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A STATISTICAL STUDY OF THE MARCH 25, 1986, SEISMIC SEQUENCE IN THE CENTRAL AEGEAN SEA

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ΣΤΑΤΙΣΤΙΚΗ ΜΕΛΕΤΗ ΤΗΣ ΣΕΙΣΜΙΚΗΣ ΑΚΟΛΟΥΘΙΑΣ ΤΗΣ 25ης ΜΑΡΤΙΟΥ 1986 ΣΤΟ ΚΕΝΤΡΙΚΟ ΑΙΓΑΙΟ

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A STATISTICAL STUDY OF THE MARCH 25, 1986, SEISMIC SEQUENCE IN THE CENTRAL AEGEAN SEA*

by
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1. INTRODUCTION

A comprehensive study of aftershock sequences must include space, time and magnitude distributions. Earthquake sequences which occurred in many parts of the world have been investigated by many authors (UTSU 1961, PAPAZACHOS et al 1967, DRAKOPOULOS 1968, RANNALLI 1969, KARAKAISIS 1984). The interest of the seismolgists in such a kind of research is due to the fact that statistical and other properties of the seismic sequences are related to several important seismological problems, such as short term earthquake prediction, identification of artificial events and determination of stress and mechanical conditions of the material in the focal regions. The statistical properties of the seismic sequences could be summarised as follows:

a) The number of the aftershocks depends on the magnitude of the main shock, its focal depth and the region. It increases with the magnitude of the main shock and decreases with the increasing of the focal depth.

b) The frequency of aftershocks (number per time unit) decreases with the increasing of time according to Omori's law (1894), which is expressed by the relation:

$$n(t) = \frac{k}{t+c}, \qquad \text{(k,c are constants)}$$

c) The magnitude – frequency distribution follows the Gutenberg – Richter's law (1944), which is expressed by the relation:

$$\log(M)\,dM = (a - bM)dM, \qquad \text{(a,b are constants)}$$

d) The epicenters of the main shock and aftershocks are usually distributed in an elliptical area, the major axis of which is parallel to the active fault segment. The size of the aftershock area is directly proportional to the magnitude of the main shock and depencds on the region.

e) The energy of the main shock is greater than the total energy of the aftershocks.

f) The duration of the seismic sequence is proportional to the magnitude of the main shock. It is also depended on the region.

g) The time interval between the main shock and the largest aftershock decreases with the increasing of the magnitude of the main shock and depends on the focal depth and the region.

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2. THE DATA

On March 25, 1986, at 01:41 an earthquake of surface wave magnitude M=5,6 occurred in Central Aegean sea. This magnitude is the mean value of the magnitudes which were given by five stations (5.7 by ATH and PRU, 5.6 by SKO and MOX, 5.4 by SRO). The epicenter is located between Euboea and Chios islands in the Aegean sea. The shock was felt in Athens (IV degrees on Mercalli–Sieberg scale).

The largest aftershock occurred on March 29, 1986, at 18:36 and it was of surface wave magnitude M=5.4, as calculated by the given magnitudes of six stations (5.8 by ATH, 5.6 by PRU, 5.4 by KRA, 5.2 by MOX and SKO, 5.0 by HFS).

The epicentral area had been in seismic quiesence since March 14, 1933, when an earthquake of surface wave magnitude M=5.5 occurred (COMNINAKIS and PAPAZACHOS 1986).

In the present case seven earthquakes of local magnitudes $M_L \geqslant 4.5$ occurred in this region in a time period of about three months. It is notable that no foreshocks occured.

The available arrival times of the longitudinal and shear waves at the stations of the Seismological Institute were used for the calculation of the origin times, the epicenters and the focal depths of the earthquakes of the seismic sequence. The records of Wood Anderson seismograph in Athens were used for the calculation of the local magnitudes. Computer program HYPO 71 (revised by Lee and Lahr 1975) was used in order to calculate the above parameters of the earthquakes. Earthquakes of local magnitude less than 2.8 were recorded. However, wishing our data to be complete, we include to our study 251 events of local magnitude $M_L \geqslant 2.8$, for the time period March 25–June 30, 1986.

Table 1 provides informations about the shocks which occured in the epicentral area between March 25 and June 30, 1986, and were of local magnitudes $M_L \geqslant 3.5$.

3. SPATIAL DISTRIBUTION

In figure 1 the epicenters of the shocks of the seismic sequence with local magnitudes $M_L \geqslant 3.5$ are shown. It is apparent that the distribution pattern of the epicenters is elliptical. The major axis of this ellipsis has a NW–SE orientation, which agrees with the orientation of the NP1 plain of the focal mecanism solution that NEIC published for the main shock. According to this solution the values are:

Principal axes:

Scale 10** 24 D–CM

T	Val= 1.60	Plg= 14	Azm= 31
N	0.80	62	273
P	–2.40	24	128

Best Double Couple: Mo = 2.0*10**24

NP1 :	Strike=168	Dip=63	Slip= –7
NP2 :	261	84	–152

4. TIME DISTRIBUTION OF AFTERSHOCKS

MOGI (1962a) showed that the frequency of aftershocks per time unit, n(t), in the

TABLE 1: The seismic parameters of the earthquakes with local magnitude $M_L \geqslant 3.5$, of the seismic sequence of March 25, 1986, in the Central Aegean sea.

