On certain aftershock and foreshock parameters in the area of Greece

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SUMMARY. — Published information ([12]) on the aftershocks and foreshocks of many principal shallow earthquakes occurred in the area of Greece between 1911 and 1973 constitutes a more or less homogeneous and complete sample of data in respect to some properties of these seismic sequences. These data have been used to determine certain parameters of these sequences.

The value of the decay parameter p, in the time distribution law of aftershocks, is independent of the magnitude range and varies between 0.7 and 1.9 in this area. The smallest value was found for the aftershock sequence of an earthquake believed to be associated with the Kremasta artificial lake, while the largest value was found for the aftershock sequence of an earthquake occurred in the volcanic part of the Hellenic arc. The probability, N, that the largest aftershock will occur T_1 days after the main shock or later is given by a relation of the form $N = c - k \log T_1$.

Representative values of the parameter b, in the frequency-magnitude relation, have been found for the foreshocks as well as for the aftershocks of the same main shocks, by a proper grouping of the data. This value is equal to 0.67 for foreshocks and equal to 0.92 for the corresponding aftershocks. The difference in magnitude between the main shock and the largest aftershock is almost independent of the magnitude of the main shock. The relation $M_0 - M_1 = 1.1$ holds on an average.

RIASSUNTO. — Informazioni ([12]) pubblicate sulle repliche e scosse premonitrici di molti importanti terremoti superficiali avvenuti nell'area della

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Grecia fra il 1911 ed il 1973, costituiscono un esempio più o meno omogeneo e completo di dati circa alcune proprietà di queste sequenze sismiche.

Il valore del decadimento del parametro p, nella legge della distribuzione nel tempo di repliche, è indipendente dalla variazione della magnitudo ed i suoi valori sono compresi, in questa zona, fra 0.7 e 1.9. Il valore più piccolo è stato trovato per la sequenza delle repliche di un terremoto che si è ritenuto associato al lago artificiale di Kremasta, mentre il più grande fu trovato per la sequenza delle repliche di un terremoto avvenuto nella parte vulcanica dell'arco ellenico. La probabilità N che la replica maggiore avverrà T_1 o più giorni dopo la scossa principale è data dalla relazione $N = c - k \log T_1$.

Valori significativi per il parametro b, nella relazione frequenza-magnitudo, sono stati trovati e per le premonitrici e per le repliche della medesima scossa principale, raggruppando i dati in modo appropriato. Questo valore è di 0.67 per le premonitrici e di 0.92 per le corrispondenti repliche. La differenza in magnitudo fra la scossa principale e le repliche più forti è pressoché indipendente dalla magnitudo della scossa principale.

La relazione $M_0 - M_1 = 1.1$, mediamente, resta valida.

Introduction

Research on several properties of seismic sequences has been carried out for several decades but this research has been much intensified during the last two decades. The interest of seismologists 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 problems are the earthquake prediction, the identification of artificial events and the stress and the mechanical conditions of the material in the focal regions.

The first attempt to investigate properties of the seismic sequences in Greece and the surrounding area has been made by the present author and his colleagues (6). Since then several other papers have been published on this subject (1,2,7). This area is bounded by the $34°$ N and $42°$ N parallels and by the $19°$E and $29°$E meridians.

Information on the origin times and magnitudes of aftershocks and foreshocks of all the main shallow shocks (= 177) with $M_0 \geqslant 5.6$ which occurred in the area of Greece between 1911 and 1973, and such information on the aftershocks and foreshocks of all the main shallow shocks (= 46) with $5.1 \leqslant M_0 \leqslant 5.5$ which occurred in the same area between 1966 and 1973 have been published by the present author and his colleagues [1,2,3]. These two samples of data can be considered homogeneous and complete, and are used to determine certain properties of the seismic sequences in the area of Greece.

