Aftershock activity and aftershock risk in the area of Greece

Basil C. PAPAZACHOS (*)

Ricevuto il 6 Luglio 1971

SUMMARY. — The geographical distribution of the aftershock activity and aftershock risk in the region of and near Greece is investigated on the basis of observations on 216 aftershock sequences. The aftershock activity is a measure of the number of aftershocks and the aftershock risk is a measure of the energy of aftershocks which follow a main shock with a certain magnitude. The statistical relation $\log N = -3.70 + 0.74\ M_o$ has been found between the number N of aftershocks of $M \geqslant 4.0$ and the magnitude M_o of the main shock. The relation $M_1 = -0.59 + 0.91\ M_o$ has been found between the magnitude of the largest aftershock of a sequence and the magnitude of the main shock. On the basis of these relations and the observations, two maps, which show the geographical distribution of the aftershock activity and aftershock risk in the area of and near Greece, have been constructed. The general patterns of these maps are similar but several differences are observed. The zones of equal aftershock activity and aftershock risk follow the general tectonic pattern of the region. Such maps are very usefull, as they describe the geographical distribution of several physical properties (homogeneity of material, stress distribution etc.) and can be used to estimate the number and magnitude of the aftershocks which follow a main shock.

RIASSUNTO. — In base ad osservazioni su 216 sequenze di terremoti, è stata studiata la distribuzione geografica delle repliche e del conseguente rischio nell'interno e nelle vicinanze della Grecia. L'attività delle repliche di una scossa è rappresentata dal numero delle repliche, mentre il rischio è l'energia liberata dalle repliche che seguono la scossa principale con una certa magnitudo. Fra il numero N di repliche con magnitudo $M \geqslant 4.0$ e la magnitudo M_o della scossa principale è stata trovata la relazione statistica $\log N = -3.70 + 0.74\ M_o$, mentre la relazione trovata fra la magnitudo della replica più forte di una sequenza e la magnitudo della scossa principale è stata $M_1 = -0.59 + 0.91\ M_o$. Servendosi di queste relazioni e delle osser-

(*) National Observatory, Seismological Institute. Athens (Greece).

vazioni, sono state costruite due mappe che mostrano la distribuzione geografica dell'attività delle repliche e il rischio nell'interno e nelle vicinanze della Grecia. In generale i modelli di queste mappe sono simili, anche se esistono alcune differenze. Le zone di uguale attività e rischio di replica seguono il modello tettonico generale della regione. Tali mappe sono molto utili poiché mettono in evidenza la distribuzione geografica di diverse proprietà fisiche (omogeneità del materiale, distribuzione delle forze etc.) e possono essere usate per valutare il numero e la magnitudo delle repliche che seguono la scossa principale.

INTRODUCTION.

Many papers on aftershock sequences have been published in the last fifteen years. Most of these papers deal with the time, the space and the magnitude distribution of the aftershocks. Some authors have investigated the dependence of the magnitude (M_1) of the largest aftershock on the magnitude (M_o) of the main shock [2, 6, 9] or the regional variation of the difference between the magnitude of the largest aftershock and the magnitude of the main shock [5].

The term "aftershock activity" has been frequently used, but it is not easy to be accurately defined. Utsu [9], for example, considers the difference between the magnitude of the largest aftershock and the magnitude of the main shock as a measure of the aftershock activity. This difference in magnitude is actually a measure of the ratio of the total energy of an aftershock sequence to the energy of the main shock, because a linear relation has been found between the logarithm of the total energy of an aftershock sequence and the magnitude of the largest aftershock of the sequence [5].

However, if we wish the term "aftershock activity" not to mean the ratio of the aftershock energy to the energy of the main shock, but the total number of aftershocks which follow a main shock with a certain magnitude, then the difference $M_0 - M_1$ is not always sufficient to indicate it. This is due to the fact that the parameter b of the recurrence curves is not the same in all aftershock sequences and, in some cases, the difference in its value between two aftershock sequences is large. For example, the difference $M_0 - M_1$ for the earthquake occurred in Anatolia and listed in Table I with number 6 is 1.0, while this difference for the earthquake occurred in the Ionian Islands and listed with number 114 is 0.9. On the basis of this observation one could conclude that the two earthquakes were followed by the same number of aftershocks about with magnitude larger than a certain value. However, the Anatolian earthquake was followed by only four earthquakes with magnitude equal to or larger than 5.0, while the Ionian earthquake was followed by thirty five aftershocks with magnitude equal to or larger than 5.0.

In this paper by the term "aftershock activity" it is meant a quantity which informs us about the large or small number of aftershocks which follow an earthquake with a certain magnitude. The logarithm of the number of aftershocks (a^*) with magnitude equal to or larger than 4.0, which follow a main shock with magnitude 5.0, is used as a measure of this quantity. By the term " aftershock risk " it is meant a quantity which informs us about the amount of seismic energy released by the aftershocks which follow a main shock with a certain magnitude. The magnitude of the largest aftershock (M_1^*) of a main shock of magnitude 5.0 is used as a measure of the " aftershock risk ".

The purpose of this paper is to investigate the geographical variation of the aftershock activity and the aftershock risk in the area of and near Greece.

THE DATA.

Several papers have been previously published on the aftershock sequences in the region of Greece. Papazachos *et al.* (6) have investigated the aftershock sequences of the large earthquakes ($M \geqslant 6.0$) which occurred between 1926 and 1964. Comninakis *et al.* (1) have investigated the aftershock and foreshock sequences of the earthquake which occurred on February 5, 1966, near Cremasta and the relation of these sequences to the Cremasta artificial lake. Drakopoulos (2) has investigated the aftershock sequences of six large earthquakes which occurred between 1912 and 1922, the aftershock sequences of the large earthquakes which occurred between 1964 and 1967 and the aftershock sequences of some smaller main earthquakes. The total number of the aftershock sequences, investigated by these authors, is about 140.

The published data do not constitute representative sample for the investigation of the geographical distribution of the aftershock activity. This is due to the fact that the aftershock sequences of the large earthquakes ($M \geqslant 6$) are not enough, and the data for the smaller main shocks are not homogeneous because in this range of magnitudes only sequences which include relatively large number of aftershocks have been considered.

An attempt has been made to collect as many homogeneous data as possible with the purpose to investigate the geographical distribution of the aftershock activity and aftershock risk in the area of Greece.

From 1911 till 1957 only low magnification instruments (Mainka or Wiechert seismographs) were working in Athens. From 1958 till 1965 instruments of high magnification were working, too, in Athens. In 1965 four stations with instruments of high magnification were established in four islands in the area of Greece, and later (1968) two other similar stations were put up in northern Greece. These stages in the installation of new instruments in the area have been taken into account to choose the lower limit of the magnitudes of the main shocks.