DATE	ORIGIN TIME	LAT N	LON E	DEPTH	M_L
1986 MAR 25	01:41:36.8	38.38	25.13	16	5.1
1986 MAR 25	01:59:22.2	38.28	25.18	11	3.7
1986 MAR 25	03:48:48.0	38.33	25.19	14	3.6
1986 MAR 25	07:39:38.6	38.40	25.18	15	3.9
1986 MAR 25	15:12:21.8	38.36	25.20	11	3.7
1986 MAR 26	11:23:01.9	38.34	25.16	14	3.5
1986 MAR 26	16:03:17.6	38.31	25.23	5	3.5
1986 MAR 28	21:50:45.5	38.37	25.18	16	3.9
1986 MAR 28	22:32:44.2	38.38	25.17	16	3.8
1986 MAR 29	13:37:00.2	38.35	25.22	5	3.7
1986 MAR 29	18:36:39.6	38.37	25.18	16	4.9
1986 MAR 29	19:22:29.9	38.38	25.19	16	4.1
1986 MAR 29	20:56:57.2	38.31	25.17	16	3.7
1986 MAR 29	21:01:50.1	38.37	25.16	16	3.6
1986 MAR 29	23:37.30.6	38.35	25.13	13	3.6
1986 MAR 30	11:01:30.0	38.36	25.18	5	3.7
1986 MAR 30	11:40:25.7	38.36	25.14	13	3.6
1986 MAR 31	02:05:43.2	38.39	25.18	16	4.2
1986 MAR 31	05:08:54.4	38.35	25.23	18	4.0
1986 APR 3	18:52:35.3	38.37	25.10	15	3.8
1986 APR 3	20:38:08.1	38.33	25.09	14	3.7
1986 APR 3	23:32:19.8	38.36	25.14	12	4.8
1986 APR 3	23:36:30.8	38.36	25.22	5	3.8
1986 APR 3	23:38:49.8	38.18	25.23	5	3.5
1986 APR 4	00:09:41.9	38.33	25.14	17	4.2
1986 APR 4	10:09:21.4	38.34	25.20	10	3.6
1986 APR 4	14:19:22.1	38.25	25.16	41	3.6
1986 APR 4	16:36:36.4	38.30	25.12	15	3.6
1986 APR 4	19:26:33.3	38.34	25.29	5	3.7
1986 APR 7	23:24:21.2	38.37	25.15	10	3.6
1986 APR 8	20:38:28.5	38.39	25.12	12	3.7
1986 APR 9	21:03:34.3	38.41	25.09	15	3.9
1986 APR 10	14:43:05.2	38.40	25.11	17	4.3
1986 APR 14	01:12:23.2	38.35	25.21	10	3.8
1986 APR 18	13:48:27.6	38.36	25.07	13	4.2
1986 APR 18	19:30:31.5	38.40	25.10	5	3.6
1986 APR 19	05:08:57.5	38.34	25.10	10	3.6
1986 APR 21	13:37:12.4	38.36	25.16	12	4.3
1986 APR 22	00:47:24.8	38.30	25.23	9	3.6
1986 APR 23	22:56:13.6	38.42	25.11	15	4.0
1986 APR 24	12:16:22.2	38.32	25.21	5	3.7
1986 APR 25	05:00:48.4	38.39	25.17	22	4.6
1986 APR 26	19:52:16.5	38.38	25.17	16	4.1

DATE	ORIGIN TIME	LAT N	LON E	DEPTH	M_L
1986 APR 26	20:23:35.6	38.27	25.23	5	4.0
1986 APR 26	22:26:01.1	38.38	25.14	17	3.6
1986 APR 28	09:08:24.2	38.36	25.18	22	3.8
1986 APR 28	14:57:44.9	38.38	25.15	16	3.6
1986 APR 28	20:32:58.0	38.35	25.19	19	3.6
1986 APR 29	16:42:15.3	38.39	25.06	17	3.6
1986 MAY 1	12:24:18.8	38.43	25.15	15	3.7
1986 MAY 1	21:45:18.0	38.39	25.24	17	3.6
1986 MAY 4	13:41:18.4	38.42	25.14	15	4.1
1986 MAY 21	20:27:20.3	38.35	25.19	17	3.7
1986 MAY 26	19:37:55.5	38.42	25.14	8	3.6
1986 JUN 3	06:16:30.7	38.35	25.12	13	4.7
1986 JUN 3	06:47:51.1	38.40	24.98	5	3.5
1986 JUN 3	08:46:07.1	38.49	24.96	5	3.6
1986 JUN 3	10:57:45.4	38.41	25.05	5	4.2
1986 JUN 3	18:35:47.8	38.35	25.02	5	3.6
1986 JUN 4	07:48:53.3	38.33	25.05	5	3.5
1986 JUN 4	08:06:05.8	38.34	25.07	19	4.6
1986 JUN 4	08:20:40.6	38.37	25.01	5	3.9
1986 JUN 6	00:41:04.8	38.45	25.04	5	3.6
1986 JUN 11	21:05:59.3	38.32	25.10	15	4.0
1986 JUN 16	01:34:27.6	38.40	25.15	5	3.5
1986 JUN 16	02:37:55.6	38.34	25.29	5	3.5
1986 JUN 17	17:54:21.6	38.34	25.10	17	4.7
1986 JUN 17	18:12:21.8	38.54	25.24	5	3.5
1986 JUN 17	19:18:58.6	38.53	25.09	13	4.4

