Investigations of the Aftershocks of July 4, 1968
Earthquake in Epidavros (*)

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SUMMARY. — The spatial and the time distribution of the aftershocks of the earthquake of July 4, 1968 in Epidavros (Greece) has been studied. It was found that the value of b in Gutenberg-Richter's relationship was nearly the same for the primary as well as the secondary or second order aftershocks of the sequence. The focal mechanism of the second order aftershocks as observed from the sense of first motion of P-waves showed some difference from that of the main shock or its primary aftershock.

RIASSUNTO. — È stata studiata la distribuzione nello spazio e nel tempo delle repliche del terremoto del 4 Luglio 1968, avvenuto ad Epidavros (Grecia). Per b nella relazione di Gutenberg-Richter, è stato trovato un valore pressocché uguale sia per le repliche primarie che per quelle secondarie (o del secondo ordine) della sequenza. Il meccanismo all'ipocentro delle repliche del secondo ordine, a seconda del verso delle onde P, ha mostrato alcune differenze da quello della scossa principale o della sua replica primaria.

1. – INTRODUCTION.

Study of aftershocks of an earthquake may possibly provide important clues for solving the mechanism of earthquake occurrence. With this end in view, some statistical features such as geographical,

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temporal and magnitude distributions of aftershocks are being exten-
sively investigated (¹). Although a few statistical laws on the oc-
currence of aftershocks are fairly well known, the detailed charac-
teristics of the sequence of aftershocks vary markedly from one region
to the other. On this account, the nature of aftershocks is far from
completely understood, particularly for formulating any theory for
earthquake prediction. The deformation and stress characteristics of
the aftershocks enable us to investigate the properties of the Earth's
structure, thus emphasizing a detailed study of individual set of after-
shocks over as many different regions of the Earth as possible. Another
reason for the study of the aftershocks of the natural earthquakes
follows from the fact that their characteristics generally differ from
those of artificial earthquakes e.g. explosions which have otherwise
contributed significantly to the science of seismology.

The object of this paper is therefore, to further our knowledge
on the occurrence of aftershocks in Greece in order to study their
distinctive characteristics and to deduce some physical properties of
the Earth's structure from their deformation characteristics. The
focal mechanism of aftershocks has also been tentatively explained
on the basis of available data.

2. – DESCRIPTION OF THE MAIN SHOCK OF JULY 4, 1968 IN GREECE.

At 21 hours 48 minutes GMT on July 4, 1968, a shallow earth-
quake of magnitude, $M_L = 5.0$ occurred with its epicentre at Lat. 37.7°N
and Long. 23.2°E in Greece. The epicentral distance of this shocks
was 60 km southwest of the standardized U.S.C.G.S. station of Athens
University. On account of the short epicentral distance of this recording
station which is in the centre of Greek Seismological network, a large
number of aftershocks of small magnitude were recorded. The focal
depth of the main shock by macroseismic data was 30 km, but there
are some indications as discussed later that this depth was probably
less than 30 km. Following the main shock, there were more than
300 aftershocks recorded with their magnitudes between 2.2 and 4.
Only one foreshock of magnitude $M_L = 2.8$, was recorded about ten
hours prior to the occurrence of the main shock.

The maximum intensity in modified Mercalli scale was VII for
the main shock. Substantial property damage was caused due to this
earthquake in the region of Argolis, particularly in Epidavros. Ac-

cording to the press reports, 5 houses collapsed, about 36 were seriously
damaged and 64 houses were slightly damaged. Earthslumping was
observed in New Epidavros.

It may be interesting to note that the epicentre of the main shock
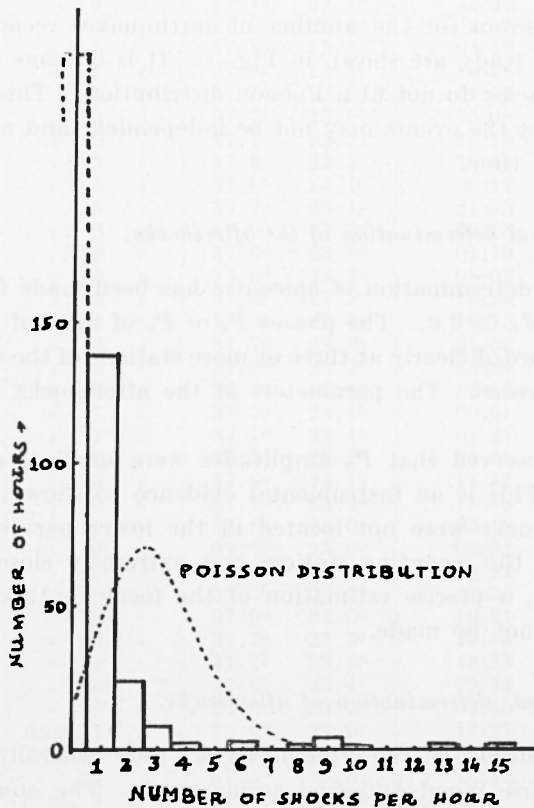was located in the region which is not characterized by high seismic

Fig. 1 – The number of hours during which zero through 15 shocks were
recorded and the corresponding Poisson distribution. A test for goodness of
fit indicated marked disagreement.

activity. From the seismicity studies ([2]), it is seen that only 21 earth-
quakes of magnitude larger than 5 have been recorded since 1922.
Out of these, three shocks had their focal depth larger than 100 km.
It is remarkable to find that none of the shocks in the region except
one was accompanied by aftershocks or preceded by foreshocks. Even
that shock had only 6 to 8 foreshocks and aftershocks. Considering

all these aspects, it is obvious that the main shock of July 4, 1968 had distinctive characteristics in so far as the seismicity of the region is concerned.

