity.

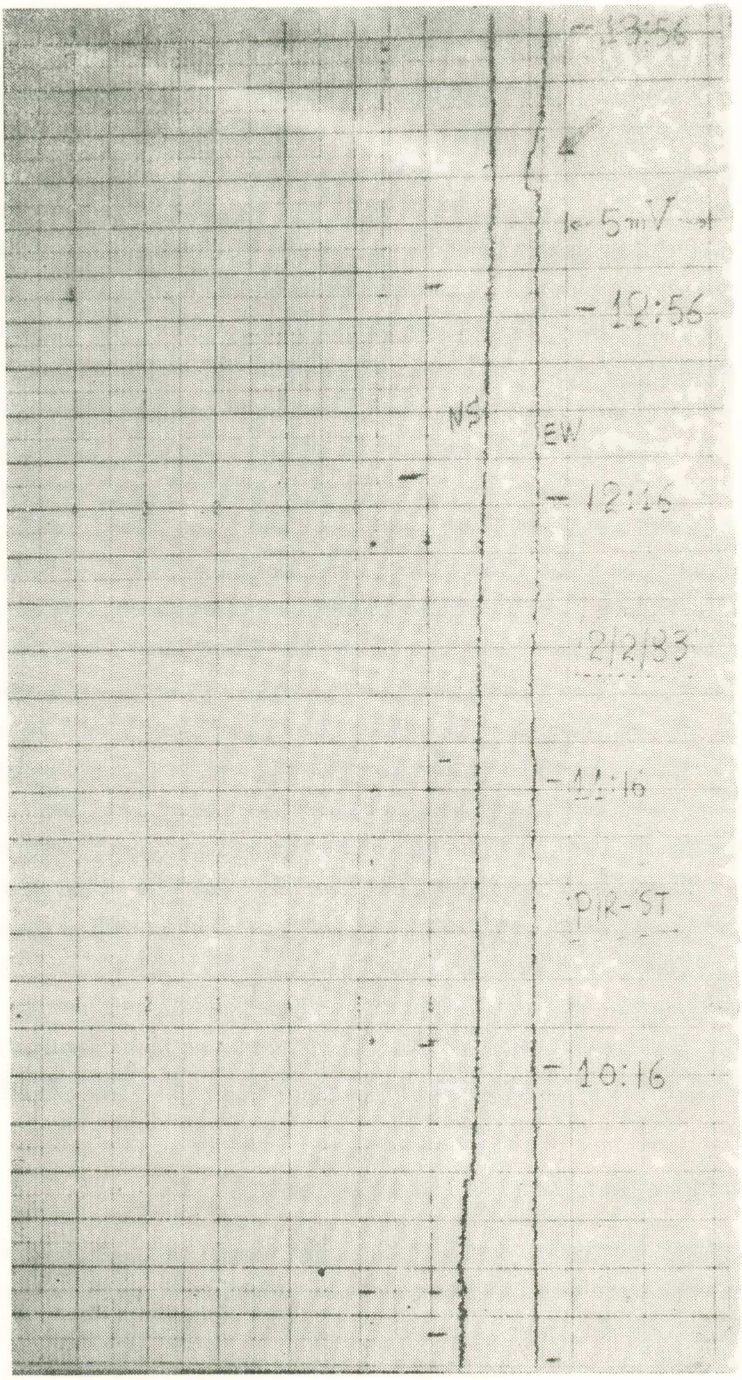


Fig. 9. A SES collected on EW line (L = 50m) of PIR with an epicenter roughly only 10 km from the station.

of the impending EQ. This is in contrast to magnetotelluric disturbances that are recorded usually at all sites (almost) simultaneously but with varying strength depending on the line (EW, NS) and the station.

Magnetotelluric disturbances are nevertheless a very serious shortcoming but we are planning to solve the problem by determining the transfer functions between the electric and magnetic field for each station. The magnetotelluric disturbances can then be separated from our data by measuring the three components of the magnetic field. An automatic on-line substraction has not been done yet but is planned in cooperation with the University of Uppsala.

The total magnetic field is continuously monitored at IOA-station with a proton magnetometer and, when necessary, with the three-component magnetic recordings of the Penteli station (10 km from Athens). Furthermore by combining the electrical recordings of all stations we can discriminate the SES from electric variations due to magnetic causes. We might remind again that *no* significant variation of the magnetic field is produced by the signal.

As expected, in most of our stations the two lines are not — in the average — equally sensitive to the magnetotelluric disturbances; this anisotropy creates difficulties when — during a magnetic disturbance — an SES is recorded on the line of the station which is strongly sensitive to magnetic variations. On the other hand this anisotropy helps towards the recognition of the SES when it is recorded on the magnetically «insensitive line». A striking example of the latter case can be seen in Fig. 10 : a clear SES has been recorded at 20:30 of June 13, 1983 on the magnetically insensitive line NS line of REN station (L = 30 m). It corresponds to the 4.3 R event that occured at 04:40 June 14, 1983 almost seven hours later at a distance 40 km south of the station. The other line (EW) of this station and the GOR EW, GOR NS and VOL EW are appreciably more sensitive to magnetic variations as can also be seen in Fig. 11 which is a continuation of Fig. 10. The magnetically insensitive line NS of REN shows a gradual deviation of the background (Chinese effect).

3.2. Electrochemical disturbances

The metal electrodes cause — especially after rain — anomalous discontinuities which are due to electrochemical effects and may be sometimes confused with SES. In order to avoid this source of error we have installed two lines in each direction, the length of which have a ratio between 2 and

4. The electrical disturbance due to the contact effects of the metal with moisture does not start and end simultaneously on both parallel lines; but even in the rare cases that they occur simultaneously they do not have ΔV – values with a ratio equal to the ratio of the corresponding lengths of the «dipoles» because they are chemical effects on the surface of the electrodes.

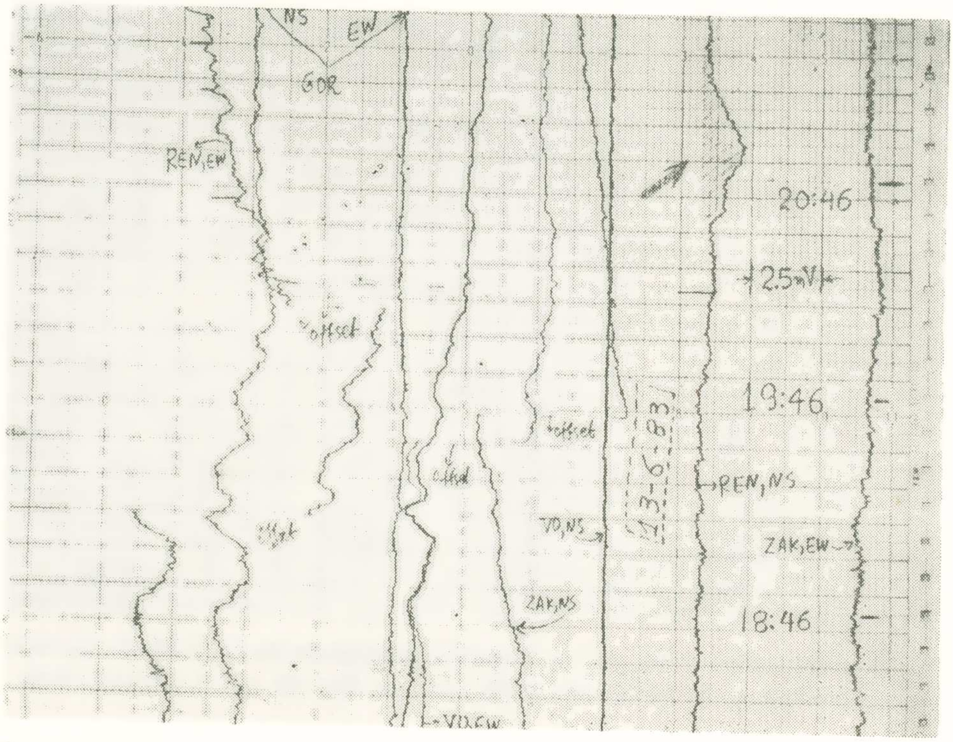


Fig. 10. A SES recorded on NS line of REN during a period of magnetic disturbances. Note the the magnetic variations induced on REN-EW, GOR-NS, GOR-EW, VOL-EW but not on NS lines of REN and VOL.

To the contrary the electrical disturbance of a true SES gives the same field-strength ΔV/L for both parallel lines. In practice if one considers a relatively strong event ($\sim$6 R) and a epicentral distance of 100 km the ΔV-value of an SES is roughly 1 mV for a line length of 50 m. The exact ΔV-value depends on the relative «resistivity» of the line as will be discussed below whereas the corresponding cultural noise is about 0.1 to 0.2 mV. It is obvious that a parallel line of L = 200 m will give a ΔV-value of 4mV and hence will allow the verification of the constancy of the ratio ΔV/L. This so called "ΔV/L-test" gives a check beyond experimental error when the ratio of the lengths is larger than 2. Furthermore the proportionality between ΔV and L is a proof

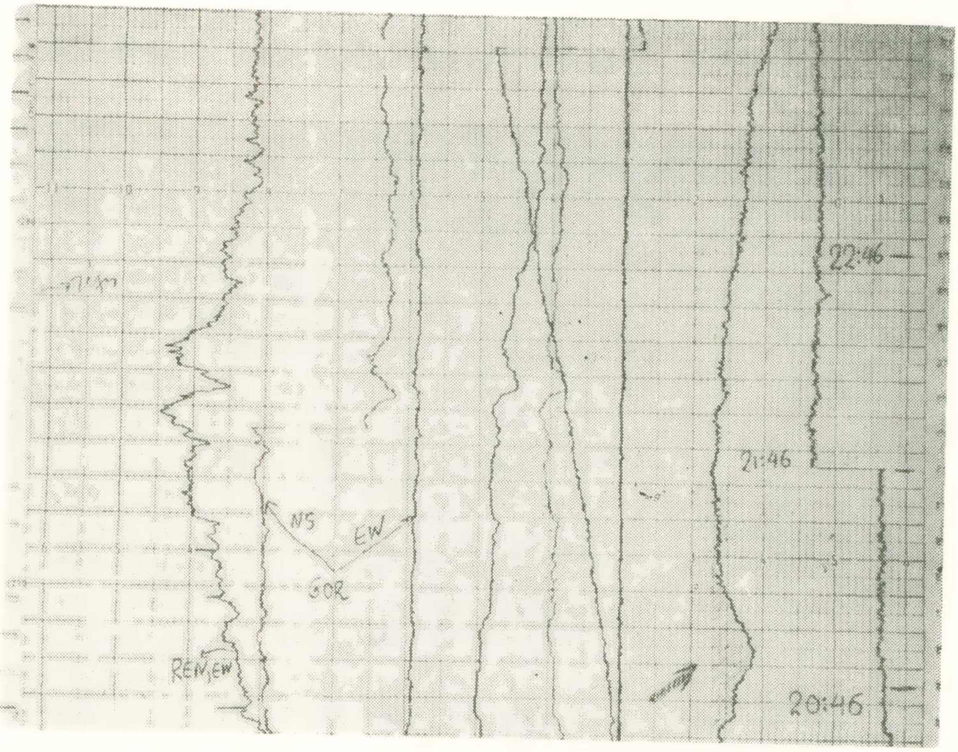


Fig. 11. Continuation of Fig. 10. No magnetic disturbancies on REN-NS. On the latter line a deviation of the background starts one hour after the signal. (Chinese effect).

that the origin of a SES is a change of the field strength. An example for the verification of ΔV/L-test for a $M = 5.8$ event is given in Figs 2 and 3.

3.3. Strong cultural electrical disturbances.

Local disturbances due to strong currents introduced into the earth for example by a factory cannot be recognized by the ΔV/L-test because they produce deviations that are proportional to L. In such cases in order to recognize SES one has to revert to the simultaneous appearance of a signal (see later) at two stations separated by a distance of tens or hundreds of kilometers. At these distances simultaneous electrical variations of artificial nature are precluded.

4. THE LEAD TIME

Extensive time-charts of SES and EQ have already been published for observations from a small number of stations [**1, 6**]. The corresponding correlation curves i.e. plots in which the ordinate gives the percentage of correlated effects tha occur within a time-span of ± 1 hour as a function of the time difference

$$\Delta t = t_{EQ} - t_{SES}$$

(where t_{EQ} is the time of the EQ and t_{SES} is the starting time of the signal) were also published for time differences between —24 and +24 hours. A maximum emerged for Δt between +6 and $13^1/_2$ hours; it exceeds the statistical background noise by almost one order of magnitude. However, after the seismic activity that started on Jan. 17, 1983 in the Ionian Sea we verified an older suspicion that the lead time in some cases can reach values up to around 115 hours [**4**].

It is appropriate to describe our present knowledge concerning the values of Δt. For reasons of brevity we classify the lead-times into two main groups. *Group I* refers to values from 6 to 13 1 /2 hours with a strong maximum around 7 h. Such lead-times regard around 60 % of the events. *Group II* refers to lead times between 43 and 60 hours with a flat maximum between 45 and 54 h. Around 25 % of all SES fall into this group. They are further two weaker groups the first between 24 and 36 hours and the other between 80 and 115 hours thus giving a total time-window between 6 and 115 hours; in very rare of cases a lead time of 7 days was found. The features of an SES do not depend on the group to which it belongs. We have not established a connection between a seismic region and the lead time; as an example we refer to Kefallinia-region which emits signals with different Δt; their lead times belong either to group I or to group II: The M = 6.5 event of Jan. 17, 1983 (Fig. 4) belonged to group II in contrast to the events of Jan. 19, Jan. 31 (Figs 5 and 6) and March 23, 1983 (M = 6, 5.8 and 6.4 respectively) which belonged to group I. In spite of the fact that the Δt-values vary by one order of magnitude (6 to 115 h) there is also no correlation between Δt and the corresponding magnitude of the earthquake.

5. EMPIRICAL RULES CONCERNING THE SIGNALS

In this chapter we describe empirical relations that connect the measured ΔV-value to the site of the station, the seismic region, the epicentral distance and the magnitude. As already mentioned the precursor signals appear either only on one of the two lines or on both of them. In order to answer the question whether a rule is independently valid or is valid only under certain restrictions we have proceeded to a systematic study in which only one of the above parameters is changed at a time while considering only a given direction (e.g. EW). The investigation is therefore separated into the following cases: a) Signal strength measured on a given line of a given station in function of magnitude of earthquakes from a given seismic region. b) Signal strength of earthquakes of a given magnitude measured on a given line of a given station but for different seismic regions i.e. for different epicentral vectors. c) Signal strength that corresponds to earthquakes of a given magnitude measured on the same line (e.g. EW) of *various* stations. In this way it will become possible to find in what way the strength is connected to the site of the station, the seismic region or the intervening route of the current. This detailed systematic approach might also give some insight on the mechanism of the current emission.

At this point we stress that the present study is possible because of the following empirical property: The ΔV-values of signals emitted from a given seismic region and registered on a given line of a given station are always the same for earthquakes of equal magnitude (in contrast to Δt and r which do not vary with M in a systematic way). Furthermore, under the same conditions i.e. for a given seismic region and at a given station, signals that once appear only on one line do so for all EQ. The explicit role of the epicentral distance on the connection between ΔV and M is found by comparing for strictly each magnitude the ΔV-values registered at a given station for various epicentral distances. Having thus clarified the influence of M and r on the ΔV-values of a given line of a given station we proceed finally to a "true" comparison of values recorded on lines of the same direction at two different stations. A direct comparison is not allowed as a ΔV-value recorded at a station is not solely influenced by the epicentral distance but also from the resistivity and the inhomogeneities under each station.

5.1. Dependence of ΔV on the magnitude

In Fig. 12 we plot log ΔV versus M for SES measured on the EW line (L = 50 m) of PIR-station (see Table I). Curve A refers to earthquakes having their epicenters in the Kefallinia region (latitude 38°N, longitude 20°E) i.e.

TABLE I.