A Table has been made which contains the magnitudes and other information on the aftershocks:

a) of all the shallow main earthquakes with $M_o > 5.5$, occurred between 1911 and 1957 in the area of and near Greece

b) of all the shallow main earthquakes with $M > 5.2$, occurred between 1958 and 1965 in the same area and

c) of all the shallow main earthquakes with $M \geqslant 5.0$, occurred between 1966 and 1969 in the above area. This area is bounded by the 34° N and 42° N parallels and by the 19° E and 29° E meridians. The Table also includes all the main earthquakes which have not recorded aftershock. In these cases, the upper limits of the magnitudes of the largest aftershocks have been calculated from the noise level and the epicentral distances. In each of these cases, the magnitude of the largest aftershock has been assumed equal to the calculated value minus 0.2. Such assumption may not be correct in all cases but the results of the present study are not affected by such discrepances. On the other hand, the knowledge of the upper limit of the magnitude of the largest aftershock is very usefull.

The aftershock sequences of 216 main earthquakes are listed in this table. For this reason it is not possible to include this table in the present paper but it will be published soon. Information on the main shocks and their aftershock sequences are listed in Table I. When the magnitude of the largest aftershock is assumed, this magnitude is put in parenthesis in Table I.

Table 1. – INFORMATION ON THE MAIN SHOCKS AND THEIR AFTERSHOCK SEQUENCES.

No.	Date	φ^{o} N	λ^{o} E	h m s	M_o	M_1	M_1*	log$N$	a*
1.	1911, Feb. 18	41	$20^{3}/_{4}$	21:35:12	6.6	5.3	3.8	1.20	0.02
2.	» , Oct. 22	$39^{1}/_{2}$	23	22:31:45	6.1	5.0	4.0	0.90	0.09
3.	1912, Jan. 24	38.1	20.8	16:22:51	7.0	5.9	4.1	1.80	0.32
4.	» , Feb. 13	41	$20^{3}/_{4}$	08:03:53	6.0	5.3	4.4	1.30	0.56
5.	» , May 17	$34^{1}/_{4}$	$23^{3}/_{4}$	16:38:08	5.9	4.9	4.1	0.70	0.04
6.	» , Aug. 9	$40^{1}/_{2}$	27	01:29:00	7.6	6.6	4.2	1.60	—0.32
7.	1913, July 6	35.9	23.2	07:05:47	5.8	5.1	4.4	0.95	0.36
8.	1914, Sept. 17	$37^{3}/_{4}$	21	13:00:48	5.6	4.5	4.0	0.78	0.34
9.	» , Oct. 17	$38^{1}/_{4}$	$23^{1}/_{2}$	06:22:32	6.0	5.6	4.7	1.58	0.84
10.	» , Nov. 27	$38^{3}/_{4}$	$20^{1}/_{2}$	14:39:46	6.3	5.1	3.9	1.08	0.12
11.	1915, Jan. 27	38.5	20.6	01:09:56	6.6	5.6	4.1	1.30	0.12
12.	» , Jun. 4	39	$21^{1}/_{2}$	17:22:02	5.8	(3.7)	3.0	—0.30	—0.89
13.	» , Jun. 24	$34^{3}/_{4}$	$24^{1}/_{2}$	05:20:36	5.9	5.2	4.4	1.00	0.34
14.	» , Aug. 7	38.5	20.6	15:04:03	6.7	6.5	4.9	2.00	0.75
15.	1916, Feb. 6	39	$23^{1}/_{2}$	14:39:40	5.8	4.7	4.0	0.70	0.11
16.	» , Sept. 27	$38^{3}/_{4}$	23	15:02:13	5.9	4.5	3.7	0.30	—0.36
17.	» , Nov. 25	(38)	(19)	02:02:48	5.7	5.2	4.6	0.95	0.44
18.	1917, May 23	39.3	21.0	05:46:37	6.1	4.5	3.5	0.48	- 0.33
19.	» , Aug. 20	$39^{3}/_{4}$	26	23:02:06	5.6	(3.6)	3.1	—0.40	—0.84
20.	» , Nov. 28	37.5	19.7	10:21:10	5.8	(3.8)	3.1	—0.20	—0.79
21.	» , Dec. 24	$38^{1}/_{2}$	$21^{3}/_{4}$	09:13:55	6.0	5.2	4.3	0.95	0.21
22.	1918, Feb. 9	39	23	12:28:42	5.6	5.0	4.3	1.00	—0.56
23.	1919, Feb. 24	36.7	21.0	01:56:00	6.3	4.4	3.2	0.48	—0.48
24.	» , Aug. 22	40	20	22:35:47	5.6	4.6	4.1	0.60	0.16
25.	» , Oct. 25	36.7	25.6	17:10:00	6.1	5.6	4.6	1.32	0.51
26.	» , Nov. 18	39.6	27.7	21:54:38	6.9	4.6	2.9	0.60	—0.80
27.	» , Dec. 22	40	$20^{3}/_{4}$	23:41:06	6.3	4.8	3.6	1.00	0.04
28.	1920, Oct. 21	$39^{1}/_{2}$	$20^{1}/_{4}$	18:57:48	5.7	5.0	4.4	0.78	0.27
29.	» , Nov. 26	$40^{1}/_{1}$	20	08:51:00	6.3	5.7	4.5	1.60	0.64
30.	1921, Mar. 30	41.8	20.4	15:06:20	5.8	5.0	4.3	0.70	0.11
31.	» , June 26	39.3	21.0	03:40:38	5.7	(3.8)	3.2	—0.22	—0.74
32.	» , Sept. 13	$38^{3}/_{4}$	$21^{3}/_{4}$	08:59:53	6.0	5.4	4.5	0.20	—0.54
33.	1922, Apr. 11	40.5	19.2	04:35:10	5.6	(3.9)	3.4	—0.10	—0.54
34.	» , June 5	35.0	22.5	04:31:05	5.9	5.5	4.7	0.70	0.04
35.	» , Aug. 8	$37^{1}/_{2}$	$23^{1}/_{4}$	03:49:06	5.6	5.1	4.6	0.85	0.41
36.	» , » 13	36.0	28.0	00:09:50	6.8	5.9	4.3	0.50	—0.83
37.	» , Nov. 4	37.0	20.5	04:20:12	5.9	(3.6)	2.9	—0.30	—0.96
38.	» , Dec. 7	$41^{3}/_{4}$	20.6	16:22:10	6.1	5.3	4.3	1.00	0.19
39.	1923, Jan. 21	37.0	20.5	04:13:30	5.6	4.4	3.9	0.30	—0.14
40.	» , Dec. 5	40	$23^{1}/_{4}$	20:56:35	6.2	4.8	3.7	0.85	—0.03
41.	1925, Feb. 7	37.0	19.0	12:14:58	5.6	4.8	4.3	0.78	0.34
42.	» , Apr. 5	35.5	29.0	03:04:25	5.9	5.6	4.8	1.48	0.82
43.	1926, Feb. 26	37.8	21.1	16:08:23	5.7	4.2	3.6	0.30	—0.21
44.	» , Mar. 18	35.5	29.0	14:06:06	6.8	5.8	4.2	1.25	—0.08
45.	» , Sept. 19	36	22	01:03:57	6.3	5.3	4.1	0.95	—0.01
46.	» , Dec. 17	41.0	19.5	11:39:55	6.1	4.8	3.7	0.90	0.09
47.	1927, Mar. 24	35.0	26.0	14:46:35	5.6	5.0	4.4	1.20	0.76
48.	» , Jun. 30	$38^{3}/_{4}$	21	22:59:36	5.6	4.5	3.9	0.48	0.04
49.	1928, Mar. 31	38	27	00:29:42	6.4	5.1	3.8	0.48	—0.55
50.	» , Apr. 18	42	$24^{3}/_{4}$	19:22:37	6.9	5.6	3.9	1.78	0.38