3. – ANALYSIS OF DATA.

The histogram for the number of earthquakes recorded and included in this study are shown in Fig. 1. It is obvious that the observed frequencies do not fit a Poisson distribution. This may be due to the fact that the events may not be independent and not randomly distributed in time.

3.1 – *Epicentral determination of the aftershocks.*

Accurate determination of epicentre has been made for all earthquakes with $M_L \geqslant 3.0$. The phases P_g or P_n of most of these shocks have been recorded clearly at three or more stations of the seismological network of Greece. The parameters of the aftershocks are given in Table I.

It was observed that P_n amplitudes were small as compared to that of P_g. This is an instrumental evidence to show that the foci of the aftershocks were not located in the lower part of the crust. Since none of the recording stations was extremely close to the epicentral region, a precise estimation of the focal depth of the aftershocks could not be made.

3.2 – *Magnitude determination of aftershocks.*

The magnitudes of the aftershocks M_L were generally determined by the standard Wood-Anderson seismograph. The cumulative frequency of the aftershocks for different values of M_L are given in Table II.

4. – RESULTS AND DISCUSSION.

4.1 – *Time distribution of aftershocks.*

The time distribution of aftershocks has been studied by many Japanese investigators. The original Omori's law was modified [3] as

$$n(t)\,dt \;=\; k\,(t + c)^{-h}\,dt \qquad\qquad [1]$$

Table I - AFTERSHOCKS OF $M_L \geqslant 3.0$

No	Date			Lat. N	Long. E	Arrival time at Athens (approximately)	Magnitude M_L
Main shock	July	4	1968	37.7°	23.2°	21:48	5.0
1	July	4	1968	37.6°	23.1°	22:42	3.0
2	»	4	»	37.7°	23.2°	23:04	3.2
3	»	4	»	37.7°	23.1°	23:28	3.0
4	»	4	»	37.7°	23.1°	23:33	3.0
5	»	5	»	37.7°	23.2°	02:13	3.1
6	»	5	»	37.8°	23.2°	04:43	3.4
7	»	5	»	37.8°	23.2°	10:28	3.2
8	»	5	»	37.7°	23.3°	14:57	3.1
9	»	5	»	37.7°	23.2°	15:08	3.6
10	»	5	»	37.7°	23.3°	15:15	3.3
11	»	5	»	37.6°	23.3°	17:49	3.3
12	»	5	»	37.8°	23.1°	20:12	3.0
13	»	5	»	37.7°	23.1°	21:05	3.0
14	»	5	»	37.6°	23.3°	22:25	3.1
15	»	6	»	37.6°	23.3°	01:13	3.0
16	»	6	»	37.6°	23.3°	08:03	3.1
17	»	6	»	37.6°	23.3°	16:26	3.5
18	»	6	»	37.6°	23.3°	19:45	3.1
19	»	6	»	37.7°	23.2°	21:55	3.9
20	»	6	»	37.6°	23.3°	22:20	3.3
21	»	6	»	37.7°	23.3°	22:43	3.2
22	»	7	»	37.7°	23.1°	00:51	3.7
23	»	7	»	37.7°	23.1°	01:27	3.0
24	»	7	»	37.7°	23.1°	05:44	3.5
25	»	9	»	37.8°	23.1°	14:32	3.0
26	»	9	»	37.7°	23.2°	16:49	3.0
27	»	10	»	37.8°	23.0°	03:48	3.5
28	»	10	»	37.7°	23.0°	05:32	3.0
29	»	10	»	37.8°	23.0°	16:22	3.0
30	»	10	»	37.7°	23.2°	21:36	3.4
31	»	12	»	37.9°	23.0°	10:21	3.1
32	»	13	»	37.7°	23.3°	19:38	3.4
33	»	14	»	37.7°	23.2°	18:33	3.7
34	»	16	»	37.6°	23.4°	22:43	3.0
35	»	22	»	37.6°	23.4°	07:46	4.0
36	Aug.	1	»	38.0°	22.9°	12:27	3.0
37	»	10	»	37.9°	23.1°	08:44	3.3
38	»	24	»	37.5°	23.5°	18:17	3.2
39	Sept.	3	»	37.4°	23.5°	03:57	3.0
40	»	3	»	37.7°	23.0°	22:59	3.1
41	»	12	»	37.8°	23.2°	10:36	3.5
42	»	18	»	37.5°	23.4°	14:26	3.2
43	»	22	»	37.8°	23.3°	09:55	3.0
44	»	26	»	37.8°	23.0°	00:59	3.2
45	Oct.	14	»	37.6°	23.3°	01:42	4.0
46	»	14	»	37.9°	23.2°	17:08	3.4
47	»	23	»	37.7°	23.4°	05:17	3.0
48	»	23	»	37.8°	23.1°	12:20	3.1
49	»	23	»	38.2°	22.9°	22:32	3.0
50	»	24	»	37.6°	23.3°	01:26	3.6
51	»	26	»	37.6°	23.4°	06:27	3.1
52	Nov.	2	»	37.6°	23.3°	22:58	3.1
53	»	2	»	37.6°	23.2°	05:17	3.3