Earthquakes collected on EW line of PIR.
L = 50 m. A: from Kefallinia region (r = 120 ± 20 km)
B: from Kalavrita region (r = 50 ~ 65 km)

Date (1983)	time (GMT)	M	ΔV (mV)	Group	
17-1	15:54	5.3	0.5	II	region A
17-1	16:54	5.3	0.75	II	
17-1	12:41	6.5	1.3	II	
19-1	05:42	5.2	0.65	II	
19-1	00:02	6	1.6	I	
22-1	16:02	4.6	0.5	II	
22-1	12:55	4.9	0.75	II	
28-1	17:43	4.4	0.45	I	
31-1	15:27	5.7	0.85	I	
15-2	03:38	4	0.3	I	
16-2	16:50	4.8	0.43	II	
2-2	04:25	4.1	0.25	I	
13-3	13:53	4	0.2	II	
15-3	21:20	4.4	0.4	II	
15-3	23:31	4.2	0.4	II	
23-3	23:51	6.4	2.1	I	
24-3	04:17	5.6	0.6	I	
13-5	23:50	5.4	0.73	II	
14-5	23:14	5.6	0.77	II	
14-5	23:26	5.3	0.75	II	
30-1	17:06	4.4	0.8	I	region B
31-1	05:33	3.4	0.35	I	
4-2	05:51	4.2	0.5	II	
9-2	12:41	3.9	0.4	II	
2-1-84	07:07	4.4	0.7	II	

at an epicentral distance of around 120±20 km. An inspection of the plot shows that there is no significant systematic difference between group I (○) and group II (□) and that a least square solution for a straight line has a slope 0.31 and a correlation factor 0.92. Considering the same station (PIR) and the component (EW) we plot in curve B the (absolute) values of ΔV for SES caused by earthquakes from a different seismic region i.e. from Kalavrita

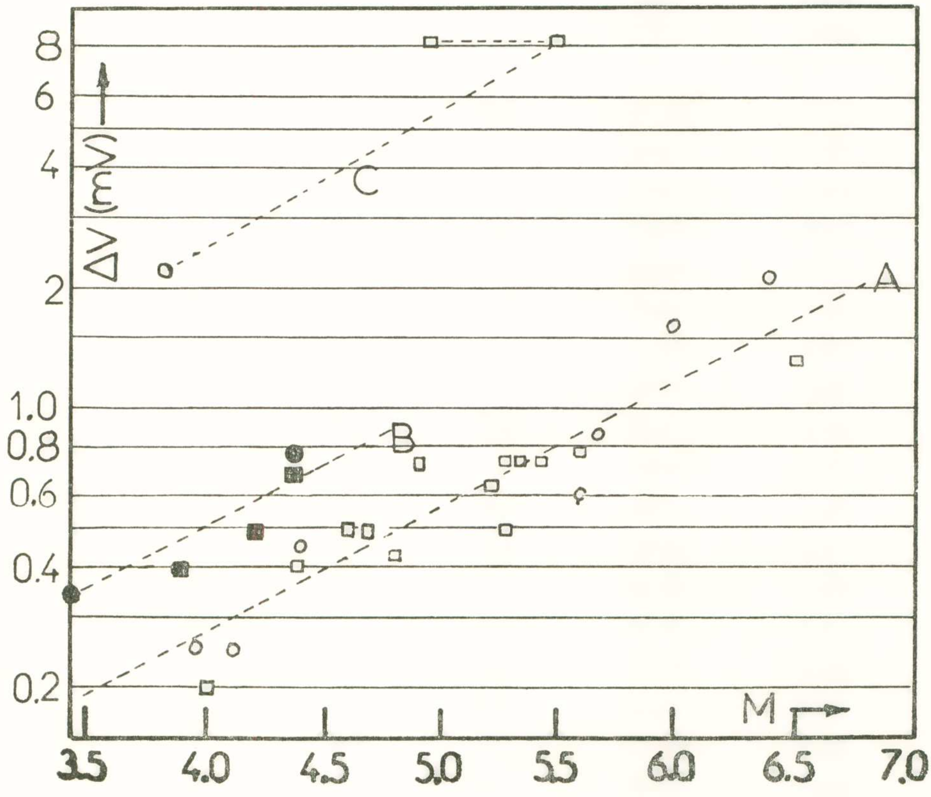


Fig. 12. Plot of ΔV log V versus M for SES collected solely on the EW line of PIR. A: Kefallinia region. B: Kalavrita region.

region; note that the epicentral distance r of the latter seismic region is almost the half (55 km) of that of the previous one and has a different azimutal angle. The best fit to a straight line has a slope of 0.33 with a correlation factor 0.91. Curve C was drawn for two strong signals that correspond to earthquakes that occurred close the station (10±5 km). As there is an uncertainty concerning the magnitude of the stronger EQ they were not further considered in the calculation made in the text. Similar graphs have been made for SES collected at other stations (see Table II) and for other seismic regions. In Fig. 13 the points of curve A were collected on the EW line (L = 100 m) of VOL and correspond to EQ from Limnos Island (235 km NE of Athens). Curve B was collected on the WNW line (L = 50 m) of GLY and corresponds to EQ from Agios Efstratios (160 km NE of Athens); they have

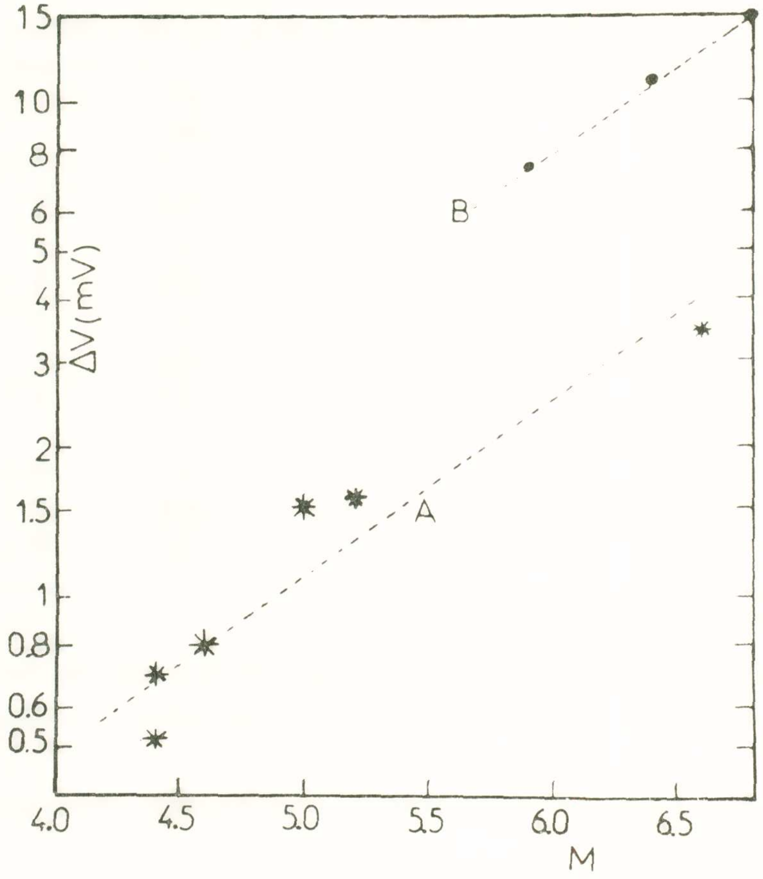


Fig. 13. Plot of log ΔV versus N for SES collected on the EW line of VOL corresponding to EQ from Limnos Island (A) and on the ENE-WSW line of GLY corresponding to EQ from Agios Efstratios (B).

slopes practically equal to the provious ones. We suggest that this slope-value (0.3 to 0.4) does not reflect a physical property of a station nor of a seismic region but has to do with the current producing mechanism.

An increase of the magnitude by 1 unit increases log ΔV by 0.3 (for r = const) which means that the amplitude of the signal increases by

TABLE II.

Earthquakes from a given seismic region and collected at a given station·

A: *EQ from Limnos Island collected on EW line of VOL (L = 100 m, r = 175 ± 20 km)*

B: *EQ from Agios Efstratios collected on EW line of GLY (L = 50 m, r = 140 ~ 160 km)*

Date	time (GMT)	M (R)	ΔV (mV)	
6-8-83	15:43	6.6	3.5	A
6-8-83	16:46	5	1.5	A
8-8-83	08:10	5.2	1.6	A
8-8-83	14:43	4.4*	0.7	A
12-8-83	07:29	4.4*	0.5	A
23-8-83	05:42	4.6	0.8	A
19-12-81	14:11	6.8	15.6	B
27-12-81	17:39	6.4	11.2	B
29-12-81	08:01	5.9	7.5	B

*Later revised by —0.1 and —0.2 respectuely.

a factor 2 to 2.5. At first glance this is unexpected: by considering the formula $E = \frac{1}{2} d^2U$, where E is the energy of the stressed *spherical* volume U, one finds:

logU = 1.5M+const (because log E = 1.5 M+const) Then the effective surface S ($\sim U^{2/3}$) is:

$$\log S = 1M + \text{const}$$

and hence one would expect (for the points for a given station and a given seismic region):

$$\log \Delta V = 1M + \text{const}$$

This comes from the consideration that the current and hence ΔV (because the resistivity is the same as we consider a given station) is proportional to the emitting surface. In other words one would expect that when the magnitude increases by 1 unit the ΔV value should increase by a factor of 10 in contrast to the experimental data. On these grounds one could make the specu-

TABLE III.

SES collected on EW line of PIR ($L = 50$ m) and corresponding to EQ with various epicentral distances but with constant magnitude
A: $M = 4 \pm 0.2$ B: $M = 4.7 \sim 5$

Date (1983)	time (GMT)	M (R)	ΔV (mV)	r (km)	group	
6-1	04:24	4.2	0.6	50	I	case A
2-2	04:25	4.1	0.25	100	I	
4-2	05:51	4.2	0.5	60	II	
9-2	12:41	3.9	0.4	65	II	
14-2	10:37	3.9	0.7	43	I	
14-2	23:14	4	0.4	78	I	
15-2	03:38	4	0.3	96	I	
19-2	23:46	4.1	0.3	86	I	
17-3	20:18	3.8	1.3	20	I	
8-5	22:44	4.7	0.8	60	I	case B
16-2	16:50	4.8	0.43	130	II	
19-2	15:56	5	0.6	84	II	
20-2	05:45	4.8	8	10	II	

lative assumption that the volume is non-spherical with axes l, w, h and that the current-emitting surface (e.g. w x h) increases appreciably slower than the other surfaces (l x h or l x W) when magnitudes increase. Our experimental data are compatible with:

$$\log (w \times h) \approx (0.3 \sim 0.4)M + \text{const}$$

and hence

$$\log l \approx (1.1 \sim 1.2)M + \text{const}$$

This last conclusion should be compared with various empirical studies of Kasahara [**9**] and of Purkaru and Berckhemer [**10**] that connect the logarithm of the length of the fault with the magnitude; in some of these studies the coefficients of M reach values up to 1.2.

The above very speculative result is based inherently on the assumption that the transient SES is not a result of the variation of any physical property of the ground under the station but is caused by precursor changes in the region of the focus. It is appropriate to indicate here that Fuye, Yulin, Mouming, Zhixian, Xiaowei and Simin [**11**] have recently reported variations of the resistivity ρ prior to earthquakes according to:

$$M = 3.84 \log \frac{\Delta\rho}{\rho} + \text{const}$$

which gives
$$\log \frac{\Delta\rho}{\rho} \simeq 0.3M + \text{const.}$$

It is curious that this expression has the same slope as logΔV vs M although the $\Delta\rho/\rho$ — technique measures variations of a physical property of the ground under the station at a depth of a few hundred meters depending on the method it is measured with while the SES has to do — according to our opinion — with the current production at the focus.

5.2. Dependence of ΔV on the epicentral distance.

We now study the ΔV-values registered on the same line of the same station for earthquakes of a given magnitude from different seismic areas; for such measurements the resistivity (and the inhomogeneities) of the station is a constant and only the epicentral azimuth and distance change (Table III). In Fig. 14 we plot the results for the EW line of PIR (L = 50 m) and for magnitude 4($\pm$0.2) in function of the epicentral distance (curve A); note that the values of ΔV and r vary by one order of magnitude and that a r^{-2} law must be excluded. On the other hand a 1/r law describes fairly well the data, at least for large distances (> 50 km). Curve B in the same figure exhibits the same feature for earthquakes with magnitude around 4.8.

The above conclusion must not be interpreted as a general 1/r-law for the attenuation of ΔV for a given EQ recorded at various epicentral distances; in other words the ΔV-values recorded at various stations with different epicentral distances for a given EQ do not follow as 1/r-dependence. In this case, as will be seen below, the quantity which should be considered as attenuating with the distance is the current density that results from the measured ΔV/L-value by dividing by an "effective" resistivity which also takes care of the local inhomogeneities. This is expected because the emitting surface of the fault emits a current that diverges in space and thus gives a diminishing current density.

It is worthwhile to clarify further the results of this paragraph by taking two examples: Consider two seismic regions A and B that are at equal distances

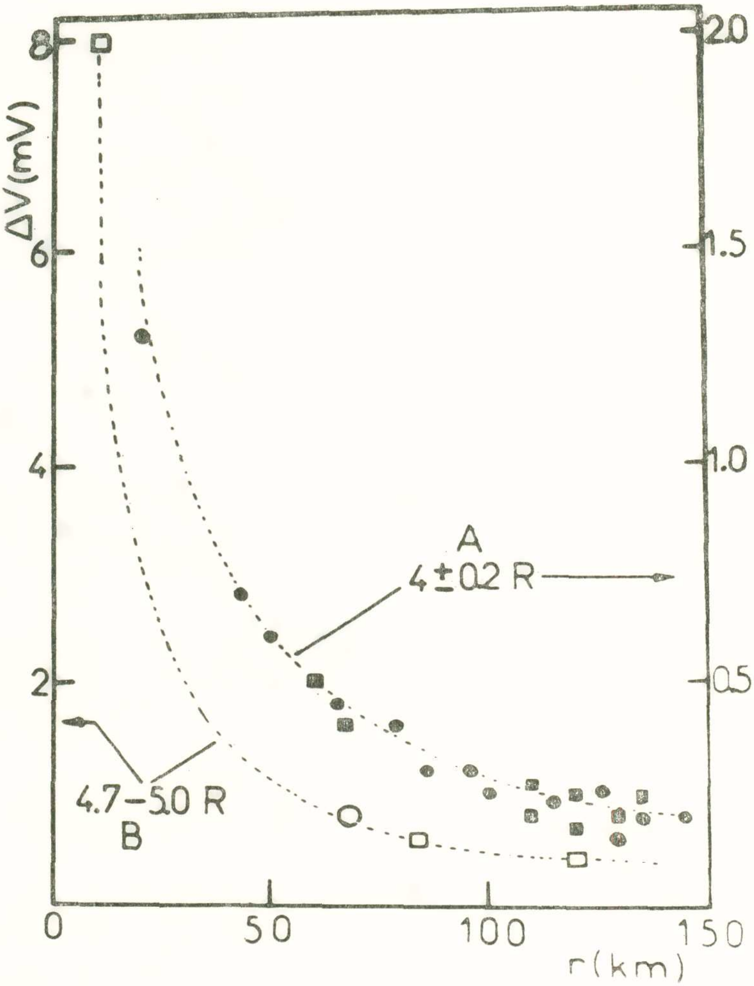


Fig. 14. ΔV-values for earthquakes with constant magnitude from various seismic regions collected on the EW line of PIR. The lines have been drawn as a guide to the eye.

e.g. r = 60 km from station C and a M = 4 earthquake from A which gives at the EW line of the station C a signal ΔV_A. If we now study another EQ with

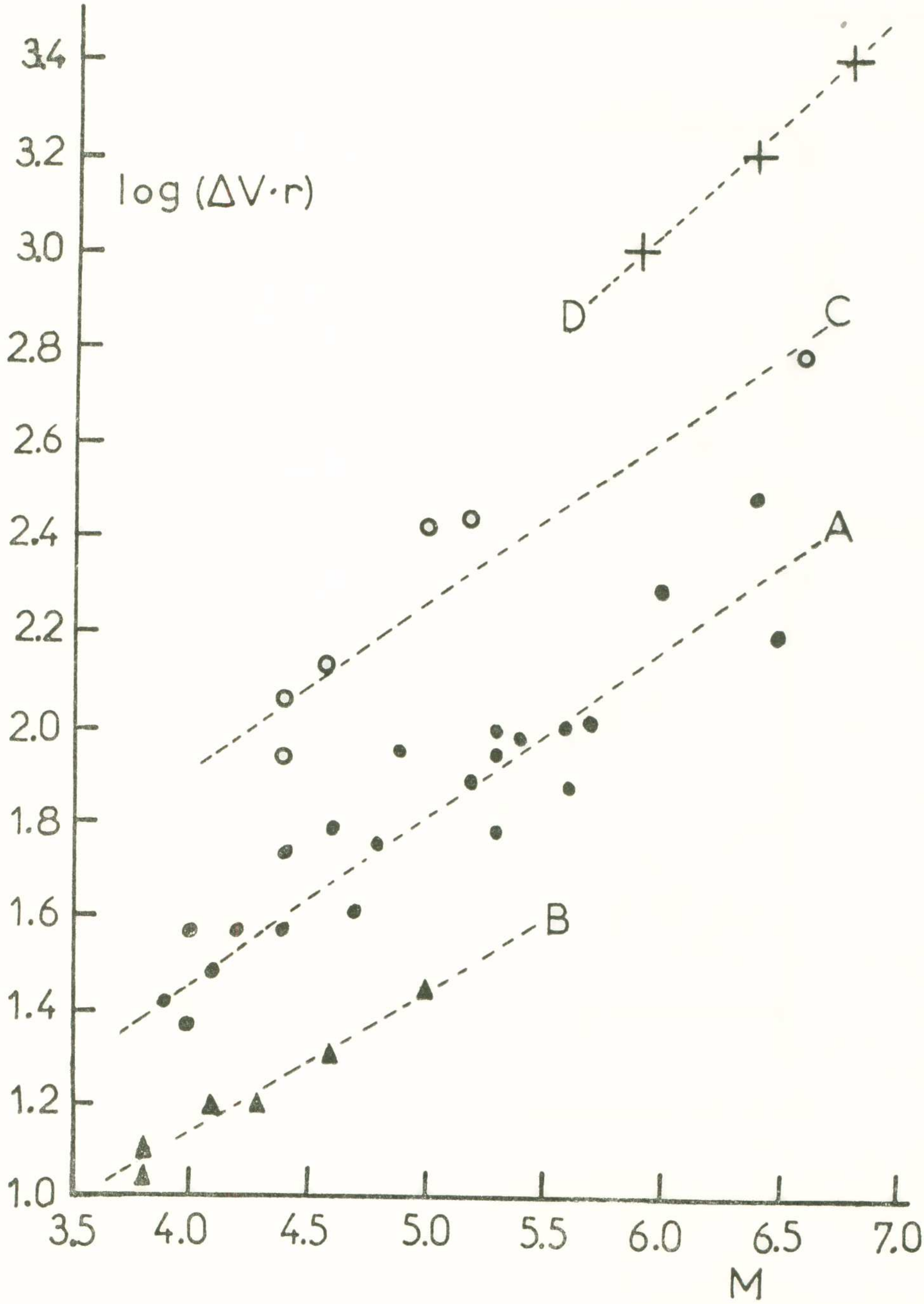


Fig. 15. Log (ΔV·r) versus magnitude from various seismic regions collected at the same station. A:PIR, B: ASS; C: VOL; D: GLY.

the same magnitude from region B it could in principle give a signal ΔV_B on the same line of station C appreciably different than ΔV_A due to eventual different geological conditions of the two regions A and B. The fact that for a given r (e.g. 50 km) Fig. 14 gives an unique value (e.g. 0.5 mV) shows that $\Delta V_A = \Delta V_B$ i.e. that ΔV does not depend on the seismic region (for M = const). This implies that not only the physical mechanism that emits the current from A or from B is the same but also that some physical quantities associated with the current emission have the same values at A and B.