Table I continued

No.	Date	φ^o N	λ^o E	h m s	M_o	M_1	M_1*	log$N$	a*
51.	1928, Apr. 22	38.0	23.0	20:13:46	6.2	5.2	4.1	0.95	0.07
52.	» , July 15	38.5	27.3	09:33:24	5.6	4.5	4.0	0.78	0.34
53.	1930, Jan. 28	$40^1/_2$	$20^3/_4$	06:25:30	5.6	(3.8)	3.3	-0.20	-0.64
54.	» , Feb. 23	$39^1/_2$	23.0	18:19:12	6.0	4.6	3.7	0.70	-0.04
55.	» , Mar. 31	$39^1/_2$	23	12:33:48	6.1	4.6	3.6	0.60	-0.21
56.	» , Apr. 17	37.8	23.1	20:06:39	5.9	4.8	4.0	0.95	0.29
57.	» , Nov. 21	$40^1/_2$	$19^1/_2$	02:00:30	6.1	5.0	1.0	1.08	0.27
58.	1931, Jan. 4	38	23	00:00:35	5.6	4.9	4.4	0.48	0.04
59.	» , » 28	40.6	20.8	05:55:15	6.0	5.0	4.1	0.80	0.06
60.	» , Mar. 8	41.0	22.5	01:50:24	6.6	5.1	3.6	1.00	-0.18
61.	1932, June 29	35.5	27.6	02:30:06	5.6	5.4	4.9	1.20	0.76
62.	» , Sept. 26	40.4	23.8	19:20:42	6.9	6.2	4.5	1.65	0.25
63.	» , » 30	36.0	22.7	06:12:16	5.6	(3.5)	3.0	-0.52	-0.96
64.	» , Oct. 23	35.5	27.6	13:36:43	5.6	4.7	4.1	0.48	0.04
65.	1933, Apr. 23	$36^3/_4$	$27^1/_2$	05:57:38	6.6	4.7	3.2	0.70	-0.48
66.	» , May 11	40.4	23.8	19:09:50	6.3	5.1	3.9	0.90	-0.06
67.	1934, Feb. 4	41.4	19.3	09:35:30	5.7	4.4	3.6	0.48	-0.11
68.	» , » 21	$34^1/_2$	$22^1/_2$	11:37:20	5.6	4.3	3.7	0.30	-0.14
69.	1935, Jan. 4	$40^1/_4$	$27^1/_2$	14:41:29	6.4	6.1	4.8	1.00	-0.03
70.	» , Mar. 31	41.1	20.4	03:21:31	5.7	4.9	4.3	0.84	0.33
71.	1938, Feb. 10	34.8	26.2	20:37:53	5.6	(3.8)	3.3	-0.22	-0.66
72.	» , Mar. 13	38.8	20.6	17:45:32	5.8	(3.8)	3.1	-0.22	-0.86
73.	» , July 20	38.3	23.8	00:23:35	6.0	5.0	4.1	0.60	-0.14
74.	1939, Sept. 22	39.0	26.9	00:36:32	6.4	4.8	3.5	0.70	-0.33
75.	1940, Jan. 6	35.7	25.9	19:04:33	5.7	4.3	3.6	0.30	-0.29
76.	» , Feb. 29	$35^1/_2$	$25^1/_2$	16:07:44	6.0	(3.7)	2.8	-0.30	-0.04
77.	1941, Mar. 1	39.6	22.5	03:52:47	6.3	5.6	4.4	1.11	0.15
78.	» , May 23	$37^1/_4$	28	19:51:52	6.0	5.4	4.5	1.00	0.26
79.	» , July 13	38	$26^1/_4$	15:39:28	5.8	4.7	4.0	0.30	-0.29
80.	» , Dec. 13	37.2	28.3	06:15:59	5.9	5.4	4.5	1.08	0.34
81.	1942, June 1	39.3	22.4	09:17:40	5.6	5.0	4.5	0.85	0.41
82.	» , » 16	33.8	26.5	04:47:30	5.8	(3.9)	3.2	-0.10	-0.69
83.	» , » 16	40.4	28.0	05:42:27	5.8	(3.9)	3.2	-0.10	-0.69
84.	» , Aug. 27	41.6	20.5	06:14:11	5.8	(4.0)	3.3	0.00	-0.59
85.	» , Oct. 28	39.0	27.5	02:22:46	6.0	5.5	4.6	0.48	-0.26
86.	1943, Feb. 14	38.0	20.0	07:28:14	5.8	5.0	4.3	0.60	0.01
87.	» , July 22	38.8	20.6	07:09:28	5.6	5.0	4.4	0.48	0.04
88.	» , Nov. 20	36.9	28.8	10:01:52	5.8	(3.8)	3.1	-0.22	-0.81
89.	1944, May 27	36	$27^1/_2$	23:52:25	6.2	4.8	3.7	0.90	0.02
90.	» , July 20	35.5	26.5	10:37:20	5.6	5.1	4.6	1.00	0.56
91.	» , » 30	36.7	22.5	04:00:35	5.8	4.6	3.9	0.66	0.01
92.	» , Oct. 6	39.4	26.7	02:34:41	6.8	5.4	3.8	1.00	-0.33
93.	1946, July 16	33.8	25.3	05:26:26	5.9	(3.7)	2.9	-0.30	-0.96
94.	1947, Apr. 12	$39^3/_4$	$25^1/_4$	14:05:09	5.8	5.0	4.3	0.70	0.11
95.	» , » 19	39.2	23.6	20:29:35	5.6	4.6	4.0	0.48	0.04
96.	» , June 1	36.6	21.5	11:18:35	5.7	4.2	3.6	0.48	-0.03
97.	» , Aug. 30	35.1	23.4	22:21:31	6.3	5.0	3.8	0.84	-0.12
98.	» , Sept. 13	37.4	20.0	15:11:17	5.6	4.9	4.4	0.48	0.04
99.	» , Oct. 6	36.9	22.0	19:55:34	7.0	5.0	3.2	0.60	-0.88
100.	1948, Feb. 9	35.5	27.2	12:58:13	7.1	5.6	3.7	1.70	0.15
101.	» , Mar. 29	35.1	23.4	10:22:40	5.8	4.5	3.8	0.48	-0.11