early stage, when the stress decreases monotonically with time, is expressed by the relation:

$$n(t) = n_1 t^{-p}$$

where t is the time measured from the origin time of the main shock, and n_1, p are parameters.

The paremeter n_1 is the frequency of aftershocks one time unit after the origin time of the main shock. The value of n_1 depends on the magnitude threshold chosen for counting the aftershocks and varies from sequence to sequence.

The parameter p measures the rate of decay of aftershock activity with time and is an important parameter characterizing an aftershock sequence. MOGI (1967) observed a consistent geographical distribution of the p values and suggested that this parameter depends on some physical conditions in the focal region. PAPAZACHOS (1974) showed that the p–value is constant for each sequence and indipendent of the lower limit of magnitude chosen for counting the aftershocks.

For the calculation of the parameters n_1 and p in the present case the data have been

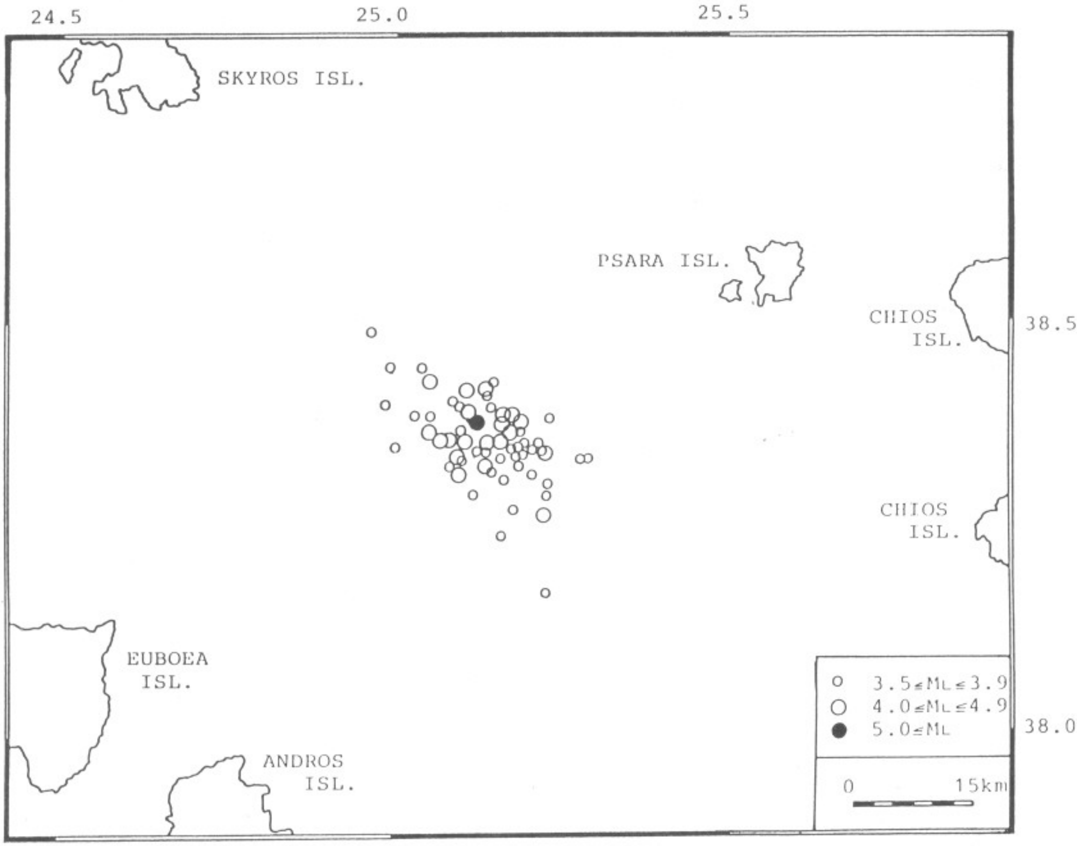

Fig. 1. The spatial distribution of the epicenters of the earthquakes with local magnitude $M_L \geqslant 3.5$ of the seismic sequence of March 25, 1986, in the Central Aegean sea, for the time period March 25 – June 30, 1986.