In the second example we assume that the epicentral distances of A and B from station C are different and have a ratio e.g. $r_A/r_B = 3$. By considering two EQ with equal magnitudes — one from A and one from B — one finds from Fig. 14 that $\Delta V_A/\Delta V_B \simeq 1/3$. The latter means not only that the mechanisms (and the properties) producing the current at A and B were the same but further that the two signals until reaching station C obeyed an attenuation according to r^{-1}-law.

By combining the conclusions drawn from the study of Figs 12, 13 and 14 we find that for a given line of a given station log (ΔV.r) should be a linear function irrespective of the seismic region. In effect if we combine the data of Curves A and B of Fig. 12, we find a unique linear connection (plot A of Fig. 15) for the EW line of PIR-station (L = 50 m). A least squares fitting to a straight line gives a slope 0.35 comparable to those of Curves A and B in Figs. 12 and 13 with a correlation factor 0.95. Curves B, C and D describe similar connections for the EW lines of VOL (L = 100 m) GLY (L = 50 m) and ASS (L = 50 m).

Due to the fact that the curves log ΔV vs M (for r = const) have the same slope irrespective of the station and that ΔV is proportional to 1/r (for M = const) the plots log (ΔV.r) vs M — for various stations — have to have the same slope.

We have already expressed our reservations about the validity of the 1/r-law for small distances because the few existing data show a trend that there is a faster decrease of ΔV on distance. As an example we show in Fig. 16 a SES of 8 mV recorded at PIR-station (L = 50 m) at 21:20 on Feb. 17, 1983; 56 hours later a M = 4.8 shallow event occurred, the epicenter of which was only 10 ± 5 km far from the station. If the 1/r-law was valid, the 8 mV measured at r = 10 km should give 2 mV at r = 50 km instead of the weaker value 1.2 mV as can be read in Fig. 14.

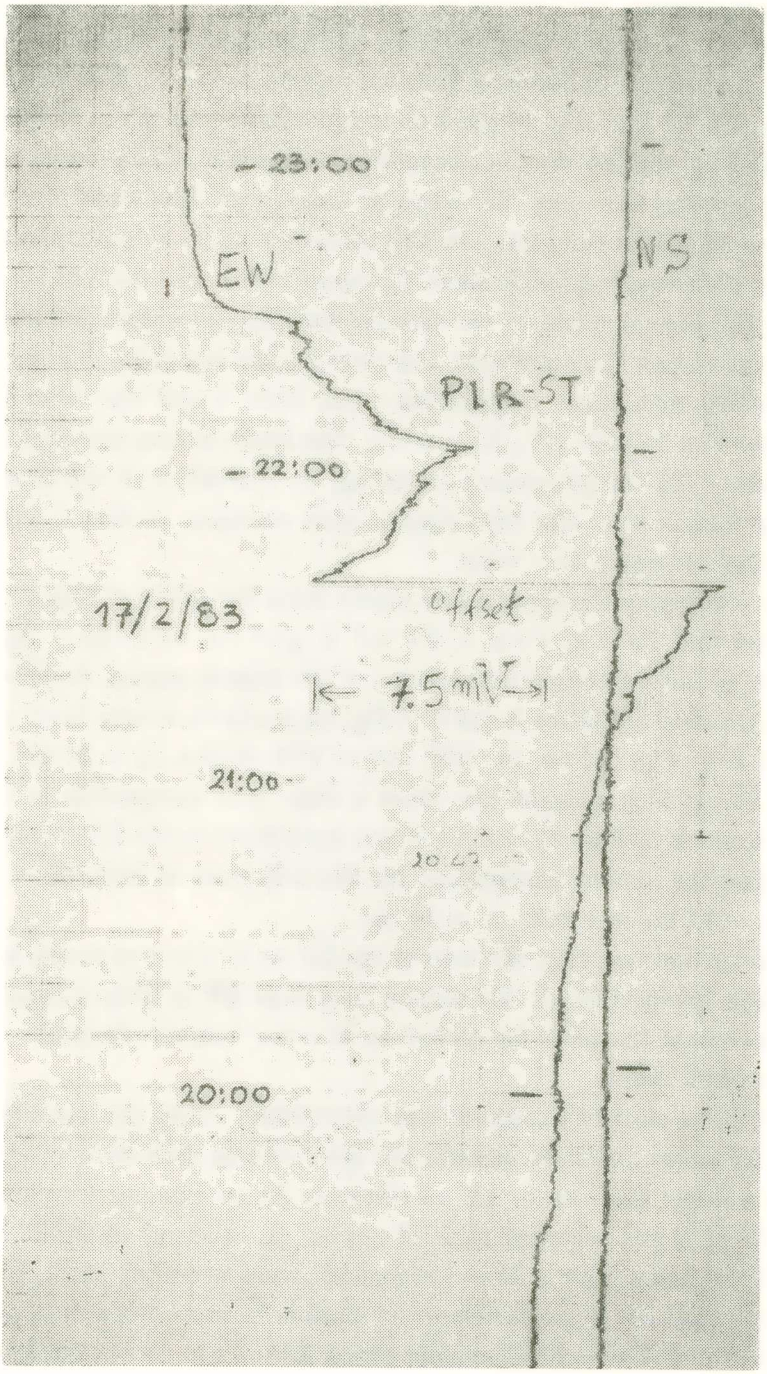


Fig. 16. A SES collected around 10 km from the epicenter.

5.3. Definition of the relative effective resistivity and the relative signal strength.

As we have seen, the plots of log (ΔV.r) for a line of the same direction (e.g. EW, L = const) do not coincide in general for two different stations. However, as mentioned, they all have the same slope and therefore their (ΔV.r)-values must have a constant ratio. The value of this ratio (for L = const), which depends on the stations (i) and (k) shall be labelled with ρ_i/ρ_k:

$$\left.\frac{\Delta V_i \cdot r_i}{\Delta V_k \cdot r_k}\right|_{EW} = \left.\frac{\rho_i}{\rho_k}\right|_{EW}$$

Once the values of ΔV and r on the left side of the equation are known (for a certain EQ) the quantity ρ_i/ρ_k can be determined for each pair of stations.

In Fig. 15 we have plotted the log (ΔV.r)-values versus M for lines of stations PIR, VOL, ASS and GLY (we intentionally present them for different lengths). By reducing the values to the same lengths the comparison of the ordinates gives

$$\rho_{EW,VOL}/\rho_{EW,PIR} \simeq 1.4 \quad \rho_{EW,GLY}/\rho_{EW,PIR} \approx 8 \text{ and } \rho_{EW,ASS}/\rho_{EW,PIR} \approx 0{\cdot}4$$

By following the same procedure we have determined such ratios for each line of the stations of the network in comparison to the corresponding line of PIR, which we consider as a base station. The ratio $\rho_{EW,i}/\rho_{EW,PIR}$ shall be called the relative effective resistivity $\rho_{i,rel}$ of the EW line of station (i).

One could write an expression of the form

$$\Delta V/L = j\,\rho.$$

The absolute value of the current density j, however cannot be determined from this equation because the actual resistivity is not known. A measurement with the usual resistance methods might not be representative of the true situation because of layers of varying resistivity under the station. However in practice when comparing signals from various stations one only needs the value of the relative effective resistivities because j can be expressed by

$$j = \frac{\Delta V/L}{\rho} = \frac{\Delta V/L}{\rho/\rho_{bas}} \cdot \frac{1}{\rho_{bas}} = \frac{\Delta V/L}{\rho_{rel}} \; \frac{1}{\rho_{bas}}$$

where ρ_{bas} is a constant for all stations.

From the two componenus one gets for the total current density

$$J = \left(\frac{\Delta V/L}{\rho_{rel}} \cdot \frac{1}{\rho_{bas}} \bigg|^2_{EW} + \frac{\Delta V/L}{\rho_{rel}} \cdot \frac{1}{\rho_{bas}} \bigg|^2_{NS} \right)^{1/2}$$

We have introduced different relative effective resistivities for EW and NS because $\rho_{i,EW}/\rho_{i,NS}$ may be far from unity, (e.g. for the VER station it is around

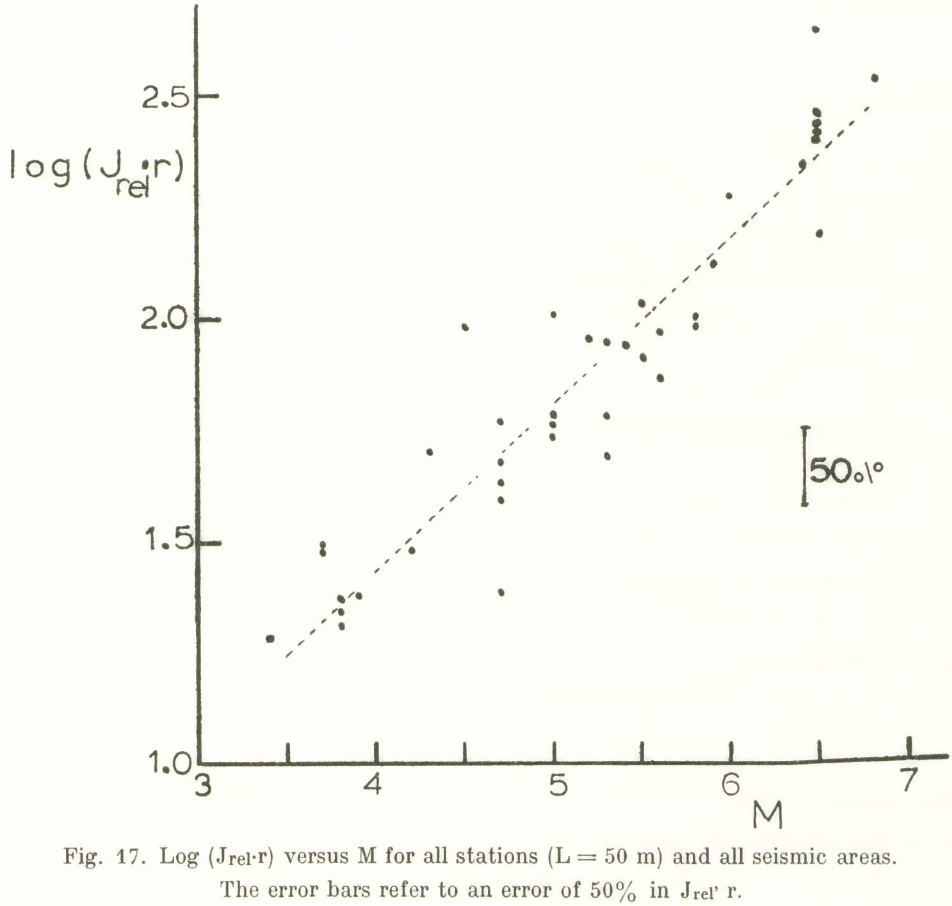


Fig. 17. Log ($J_{rel} \cdot r$) versus M for all stations (L = 50 m) and all seismic areas. The error bars refer to an error of 50% in J_{rel}' r.

1/3) because of local inhomogeneities. Setting for the base station $\rho_{rel,EW}$ and $\rho_{rel,NS}$ equal to 1 we obtain a working formula for a quantity that shall be called the *relative signal strength* defined by

$$J_{rel} = \left(\frac{\Delta V/L}{\rho_{rel}} \bigg|^2_{EW} + \frac{\Delta V/L}{\rho_{rel}} \bigg|^2_{NS} \right)^{1/2}$$

TABLE IV.

Complementary list of Earthquakes inserted in Fig. 17.

Date	time	M	Epicenter
18-1-82	19:27	6.8	230 km NE of ATH
23-3-83*	19:04	5.3	90 km S of IOA
15-4-83*	06:02	3.8	35 km ENE of REN
»	06:12	3.6	»
1-6-83	14:44	5	300 km E of GLY
9-6-83	02:39	4.5	330 km E of GLY
13-6-83	17:14	3.7	140 km WNW of GLY
14-6-83	04:40	4.3	40 km S of REN
5-7-83	12:01	6.5	Dardanells
14-7-83	02:55	5.8	150 S of KAL

*Announced from THES – seismic network.

5.4. Dependence of the relative signal strength on the magnitude.

By using the values $\rho_{rel,EW}$(ASS) = 0.4, $\rho_{rel,EW}$(VOL) = 1.4 and $\rho_{rel,EW}$ (GLY) = 8 we obtain the plot of Fig. 17 for log (J_{rel} r) versus M from the data mentioned in Tables I to III. In the figure we also insert points corresponding to EQ mentioned on Table IV. A least squares fitting to a straight line gives a slope of 0.37 with a correlation factor 0,92. We remind that the events of these tables were chosen so as to have no NS components. Experimental points for events registered only in the NS direction or in both directions fall onto the same line. It is therefore clear that J_{rel}r is an unique function of M, valid for all stations and seismic areas.

6. SIMULTANEOUS SEISMIC SIGNALS

The SES are changes of the electric field and propagate with a velocity of the order of the velocity of the light. Therefore, at all stations where they are observable, they appear simultaneously. This fact is of importance in recognizing an SES which is imbedded in noise. In the present paragraph we give two examples for a weak and a strong signal.

In Fig. 18 we see an electric disturbance recorded on the EW line of HAL (L = 200m) at 21:38 on June 7, 1983 whereas it does not appear on any line of THI and IOA stations the 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. 19 we show an electric signal of magnetic origin that appears simultaneously at 12:25 on June 9, 1983 at the same three stations as in Fig. 18. A comparison of these two figures indicates that if the electrical disturbance depicted in Fig. 18 were of magnetic origin it should have been

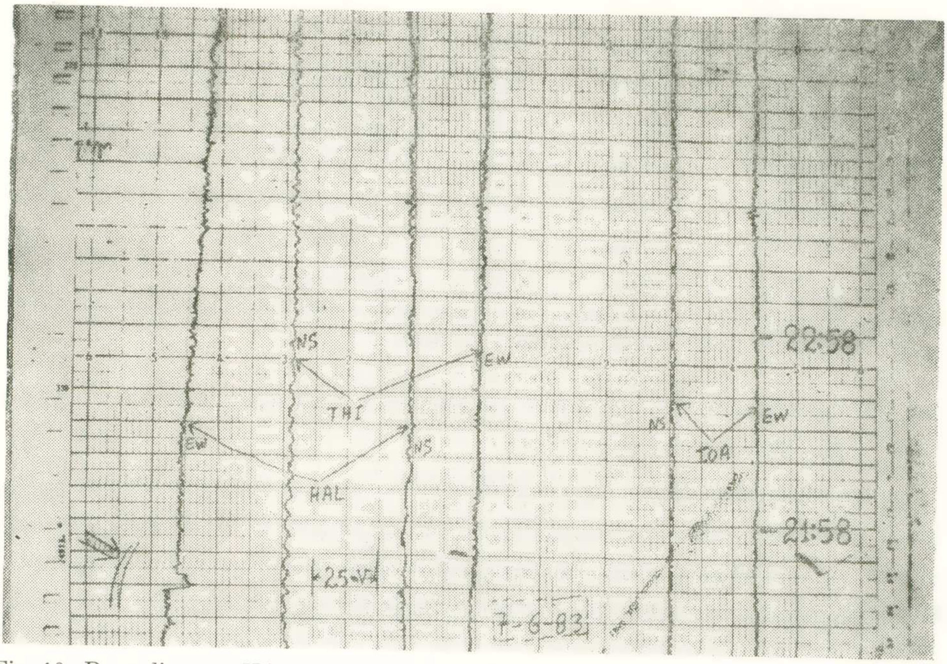


Fig. 18. Recordings at HAL, THI and IOA. Note that the precursor to the 4.5 R event was not recorded at THI although expected according to a 1/r-law.

recorded at the other two stations — THI and IOA — as well. In Fig. 20 we clearly see that the electrical disturbance of Fig. 18 has been simultaneously recorded on the NS line of VER (L = 100 m) whereas on the EW line of the same station it can be seen with difficulty. (Note that the distance VER-HAL is 240 km). No signal is present on the lines of PAT and ASS. In Fig. 21 we see that this signal has also been recorded on the NS line of NAF (L = 100 m). It could not have been recognized if the SES had not appeared simultaneously at HAL (Fig. 18) and VER (Fig. 20). These SES — simultaneously recorded at three stations — are precursors of a 4.5 R event that occurred at 02:39 on June 9, 1983 with an epicenter at (37.8°N; 27.7°E). The correlation of the SES to the above EQ is not arbitrary but, as we shall see in paragraph

7, the combination of the ΔV-values of Figs. 18, 20 and 21 — after a proper reduction — can lead to a good estimation of the epicenter and the magnitude of the impending EQ.