Table I continued

No.	Date	φ° N	λ° E	h m s	M_o	M_1	M_1^*	$\log N$	a^*
102.	1948, Apr. 22	$38^1/_2$	$20^1/_4$	10:42:45	6.5	6.3	4.9	0.95	—0.16
103.	» , Aug. 27	41.7	19.5	10:44:06	5.6	5.0	4.5	0.48	0.04
104.	» , Oct. 10	35.1	23.4	17:43:01	5.8	4.8	4.1	0.95	0.36
105.	1949, July 23	38.6	26.3	15:03:30	6.6	5.9	4.4	1.04	—0.14
106.	1951, Aug. 31	35.5	22.8	12:29:37	5.7	5.2	4.6	0.70	0.19
107.	1952, Mar. 19	39.8	28.7	01:27:23	5.7	(3.9)	3.3	—0.10	—0.61
108.	» , Oct. 5	37.5	20.8	10:54:56	5.8	5.3	4.6	0.90	0.31
109.	» , Dec. 17	34.4	24.5	23:03:57	6.8	5.7	4.1	1.14	—0.19
110.	1953, Jan. 7	41.5	20.0	01:18:57	5.7	(3.9)	3.3	—0.10	—0.61
111.	» , Mar. 18	40.0	27.3	19:06:13	7.2	5.7	3.7	1.49	—0.13
112.	» , May 2	$38^3/_4$	$26^1/_2$	18:37:38	5.6	5.0	4.4	0.84	0.40
113.	» , June 3	40.1	28.8	16:05:24	5.7	5.0	4.4	0.48	—0.03
114.	» , Aug. 12	38.3	20.8	09:23:52	7.2	6.3	4.3	2.35	0.73
115.	» , Sept. 5	38.0	23.0	14:18:41	5.7	3.9	3.3	0.00	—0.51
116.	1954, Apr. 30	39.3	22.2	13:02:36	7.0	5.7	3.9	1.76	0.28
117.	» , Aug. 3	40.1	24.5	18:18:13	5.9	5.1	4.3	1.11	0.45
118.	» , Dec. 23	37.9	21.1	16:27:18	5.8	5.5	4.8	0.70	0.11
119.	1955, Apr. 13	37.3	22.6	20:45:46	5.8	3.7	3.0	—0.30	—0.90
120.	» , » 19	39.3	23.1	16:47:19	6.2	5.8	4.7	1.00	0.12
121.	» , July 16	37.6	27.2	07:07:10	6.8	5.1	3.5	1.40	0.07
122.	1956, July 9	36.7	25.8	03:11:40	7.5	6.8	4.5	1.93	0.08
123.	» , » 30	35.9	26.0	09:14:57	6.0	5.6	4.7	1.18	0.44
124.	1957, Feb. 19	36.2	21.6	07:43:59	5.9	4.5	3.7	0.84	0.18
125.	» , Mar. 8	39.3	22.6	12:21:13	6.8	6.0	4.4	1.62	0.29
126.	» , Apr. 25	36.5	28.6	02:25:42	7.2	6.1	4.1	1.30	—0.32
127.	» , Oct. 30	35.2	27.2	01:42:59	5.6	5.4	4.9	0.95	0.51
128.	1958, Jan. 2	36.2	22.3	02:08:14	5.7	4.7	4.1	1.08	0.57
129.	» , » 16	39.5	25.5	04:18:15	5.6	4.7	4.2	1.08	0.64
130.	» , Mar. 15	40.8	21.1	06:27:07	5.4	(3.6)	3.3	—0.15	—0.44
131.	» , Apr. 3	41.1	19.9	02:23:42	5.6	5.1	4.6	1.00	0.56
132.	» , May 9	36.4	27.7	02:40:45	5.3	4.2	3.9	0.48	0.26
133.	» , July 17	40.6	23.4	05:37:06	5.6	4.4	3.8	0.78	0.34
134.	» , Aug. 27	37.4	20.7	15:16:34	6.4	5.4	4.1	1.04	0.01
135.	» , Sept. 4	36.6	26.7	00:02:56	5.4	4.9	4.5	0.48	0.19
136.	1959, Apr. 25	37.0	28.5	00:26:39	6.2	5.4	4.3	0.60	—0.28
137.	» , May 14	35.1	24.6	06:36:56	6.3	5.5	4.3	0.78	—0.18
138.	» , Sept. 1	40.9	19.8	11:37:40	6.4	5.7	4.4	1.10	0.07
139.	» , Nov. 15	37.8	20.5	17:08:43	6.8	5.7	4.1	1.11	—0.22
140.	» , » 19	38.9	26.6	14:00:28	5.3	4.1	3.7	0.00	—0.22
141.	1960, Feb. 1	35.3	23.0	11:59:39	5.3	(3.6)	3.3	—0.40	—0.62
142.	» , » 23	39.0	20.6	07:34:31	5.4	5.2	4.8	0.00	—0.29
143.	» , Mar. 12	41.8	20.9	11:54:00	5.6	4.5	3.9	0.48	0.04
144.	» , May 26	40.5	20.6	05:10:11	6.5	4.9	3.5	0.48	—0.63
145.	» , July 13	40.6	23.4	13:01:01	5.3	(3.9)	3.6	—0.10	—0.32
146.	» , Nov. 5	39.1	20.6	20:20:48	5.7	5.6	4.9	1.11	0.60
147.	1961, Feb. 23	36.7	27.1	21:46:36	5.5	5.3	4.8	0.95	0.58
148.	» , July 19	37.7	20.1	23:00:56	5.3	4.4	4.1	0.60	0.38
149.	» , Oct. 2	36.6	21.9	07:21:39	5.7	4.2	3.6	0.00	—0.51
150.	1962, Jan. 19	38.5	22.1	19:38:04	5.3	5.2	4.9	1.00	0.78
151.	» , » 26	35.1	22.8	08:17:40	6.3	(3.7)	2.5	—0.30	—1.26
152.	» , Mar. 18	40.6	19.5	15:30:33	6.0	4.7	3.8	0.90	0.16