Table II – CUMULATIVE FREQUENCY
OF AFTERSHOCKS VERSUS MAGNITUDE

M_L	Cumulative frequency
2.2	308
2.3	277
2.4	243
2.5	193
2.6	157
2.7	120
2.8	91
2.9	71
3.0	53
3.1	36
3.2	26
3.3	20
3.4	15
3.5	11
3.6	7
3.7	5
3.8	3
3.9	3
4.0	2

where t is the time after the main shock, $n(t)dt$ is the number of after-shocks occurring in the time interval t and $t + dt$ and k, c and h are constant chosen to fit the data. When $h = 1$, the equation [1] ex-presses the Omori's law. Mogi ([4]) showed that the time distribution of aftershocks in the early stage after the occurrence of the main shock is expressed by the relation

$$n(t)dt = n_1 t^h dt \qquad 0 < t < t_o \qquad [2]$$

where n_1 is a constant.

Drakopoulos ([5]) determined the cumulative frequency of many earthquakes in Greece using

$$N(t) = \int_t^{t_o} n_1(t) \, dt . \qquad [3]$$

This author found that the functions of the following type fit the data

$$N = N_1 t^{-H} \qquad t < t_o \qquad [4]$$

or

$$\log N = B - H \log t . \qquad [5]$$

$$\text{I} \quad \log N = (2{\cdot}36 \pm 0{\cdot}02) - (0{\cdot}34 \pm 0{\cdot}01) \log t$$

$$\text{II} \quad \log N = (2{\cdot}98 \pm 0{\cdot}07) - (0{\cdot}73 \pm 0{\cdot}03) \log t$$

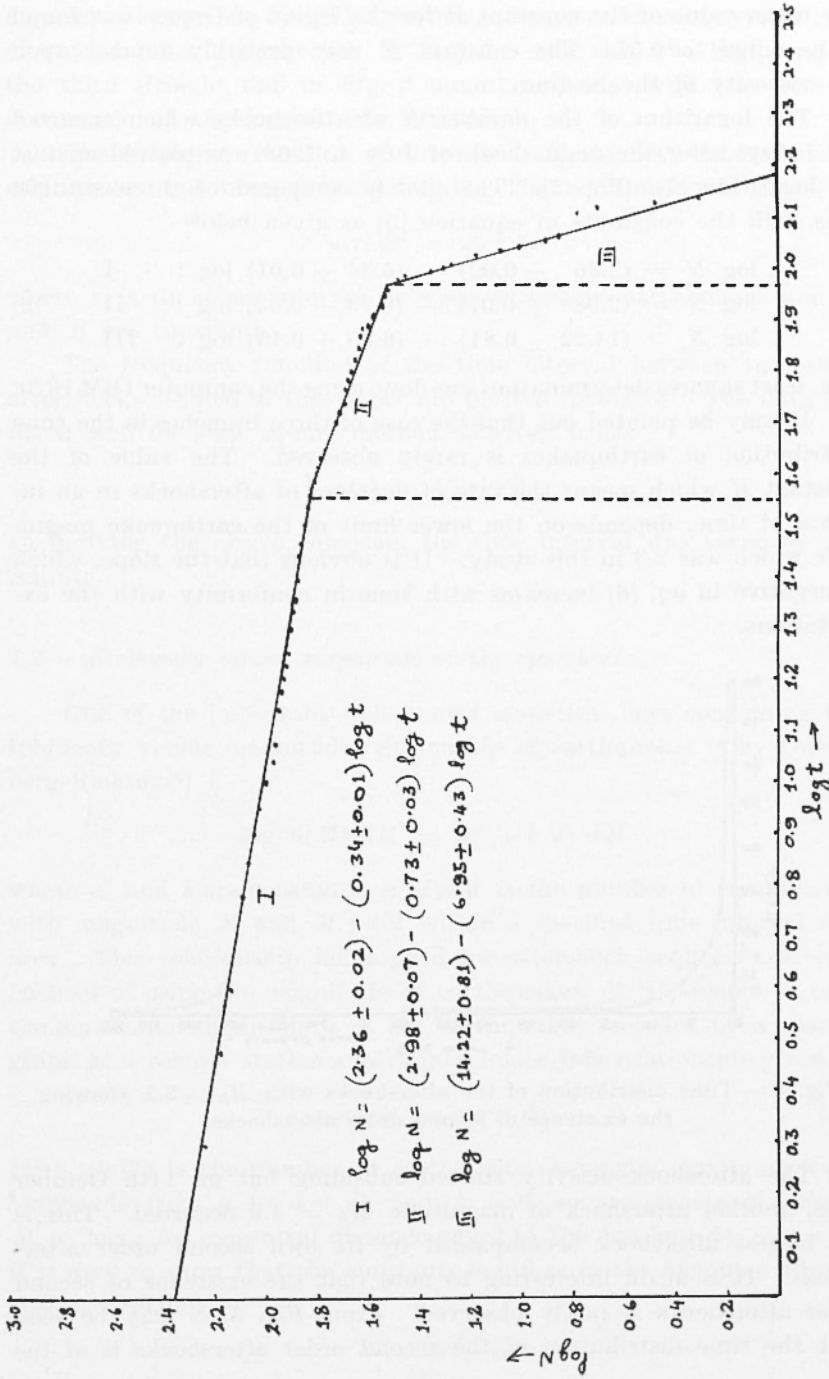$$\text{III} \quad \log N = (14{\cdot}22 \pm 0{\cdot}81) - (6{\cdot}95 \pm 0{\cdot}43) \log t$$

Fig. 2 – Time distribution of the aftershocks with magnitude $M_L \geq 2.3$.