We now show simultaneous signals collected on both lines of the following four stations installed far apart: VER, ZAK, REN and PIR. Figure 22 shows a recording on both lines of VER (L_{EW} = 200 m., L_{NS} = 100 m). The relative effective resistivities are $\rho_{EW} = 1$ and $\rho_{NS} = 3$. This SES is a precursor of a

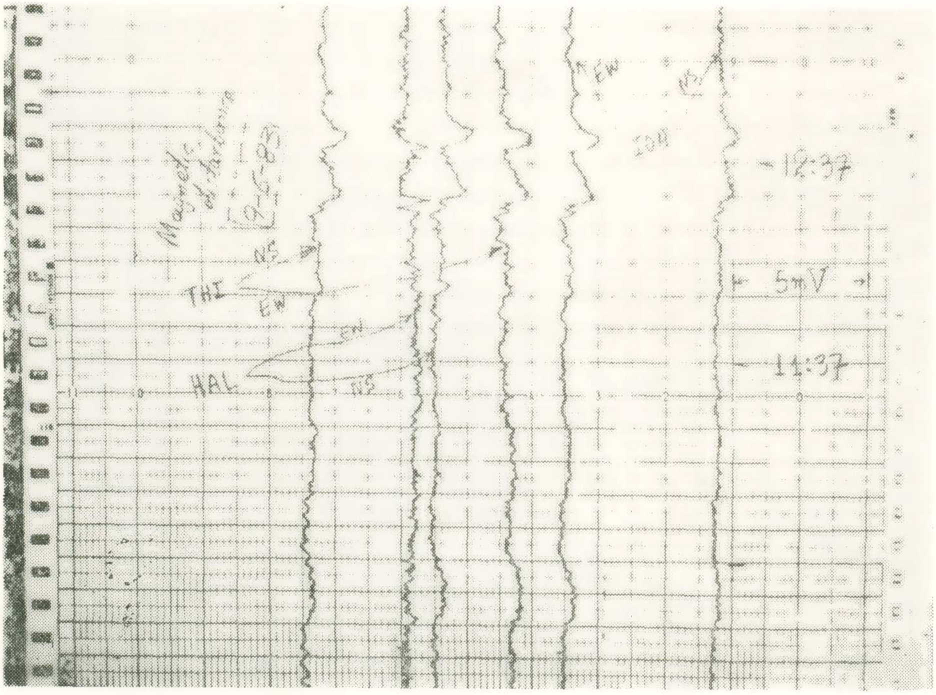


Fig. 19. Recordings at the stations of Fig. 18. during a magnetic storm.

6.5 R event that occurred near the Dardanells (40.2°N; 27.2°E) on July 5, 1983 i.e. at an epicentral distance around 400 km. The "directivity effect" is evident: The SES did not appear at all at ASS although it has been simultaneously recorded at ZAK, PIR and REN as is visible in the next figures. Figure 23 shows the recording at ZAK ($L_{EW} = L_{NS}$ = 150 m) and REN ($L_{EW} = L_{NS}$ = 30) at epicentral distances of 610 and 300 km respectively. The signal on the EW line of ZAK is seen with difficulty due to the bad quality of the pen. Figure 24 is the simultaneous recording at PIR ($L_{EW} = L_{NS}$ = 50 m) at an epicentral distance of 570 km. Further in Fig. 25 we show the same SES in the EW direction of VER station on a line of one third the length compared to line used in Fig. 22. As the ΔV-values have the same ratio (e.g.3) this is a good confirmation that the relevant quantity is V/L i.e. the electric field strength and hence the current density. In Fig. 26 we show the same SES recorded at PIR-station (L = 50 m), but with unpolarised CuSO, electrodes, for the sake of comparison to Fig. 24, in which the SES has been collected with brass electrodes.

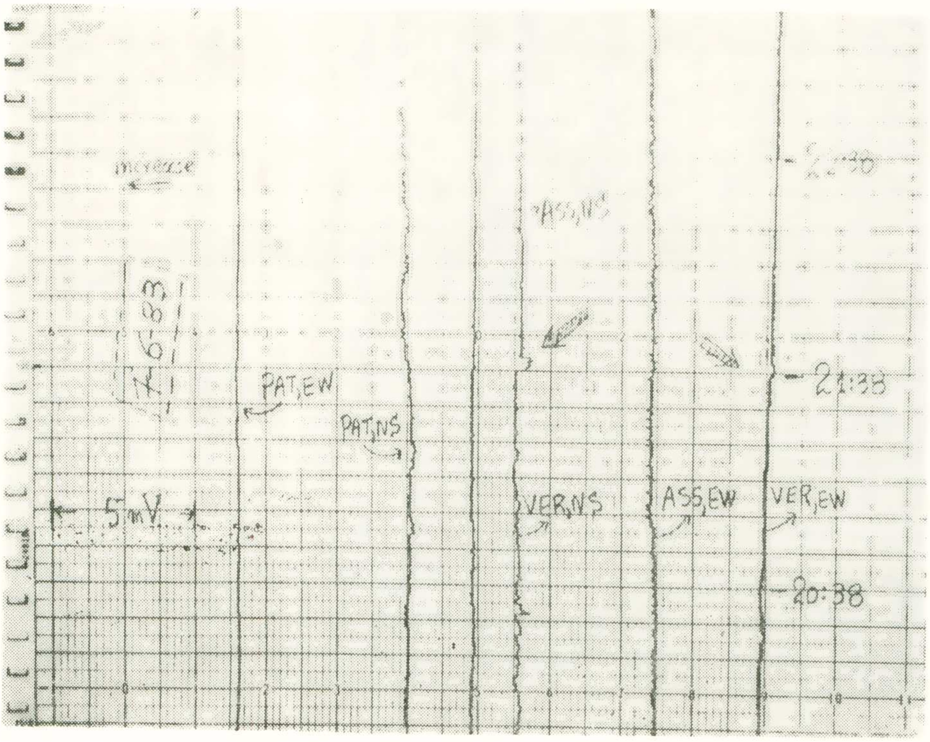


Fig. 20. Signal recorded at VER on the NS line. It can also be seen on the EW line with some difficulty. It is simultaneous to Fig. 18.

7. DETERMINATION OF THE EPICENTER

As will be shown in the next paragraph in certain combinations of seismic regions and stations the intensity of the ESS is found to be zero for some unexplained reason. We are inclined to believe that this is a property not only due to the state of the substratum of the station — because such a station would not register any signals at all — but also to an anomaly of the

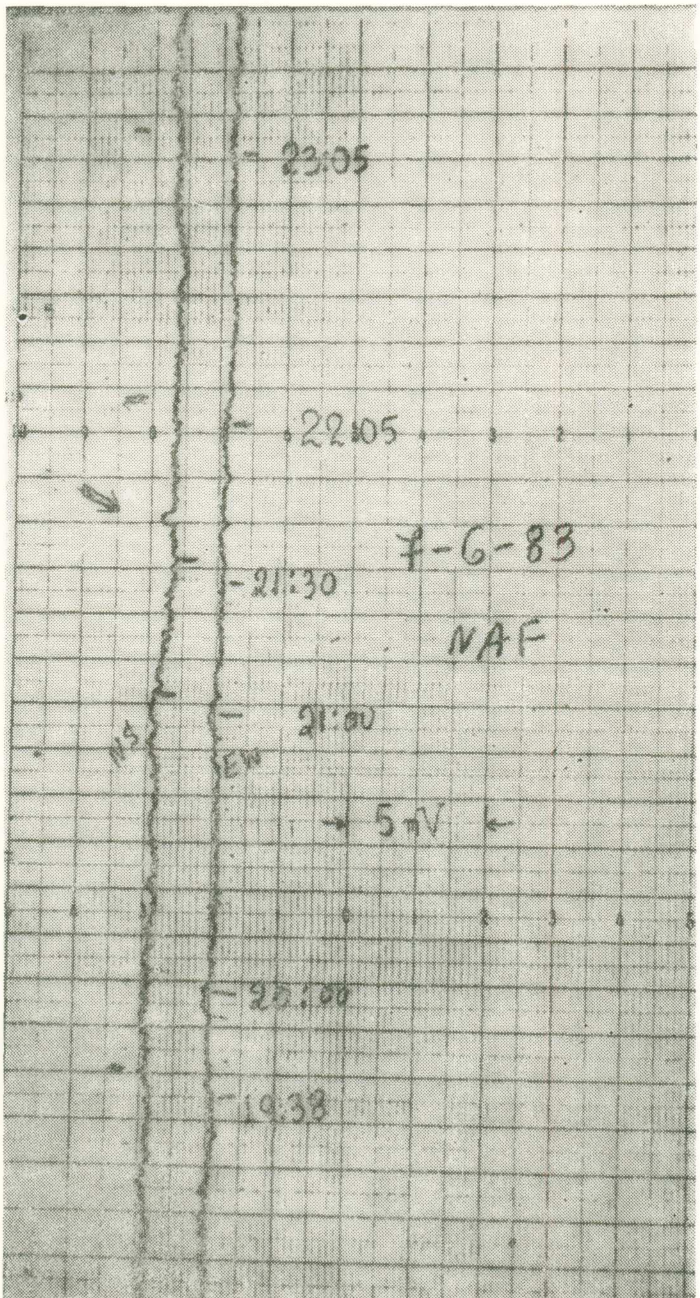


Fig. 21. Signal on the NS line of NAF simultaneous to Fig. 18.

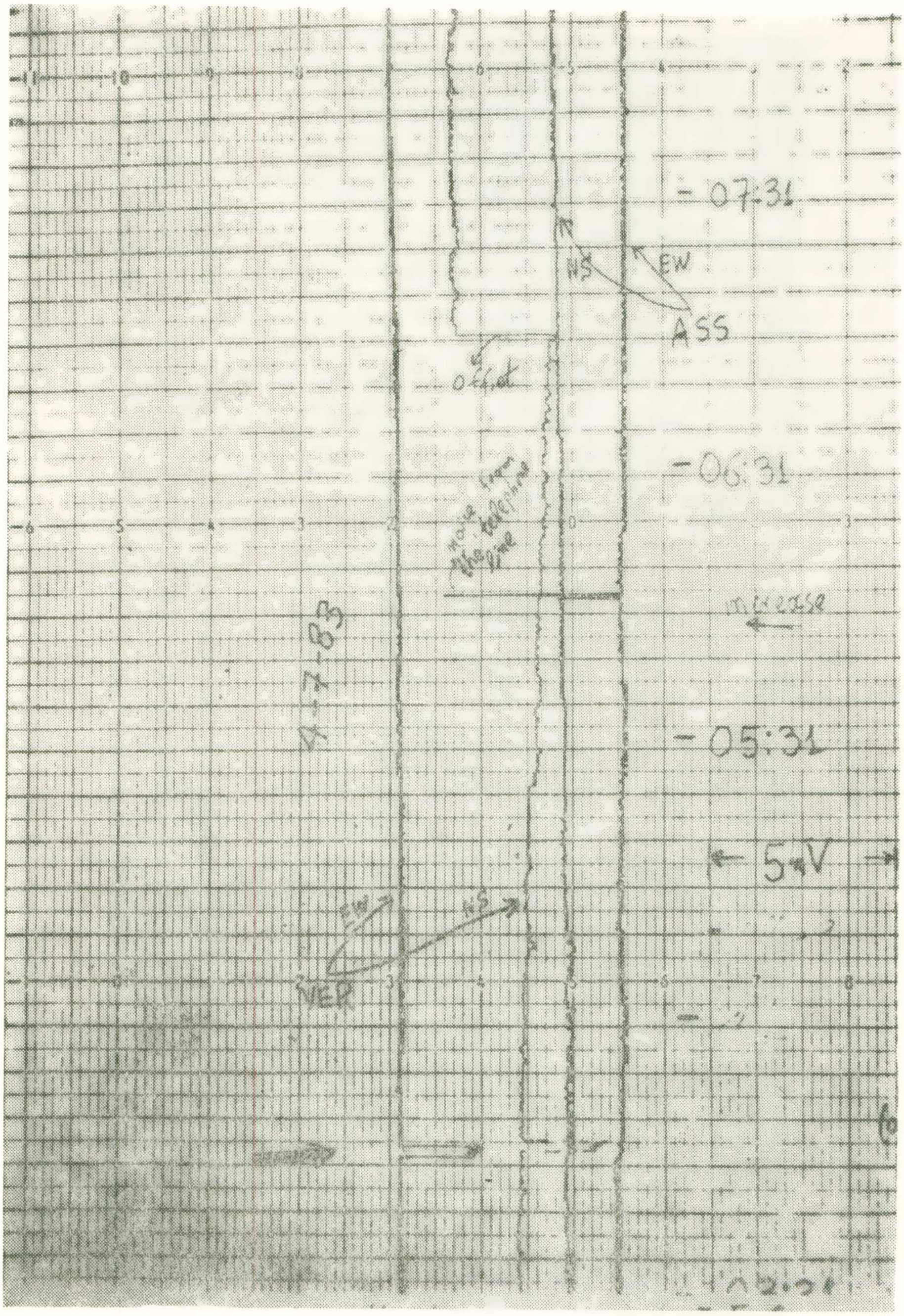


Fig. 22. Recording of a 6.5 R precursor collected on both lines of VER. Due to the directivity the SES does not appear at ASS.

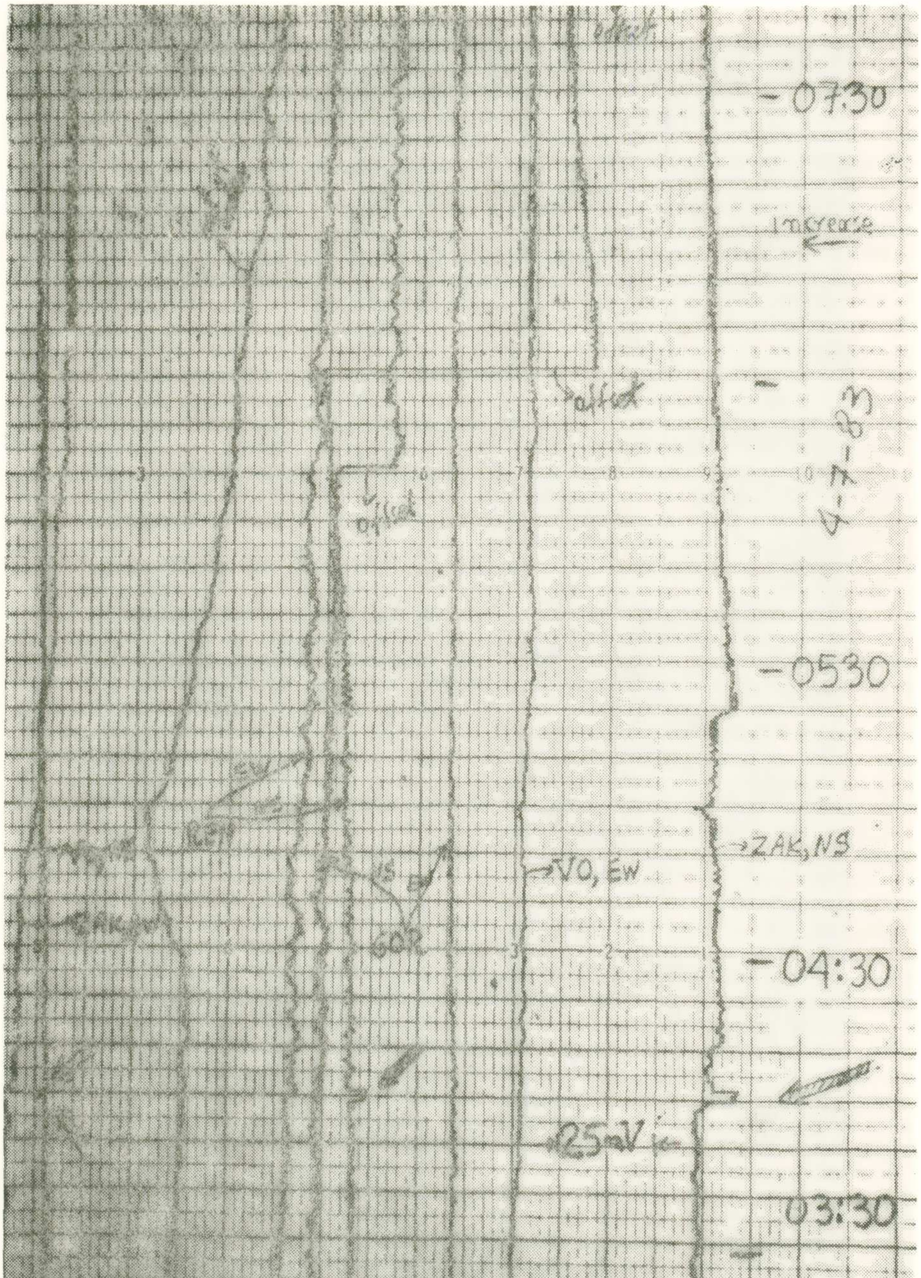


Fig. 23. Simultaneous signals to Fig. 22 collected at ZAK and REN.