Table I continued

No.	Date	$\varphi°$ N	$\lambda°$ E	h m s	M_o	M_1	M_1*	log$N$	a*
153.	1962, Apr. 10	37.6	20.1	21:37:13	6.3	5.6	4.4	1.65	—0.69
154.	» , » 28	36.1	27.0	11:18:53	5.8	5.6	4.9	0.30	—0.29
155.	» , July 6	38.0	20.2	09:16:15	6.1	4.6	3.6	1.38	0.57
156.	» , Sept. 10	35.6	27.5	09:36:28	5.3	4.0	3.7	0.00	—0.21
157.	1963, Mar. 4	35.2	25.3	15:10:16	5.3	4.5	4.2	0.48	0.26
158.	» , July 26	42.1	21.5	04:17:11	6.0	4.4	3.5	0.48	—0.26
159.	» , Sept. 18	40.8	29.1	16:58:09	6.3	5.0	3.8	0.90	—0.06
160.	» , Dec. 16	37.3	20.9	13:47:59	5.9	(3.5)	2.7	0.52	—1.18
161.	1964, Feb. 23	39.3	23.7	22:41:07	5.5	4.9	4.4	0.60	0.23
162.	» , Apr. 29	39.1	23.8	04:21:07	5.8	5.2	4.5	0.78	0.19
163.	» , Aug. 25	35.6	29.0	11:11:49	5.8	5.6	4.8	1.08	0.49
164.	» , Oct. 6	40.3	28.2	14:31:19	7.0	4.5	2.7	0.48	—1.00
165.	1965, Mar. 9	39.3	23.8	17:57:53	6.2	5.7	4.6	1.41	0.53
166.	» , Apr. 5	37.4	21.9	03:12:50	6.1	4.0	3.1	0.30	—0.44
167.	» , Aug. 23	40.2	26.2	14:08:57	5.4	4.4	4.0	0.30	0.01
168.	1966, Jan. 2	37.6	23.4	23:12:17	5.0	2.7	2.7	—1.30	—1.30
169.	» , » 20	39.0	24.4	00:39:00	5.0	4.0	4.0	0.00	0.00
170.	» , Feb. 5	39.1	21.6	02:01:43	6.2	5.2	4.1	2.02	1.14
171.	» , May 7	37.7	27.9	13:08:15	5.3	3.4	3.1	—0.70	—0.92
172.	» , » 9	34.5	26.0	00:42:55	5.8	5.0	4.3	1.55	0.96
173.	» , » 24	37.4	22.1	09:39:28	5.1	4.7	4.6	0.70	0.63
174.	» , » 25	40.2	19.7	09:06:57	5.0	4.8	4.8	0.70	0.70
175.	» , June 19	38.7	27.3	17:55:28	5.1	4.3	4.2	0.00	—0.07
176.	» , July 12	35.5	22.2	02:56:21	5.2	4.2	3.9	0.00	—0.22
177.	» , Aug. 16	39.8	19.9	03:53:38	5.1	3.9	3.8	0.00	—0.07
178.	» , » 21	40.3	27.6	01:30:43	5.5	3.5	3.0	—0.22	—0.59
179.	» , Sept. 1	37.4	22.1	14:22:54	5.9	4.0	3.3	0.00	—0.66
180.	» , Oct. 29	38.8	21.0	02:39:26	5.9	4.1	3.3	0.70	0.04
181.	» , Nov. 19	34.9	23.7	07:12:39	5.3	3.1	2.8	—0.52	—0.74
182.	1967, Jan. 4	38.3	22.0	05:58:56	5.4	4.1	3.7	0.30	0.01
183.	» , Feb. 9	40.0	20.3	14:08:19	5.7	4.5	3.9	0.78	0.27
184.	» , Mar. 4	39.1	24.6	17:58:06	6.8	5.5	3.8	1.30	—0.03
185.	» , May 1	39.5	21.2	07:09:02	6.3	5.4	4.2	1.60	0.64
186.	» , July 5	36.7	21.5	00:53:15	5.0	4.6	4.6	0.85	0.85
187.	» , Aug. 4	41.5	19.2	14:54:53	5.0	(3.0)	3.0	—1.00	1.00
188.	» , Sept. 6	35.1	23.2	04:59:20	5.0	4.3	4.3	0.30	0.30
189.	» , » 8	40.9	20.2	02:04:46	5.1	4.9	4.8	0.30	0.23
190.	» , Oct. 5	37.7	20.7	12:00:49	5.2	2.4	2.2	—1.30	—1.44
191.	» , Nov. 30	41.4	20.5	07:23:49	6.4	5.5	4.2	1.90	0.87
192.	1968, Feb. 19	39.3	25.0	22:45:44	7.1	5.6	3.7	1.95	0.40
193.	» , Mar. 10	38.9	24.2	07:10:57	5.8	4.8	4.1	0.85	0.26
194.	» , » 28	38.1	20.8	07:40:02	5.9	4.2	3.4	0.90	0.24
195.	» , » »	39.5	20.4	16:37:45	5.2	4.5	4.3	0.48	0.34
196.	» , May 30	35.4	28.0	17:40:25	6.0	5.7	4.8	1.75	1.01
197.	» , July 4	37.7	23.2	21:47:50	5.5	4.4	3.9	0.84	0.47
198.	» , » 8	34.4	25.2	17:41:06	5.2	4.9	4.7	1.00	0.86
199.	» , » 25	40.9	20.2	22:05:28	5.1	(3.3)	3.2	—0.70	—0.77
200.	» , Aug. 15	35.6	27.0	02:29:46	5.2	4.9	4.7	0.48	0.34
201.	» , Sept. 28	40.4	26.7	00:53:26	5.1	(3.2)	3.1	—0.80	—0.87
202.	» , Oct. 28	38.9	25.9	12:54:29	5.2	5.0	4.8	0.30	0.16
203.	» , Nov. 3	42.0	19.3	04:49:33	5.3	4.3	4.0	0.30	0.08

Table I continued

No.	Date	φ^{o} N	λ^{o} E	h m s	M_o	M_1	M_1^*	log$N$	a^*
204.	1968, Nov. 3	38.8	29.0	18:40:00	5.1	4.2	4.1	0.00	—0.07
205.	» , Dec. 5	36.6	27.0	07:52:09	6.1	5.4	4.4	1.20	0.39
206.	1969, Jan. 14	36.2	29.1	23:12:09	6.3	4.3	3.3	0.30	—0.66
207.	» , Mar. 3	40.1	27.4	00:59:11	5.8	5.1	4.4	0.70	0.11
208.	» , » 28	38.6	28.4	01:48:29	6.6	5.6	4.1	1.40	0.22
209.	» , Apr. 3	40.7	20.0	22:12:24	5.9	4.9	4.1	1.08	0.42
210.	» , » 6	38.5	26.5	03:49:33	5.9	4.2	3.4	0.60	—0.06
211.	» , » 21	39.4	25.2	20:36:45	5.0	3.8	3.8	—0.20	0.20
212.	» , May 1	35.3	27.8	18:02:16	5.6	5.3	4.8	1.48	1.04
213.	» , June 12	34.5	25.0	15:13:33	6.1	5.5	4.5	1.40	0.59
214.	» , July 8	37.6	20.3	08:09:15	6.0	4.8	3.9	0.78	0.04
215.	» , Aug. 26	41.8	19.9	02:15:32	5.2	(3.2)	3.0	—0.80	—0.94
216.	» , Oct. 12	39.8	20.7	01:02:32	6.0	4.7	3.8	1.18	0.84

RELATION BETWEEN THE NUMBER OF AFTERSHOCKS AND THE MAGNITUDE OF THE MAIN SHOCK.

The number of the aftershocks, which follow an earthquake, depends not only on the physical condition of the matter in the aftershock region but also on the magnitude of the main shock. Therefore, in order to use the number of aftershocks to investigate differences in the physical conditions of several regions, it is necessary to use aftershock sequences which follow main earthquakes with the same magnitude. However, it is difficult to obtain many data to apply this method even in very active regions. For this reason we must first establish a relation between the number of the aftershocks and the magnitude of the main shock.

The logarithm of the number of aftershocks with magnitude 4.0 or larger is plotted in Figure 1 as a function of the magnitude of the main shock. The data of the columns (6) and (9) of the Table I have been used for this plot. The data are fitted, in the least square sense, by a straight line which has the equation:

$$\log N = (-3.70 \pm 0.38) + (0.74 \pm 0.06)\, M_o \qquad [1]$$

The correlation coefficient is equal to 0.62.