grouped according a procedure suggested by UTSU (1962) and RANNALLI (1969). The common logarithm of the frequency of aftershocks versus the logarithm of time in days after the origin time of the main shock is plotted in figure 2. The central line, which fits the data, has been found by the least squares method and is represented by the equation:

$$\log n(t) = (1.07 \pm 0.06) - (0.50 \pm 0.06)t$$

This equation in exponential form is:

$$n(t) = 11.75t^{-0.50}$$

The two outer lines express the 95% confidence intervals. All the points fall between these two lines except one, which expresses the number of aftershocks in the time interval round the largest aftershock. We could assume that the high number of aftershocks in this time interval is related to the aftershocks due to the largest aftershock.

The p – value which is found here is significant small compared with the p – values which had been found by other investigators for the area of Greece. So, PAPAZACHOS (1974) found p-values between 0.7 and 1.9, while KARAKAISIS (1984) found p-values between 0.70 and 1.45.

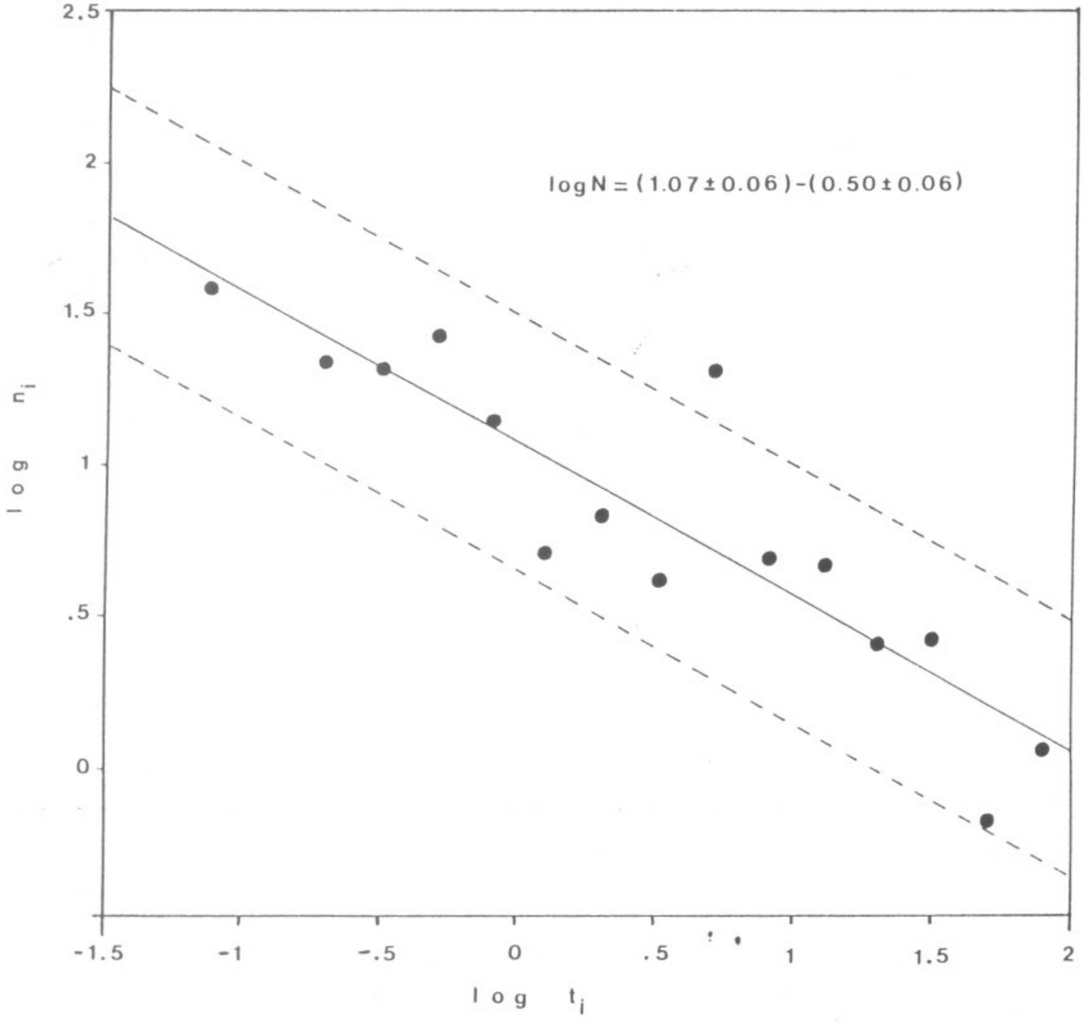

Fig. 2. The time distribution of the aftershocks of the March 25, 1986, main shock.