The mean value of the constant H for the region of Greece was found to be equal to 0.57. The constant H may probably depend upon the viscosity of the medium.

The logarithm of the number N of aftershocks which occurred $t - 1$ days after the main shock of July 4, 1968 was plotted against the logarithm of t (Fig. 2). This plot is composed of three straight lines with the constants in equation [5] as given below

$$\log N = (2.36 \pm 0.02) - (0.34 \pm 0.01) \log t \qquad \text{I}$$
$$\log N = (2.98 \pm 0.07) - (0.73 \pm 0.03) \log t \qquad \text{II} \qquad [6]$$
$$\log N = (14.22 \pm 0.81) - (6.95 \pm 0.43) \log t \qquad \text{III}$$

The least squares determination was done using the computer IBM 1620.

It may be pointed out that the case of three branches in the time distribution of earthquakes is rarely observed. The value of the constant H which means the rate of decrease of aftershocks in an interval of time, depends on the lower limit of the earthquake magnitude which was 2.3 in this study. It is obvious that the slope, which is negative in eq. [6] increases with time in conformity with the expectations.
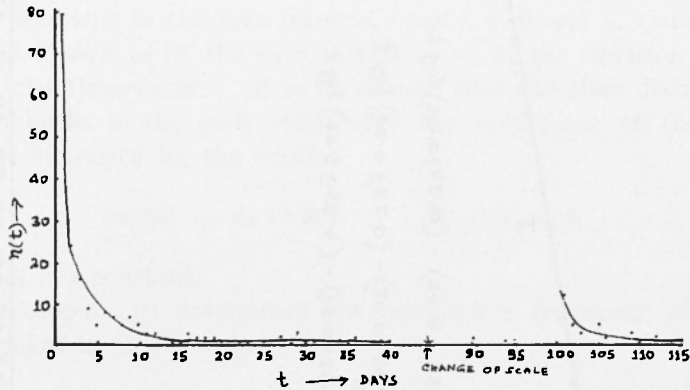

Fig. 3 – Time distribution of the aftershocks with $M_L \geqslant 2.3$, showing the existence of second order aftershocks.

The aftershock activity started subsiding but on 14th October 1968, another aftershock of magnitude $M_L = 4.0$ occurred. This is the largest aftershock accompanied by its own second order aftershocks. It is again interesting to note that the existence of second order aftershocks is rarely observed. From Fig. 3, it may be seen that the time distribution of the second order aftershocks is of the

exponential type [eq. 2]. This confirms the occurrence of typical case of second order aftershocks. It may be seen that the beginning of the third straight line in Fig. 2 almost coincides with the time of occurrence of the largest late aftershock.

The frequency function of the time interval between successive earthquakes has been investigated [3]. The relationship is given by

$$n(\tau) \, d\tau \, = \, A e^{-B} \, d\tau \qquad [7]$$

where τ is the time interval between successive earthquakes and A and B are constants.

The frequency function of the time interval between successive aftershocks studied in this paper are plotted in Fig. 4. The data are fitted well by least square method as given below

$$n(\tau) \, = \, 17 \, \tau^{-0.75} \qquad [8]$$

In deriving the above equation, the time interval was taken as one minute.

4.2 – Frequency versus magnitude of the aftershocks.

One of the important well known statistical laws concerning the frequency versus magnitude relationship of earthquakes is by Gutenberg-Richter [6]

$$\log n(M) \, dM \, = \, (a' - bM) \, dM \qquad [9]$$

where a' and b are constants, $n(M)dM$ is the number of earthquakes with magnitude M and $M + dM$ within a specified time interval and area. This relationship holds good for aftershock sequences as well. Instead of using the magnitude of earthquakes, it is possible to take the maximum amplitude a of the earthquakes recorded by a seismograph at a certain station applying Ishimoto-Iida relationship given by

$$n(a) \, da \, = \, k \, a^{-m} \, da \, . \qquad [10]$$

Here $n(a)da$ is the number of earthquakes having a maximum trace amplitude from a to $a + da$ and k and m are constants. Since $M = \log a$ for epicentral distance equal to 100 km and $da = a \, dM$, it is easy to show that the constants b and m in the formulae [9] and [10] are related by