The mean values of the logarithms of the number of aftershocks with $M \geqslant 4.0$, which belong to main shocks with magnitudes $M_o \pm 0.2$, are plotted versus M_o in Figure 2. This Figure indicates that, in a first approximation, the logarithm of the number of aftershocks with magnitude larger than a certain value is a linear function of the magnitude of the main earthquake. On the other hand, the large scattering

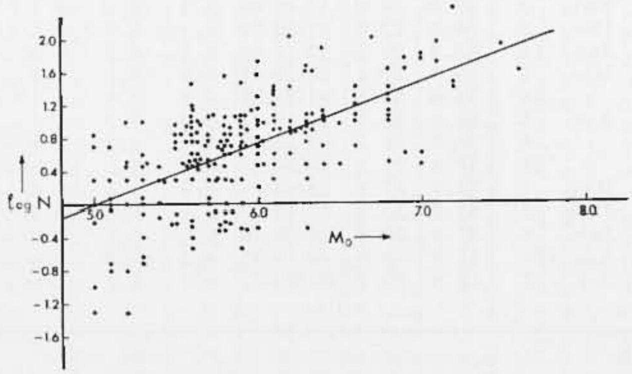

Fig. 1. – Variation of the logarithm of the number of aftershocks ($M \geqslant 4.0$), with the magnitude of the main shock.

of Figure 1 shows that the affect of the physical conditions in the focus, such as the homogeneity of the material, stress distribution etc., is considerable.

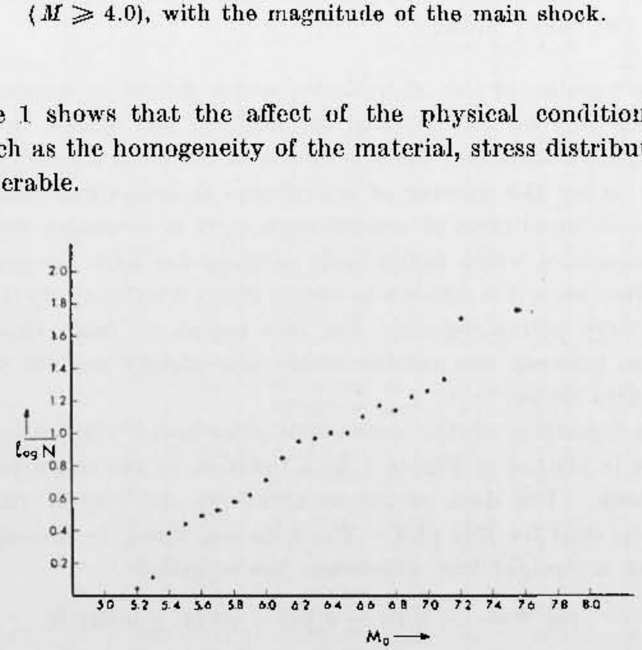

Fig. 2. – Variation of the mean value of the logarithms of the number of aftershocks ($M \geqslant 4.0$), which belong to main shocks of $M_o \pm 0.2$, with the magnitude of the main shock.

AFTERSHOCK ACTIVITY.

The equation [1] and the data of the columns (6) and (9) of the Table I have been used to determine the logarithm of the number of aftershocks with magnitude equal to or larger than 4.0, which corresponds to a main shock with magnitude 5.0 in each case. These values, measures of aftershock activity, are denoted by a^* and are listed in the last column of the Table I.

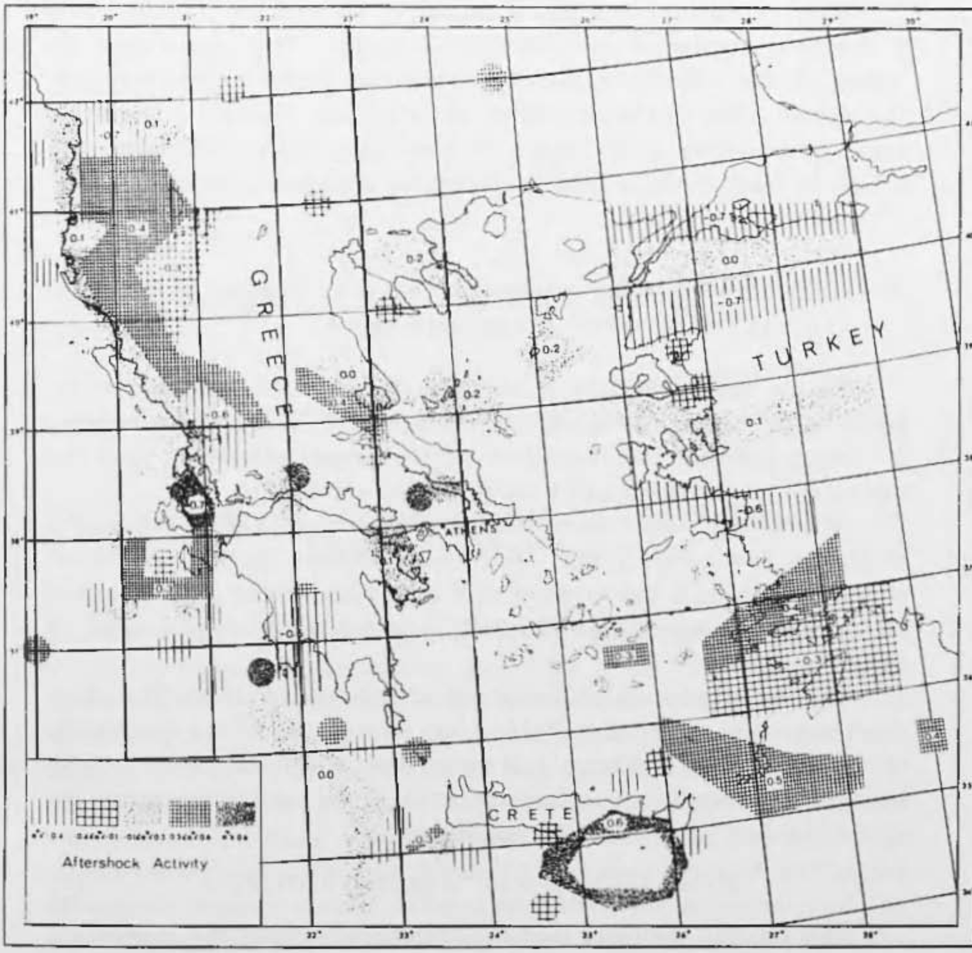

Fig. 3. – Geographical distribution of the aftershock activity in the area of Greece.

The values of the a^* have been plotted on the epicentres of the corresponding earthquakes. These values have been used to make the map of Figure 3. Five different symbols have been used to represent five ranges of aftershock activity. The seismic area is divided in several zones. The measures of the aftershock activity in each zone have values distributed around a mean value. This mean value is written in each zone. In some regions the data are not sufficient or consistent. In these cases, the epicenters of the earthquakes are indicated by circles and by the symbols of the corresponding value of the aftershock activity.

If we put $M_0 = 5$ in the equation [1], we find $\log N = 0$. This is the normal value of the aftershock activity. This means that the values of the aftershock activity, which are larger or smaller than the normal value of the aftershock activity, are positive or negative, respectively. This is the reason why we have chosen the magnitude 5.0 of the main shock in order to define the aftershock activity.