Figure 1 is an index map of the locations of the epicenters of all the main shocks with $M_0 \geqslant 5.6$, which occurred in the area of Greece

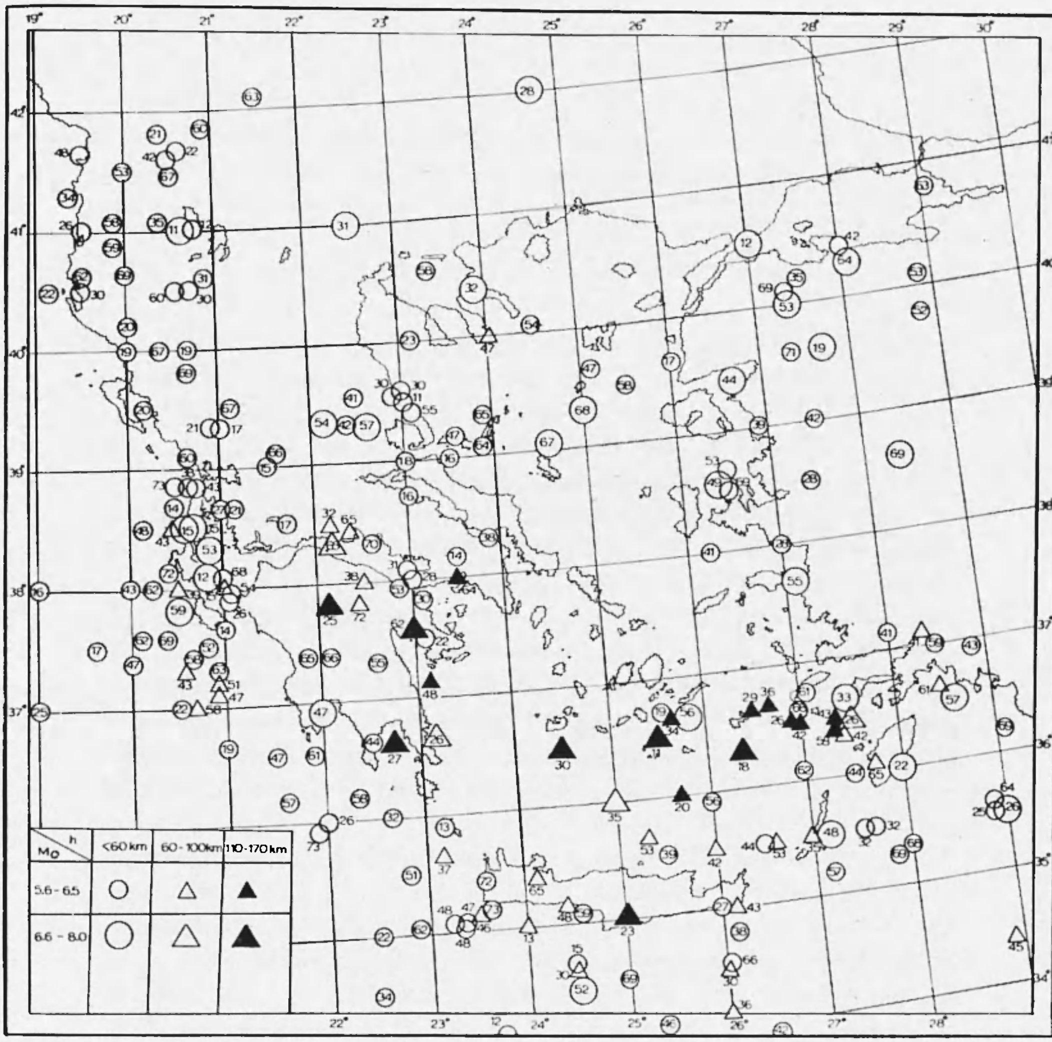

Fig. 1 – Index map of the location of all main shocks which occurred in the area of Greece between 1911 and 1973 and had $M_0 \geqslant 5.6$.

between 1911 and 1973. Six symbols have been used to denote two magnitude ranges and three ranges of focal depths. The numbers in or close to each symbol are the last two numbers of the year of occurrence.

THE TIME DISTRIBUTION OF AFTERSHOCKS AND FORESHOCKS

It has been shown by several seismologists that the number, $n(t)$, of aftershocks of a sequence per time unit is given by the relation

$$n(t) = n_1 t^{-p} \qquad [1]$$

where t is the time measured from the origin time of the main shock, n_1 is the frequency of shocks one time unit after the origin time of the main shock and p the decay parameter. Relation [1] is valid for complete sets of data, that is, for sequences which include all earthquakes with magnitudes above certain magnitude threshold.