$$b \, = \, m - 1 \, . \qquad [11]$$
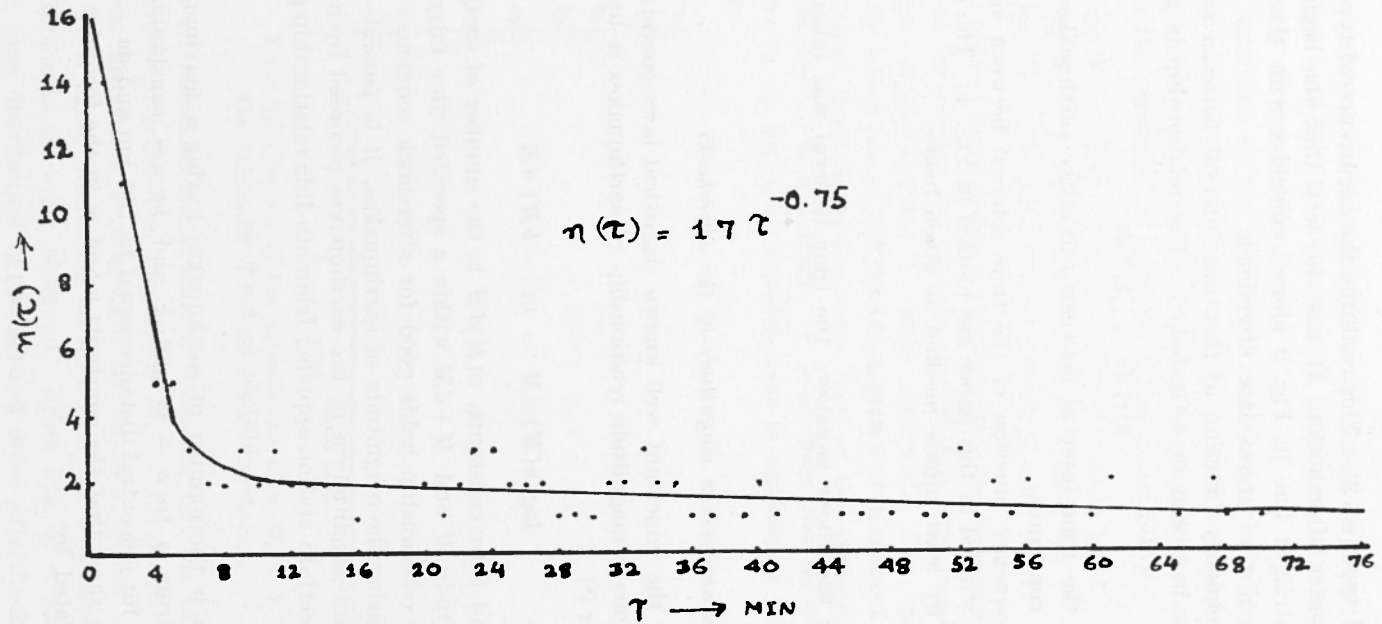
$$\eta(\tau) = 17\,\tau^{-0.75}$$

Fig. 4 – Frequency function of the time interval between successive aftershocks.

Instead of using equation [8], many investigators use the cumulative frequency function expressed by

$$\log N = a - bM .\qquad [12]$$

The constant b of this equation is related to the tectonic structure of the seismic region. Mogi [7] showed experimentally, that this constant depends on the homogeneity of the material in the seismic region and on the distribution of the applied stress. The value of b increases as the degree of heterogeneity increases and as the degree of symmetry of the applied stress decreases. Mogi has also found that the slope b for microfracturing in rock samples is similar to that obtained in the seismicity of the Earth. A decrease of b with focal depth has been observed by several seismologists [8, 9, 10]. Based on many aftershock sequences, Drakopoulos [5] found the value of b between 0.4 and 1.7 and inferred that its variation is more marked in the vertical as compared to that in the plane parallel to the surface of the Earth. Many seismologists [11] have found that the value of b is larger for aftershocks as compared to that for foreshocks. Mogi [12] showed experimentally that when foreshocks and aftershocks occur in the same region, the value of b is smaller for foreshocks than for aftershocks, because the main shock causes new cracks and thus the number of irregular points increases. Drakopoulos [5] found that the constants b_f and b_a of the foreshock and the aftershock sequences of the same main shock are connected by the relation

$$b_f = (0.11 \pm 0.13) + (0.65 \pm 0.11)b_a .\qquad [13]$$

This author has also found that the value of b for foreshock and aftershock sequences has a tendency to decrease with the magnitude of the main shock.

The logarithm of the cumulative frequency function $N(M)$ versus the magnitude M of the aftershocks of the Epidavros earthquake is plotted in the Fig. 5. The following relation was obtained by the least squares method,

$$\log N = (5.44 \pm 0.07) - (1.25 \pm 0.02) M .\qquad [14]$$

The same value of b was obtained using the relationship by Utsu [13]

$$b = 0.4343/(M' - M_{mtn})$$

where M' is the average magnitude for the series and M_{min} is the minimum magnitude.

The value of b for this sequence is rather large and is attributed to the small focal depth of the aftershocks.
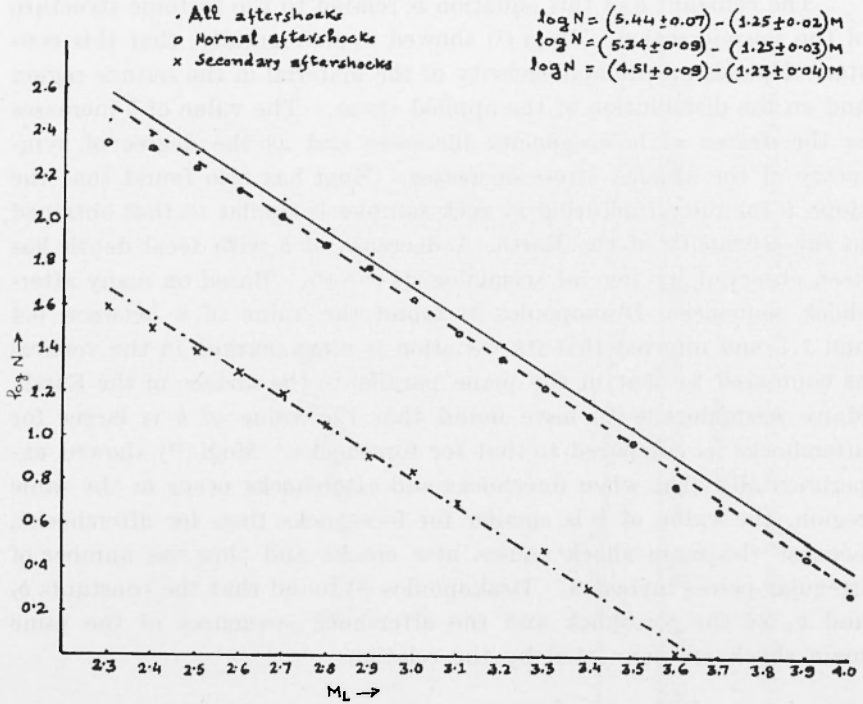