Relation between the magnitude of the largest aftershock and the magnitude of the main shock.

To use the magnitude of the largest aftershock for the investigation of differences in the physical conditions of the aftershock regions, a relation between the magnitude of the largest aftershock and the magnitude of the main shock must be first established.

In previous works such relations for earthquakes in the region of Greece have been found. But these relations have been based either on aftershock sequences of only large main shocks or on selective aftershock sequences, most of which have relatively large number of earthquakes [2, 8].

The magnitudes M_1 of the largest aftershocks of all the 216 aftershock sequences, as listed in Table I, are plotted versus the magnitude of the main shock in Figure 4. A correlation coefficient equal to 0.64 has been determined. The data are fitted, in the least square sense, by a straight line which has the equation:

$$M_1 = (-0.59 \pm 0.45) + (0.91 \pm 0.07)\, M_0 \,. \qquad [2]$$

This relation indicates that the difference between the magnitude of the largest aftershock and the magnitude of the main shock is almost independent of the magnitude of the main shock. Thus, for a main shock with magnitude 8.0, the magnitude of the largest aftershock is 6.7, while for a main shock with magnitude 5.0, the magnitude of the largest aftershock is 4.0. The difference is 1.3 in the first case and 1.0 in the second. These differences are almost equal to that predicted by Båth's law, according to which difference of 1.2 for large earthquakes is expected. We can, therefore, conclude that Båth's law is valid in the area of Greece in the case of small earthquakes, too. Since the quantity $M_0 - M_1$ is almost independent of M_0, this quantity can also be used as a measure of the aftershock risk.

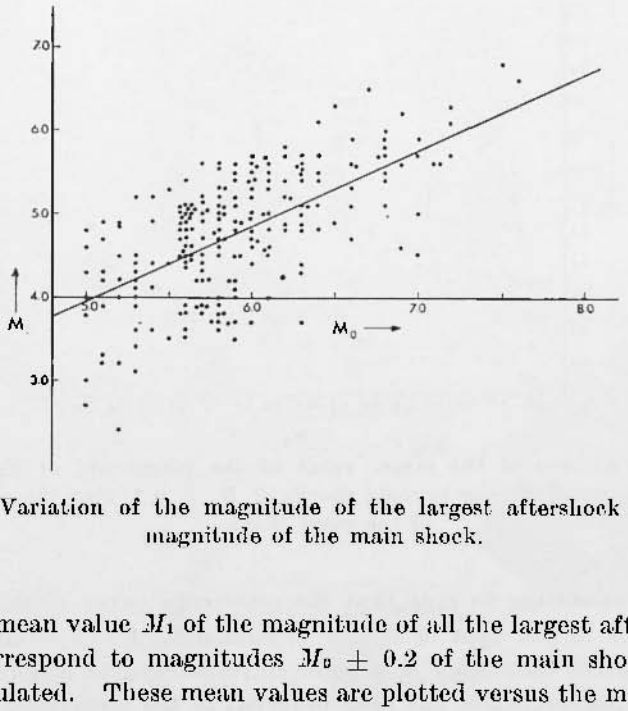

Fig. 4. – Variation of the magnitude of the largest aftershock with the magnitude of the main shock.

The mean value M_1 of the magnitude of all the largest aftershocks, which correspond to magnitudes $M_0 \pm 0.2$ of the main shocks, have been calculated. These mean values are plotted versus the magnitudes M_0 in Figure 5. This figure shows that there is a clear statistical relation between the magnitude of the largest aftershock and the magnitude of the main shock. In a first approximation this relation can be considered linear. It is observed, however, that, for magnitudes of the main shock between 6.7 and 7.1, the magnitude of the largest aftershock remains almost constant and that, for magnitudes of the main shock larger than 7.1, a second curve with large slope can fit the data. It is probable that this observation is not a result of lack of sufficient data but it has some physical meaning. To check this we have made the same plot for all the earthquakes followed by aftershocks and occurred in the European area, out of the region of Greece, between 1910 and 1955. These data have been taken from a table published by Karnik [3]. It has been observed that, for about the same range of values of the main shocks (6.7 to 7.1), the magnitude of the largest aftershocks has tendency not to increase.

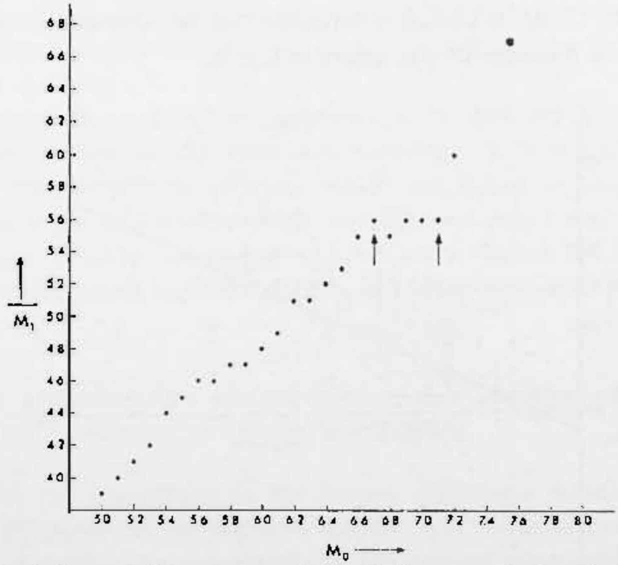

Fig. 5. – Variation of the mean value of the magnitude of the largest aftershocks, which belong to main shocks of $M_0 \pm 0.2$, with the magnitude of the main shock.

It is interesting to note that the recurrence curve of the shallow earthquakes in the area of Greece is consisted of two straight lines which intersect each other at a point corresponding to magnitude 6.7. The same phaenomenon has been observed in the recurrence curve of the intermediate earthquakes [7]. All these observations indicate that the value 6.7 is a critical one. This value is probably related to the linear dimension of the unit block of this area.

AFTERSHOCK RISK.

The equation [2] and the data of the columns (6) and (7) of the Table I have been used to determine the maximum aftershock $M_1{}^*$, which corresponds to a main shock with magnitude 5.0 in each case. The values M_1^* are measures of the aftershock risk and are listed in column (8) of Table I. These data have been used to make the map