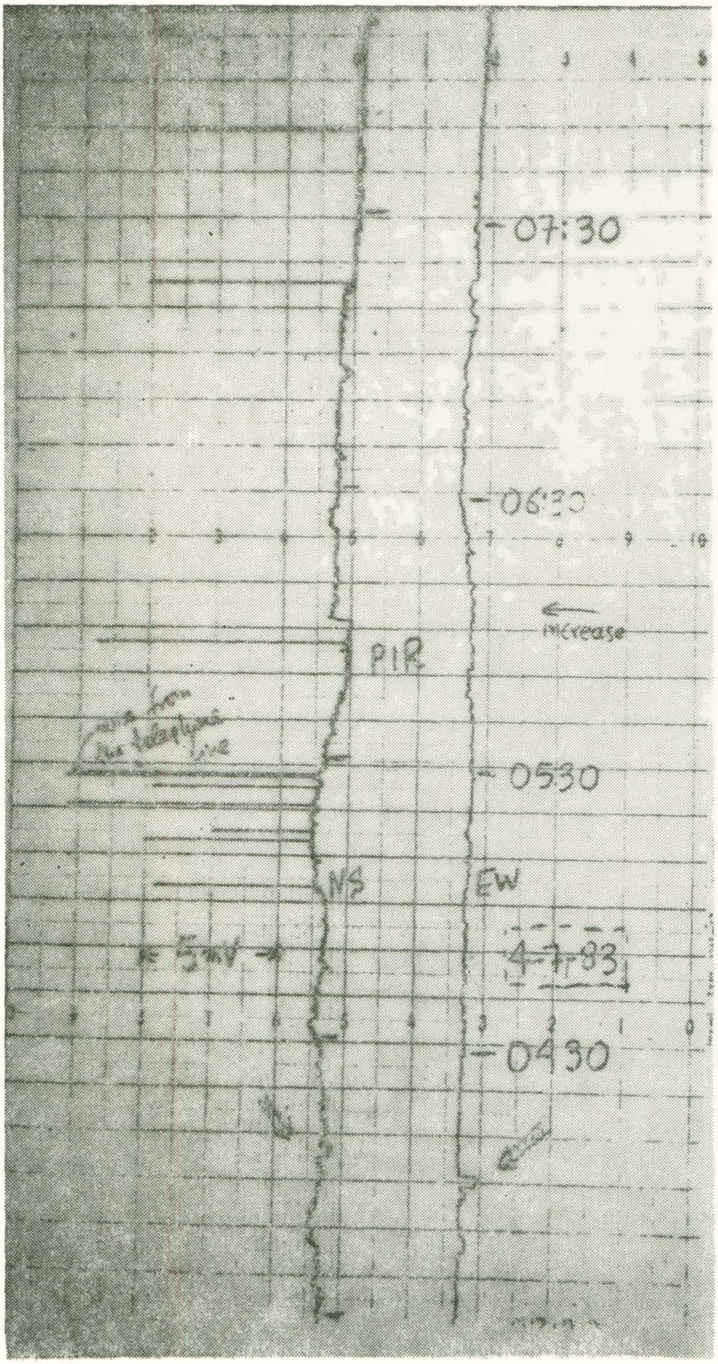


Fig. 24. Signals simultaneous to Fig. 22 recorded on both lines with brass electrodes at PIR.

current flow in the area between the seismic region and the station and possibly a non-isotropic emission of the current from its source. Excluding such anomalous absence of a signal the determination of the epicenter is, in practice straightforward.

Consider an SES that has been simultaneously recorded at a number of stations (i, j); from the recorded ΔV-values (those with an amplitude 2 - 3 times larger than the background noise) and the known effective relative

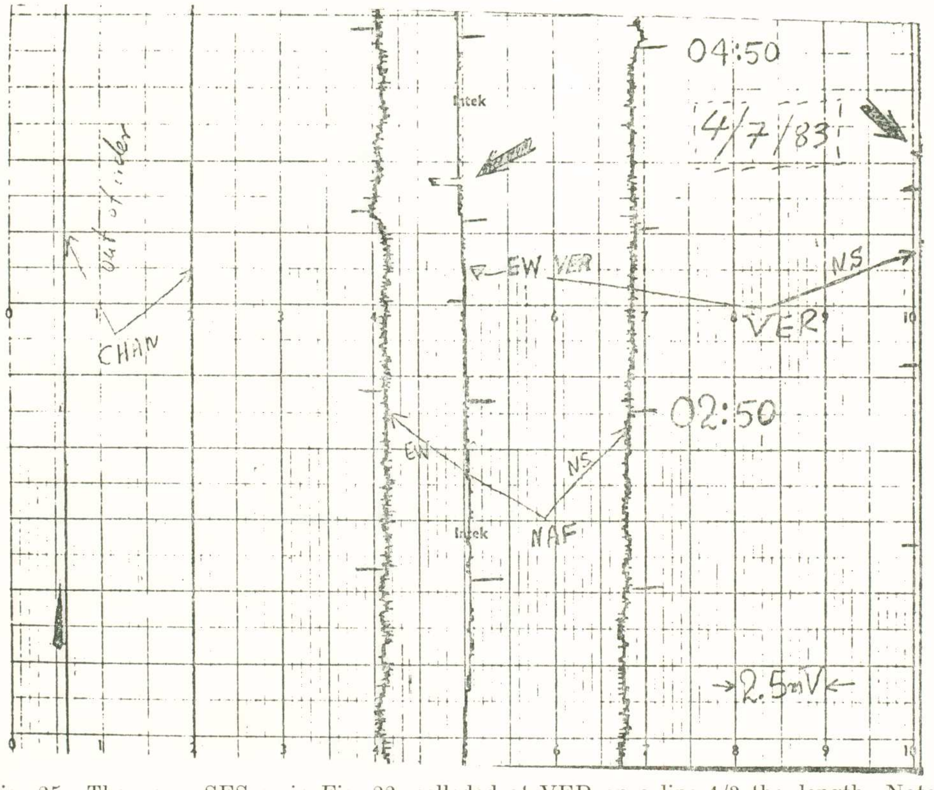


Fig. 25. The same SES as in Fig. 22. colleded at VER on a line 1/3 the length. Note that the ΔV-values are strictly proportional to L. The signal on the NS line of VER is only partially visible because the pen was just outside the chart. This multipen-recorder has no memory.

resistivities of each line of each station we find the intensities $J_{rel,i}$, $J_{rel,j}$; then by taking into account that J_{rel} attenuates according to 1/r-law we apply the minimization procedure:

$$\underset{k}{S}\left(J_{rel,i}\, r_j - J_{rel,j}\, r_i\right)^2 = \min$$

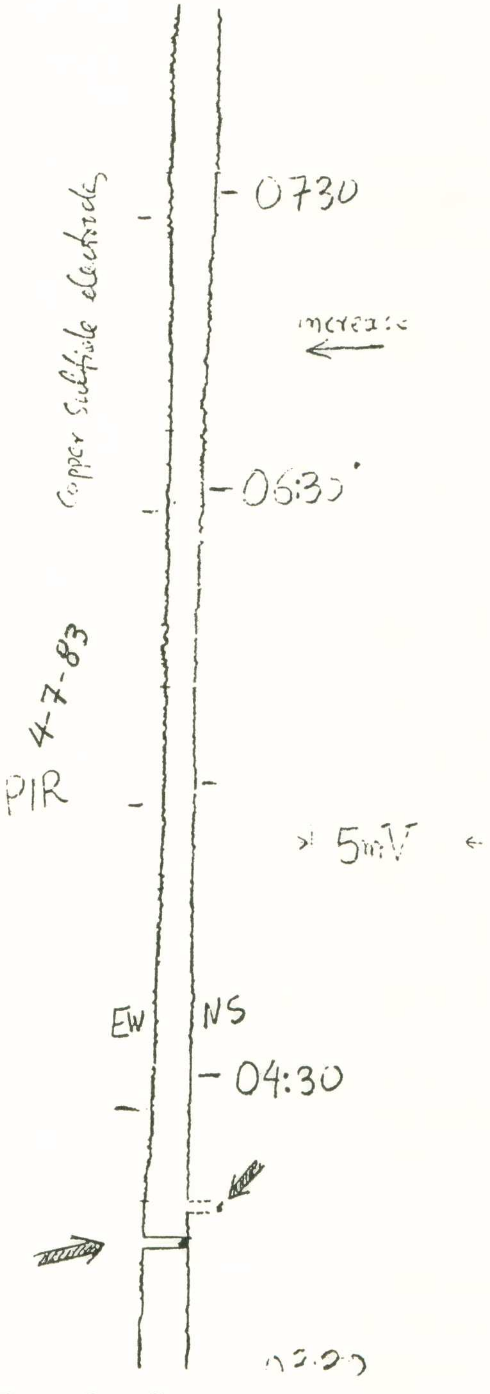


Fig. 26. Recording as in Fig. 24 collected
with copper sulfide electrodes.

where k denotes pairs of stations (i,j) and r_i, r_j are the unknown epicentral distances; the epicentral distance r_i of each station (i) is expressed in terms of its known coordinates (χ_i, ψ_i) and the unknown coordinates (χ_o, ψ_o) of the epicenter and hence the computer minimization procedure leads to the determination of (χ_o, ψ_o). We should stress once more that in this minimization procedure we must not include a station which has not recorded the SES (i.e. $J_i = 0$) because then there are two possibilities: either the station is so far from the epicenter that — due to the attenuation because of distance — the intensity is hidden in the noise or alternately the intensity of SES is zero — although the station is close to the epicenter — due to the "directivity" effect (§ 9). Alternately the epicenter can be determined [**2**] graphically with the method of Apollonian circles as will become clear below with some examples

Let us first consider a case of a weak EQ that was recorded only at *two* stations installed at a distance of 150 km. If the ratio of the two intensities is considerably different than unity — e.g. 2 to 5 — the epicenter can be directly determined with an accuracy of a few decades of kilometers because it will be 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 EW line of HAL-station; at the same time the SES is also recorded on NS-line of NAF-station ($\Delta V \approx 0.4$ mV) while no signal was detected at THI (located close to the epicenter). By taking — as mentioned above — as unity the length of a line of 50 m and considering that a) the relative resistivities of the above lines of HAL and NAP (in comparison to that of PIR) are around unity and b) the above values refer to lines with a length $L = 100$ m which is double the length of the basic station (and hence $L_{rel} = 2$) we have the following numbers:

for HAL: $\Delta V = 1\text{mV}$, $L_{rel} = 2$, $\rho_{EW} \simeq 1$ $J_{rel} = 0.5$
for NAF: $\Delta V = 0.4\text{mV}$, $L_{rel} = 2$, $\rho_{NS} = 1$ $J_{rel} = 0.2$

Therefore the epicenter should lie on an Apollonian circle the points of which have distances from HAL and NAF-station building a ratio 0.5 /0.2 (Fig. 27); on the same figure we give with an asterisk the true epicenter of a 3.9-event that occurred almost 8 hours later (18:54 on May 28, 1983). One should notice that — in spite of the fact that in this case the exact epicenter cannot be determined as a single point — a guess as to the magnitude of the expected event could be done as follows: the points of the Apollonian circle have a distance from HAL-station around 40km or 50km and hence we have $J_{rel} \cdot r = 20$ which means — according to Fig. 17 — that $M = 3.7$ with a plausible uncertainty of ± 0.5 R. The anomalous directivity of the effect in the above example is evident; although the SES should have been recorded at THI which is nearer to the epicenter than NAF no trace was collected at this station. This will be discussed later.

We proceed now to the determination of the epicenter of another event

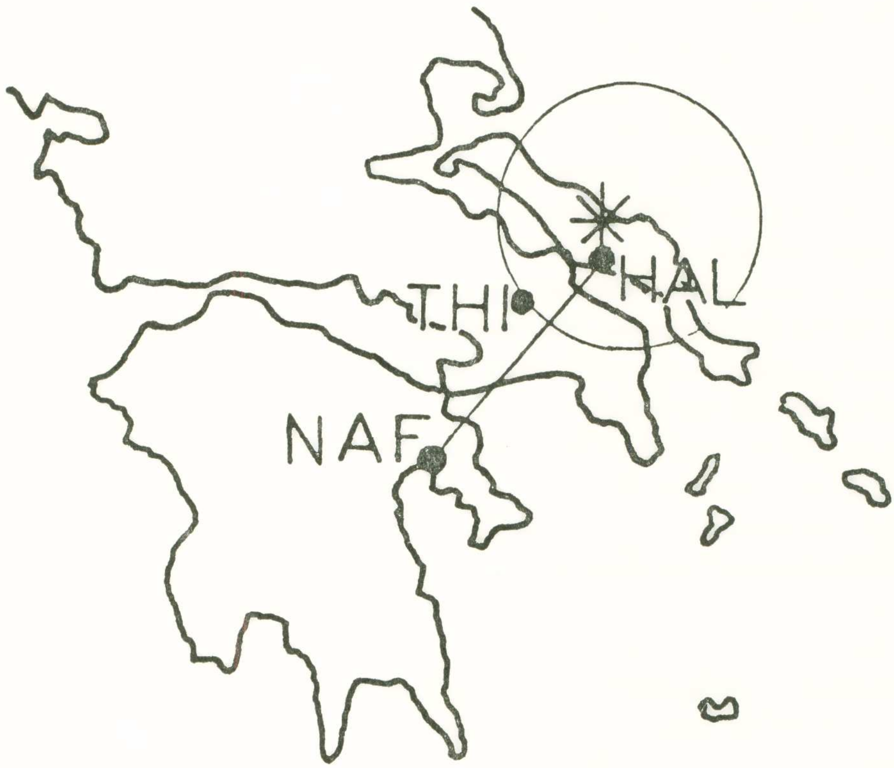


Fig. 27. Graphical determination of the epicenter from signals collected at two stations.

recorded at three stations with an epicenter lying outside the network.

Consider the SES which has been simultaneously recorded at 21:38 on June 7, 1983 at the following stations: HAL, VER and NAF (see Figs. 18, 20 and 21). The ΔV-values extracted from these figures and the procedure for the calculation of J_{rel} for these three stations are given in Table V. In Fig. 28 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 circles intersect at two points the one of which is $\sim$ 80 km far from the true epicenter;

TABLE V.

Calculation of J_{rel} for simultaneous SES corresponding to the 4.5 event of 02:39 June 9th 1983.*

	HAL		NAF		VER	
	EW	NS	EW	NS	EW	NS
ΔV-values from Figs. 17, 19 and 20 (mV)	1 (L=200m)	—	—	0.4 (L=100m)	0.1 (L=150m	0.45 (L=50m)
ΔV-values for L=50m (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 value has been later revised by —0.2 units.

the latter is indicated with an circle. Only the eastern intersection was announced (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 was independently announced (telegram 113) with an accuracy ΔY = 0, ΔM = 0.3. By considering the distances of the intersection from the stations one finds that the product $J_{rel} \cdot r$ is around 80 - 90 and hence the expected magnitude determined from Fig. 17 is around 5 whereas the true one was 4.5.

As a last example we discuss the strong event (6.5 R) that occurred close to Dardanells at 12:01 on July 5, 1983. The simultaneous signals collected at four stations are given in Figs. 22 to 26 whereas the corresponding ΔV-values are written in Table VI. In Fig. 29 we plot the Apollonian circles for the following pairs of stations REN-VER, REN-PIR and VER-ZAK using the J_{rel} values given in the same table. According to the figure the calculated epicenter lies either 150 - 180 km NE of Athens or 350 km NE of Athens. The latter region is roughly 80 km from the true epicenter which is indicated with an asterisk. Note that the calculated $J_{rel} \cdot r$-values (from any of the four stations) actually indicated in Fig. 17 that the expected magnitude (6.0 to 6.8) of the impending EQ was large.

TABLE VI.

Calculation of J_{rel} for simultaneous SES corresponding to the 6.5 R event of 12:01 July 5th 1983.

	VER		REN		PIR		ZAK	
	EW	NS	EW	NS	EW	NS	EW	NS
ΔV-values from Figs 6.7 and 8 (mV)	2.25 L = 200m	2.4 L = 100m	0.35 L = 30m	0.5 L = 30m	0.4 L = 50m	0.3 L = 50m	0.9 L = 150m	L = 150m
ΔV-values for L = 50m (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	

In order to visualise the degree of reliability of 1/r-law we plot in Fig. 30 the J_{rel}-values in function of the true epicentral distances for the last two examples discussed above. A $1/r^2$-law is clearly excluded.

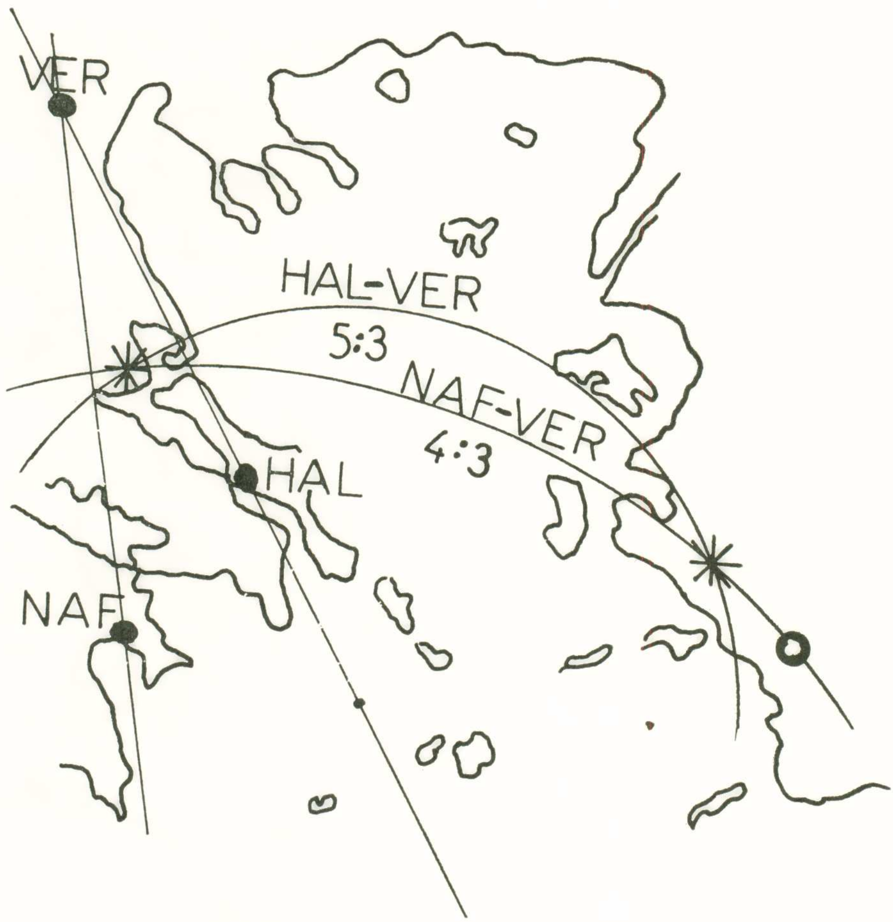


Fig. 28. Graphical determination of the epic enter from signals collected at three stations.