Fig. 5 – Cumulative frequency function of the magnitude of aftershocks·

The magnitude distribution of the second order aftershocks which occurred after 14th October was examined separately. The relationship between $\log N$ versus M is given by

$$\log N = (4.51 \pm 0.09) - (1.23 \pm 0.04) M .\qquad [15]$$

The magnitude distribution of the aftershocks excluding the second order aftershocks is expressed by

$$\log N = (5.34 \pm 0.09) - (1.25 \pm 0.03) M .\qquad [16]$$

It may be noted thus that the value of b remains more or less the same as found previously i.e. $b = 1.25$. This is quite reasonable

because the value of b is related to the tectonic structure of the region. It may also be inferred that there was no migration of seismic activity in the vertical direction otherwise the value of b being dependent upon the focal depth would have been changed. All the relations discussed above for this sequence of the aftershocks hold good for $M_L \geqslant 2.3$.
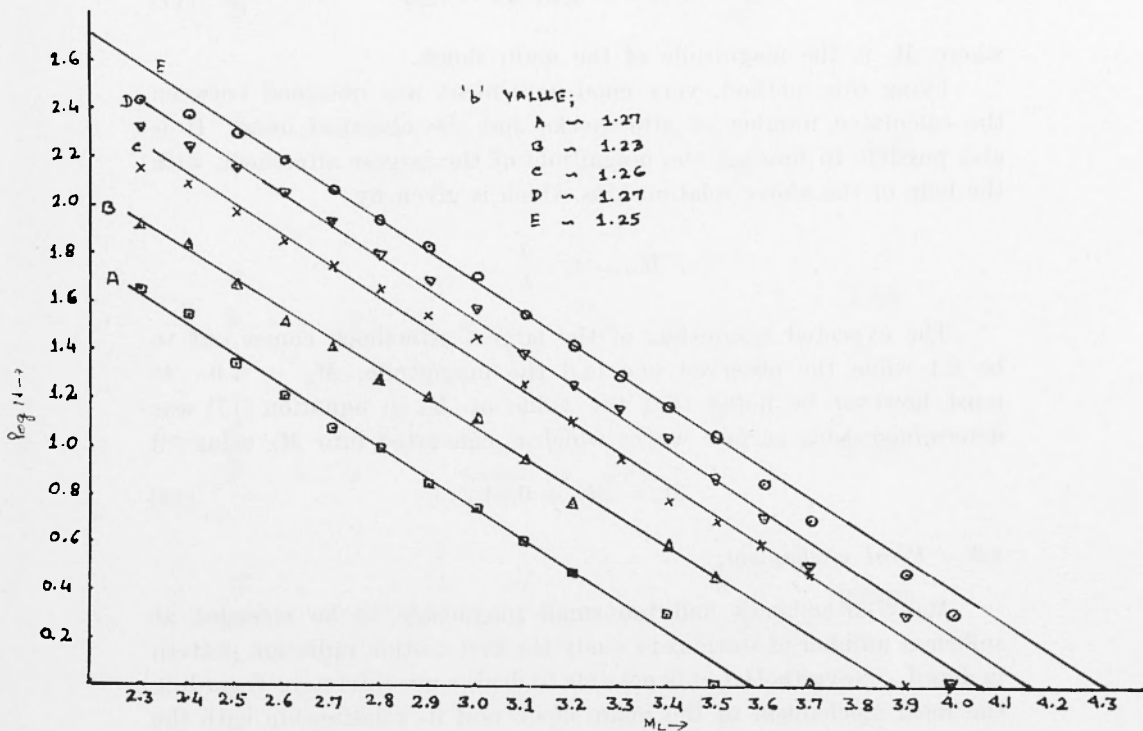

Fig. 6 – Cumulative frequency distribution of magnitude for some different time intervals after the occurrence of the main shock.

The magnitude frequency relationship for the aftershocks for various periods of time is shown in Fig. 6. Here $N(M)$ is the cumulative frequency i.e. the number of shocks with magnitude $\geqslant M_L$. The plots marked with the letters A, B, C, D and E indicate the various periods of time. It may be seen that these lines are more or less parallel, signifying that the value of b remains constant with time. It appears thus possible to estimate the values of b only a few minutes or hours after the occurrence of the main shock without waiting till the end of the sequence. Knowing b it is relatively easy to antici-

pate the number of aftershocks which may be expected in the order
of magnitudes, using the relationship

$$\log N = a - b M$$

since the constant a may be calculated from the equation ([5])

$$a = 3.64 \, b + 0.48 \, M_o - 1.49 \qquad [17]$$

where M_o is the magnitude of the main shock.