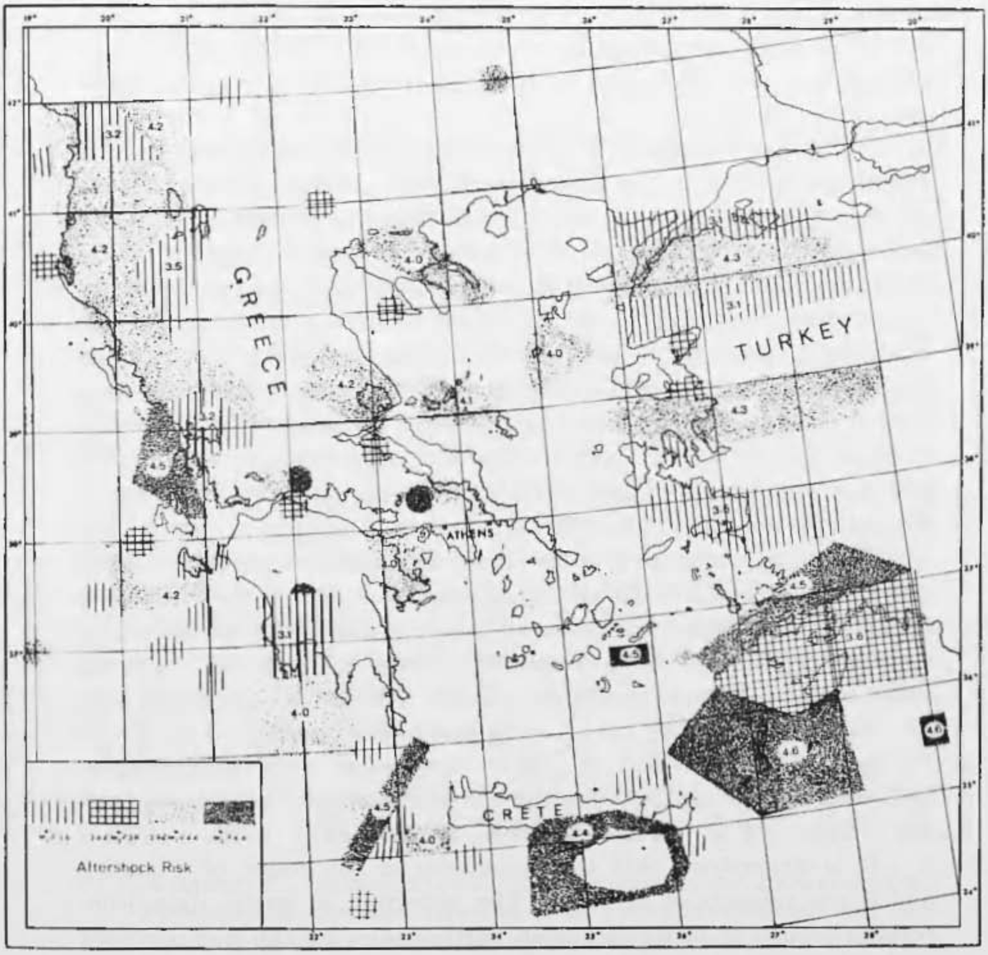

Fig. 6. – Geographical distribution of the aftershock risk in the area of Greece.

of Figure 6. Four different symbols have been used to represent the corresponding ranges of the aftershock risk. The seismic area is divided in several zones. The number written in each zone is the mean value of the aftershock risk of this zone. In the regions where there are not sufficient epicenters or the data are not consistent, the epicenters are indicated by circles and by the symbol of the corresponding value of the aftershock risk.

If we put $M_0 = 5.0$ in equation [2], we find $M_1 = 4$. This is the normal value of the aftershock risk.

Discussion.

Figure 3 and Figure 6 indicate that the distributions of the aftershock activity and the aftershock risk are generally similar. There are, however, many regions where the distribution patterns of the two quantities are not the same. The zones of aftershock activity are, in general, parallel to the main trend of the morphology of the area. In the western part of the area the zones, as a rule, have a direction NNW-SSE, that is they are parallel to the Alpine folding. In the eastern part the zones have, approximately, an east to west direction. It is very interesting to note that the zones of the aftershock activity in northwestern Turkey are parallel to the well known Anatolian fault. Zones of very low aftershock activity or risk are succeded by zones of normal aftershock activity or risk.

The exact physical explanation of the distribution of the aftershock activity and aftershock risk is not easy. This is mainly due to the lack of sufficient theoretical and laboratory information. According to Mogi (1967) the zones of different aftershock activity represent zones of different structure state. Zones with large aftershock activity are not much fractured. According to this opinion the zones of Figure 3 indicate regions of higher, normal or lower homogeneity. Laboratory experiments show that the aftershock activity depends on the distribution of stress, too (Mogi, 1962, Scholz, 1968).

It is understood that the bounderies of the zones of Figure 3 and 6 are subjects of revision. The collection of many data, concerning sequences of smaller main earthquakes, by the new network of station in the area, will help to make more accurate maps of aftershock activity and aftershock risk.

Summary and Conclusions.

The geographical distribution of the aftershock activity and aftershock risk in the area of and near Greece has been investigated. The aftershock activity and aftershock risk are measures of the number and the energy of the aftershocks which follow an earthquake of a certain magnitude, respectively.

In the present paper the logarithm of the number of aftershocks with $M \geqslant 4.0$, which follow a main shock of magnitude 5.0, is defined as a measure of the aftershock activity. The magnitude of the largest aftershock, which follow a main shock of magnitude 5.0, is defined as a measure of the aftershock risk. The symbol a^* is used for the measure of the aftershock activity and the M^*_1 for the measure of the aftershock risk.

A number of 216 aftershock sequences have been used to find the statistical relation $\log N = -3.70 + 0.74\ M_0$ between the number N of aftershocks of $M \geqslant 4.0$ and the magnitude M_0 of the main shock. The relation $M_1 = -0.59 + 0.91\ M_0$ has been found between the magnitude M_1 of the largest aftershock and the magnitude of the main shock. The quantities a^* and M^*_1 have been determined, for all aftershock sequences, on the basis of these relations and the observations.

The distributions of the aftershock activity and aftershock risk are shown in Figure 3 and 6, respectively. The two patterns of distribution are mostly similar and follow the pattern of other geological and geophysical features. These maps are useful because they show the distribution of several physical properties, such as the homogeneity of the material, the distribution of stress and they can be used to estimate the number and magnitude of the aftershocks which follow a principal earthquake.

REFERENCES

(1) Comninakis P., Drakopoulos J., Moumoulidis G. and Papazachos B., *Foreshock and aftershock sequences of the Cremasta earthquake and their relation to the waterloading of the Cremasta artificial lake*, "Ann. di Geof.", **21**, (1), 1968.

(2) Drakopoulos J., *Characteristic parameters of the fore and aftershock sequences in the area of Greece*, "Thesis, Univer. of Athens", 105pp., 1968 (in Greek).

(3) Karnik V., *Seismicity of the European Area*, Part. 1, "D. Reidel Publishing Company, Dordrecht-Holland", 364 pp., 1969.

(4) Mogi K., *Study of elastic shocks caused by the fracture of heterogeneous material and its relations to earthquake phenomena*, "Bull. Earthq. Res. Inst.", **40**, 1962 b.

(5) Mogi K., *Regional variation of aftershock activity*, " Bull. Earthq. Res. Inst.", **45**, 1967.

(6) Papazachos B., Delibasis N., Liapis N., Moumoulidis G. and Purcaru G., *Aftershock sequences of some large earthquakes in the region of Greece*, "Ann. di Geof. ", **20**, (1), 1967.

(7) Papazachos B. and Comninakis P., *Geophysical and tectonic features of the Aegean arc*, "J. Geophys. Res. ", 1971.

(8) Scholz C. H., *Experimental study of the fracturing process in brittle rock*, " J. Geophys. Res. ", **73**, (4), 1968 b.

(9) Utsu T., *A statistical study on the occurrence of aftershocks*, " Geophysical magazine ", **30**, (4), 1961.