8. DETERMINATION OF THE MAGNITUDE

After determining the epicenter, the magnitude of an impending EQ can be determined from the empirical plot of log (J_{rel} r) versus M because J_{rel} and r are known.

The error in the predicted value of M depends on the errors of ΔV and r. The influence of the error in r depends strongly on the site of the epicenter in relation to the stations. When it lies within the polygon of stations a relatively small error results. This can be understood by studying Fig. 31 where 1, 2 and 3 are stations and E the true epicenter. If, due to errors in the resistivities and the epicentral distances the epicenter is predicted to be at E′

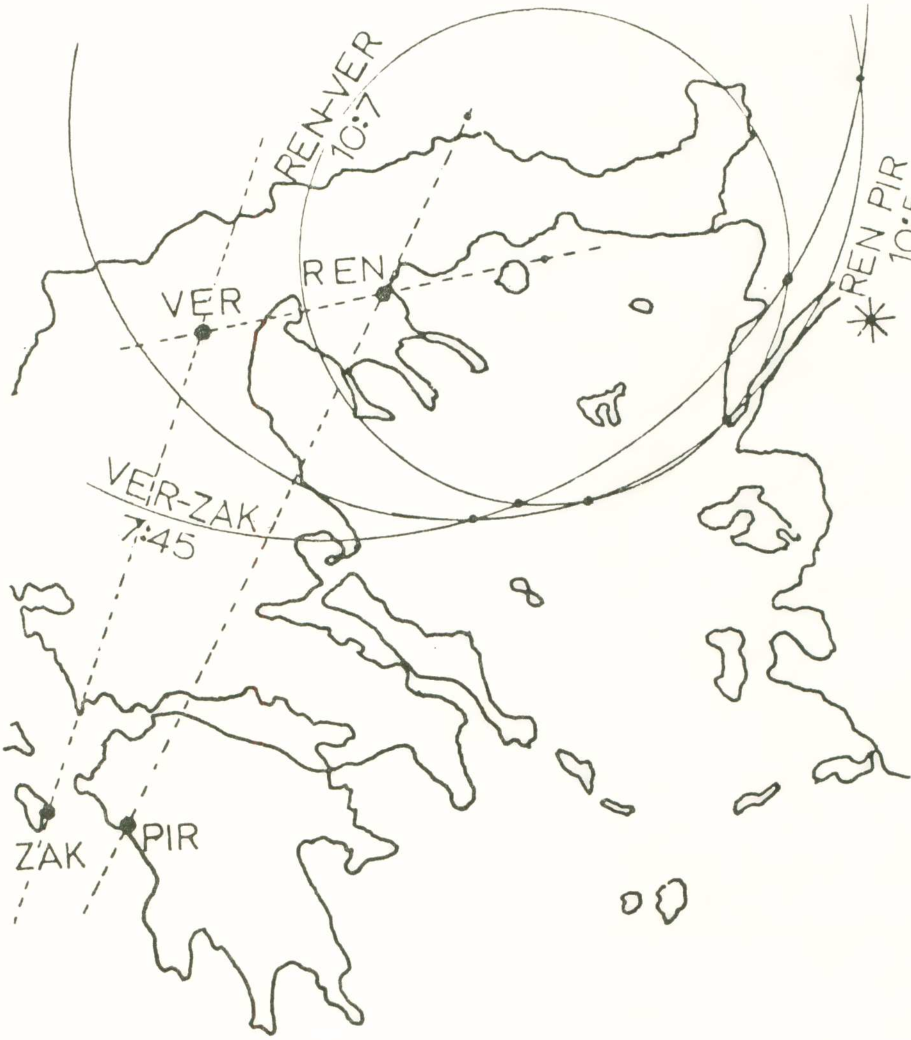


Fig. 29. Graphical determination of the epicenter from signals collected at four stations.

then r_1 will be larger than the true value and r_2 smaller. The two points on the plot of Fig. 16 will lie on either side of the line and their mean will give a relatively reduced error. To the contrary if the epicentre lies outside and far from the polygon e.g. at X while the predicted position is at X′ both values r_1 and r_2 will be too large so that the predicted magnitude will be too large.

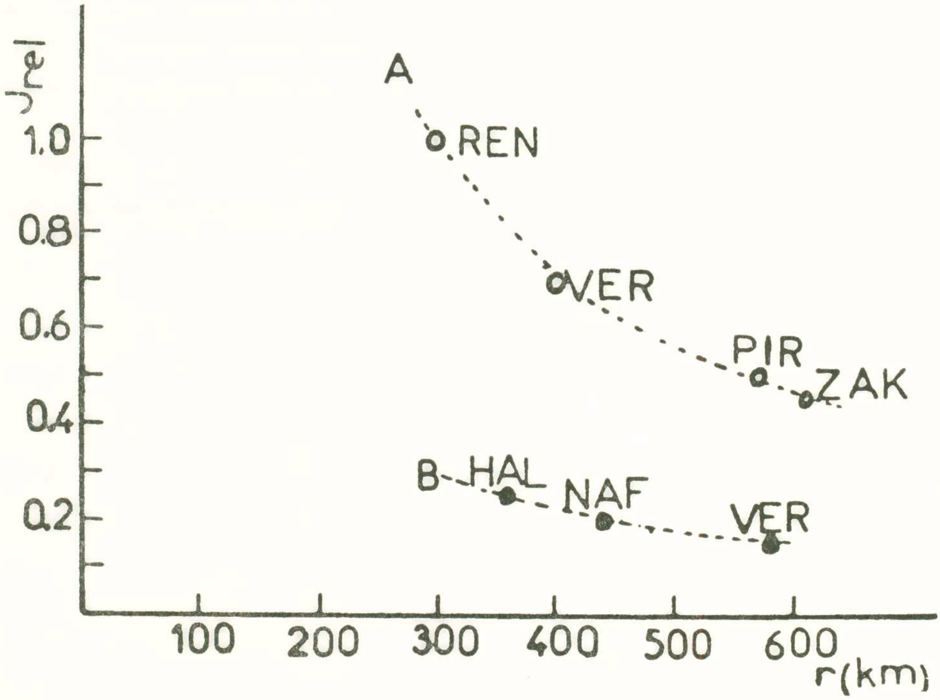


Fig. 30. Signal intensity versus epicentral distance. A: case of Fig. 29. B: case of Fig. 28.

If the predicted distance is about double the correct value the logarithm will be too large by log 2 i.e. by 1 unit according to Fig. 17.

9. DIRECTIVITY AND POLARITY

One would expect all stations lying at equal distances from an epicenter to register for equal magnitudes the same value of the relative signal strength. The study of the totality of events shows that this does often not hold in the following sense:

The simultaneous SES of a given EQ do not appear at all the stations for which the 1/r-law would warrant their detection. A detected signal, however, obeys this 1/r-behaviour.

As a striking example we refer to earthquakes from the Kefallinia region (38.0°N, 20,0° E); the corresponding SES are clearly recorded in PIR

(Figs. 4 to 6) but they do not appear at all at PAT which has approximately the same epicentral distance; on the other hand they appear at GOR and IOA although they have larger epicentral distances. As a second example one should consider the strong EQ that occurred near the Dardanells; an inspection of Figs. 22, 23 and 24 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 d i r e c t i v i t y e f f e c t is not reversible, in the sense that a current source at A can be detectable at B but not the

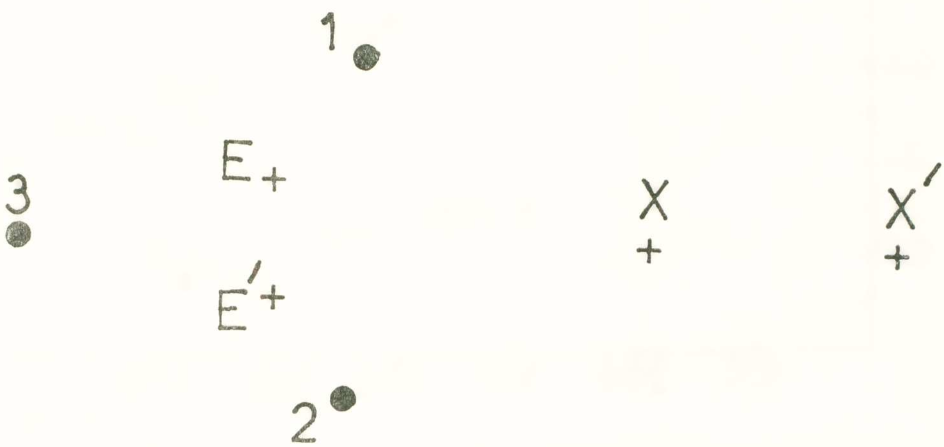


Fig. 31. Influence of errors of the epicenter on the magnitude. (E) inside and (X) outside the network.

inverse. Such cases have been observed for some pairs of stations in Greece e.g. earthquakes having epicenters close to PIR are never recorded at PAT although eartquakes that have their epicenters close to PAT (at Kalavrita, 38.0° N, 22.0°E) are always clearly recorded at PIR (see Figs. 7, 8 and 9).

Another important property is the p o l a r i t y of the SES. It is an empirical fact that the direction of the vector of J_{rel} at a given station is always the same for earthquakes coming from a given seismic area. As an example, all earthquakes from the region of Kefallinia are always recorded on the EW line of PIR as a decrease of this component.

The directivity and polarity effects although decreasing the number of available data of the signal intensity are often usefull as criteria for the correctness of a epicenter determined according to paragraph 7. It is obvious that simultaneous SES are observed only in cases when the "directivity effect" allows the appearance at more than one station.

10. COMPARISON TO OTHER ELECTRIC ANOMALIES PRECEDING EARTHQUAKES.

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

China. Both resistivity and telluric current anomalies have been studied in relation to earthquakes. Fuye et al. [**11**] have reported on resistivity changes. Telluric current variations associated with EQ have been observed and described by Coe [**12**]. The anomalies consist of changes of in the electric field about 5 hours before an EQ that 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 6.4 R event of Kefallinia on March 23, 1983, and of the 4.3 R 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 (Figs. 10 and 11) 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 occur also in China; considering Fig. 11 of the report of Wallace and Teng [**13**] 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 hours 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 [**14**] 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 in based. In 21 cases among the 30 examples, for which a coseismic resistivity step was recorded, a premonitory gradual decrease of the resistivety 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 currant 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 anyhow be hidden in the noise. The Japanese observations are analogous to the SES as concerns to the lead time on one hand, (the premonitory resistivity changes start a few hours before concerns to the lead-time 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 [**15**] and later Rikitake et al [**16**] have reported some precursor "self-potential" anomalies but their form and the lead time — a few months before the EQ — has no similarity with the present SES. Further, as noticed by Honkura [**17**], 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 in SES-case.

Soviet Union: Pioneering electric field measurements have been made in Kamchatka since 1966 by Sobolev and coworkers [**7, 8**]. They have installed a network of coastal stations at distances of 100 - 200 km and concluded that changes of telluric currents correlate with earthquakes. However, no attempt for 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 find that their forecasts (made for scientific purposes) have a too low probability for practical applications [**7**].

The most significant anomaly (100 - 300 mV/km) was reported by Myachkin et al [**8**]; it starts 3 - 16 days before the shock and has 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.

11. RELIABILITY OF THE SES METHOD

In order to examine the reliability of the SES-method for EQ-prediction in an unbiased way we have followed a method similar to that mentioned by Sobolev [**7**]. After the detection of an SES and after having checked that it is not due to some other cause (e.g. 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 are in each case officially documented always before the EQ-occurence. They were registered in the form of telegrams charged by the Telecommunication Authority on an unique telephone number (8949849) that was exclusively used for this purpose (see Fig. 32). Photocopies of two such telegrams are given as an example in Figs. 33 and 34. The telegrams were numbered in the sequence they were issued; their numbers have been added to Fig. 32 on the right.

Earthquakes with $M \geqslant 5$: In Table VII we give ALL earthquakes with $M \geqslant 5$ that occurred within or close to the perimeter of the telemetric network from Jan. 18, 1983 until Oct. 21, 1983. The starting date comes from the fact that the ZAK-station was installed on Jan. 18, 1983 while the end-date refers to the last telegram that has been sent to the Minister of Public Works. In the same table we have added the running number of the issued telegram, 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. A reasonable tolerance for a prediction to be considered as successful could be 120 km and 0,8. An inspection of the table gives the following results: For a totality of 23 earthquakes 21 telegrams were expedited from which 18 were successful. This gives a truth rate of 18/21 = 0.86 and an alarm rate 18/23 = 0.78. The missed EQ of Febr. 19, 1983 gave a signal that has been recognized in retrospect. The case of the other missed EQ at 23:26 on May 14, 1983 refers to an EQ that occurred only 13 min after the previous event from the same area; nevertheless after re-examining the recordings we saw that two consecutive SES were present which by mistake were taken as a single SES and hence only a single prediction was issued.

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. As an example for the last EQ of Table VII with an epicenter