5. MAGNITUDE – FREQUENCY DISTRIBUTION

According to the Gutenberg – Richter's statistical law (1944), the number of earthquakes with magnitude between M and M + dM occurred in a certain region during a certain time period is expressed by the formula:

$$\log(M)dM = (a - bM)dM$$

This relation holds for ordinary earthquakes as well as for foreshocks and aftershocks sequences and for swarms. Most investigators use the cumulative frequency distribution expressed by:

$$\log N(M) = A - bM$$

where N(M) is the number of earthquakes with magnitude M and larger and A and b are parameters.

The parameter b has a clear physical meaning. MOGI (1962b) showed experimentally that b depends on the homogeneity of material in the seismic region and on the distribution of applied stresses. SCHOLZ (1968) found that the state of stress rather than the heterogeneity of the material plays the most important role in the determination of parameter b.

A decrease of b with the depth has been found for the area of Greece (PAPAZACHOS et al 1967, DRAKOPOULOS 1968).

Parameter b is one of the most important parameters in Seismology, as it is used in problems related to seismicity (KAILA and RAO 1975) and earthquake prediction (SUYEHIRO 1966, PAPAZACHOS et al 1967), DRAKOPOULOS 1968, PAPAZACHOS 1975).

It was found (PAPAZACHOS et al 1967, DRAKOPOULOS 1968, KARAKAISIS 1984) that the b value varies between 0.33 and 2.58 for the aftershock sequences in the area of Greece. HATZIDIMITRIOU et al (1985) found that the average values of b in the area of Greece are 1.03, 0.84 and 0.60 for the external, middle and innermost seismic zones respectively.

Figure 3 shows the cumulative distribution of the magnitudes of the shocks in the present sequence. The data are fitted according to the least squares method by the relation:

$$\log N = (5.45 \pm 0.10) - (1.04 \pm 0.03) M_L$$

which is represented by the central line. The two outer lines represent the 95% confidence intervals. This b value is close to the b value that HATZIDIMITRIOU et al (1985) found for the seismic zone, where the aftershock area of the present case is located.

6. DEFORMATION CHARACTERISTICS

The Bath – Duda's relation (1964) gives the deformation D as a function of magnitude M:

$$\log D = 5.17 + 1.46M$$

Figure 4 is a graph of cumulative deformation as a function of time in semilogarithmic paper. The time is measured in days after the origin time of the main shock. It is noted that the points fall on two distinct curves, which represent the compressional and the shear phases respectively, as BENIOFF (1951) first proposed for the energy release.

The first phase begins just after the main shock at t=0.01 day and continues till t=4.7 days. It represents a compressional elastic creep phase. The shear phase begins at t=4.7 days and continues till t=93 days. The energy in the compressional phase was released by small aftershocks which occurred just after the main shock, while the largest part of the energy was released during the shear phase, which began with the strongest aftershock.