The parameter n_1 depends on the magnitude threshold, which varies from sequence to sequence, but according to Gibowicz (3) its reduced value to the same magnitude level depends on the fault area and the stress drop in the focal region. The values of the decay parameter p are frequently a little larger than 1 but values between 0,9 and 1.9 have been reported by several authors (16, 20). Evidence has been presented by Mogi (4) that this parameter depends on some physical conditions in the focal region. He has observed a consistent geographical distribution of the values of this parameter in the area of Japan.

No much quantitative work has been done on the time variation of the frequency of foreshocks. This is due to the lack of sufficient data. The present author (8) has shown that the time dependence of the frequency of foreshocks of four earthquakes believed to be associated with artificial lakes can be described by the relation $n(t)=n_0(\tau - t)^{-h}$, where $n(t)$ is the number of foreshocks per time unit, t is the time measured from the time t_0 at which $n(t) = 1$, and n_0, τ, h are parameters.

The validity of the time law for aftershocks in the area of Greece

Ranalli [16] has concluded that the time distribution of the aftershocks of some sequences in the area of Greece show some departure from the statistical law which is described by [1], because he has found that in these cases a considerable percentage of the observations are out of the ninety five per cent confidence intervals. He has attributed it to some geotectonic reasons and partly to poor data, since these data have been received by old instruments.

One of the reasons for this anomaly is that the data used by Ranalli are not complete below certain magnitude threshold in some cases. Therefore, we can decrease the number of the observations which are outside of the ninety five per cent confidence intervals by considering only the earthquakes with magnitudes above this threshold.

Papazachos [9] has grouped the data of 37 complete aftershock sequences in this area and found that all points are well within the ninety five per cent confidence intervals. This shows that the time distribution law holds, in general, in this area. It is, however, possible that individual aftershock sequences are multiple sequences similar to those observed by Utsu [21] in Japan where the geotectonic conditions are similar to those in Greece. Such phenomena are sometimes observed in this area and can explain the departure from the law at least partly.

We have found that even if some points are outside of the ninety five per cent confidence intervals, whenever the grouping has been made in the way suggested by Utsu [19] and Ranalli [16], we can still determine a reliable value of p in many cases, by changing slightly the method of grouping. By putting the requirement that each frequency value must be calculated by a number of shocks larger than a cergtain value n (e.g. $n = 3$), we can have the data even fully satisfying the statistical criterion. This can be done by considering two or more neihbouring time intervals as one and by making the proper calculations of the frequency and of the corresponding time.

Representative values of p and h for the area of Greece

Papazachos [9] has proposed a way of grouping the data of several aftershock sequences in a region to determine a representative value of

p for this region. He has applied this method to the data of 37 aftershock sequences for which the number of aftershocks is larger than 16 to determine a representative value of this parameter for the area of Greece. Its value has been found equal to 1.13 with 1.08 and 1.18 ninety five per cent confidence intervals.

By the same method it has been found (9) that the ordinary foreshock sequences follow a statistical law of the form:

$$n(t) = n_1(\tau_0 - t)^{-h} \qquad [2]$$

where $n(t)$ is the number of foreshocks per day, t is the time measured from the time t_0 for which $n(t)=1$, τ_0 is the time between t_0 and the origin time of the main shock, and n_1 and h two other parameters. By the use of the existing data for all the complete sets of foreshocks in the area of Greece a value for h equal to 1.34 with 1.08 and 1.60 ninety five per cent confidence intervals has been found.

Dependence of p on the magnitude range

It is usually assumed that the value of the decay parameter p is constant for each sequence, that is, independent of the minimum magnitude threshold M_s chosen for counting the frequency of aftershocks. This assumption is very important because if it is not valid the p values determined for different aftershock sequences cannot be compared.

In order to confirm or reject the validity of this assumption we have used the existing data of the aftershock sequence of an earthquake of magnitude $M = 6.3$ which occurred on February 5, 1966, near the Kremasta artificial lake and which is believed to be associated with the water impounding in this lake (1,8). We have used these data because in this case a very large number of aftershocks has been recorded by modern instruments.

Figure 2 shows the time distribution of the aftershocks of the Kremasta earthquake for three minima magnitude thresholds. The dots, tringles and open circles show the time distribution of the aftershocks which occurred within 100 days after the main shock and had magnitudes $M_L \geqslant 2.3$, $M_L \geqslant 2.9$ and $M_L \geqslant 3.5$, respectively. The corresponding numbers of the aftershocks are 1918, 426, 94 and the values of p determined by the least squares method are 0.68, 0.71, 0.72.