ΟΤΕ

ΑΝΑΛΥΤΙΚΟΣ ΛΟΓΑΡΙΑΣΜΟΣ
ΥΠΕΡΑΣΤΙΚΩΝ - ΤΗΛΕΓΡΑΦΙΚΩΝ ΤΕΛΩΝ

ΑΡ. ΔΙΑΝΟΜΗΣ	ΤΗΛ. ΚΕΝΤΡ.	ΑΡ. ΣΥΝΔΕΣΕΩΣ	ΧΡΟΝΙΚΗΣ ΠΕΡΙΟΔΟΥ
9104741	089400	8949849	ΜΕΧΡΙ 30.10.83

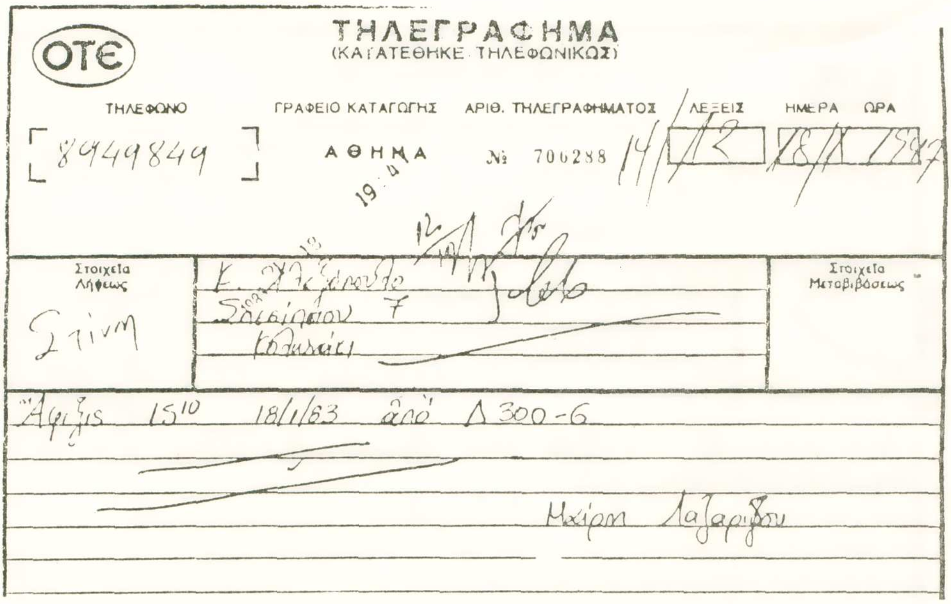
ΚΑΤΗΓΟΡΙΑ ΣΥΝΔ/ΣΕΩΣ Ή ΤΗΛΕΓΡ.	ΗΜΕΡΟΜΗΝΙΑ	ΑΡΙΘΜΟΣ ΣΥΝΔ/ΣΕΩΣ Ή ΤΗΛΕΓ/ΤΟΣ	ΠΡΟΟΡΙΣΜΟΣ: ΤΟΠΟΣ	ΠΡΟΟΡΙΣΜΟΣ: ΤΗΛΕΦΩΝΟ	ΔΙΑΡΚ. 1' Ή ΛΕΞΕΙΣ	ΠΟΣΟ	
ΝΥΚΤΕΡΙΝΗ	0308		ΝΠΑ		03	490	
ΝΥΚΤΕΡΙΝΗ	0529		ΝΠΑ		03	490	
ΣΥΝΗΘΗΣ	1909		ΙΩΝ		04	1280	
ΣΥΝΗΘΗΣ	1908		ΙΩΝ		06	1900	
ΣΥΝΗΘΗΣ	3008		ΝΠΑ		04	860	
ΤΕΛΗ ΥΠΕΡΑΣΤ.ΣΥΝΔ.ΕΣΩΤ.				502,00			
ΤΗΛΕΓΡ.ΕΣ	1107		ΑΘΝ		20	640	126
ΤΗΛΕΓΡ.ΕΣ	1507		ΑΘΝ		17	580	128
ΤΗΛΕΓΡ.ΕΣ	2007		ΑΘΝ		19	620	129
ΤΗΛΕΓΡ.ΕΣ	2607		ΑΘΝ		21	710	130
ΤΗΛΕΓΡ.ΕΣ	3007		ΒΟΥΛΙΑΓΜΕΝ		21	1260	131
ΤΗΛΕΓΡ.ΕΣ	3007		ΒΟΥΛΙΑΓΜΕΝ		22	1320	132
ΤΗΛΕΓΡ.ΕΣ	0608		ΒΟΥΛΙΑΓΜ		26	1480	133
ΤΗΛΕΓΡ.ΕΣ	0608		ΒΟΥΛΙΑΓΜ		19	620	134
ΤΗΛΕΓΡ.ΕΣ	1208		ΒΟΥΛΙΑΓΜΕΝ		21	1280	135
ΤΗΛΕΓΡ.ΕΣ	1208		ΕΝΤ		21	710	137
ΤΗΛΕΓΡ.ΕΣ	1608		ΒΟΥΛΙΑΓΜΕΝ		18	600	→136
ΤΗΛΕΓΡ.ΕΣ	1608		ΒΟΥΛΙΑΓΜΕΝ		20	640	→138
ΤΗΛΕΓΡ.ΕΣ	1908		ΑΘΝ		17	580	→140
ΤΗΛΕΓΡ.ΕΣ	2408		ΕΝΤ		15	540	[illegible]
ΤΗΛΕΓΡ.ΕΣ	2608		ΑΘΝ		19	620	→141
ΤΗΛΕΓΡ.ΕΣ	2708		ΚΖΝ		23	1360	→142
ΤΗΛΕΓΡ.ΕΣ	0109		ΚΟΛΩΝΑΚΙ		20	640	→143
ΤΗΛΕΓΡ.ΕΣ	0309		ΒΟΥΛΙΑΓΜΕΝ		24	1400	→145
ΤΗΛΕΓΡ.ΕΣ	0309		ΑΘΝ		20	1190	→144
ΤΗΛΕΓΡ.ΕΣ	0409		ΑΘΝ		24	1400	→146
ΤΗΛΕΓΡ.ΕΣ	0909		ΚΟΛΩΝΑΚΙ Α		18	600	→147
ΤΗΛΕΓΡ.ΕΣ	1209		ΑΤΙΚΗ		20	640	→149
ΤΗΛΕΓΡ.ΕΣ	1309		ΑΘΝ		19	620	→150
ΤΗΛΕΓΡ.ΕΣ	1609		ΚΟΛΩΝΑΚΙ		20	640	→148
ΤΗΛΕΓΡ.ΕΣ	1709		ΑΘΝ		23	1360	→151
ΤΗΛΕΓΡ.ΕΣ	1909		ΑΘΝ		22	730	→152
ΤΗΛΕΓΡ.ΕΣ	2309		ΕΝΤ		24	770	→153
ΤΗΛΕΓΡ.ΕΣ	2309		ΒΟΥΛΙΑΓΜΕΝ		18	600	→154
ΤΗΛΕΓΡ.ΕΣ	2609		ΑΘΝ		18	600	→155
ΤΗΛΕΓΡ.ΕΣ	2609		ΑΘΝ		23	750	→156
ΤΗΛΕΓΡ.ΕΣ	3009		ΑΘΝ		37	1920	
ΤΗΛΕΓΡΑΦΙΚΑ ΤΕΛΗ ΕΣΩΤ.				2.744,00			
ΣΥΝΟΛΟΝ						32460	

Ο.Τ.Ε. ΥΠΟΔ. ΜΗΧ. Α 410 Κ.Α. 955-28.86-1982

Fig. 32. List of telegrams charged to the telephone number 8949849. On the right side the number of words, the charges and (by hand) the running number are given.

in Continental Greece, i.e. an area within which no event with magnitude larger 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 $M \geqslant 5$ had occurred in the whole network since May 14, 1983. The method will be described in § 12.

Weaker earthquakes. In order to evaluate the reliability of


ΤΗΛΕΓΡΑΦΗΜΑ
(ΚΑΤΑΤΕΘΗΚΕ ΤΗΛΕΦΩΝΙΚΩΣ)
ΟΤΕ

ΤΗΛΕΦΩΝΟ	ΓΡΑΦΕΙΟ ΚΑΤΑΓΩΓΗΣ	ΑΡΙΘ. ΤΗΛΕΓΡΑΦΗΜΑΤΟΣ	ΛΕΞΕΙΣ	ΗΜΕΡΑ	ΩΡΑ
8949849	ΑΘΗΝΑ	№ 706288	14	18/1	1947

Στοιχεία Λήπτου

Στοιχεία Μεταβιβάσεως

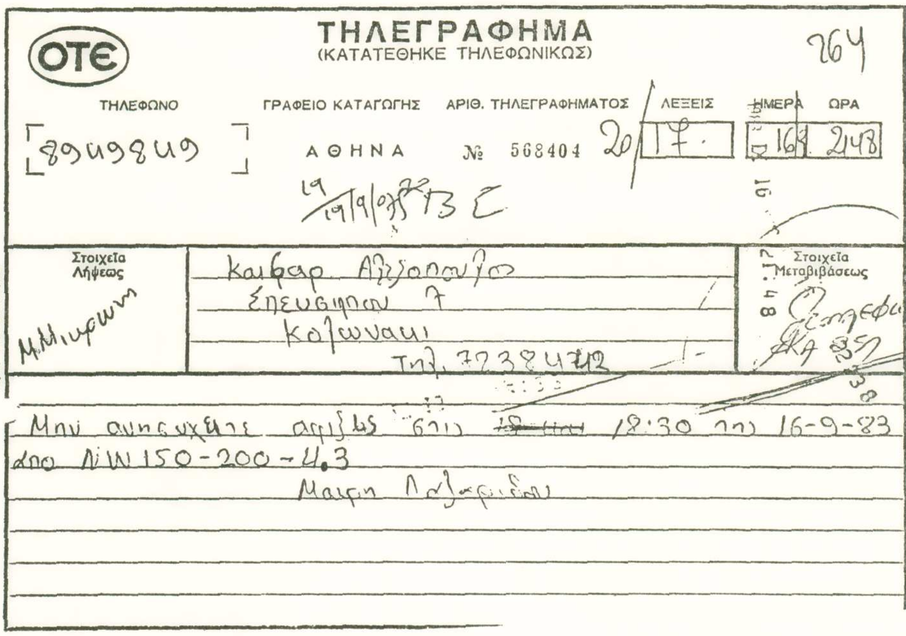
Αφίξις 15^10 18/1/83 από Δ 300-6

Μαίρη Λαζαρίδου

Fig. 33. Telegram expedited at 19:47 (Local Time) Jan. 18 1983 stating that an SES has been recorded at 15:10 (L.T.) Jan. 18th and that a 6 R event will occur with an epicenter 300 km W of Athens. Actually $6\frac{1}{2}$ h (i.e. 00:02 GMT Jan. 19th) after expediting the telegramm a 6 R event occurred with an epicenter 330 km W of Athens. Running number 32.

the network for even weaker EQ we have separated the area of Greece that is covered by the network into 8 parts according to Fig. 1 and have studied each one separately. Table VIII gives the data of all shallow EQ that occurred within each region from the time the telemetric system was set into operation (October 1982) until Oct. 21, 1983, i.e. continuously for nearly one year. The table contains all EQ with epicenters listed in the preliminary readings of the National Observatory of Athens with magnitudes larger than the threshold mentioned in the table; the latter were selected so as to contain a significant number of events in each case. Along with the deviations of the documented prediction issued for each event the running numbers of the corresponding telegrams are noted. The results are depicted in the time chart of Fig. 35. The periods during which stations did not cover that region have been shaded.

The inspection of Table VIII shows that for a totality of 48 events 34 telegrams were expedited from which 28 were "successful" which gives 28/34 =0.82 and 28/48 = 0.58 for the truth rate and the alarm rate. Concerning the missed events the following remarks can be made: The events marked



ΤΗΛΕΓΡΑΦΗΜΑ
(ΚΑΤΑΤΕΘΗΚΕ ΤΗΛΕΦΩΝΙΚΩΣ)

OTE 264

ΤΗΛΕΦΩΝΟ	ΓΡΑΦΕΙΟ ΚΑΤΑΓΩΓΗΣ	ΑΡΙΘ. ΤΗΛΕΓΡΑΦΗΜΑΤΟΣ	ΛΕΞΕΙΣ	ΗΜΕΡΑ	ΩΡΑ
8949849	ΑΘΗΝΑ	№ 568404	20 / 17	16	2148

Στοιχεία Λήψεως

Στοιχεία Μεταβιβάσεως

Μην ανησυχείτε ... 18:30 της 16-9-83
απο NW 150-200-4.3

Fig. 34. Telegram expedited at 21:48 (Local Time) of Sept. 16, 1983 stating that a SES has been collected at 18:30 (Local Time) of Sept. 16, 1983 and that a M = 4.3 event is predicted 150 to 200 km North West of Athens. A M = 5 event actually occurred 54 hours later after the emission (i.d. at 01:18 GMT Sept. 19, 1983) with an epicenter 140 km NorthWest of Athens. Running number 148 (see Table VIII).

with an asterisk refer to cases when the central station was not supervised due to the absence of the authors. This increases the alarm rate of the method to 32/48 = 0.67. In retrospect an examination of the charts showed that SES were present and could have warranted a prediction. Events with a double asterisk refer to cases in which although SES were actually present they were not recognized before the EQ-occurence. Finally in one case (Febr. 6, 1983) the central station was out of operation due to a blackout that started on

TABLE VII

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

EARTHQUAKE				TELEGRAM		
Date	time	M	Epicenter	Δr (km)	ΔM	n° of telegram
19-1-83	00:02	6.0	38.21N, 20.28E	10	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	70a
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	70b
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 EQ on Jan. 22, 1983 have been later slightly revised.

TABLE VIII.

All earthquakes from Oct. 1982 until Oct. 21, 1983
for various regions of Greece.

EARTHQUAKES				TELEGRAM			REGION
Date	time	Epicenter	M_S	Δr (km)	$Δ_M$	n° of telegram	
6- 2-83	18:14	38.4 23.2	4.0	missed		48	
18- 5-83	16:48	38.6 24.1	4.2	40	0.4	99	ATH
3-6-83	19:16	38.2 23.2	4.1	50	0.1	109	37.8 to 38.8°N
10- 6-83	22:56	38.7 23.6	4.3	0	0.3	113	22.6 to 24.3°E
12- 8-83	17:17	38.2 23.1	4.7	missed		*	$M_S \geqslant 4$
13- 8-83	14:52	38.7 24.1	4.1	85	-0.5	135a	
4-10-82	20:51	40.6 23.5	3.8	25	-0.2	3	
14-11-82	21:44	40.1 23.7	3.8	missed		*	THES
27-12-82	08:15	40.7 23.0	4.2	0	0.2	19	40.0 to 41.4°N
6- 4-83	04:55	40.8 23.0	4.3	missed		**	22.0 to 24.0°E
25- 4-83	06:02	40.6 23.9	3.8	130	-0.2	86	$M_S \geqslant 3.8$
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	
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	PAT
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 to 38.5°N
15- 3-83	15:41	38.1 21.5	4.3	0	0.3	63	21.4 to 22.6°E
11- 4-83	17:23	37.9 21.9	4.7	missed		*	$M_S \geqslant 4$
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	

Date	Time	Epicenter	M_S	Δr (km)	ΔM	n° of telegram	
31-10-82	22:22	39.2 22.9	3.5	0	-0.7	6	
7-11-82	10:26	39.5 22.8	3.9	missed			VOL
23-11-82	00:19	39.34 23.98	3.6	90	–0.4	14	38.8 to 40.0 N
27- 2-83	03:52	39.6 23.5	3.5	145	–0.5	58a	22.6 to 24.0 E
19- 4-82	22:35	39.6 23.4	3.6	50	–0.4	82	$M_S \geqslant 3.5$
19- 9-83	20:21	39.6 20.4	4.4	140	0	152	IOA
							39.0 to 40.0 N
							20.0 to 21.0 E
							$M_S \geqslant 4.3$
17- 1-83	15:53	38.3 20.6	5.3	missed			
20- 2-83	12:42	37.7 20.9	5.4	170	–0.1	53	ION, Islands
16- 3-83	21:19	38.8 20.6	5.4	90	0.6	65	36.5 to 39.0 N
23- 3-83	19:04	38.8 20.6	5.3	120	1.3	68	20.5 to 21.4 E
13- 5-83	23:50	38.4 20.3	5.3	70	–0.8	96	$M_S \geqslant 5$
8- 9-83	22:04	38.0 21.2	5.4	100	–0.1	146	
7- 4-83	01:52	38.7 22.4	4.0	100	0	78	
11- 6-83	23:31	39.3 21.2	4.1	missed			
1- 7-83	11:34	38.8 21.2	4	30	—	123	
28- 8-83	03:31	39.6 22.0	4.1	missed			C. GREECE
11- 9-83	10:50	38.7 22.4	4.4	missed		*	38.5 to 40.0 N
15- 9-63	00:05	38.8 22.4	4.1	missed			21.0 to 22.6 E
19- 9-83	01:18	38.7 22.4	5.0	40	0.7	148	$M_S \geqslant 4$
19- 9-83	01:30	38.7 22.4	5.0	missed		**	
9-10-83	21:27	39.1 21.9	4.2	0	0	158	
19- 2-83	15:55	36.9 21.5	5.0	missed			
24- 2-83	17:58	36.72 22.27	4.6	100	–0.4	54	S. PEL.
20- 8-83	08:15	37.6 22.6	4.1	missed			36.5 to 37.8 N
							21.4 to 24.3 E
							$M_S \geqslant 4.1$

Febr. 4, 1983 and finished on Febr. 7, 1983; telegram 48 announced the initiation of this blackout.

In summary our present experience indicates that e v e r y s i z a b l e E Q i s p r e c e d e d b y a n S E S and inversely e v e r y S E S i s a l-

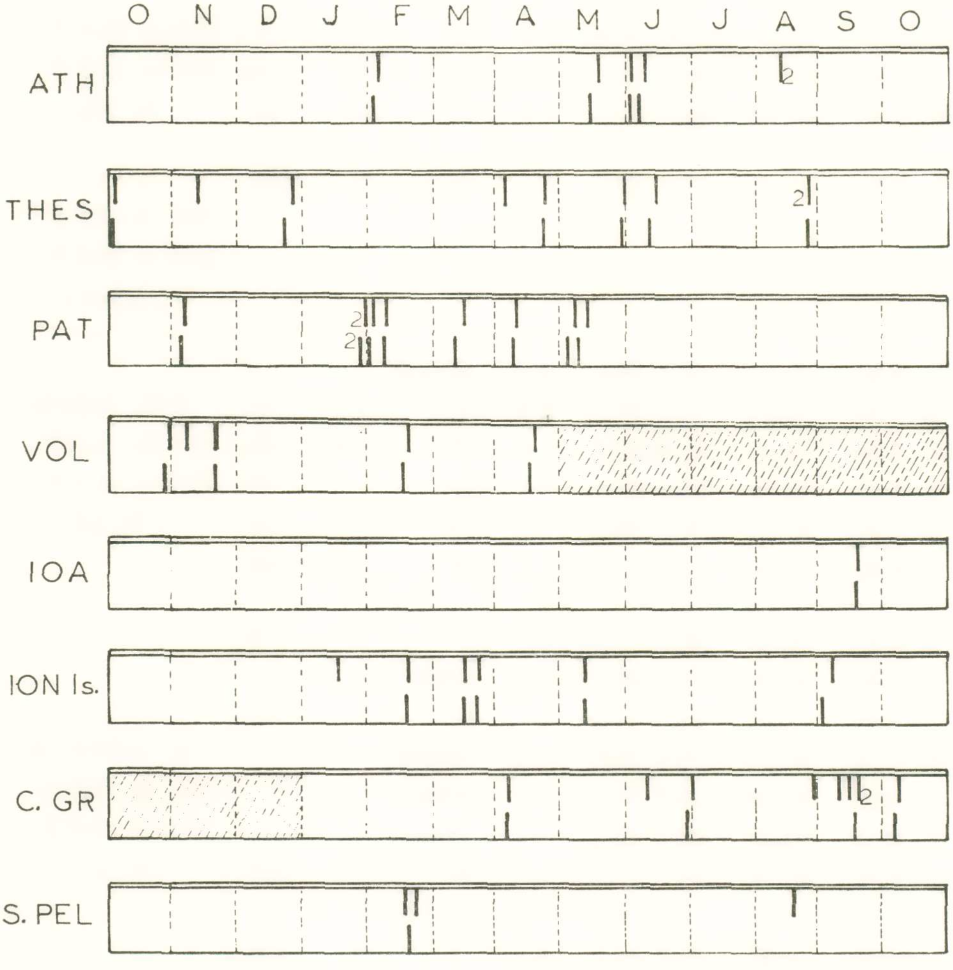


Fig. 35. Time chart for EQ (above) and telegrams (below) from Oct. 1982 to Oct. 1983 according to Table VIII. The numerals give the number of events that could not be drawn separately.

w a y s f o l l o w e d b y a n E Q the magnitude and the epicenter of which can be reliably predicted.