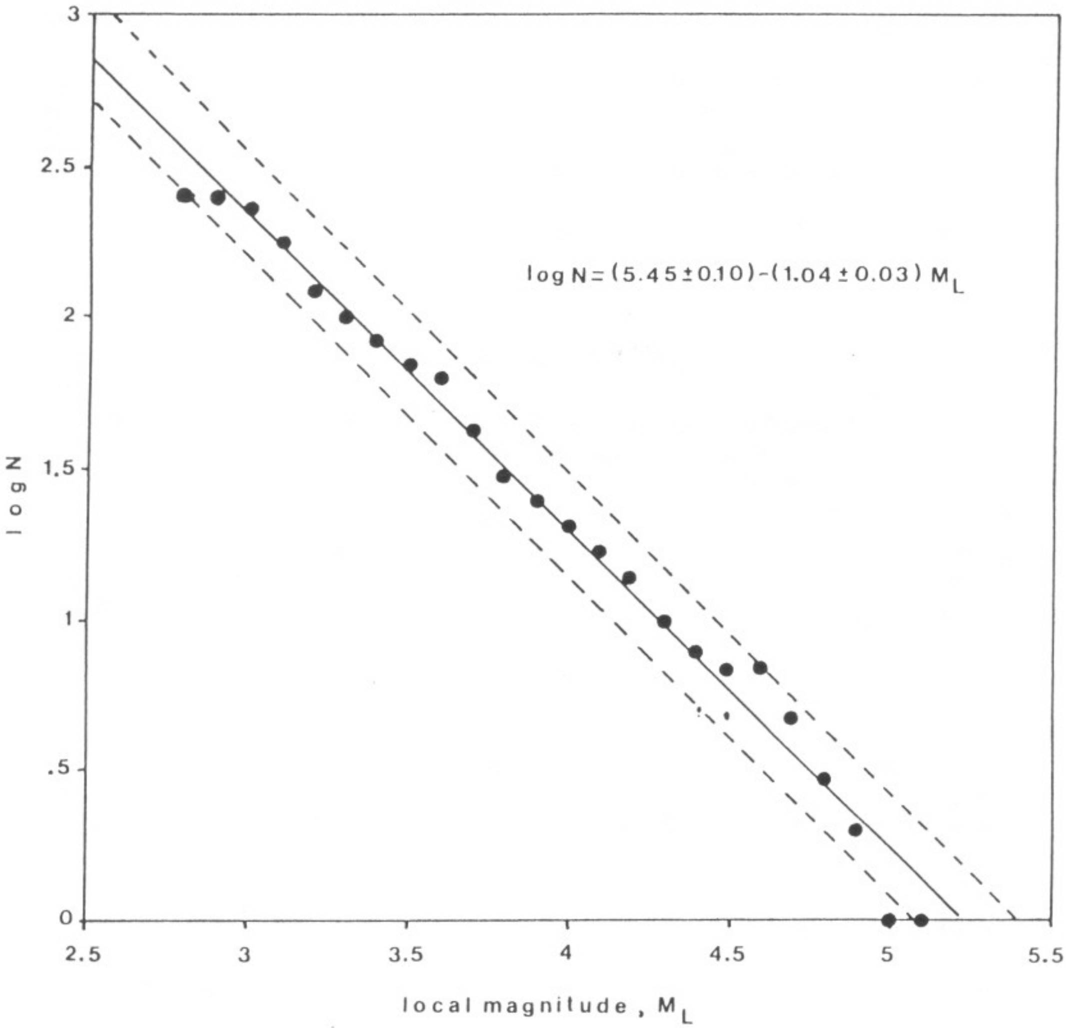

Fig. 3. The cumulative magnitude distribution of the aftershocks of the March 25, 1986, seismic sequence in the Central Aegean sea.

7. MAGNITUDE STABILITY IN TIME

According to the law of magnitude stability in aftershock sequences (LOMNITZ 1966), during an aftershock sequence the mean magnitude of the shocks remains constant in time.

The overall mean magnitude, M_L, has been calculated for the whole sequence as:

$$\overline{M}_L = \frac{1}{k} \sum_{i=1}^{k} M_L, \qquad \iota, = 1,2,3,\ldots k$$

where k is the total number of aftershocks in the sequence. Then the mean magnitude, M^*_L, for each group of 10 successive aftershocks is computed, in order to elimin-