Using this method, very good agreement was obtained between
the calculated number of aftershocks and the observed ones. It is
also possible to forecast the magnitude of the largest aftershock with
the help of the above relationships which is given by

$$M_{max} = -\frac{a}{b} .$$

The expected magnitude of the largest aftershock comes out to
be 4.1 while the observed one had the magnitude, $M_L = 4.0$. It
must however be noted that the value of M_o in equation [17] was
determined using surface waves which is converted into M_L using ([14])

$$M_s = M_L + 0.44 . \qquad [18]$$

4.3 – *Focal mechanism.*

Many aftershocks had too small magnitude to be recorded at
sufficient number of stations to study the first motion radiation pattern
in detail. Nevertheless, it is possible to draw some inferences regarding
the focal mechanism of the main shock and its relationship with the
first and the second order aftershocks. The relative changes in the
focal mechanism may be observed simply by noting the sense of
first motion at a given number of stations throughout the aftershock
sequence. Fig. 7 shows the sense of first motion (where measurable)
at eight stations of Greece during the aftershock period. It may be
noted that the sense of first motion remains rather unchanged through-
out the sequence except after 98 days (indicated by arrows). This
suggests that the focal mechanism of shocks in this sequence is related
to that of the main shock. This is confirmed by the results of Udias ([15]),
Mc Evilly ([16]) and Pshennikov ([17]). However, the second order after-
shocks have a focal mechanism which is different from that of the
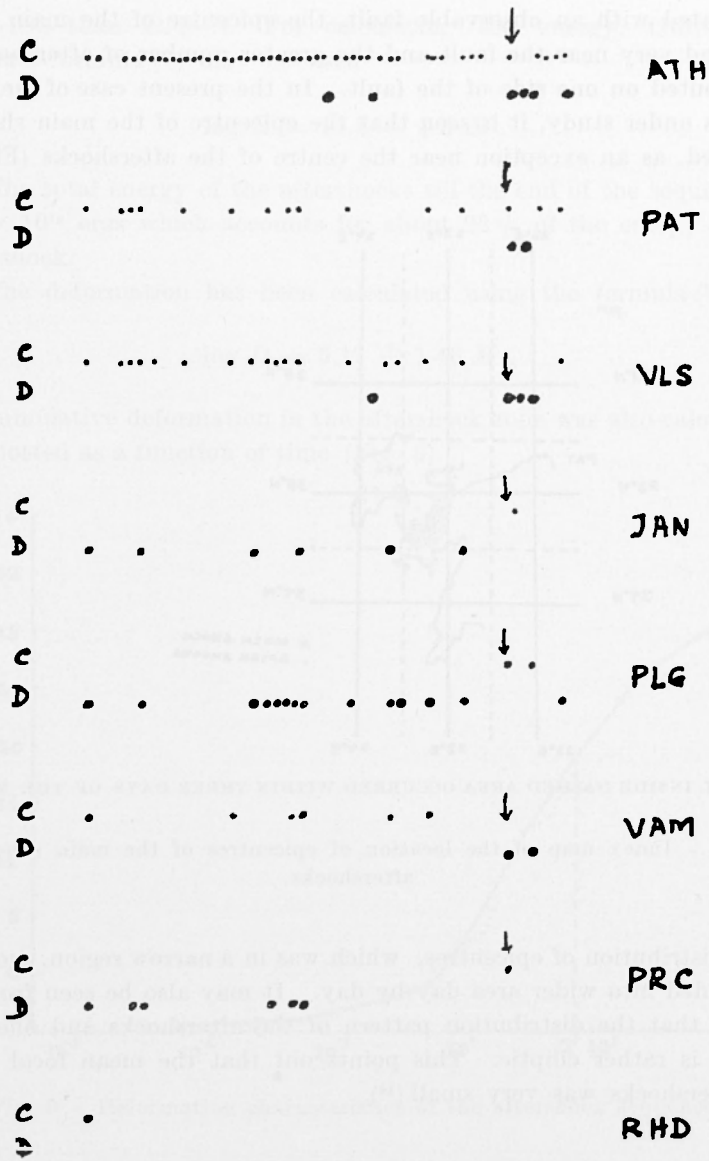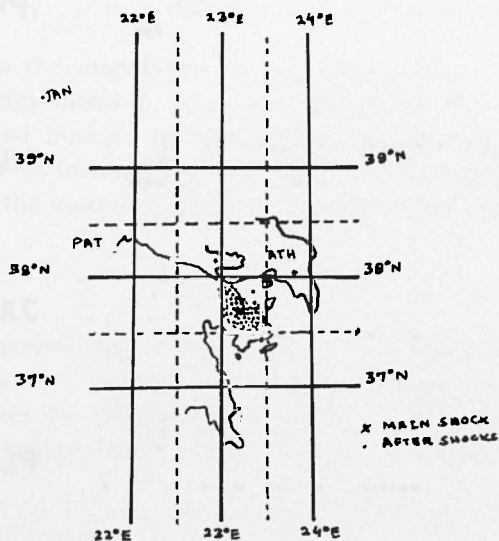main shock.

Fig. 7 – First motion sense of the aftershocks at the Greek Seismological Network.