12. Probability of a prediction being made by chance.

It is of interest to calculate for each earthquake the number of telegrams that should have been expedited by chance until an event had occurred fulfilling the achieved margins of the time window, epicentral error and magnitude deviation.

As a first example we consider the $M_s = 4.2$ EQ that occured close to Thessaloniki (epicenter 40.71°N, 23.01°E) at 08:15 on Dec. 27, 1982 (see Table VIII). Figure 36 shows the prediction issued for this event: the telegram-expedited at 19:40 (local time) on Dec. 23, 1982 i.e. the SES appeared 91 hours *before* the occurrence of the event, states:

"a SES has been recorded at 15:00 Dec. 23 and an event $M = 4$ is predicted with an epicenter close to ASS".

The probabilities of the three parameters being predicted by chance are roughly calculated as follows: by drawing a circle with radius R = 100 km around the predicted point we find that for *nine months* (i.e. since May 6, 1982) no event with $M \geqslant 4$ had occurred in that area. Therefore the probability of predicting the time is:

$$n_t = \frac{5 \text{ days}}{9 \text{ months}} \sim 1.8 \times 10^{-2}$$

In spite of the fact that the predicted epicenter coincides with the real one we accept a plausible deviation of $\Delta r \approx 10$ km· therefore the probability n_{ep} of predicting the epicenter with an accurracy $\Delta r = 10$ km within an area of π (100 km)^2 is:

$$n_{ep} = \frac{\pi \text{ (10 km)}^2}{\pi \text{ (100 km)}^2} \sim 10^{-2}$$

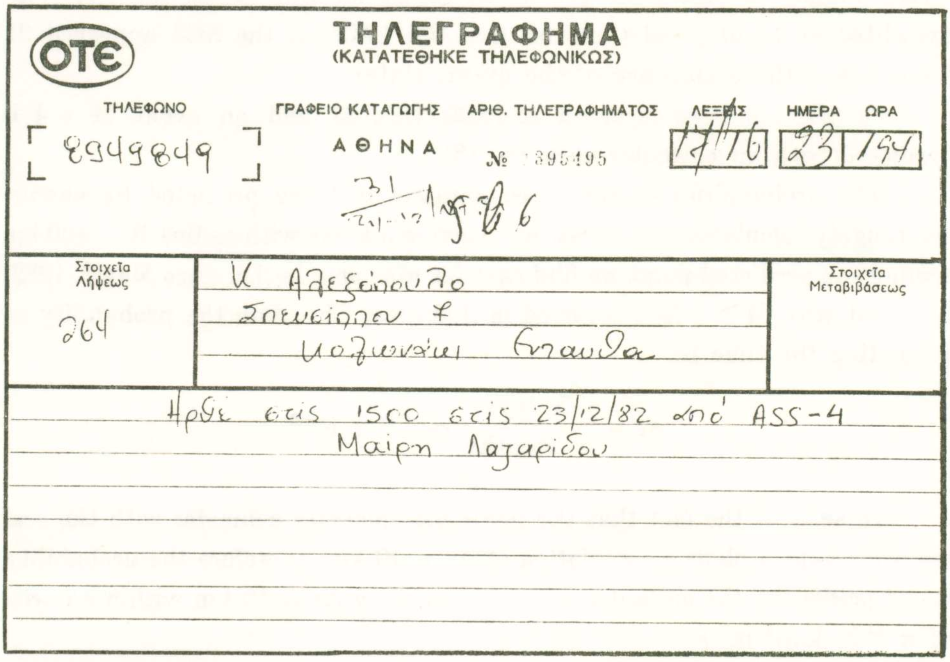
In order to predict the magnitude with the achieved accurracy of $\Delta M =$ 0.2 units one should have sent various telegrams with intervals of 0.4 units i.e. 4, 4.4, 4.8. etc. up to the highest M-value that could be expected for that area ($M \sim 6.8$)· however to be more conservative we take a maximum value of $M \sim 5.4$ and hence the probability of predicting the magnitude is:

$$n_M = 2 \times \frac{0.2}{5.4 - 4.2} \sim \frac{1}{3}$$

The probability n for predicting simultaneously the three parameters is:

$$n \sim 1.8 \times 10^{-2} \times 10^{-2} \times \frac{1}{3} \sim 6 \times 10^{-5}$$

The above result means that in the period May 6, 1982 until Dec. 23, 1982 one should have sent $(6 \times 10^{-5})^{-1}$ or around 16000 telegrams ONLY for the above area $\pi\,(100\ \text{km})^2$ close to Thessaloniki -- in order for one of them to have achieved the succesful prediction depicted in Fig. 36.


ΟΤΕ
ΤΗΛΕΓΡΑΦΗΜΑ
(ΚΑΤΑΤΕΘΗΚΕ ΤΗΛΕΦΩΝΙΚΩΣ)

ΤΗΛΕΦΩΝΟ 8949849
ΓΡΑΦΕΙΟ ΚΑΤΑΓΩΓΗΣ ΑΘΗΝΑ
ΑΡΙΘ. ΤΗΛΕΓΡΑΦΗΜΑΤΟΣ № 395495
ΛΕΞΕΙΣ 17/16
ΗΜΕΡΑ 23
ΩΡΑ 1954

Στοιχεία Λήψεως 264
Στοιχεία Μεταβιβάσεως

Ηρθε στις 1500 στις 23/12/82 από ASS-4
Μαίρη Λαζαρίδου

36. Telegram nr 19 stating that an SES was recorded at 15:00 (local time) of Dec. 23, 1982 announcing a M = 4 –event close to ASS. The telegram was expedited at 19:40 Dec. 23, 1982. In effect 91 h later a $M_S = 4.2$ event occurred at the predicted point.

We should emphasize that if one selects another value of R the product $n_t \times n_e$ varies only slightly; for instance if we select a circle with radius R = 200 km around the predicted point we find that no EQ with $M_s \geqslant 4$ had occurred for two months (i.e. since Oct. 25, 1982); then the probability n_t becomes 4 times larger and n_{ep} four times smaller and therefore the total probability is again 7×10^{-5}.

As a second example we consider the M = 4.7 –event that occurred close to Patras (epicenter 38.0°N, 22.0°E) at 22:44, May 8, 1983. The prediction issued for that event was telegram n^r 91 expedited at 21:27 (local time) May 5, 1983 i.e. $\sim$3 days *before* the event and stating the following:

"a SES was recorded at 19:50 May 5, 1983 and a M = 4.2 -event is predicted with an epicenter 160 km West (i.e. Δ) of Athens." One can see that the deviation in the magnitude was $\Delta M = 0.5$ units· as far as the value of Δr we take $\Delta r = 10$ km although the predicted epicenter coincided with the real one.

In this example we intentionally select an appreciably larger area around the predicted point e.g. the area included by the coordinates 36°N to 41°N and 19.5°E to 27°E. We find that for this area which is roughly 600 km × 700 km no earthquake with $M \geqslant 4.5$ occurred for 27 days i.e. since April 11, 1983. The probabilities are:

$$n_t = \frac{5 \text{ days}}{27 \text{ days}} = 1.8 \times 10^{-1}$$

$$n_{ep} = \frac{\pi\ (10 \text{ km})^2}{600 \text{ km} \times 700 \text{ km}} = 7.5 \times 10^{-4}$$

$$n_M = 2 \times \frac{0.5}{5.7 - 4.7} = 1$$

Therefore the total probability n of the above prediction being issued by chance is:

$$n = 1.8 \times 10^{-1} \times 7.5 \times 10^{-4} \times 1 = 1.35 \times 10^{-5}$$

which means that during the above period of 17 days one should have issued $(1.35 \times 10^{-5})^{-1} = 74000$ telegrams in order for one of them to have achieved the succesful predictions of telegram 91.

In cases where the accurracy in the epicenter is 50 - 100 km and in magnitude 0.5 the above procedure indicates that the probability n has a value around 10^{-3}.

The combination of even three such predictions gives an exceedingly low value (10^{-9}) which should be sufficient to convince about the reality of the present effect and should invalidate any suggestions that "succesful predictions can be fortuitously made in Greece due to the high seismicity".

Of course, telegrams expedited within a period shorter than the time window and predicting events of comparable magnitude occurring in the same region (telegrams 30 and 32 of Table VII) cannot be uniquely cross-correlated to the ensuing earthquake. However, the announcement of e.g. two strong signals that are followed by two strong earthquakes constitute an excellent check of the reliability of the method.

13. 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 temperature or stress on a body is an effect that Solid State Physics describe as "pressure induced (de)polarization" [**18**]. The electric current comes from the orientation of the dipoles of the form "aliovalent impurity plus a vacancy" (or interstitial) which anyhow exist in the volume close to the focus; the relaxation time of these dipoles varies with pressure or temperature. Before an EQ the stress gradually increases (at a rate b) and reaches a certain critical value σ_{cr} for which the relaxation time becomes short and a transient current is emitted; on the other hand the earthquake occurs when the stress reaches the fracture stress σ_f and hence the time-lead is given by:

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

The suggestion of the authors that a rock subjected to a gradually increasing stress emits a transient electric current well before its rupture has been recently experimentally confirmed in a large granite sample by Sobolev et al [**19**]; the reproducibility of the phenomenon (see Fig. 7 of their paper) indicates a high reliability of their findings. Dologlou-Revelioti [**20**] found a similar effect when the temperature of granite is changed.

As the values of σ_f and σ_{cr} more or less are 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. Other empirical rules cannot find an explanation so easily. As an 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 (array of 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 given tentatively an explanation 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 l.

On the other hand the effect of "directivity" finds some sort of explanation 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 main puzzling problems are the duration of the signal and the time-lead both of which are n o t connected to the magnitude.

A similar important problem arises for the value of duration τ of the signal (1 to 70 min). Assuming that current is emitted when $\sigma = \sigma_{cr}$ and that the stress distribution in the earth is heterogeneous one does not expect that the (de)polarization effect occurs 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 to 10 km must be:

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

i.e of the order of 1 to 200 m/sec. Such values are not far from slip-velocities of EQ but no immaginable 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 [**21**] 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 a focal area during the preseismic stage.

A c k n o w l e d g m e n t s: The present paper could not have been completed without the help of K. Nomicos who constructed and kept in order the network, M. Lazaridou - Varotsou for caring the main station and E. Dologlou-Revelioti for all seismological information.

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ΠΕΡΙΛΗΨΙΣ

Αἱ μεταβολαὶ τοῦ ἠλεκτρικοῦ πεδίου τῆς γῆς αἱ ὁποῖαι προηγοῦνται τῶν σεισμῶν ἐμελετήθησαν εἰς δίκτυον 18 σταθμῶν κατανεμημένων ἀνὰ τὴν Ἑλλάδα. Τὰ πρόδρομα ταῦτα ἠλεκτρικὰ σήματα ἐμφανίζονται 6 ἕως 115 ὥρας πρὸ ἑκάστου σεισμοῦ καὶ διαρκοῦν 1 ἕως 70 λεπτά. Ἡ διάρκεια καὶ ὁ πρόδρομος χρόνος, ἐν ἀντιθέσει πρὸς ἄλλου εἴδους πρόδρομα σήματα δὲν ἐξαρτῶνται ἀπὸ τὸ μέγεθος τοῦ σεισμοῦ. Τὰ σήματα εἶναι πρόσκαιροι μεταβολαὶ τῆς διαφορᾶς δυναμικοῦ V μεταξὺ δύο ἠλεκτροδίων καὶ ἐξαρτῶνται ἀπὸ τὸ μέγεθος M, τὴν ἐπικεντρικὴν ἀπόστασιν r καὶ τὰς τοπικὰς ἀνομοιογενείας τῆς γῆς. Αἱ συνιστῶσαι τοῦ ἠλεκτρικοῦ πεδίου μετρῶνται κατὰ τὰς διευθύνσεις Βορρᾶς - Νότος καὶ Ἀνατολὴ - Δύσις. Τὸ σύνολον τῶν πειραμάτων ἔδειξεν ὅτι τὸ ἐνδιαφέρον μέγεθος ἑκάστου σήματος εἶναι ἡ μεγίστη τιμὴ τῆς ἐπερχομένης μεταβολῆς ΔV. Τὰ σήματα ἐμφανίζονται ταυτοχρόνως εἰς πολλοὺς σταθμοὺς καὶ δὲν συνοδεύονται ἀπὸ μεταβολὴν τοῦ μαγνητικοῦ πεδίου. Οἱ κάτωθι κανόνες ἀνευρέθησαν:

1. Τὰ σήματα τὰ καταγραφόμενα εἰς δεδομένην γραμμὴν δεδομένου σταθμοῦ καὶ προερχόμενα ἀπὸ διαφόρους σεισμογόνους περιοχὰς ἐξασθενοῦνται μὲ τὴν ἐπικεντρικὴν ἀπόστασιν κατὰ τὸν νόμον $1/r$ (διὰ $r > 50$ km).

2. Διὰ δεδομένην γραμμὴν δεδομένου σταθμοῦ καὶ διὰ δεδομένην σεισμογόνον περιοχὴν τὰ μεγέθη τῶν σημάτων αὐξάνονται μὲ τὸ μέγεθος τοῦ σεισμοῦ. Ἡ σχέσις $\log \Delta V$ συναρτήσει τοῦ M εἶναι γραμμικὴ μὲ κλίσιν μεταξὺ 0.3 καὶ 0.4. Ἐὰν μελετηθῇ ἄλλη σεισμογόνος περιοχή, ἡ ἀντίστοιχος εὐθεῖα εἶναι παράλληλος πρὸς τὴν προηγουμένην ἀλλὰ μετακινημένη κατὰ σταθερὰν ποσότητα ἡ ὁποία ἐξαρτᾶται μόνον ἀπὸ τὸν λόγον τῶν ἐπικεντρικῶν ἀποστάσεων. Ἐάν, συνεπῶς, σχεδιασθῇ τὸ μέγεθος $\log (\Delta V.r)$ συναρτήσει τοῦ M, προκύπτει μία εὐθεῖα ἰσχύουσα δι' ὅλας τὰς σεισμογόνους περιοχάς.

3. Τὰ ταυτόχρονα σήματα τὰ καταγραφόμενα εἰς διαφόρους σταθμοὺς δὲν ἀκολουθοῦν ἕνα νόμον $1/r$. Τὸ μέγεθος $\Delta V/L$ διαιρεθὲν διὰ καταλλήλου συντελεστοῦ — τῆς ἐμπειρικῶς προσδιοριζόμενης ἐνεργοῦ εἰδικῆς ἀντιστάσεως — εἶναι χαρακτη-

ριστικὸν διὰ τὴν μεταβολὴν τῆς πυκνότητος ρεύματος. Συνδυάζοντες τὰς συνιστώσας κατὰ τὰς δύο διευθύνσεις λαμβάνομεν τὸ μέγεθος τοῦ σήματος J_{rel}. Τὸ μέγεθος τοῦτο ἐξασθενεῖται πάντοτε κατὰ τὴν σχέσιν 1/r ὥστε ἡ ἔκφρασις $\log(J_{rel} \cdot r)$ συναρτήσει τοῦ M νὰ εἶναι γραμμικὴ συνάρτησις ἰσχύουσα δι' ὅλους τοὺς σταθμοὺς καὶ ὅλας τὰς σεισμογόνους περιοχάς.

Μετρῶντες τὸ J_{rel} εἰς διαφόρους σταθμοὺς καὶ θεωροῦντες τὸν νόμον 1/r, εἶναι δυνατὸν νὰ προβλέψωμεν τὸ ἐπίκεντρον μὲ ἀκρίβειαν περίπου 100 km. Μετὰ τὴν ἀνεύρεσιν τοῦ ἐπικέντρου προσδιορίζεται καὶ τὸ μέγεθος ἀπὸ προηγουμένως ἀνευρεθεῖσαν ἐμπειρικὴν σχέσιν μεταξὺ $\log(J_{rel} \cdot r)$ καὶ M, μὲ ἀκρίβειαν ± 0.5 R.

Διὰ μίαν στατιστικὴν ἐλευθέραν προκαταλήψεων ἑκάστη πρόβλεψις ἐπισημοποιεῖται διὰ τηλεγραφήματος. Ἐπὶ 23 σεισμῶν ἰσχυροτέρων τῶν 5 R ἐστάλησαν 21 τηλεγραφήματα μὲ σφάλμα μικρότερον τῶν 120 kn καὶ 0.8 R. Ἡ πιθανότης αἱ παράμετροι μιᾶς προβλέψεως νὰ γίνουν τυχαίως εἶναι μεταξὺ 10^{-3} καὶ 10^{-4}.

Ἡ παροῦσα μέθοδος συγκρίνεται διεξοδικῶς μὲ ἠλεκτρικὰς μετρήσεις ἄλλου εἴδους εἰς τὴν Κίναν, τὴν Ἰαπωνίαν καὶ τὴν Σοβιετικὴν Ἕνωσιν. Παρὰ τὸ γεγονὸς ὅτι ἡ μέθοδος φαίνεται νὰ ἔχῃ πρακτικὴν σημασίαν διὰ τὴν πρόγνωσιν σεισμῶν, ἡ προέλευσις τοῦ φαινομένου, ἡ κατευθυντικότης καὶ ἡ ἐξασθένησις λόγῳ ἀποστάσεων δὲν εὗρον ἀκόμη ἐξήγησιν.

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