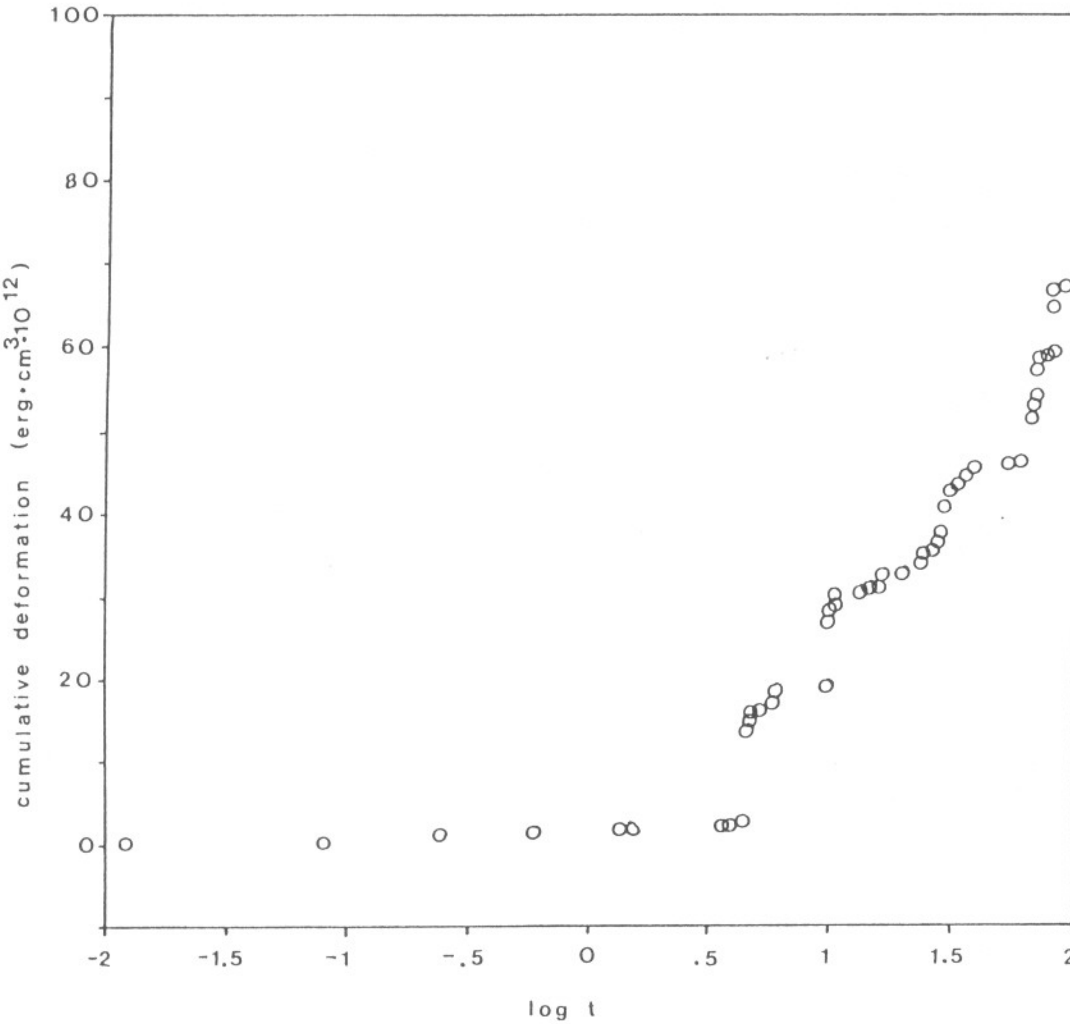

Fig. 4. The cumulative deformation of the aftershocks of the March 25, 1986, seismic sequence, plotted versus time.

ate large individual fluctuations. In the present case the value of $\overline{M}_L$ is found to be 3.3.

Figure 5 gives the magnitude stability in time for the present case. Each point represents the mean magnitude, M^*_L, of each group of 10 successive aftershocks. The full line represents the overall mean magnitude, $\overline{M}_L$, during the whole sequence, and the two dashed lines represent the $\overline{M}_L \pm 0.20$ intervals. The percentage of the points that fall within this interval is 84%, which means that the present seismic sequence holds well the magnitude stability law.

8. CONCLUSIONS

On March 25, 2986, an earthquake of surface wave magnitude M = 5.6 occured in

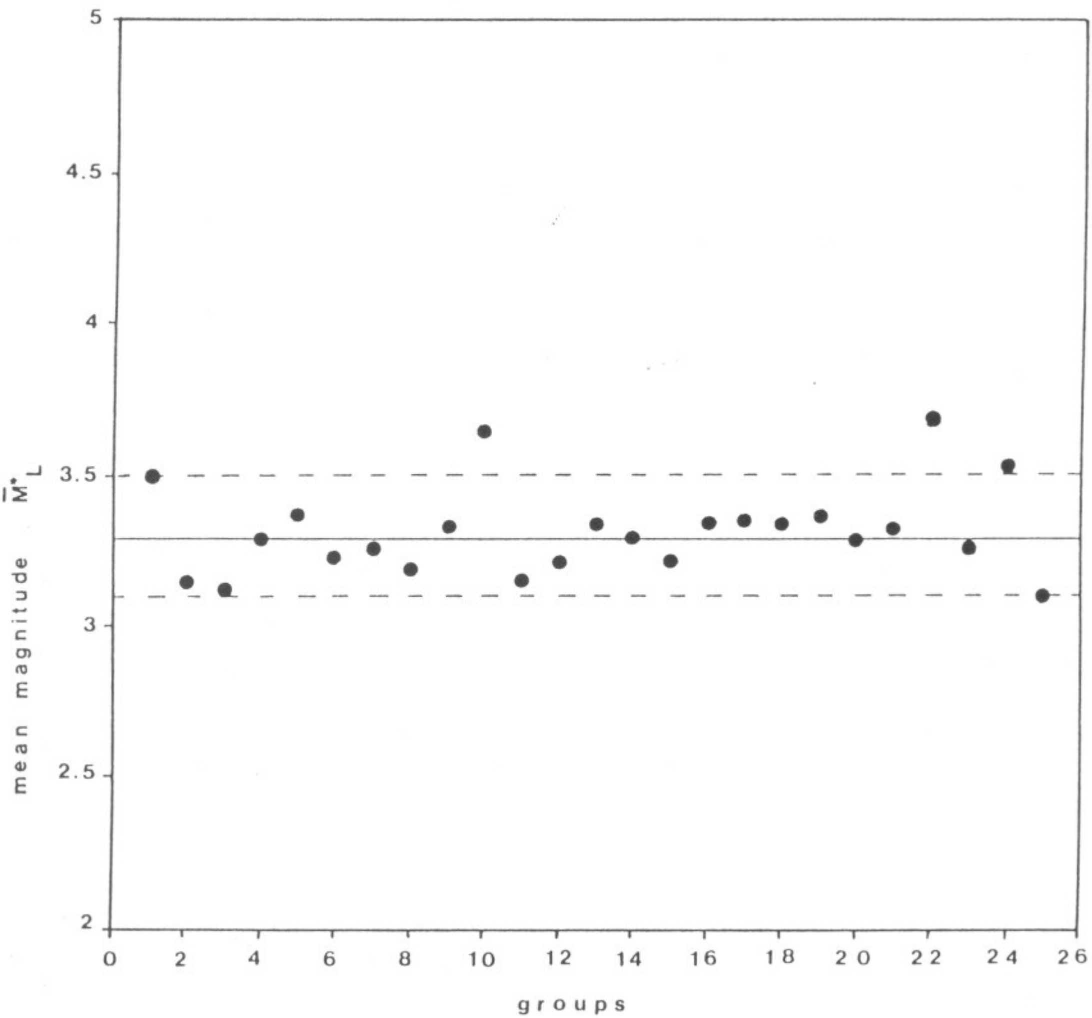

Fig. 5. The stability of mean magnitude during the March 25 – June 30, 1986, seismic sequence in the Central Aegean sea.