4.4 – *Areal distribution of aftershocks.*

Matuzawa [18] pointed out that the epicentre of the main shock is often near the edge of the aftershocks area.   In the case of earthquakes

associated with an observable fault, the epicentre of the main shock
is found very near the fault and the greater number of aftershocks is
distributed on one side of the fault. In the present case of the after-
shocks under study, it is seen that the epicentre of the main shock is
situated, as an exception near the centre of the aftershocks (Fig. 8).

EPICENTRAL INSIDE DASHED AREA OCCURRED WITHIN THREE DAYS OF THE MAIN SHOCK

Fig. 8 – Index map of the location of epicentres of the main shock and
aftershocks.

The distribution of epicentres, which was in a narrow region, suddenly
expanded into wider area day by day. It may also be seen from the
figure that the distribution pattern of the aftershocks and one fore-
shock is rather elliptic. This points out that the mean focal depth
of aftershocks was very small ([19]).

4.5 – *Aftershock activity and deformation characteristics.*

The aftershock activity of an earthquake is indicated by the
ratio of the total energy of aftershocks E_a to the energy of the main
shock E_o. Instead, $M_o - M_1$ may be used as a rough measure of
the aftershock activity. For some cases, E_a exceeds E_o while usually

E_a is less than E_o [5,13]. For calculating the energy, Gutenberg-Richter's formula [20] may be used

$$\log E = 11.8 + 1.5 \, M \, . \qquad [17]$$

The total energy of the aftershocks till the end of the sequence is 17.6×10^{18} ergs which accounts for about 22% of the energy of the main shock.

The deformation has been calculated using the formula [21]

$$\log D = 5.17 + 1.46 \, M \, . \qquad [18]$$

The cumulative deformation in the aftershock zone was also calculated and plotted as a function of time (Fig. 9).
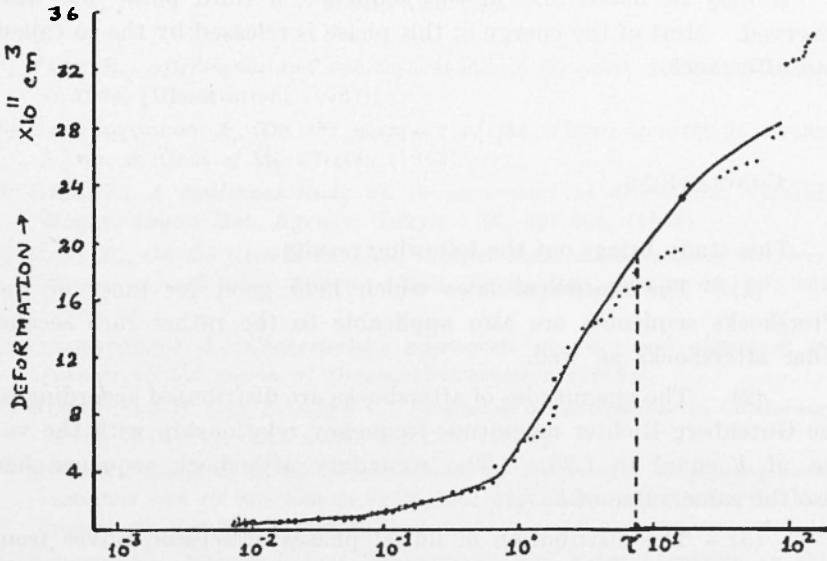
Fig. 9 – Deformation characteristics of the aftershock sequence.

The release of strain as noticed by Båth and Duda [21] occurs in two phases, the compressional and the shear. The energy in the compressional phase is released by small aftershocks. This phase commences immediately after the main shock. The shear phase starts a few hours after the main shock. Most of the energy in this phase is released by rather large aftershocks. The relaxation-time of the

second phase is 8.0 days. Assuming that the relaxation-time τ is related with the coefficient of viscosity η and the coefficient of rigidity μ

$$\tau = \frac{\eta}{\mu} \qquad\qquad [19]$$

we may estimate the value of η using the above equation. The probable focal depth of these aftershocks is about 25 km and the velocity of the shear waves at this depth is approximately equal to S_η velocity ($S_\eta \approx 4.55$ km/sec in this region ([22]). Taking the density as 3.2 gm/cm³, the value of rigidity comes out to be 0.66×10^{12} dynes/cm². Thus the value of the coefficient of viscosity or better the mobility of the medium at this focal depth is of the order of 4.55×10^{17} gm cm⁻¹sec⁻¹ which agrees with that reported by Pshennikov ([17]).

It may be noted that in this sequence, a third phase was also observed. Most of the energy in this phase is released by the so called late aftershocks.

5. – CONCLUSIONS.

This study brings out the following results:

(1) – The statistical laws which hold good for most of the aftershocks sequences are also applicable to the rather rare second order aftershocks as well.

(2) – The magnitudes of aftershocks are distributed according to the Gutenberg-Richter magnitude-frequency relationship with the value of b equal to 1.25. The secondary aftershock sequence has also the same value of b.

(3) – The distribution of initial phases of seismic waves from the aftershock and the main shock shows marked similarity. However, the focal mechanism of the second order aftershock was found to be different from the main shock.

(4) – In addition to the compressional and shear phases as are generally observed, a third phase was also noticed. Most of the energy in the third phase was released by the major late aftershock.

(5) – The relaxation-time for the shear phase was found to be 8.0 days. The coefficient of viscosity in the region was estimated to be of the order of 4.55×10^{17} gm sec⁻¹cm⁻¹.

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