Central Aegean Sea. This earthquake was followed by a large number of aftershocks, the largest of which was of surface wave magnitude M=5.4. Generally, 251 events of local magnitudes $M_L \geqslant 2.8$ are investigated, seven of which were of magnitudes $M_L \geqslant 4.5$.

The spatial distribution of the aftershocks determines an elliptical area, the long axis of which has a NW – SE orientation.

The decay parameter p is found to have a low value (0.50), compared with the p – values, that other investigators have found for the area of Greece.

The known Gutenberg – Richter's law for the magnitude – frequency distribution holds well in the present case, and the b – value that has been found (1.04) is close to the b – values that other authors found.

The seismic sequence shows similar deformation – time characteristics like the most aftershock sequences, which means that the energy was released in two phases: the compressional phase between t = 0.01 days and t = 4.7 days and the shear phase between t = 4.7 days and t = 93 days. The largest part of energy was released during the shear phase.

The magnitude stability law holds well for the present seismic sequence, as 84% of the plotted points fall between the intervals $\overline{M}_L \pm 0.20$.

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ΣΥΝΟΨΗ

Στην εργασία γίνεται στατιστική ανάλυση της σεισμικής ακολουθίας του σεισμού της 25ης Μαρτίου 1986 στο Κεντρικό Αιγαίο με στοιχεία H = 01:41, φ_o = 38.38 N, λ_o = 25.13 E, h = 16 km, M_s = 5.6. Η μελέτη γίνεται με δείγμα 251 σεισμών για τη χρονική περίοδο 25 Μαρτίου – 30 Ιουνίου 1986 και περιλαμβάνει την κατανομή των επικέντρων, τη χρονική κατανομή, την κατανομή μεγέθους–συχνότητας, τα χαρακτηριστικά παραμόρφωσης και τη σταθερότητα των μεγεθών ως προς το χρόνο. Τα συμπεράσματα μπορούν να συνοψισθούν ως εξής:

Τα επίκεντρα των σεισμών της ακολουθίας ορίζουν μια ελλειπτική περιοχή, ο μεγάλος άξονας της οποίας έχει διεύθυνση ΒΔ–ΝΑ. Η διεύθυνση αυτή συμφωνεί με τη διεύθυνση του ενός επιπέδου της λύσης του μηχανισμού γένεσης του κύριου σεισμού.

Η παράμετρος p της σχέσης της χρονικής κατανομής βρέθηκε ίση προς 0.50, τιμή που είναι σχετικά μικρή συγκρινόμενη με τις αντίστοιχες τιμές, που έχουν υπολογίσει άλλοι ερευνητές για τον ελληνικό χώρο.

Η γνωστή σχέση της κατανομής μεγέθους–συχνότητας δίνει b=1.04, τιμή που συμφωνεί με τις τιμές, που αναφέρουν άλλοι ερευνητές για την αντίστοιχη μεταβολή.

Η σεισμική ενέργεια έδειξε ότι απελευθερώθηκε σε δύο φάσεις, αυτή της συμπίεσης και αυτή της διάτμησης. Το μεγαλύτερο μέρος της ενέργειας απελευθερώθηκε κατά τη διάρκεια της φάσης της διάτμησης.

Τέλος η εφαρμογή του νόμου του LOMNITZ (1966) έδειξε ότι το μέσο μέγεθος της σεισμικής ακολουθίας παρέμεινε σταθερό κατά την εξέλιξή της.

ABSTRACT

A statistical study of the seismic sequence which occurred in the Central Aegean sea on March 25, 1986, is attempted in this paper.

The data used were 251 earthquakes between March 25 and June 30, 1986, with local magnitudes $M_L \geqslant 2,8$.

In particularly the spatial distribution, the time distribution, the magnitude-frequency distribution, the deformation characteristics and the magnitude stability in time are investigated and the conclusions could be summarized as follows:

The distribution of the epicenter shows an elliptical pattern whith the long axis of the ellipse having a NW-SE orientation.

The decay parameter p is found to have a low value (0.50), compared with the p-values that other authors have found for the area of Greece.

The b-value of the known Gutenberg-Richter's law for the magnitude-frequency distribution is calculated equal to 1.04.

The seismic energy was released in two phases, compressional and shear, and the largest part of the energy was released during the shear phase.

During the aftershock sequence the mean magnitude remained constant in time.

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