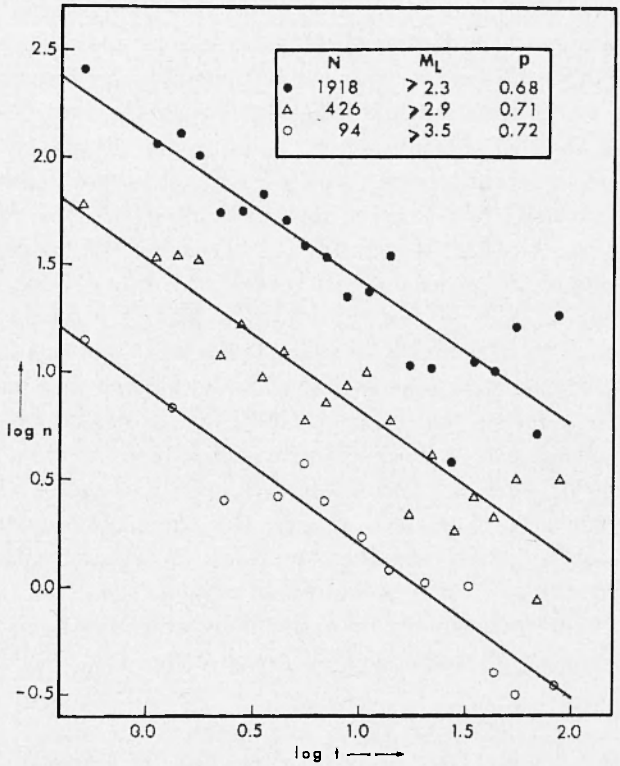

Fig. 2 – The time distribution of aftershocks of the Kremasta earthquake for three minima magnitude thresholds. The corresponding values of the total number of aftershocks, N, and those of the decay parameter, p, are also shown.

To group the data in the first two cases ($N = 1918$, $N = 426$) the method mentioned above ([16,19]) has been applied except that the frequency of aftershocks of the first day has been also counted since we found no reason to reject the data of the first day in the present case. In the last case ($N = 94$) the same method of grouping has been also applied but when the number of shocks in a time interval was smaller than 3 two neighbouring intervals were considered as one and the proper calculations of the frequency and of the corresponding time were made.

It can be observed that the magnitude range has essentially no effect on the calculated value of the parameter p. Utsu ([20]) has arrived at the same conclusion.

In a previous paper (1) a value equal to 0.78 has been found for the parameter p of the Kremasta aftershock sequence. The difference between this value and the value determined in the present paper is partly due to the different methods of grouping the data. The method of grouping used in the present work has some advantages over the method used to determine the value 0.78. On the other hand the value 0.70 has been determined in the present work by the use of the data of the first one hundred days after the occurrence of the main shock while the value 0.78 has been determined by the data of a longer period.

The value 0.70 is one of the lowest values of p observed so far. It is much smaller than 1.13 which is the most representative value for the area of Greece and lower than all values of this parameter determined in the present paper for six ordinary aftershock sequences in this area. For the aftershock sequences in Japan the value of p falls in the range between 0.9 and 1.9 but values between 1.0 and 1.4 are most frequent. The low value of p for the aftershock sequence of the Kremasta earthquake is probably due to its association with the Kremasta artificial lake. There is additional evidence that the time distribution of the aftershocks of the earthquakes which are associated with artificial lakes are characterized by low p values (10).

The range of variation of p in the area of Greece

In order to get an idea about the range of variation of the decay parameter p in the area of Greece, values of this parameter have been determined for the aftershock sequences of the main shocks for which the number of the listed aftershocks is larger than 100. There are six such sequences. The time distribution of these six sequences is shown in figure 3. The code Number, N_0, in the tables I and II of the publication (12), the total number, N, of aftershocks, the minimum magnitude threshold, and the determined, by the least squares method, value of the decay parameter p are also shown in this figure. The method of grouping is that applied for the Kresmata aftershock sequence.

It can be observed that the values of p range between 0.83 and 1.86. Their mean value is equal to 1.12 which is almost identical with the value based on the data of 37 aftershock sequences of this area (9). The largest value of p has been found for the aftershock sequence of the big earthquake ($M = 7.5$), which occurred on July 6, 1956 in the volcanic part of the Hellenic arc.

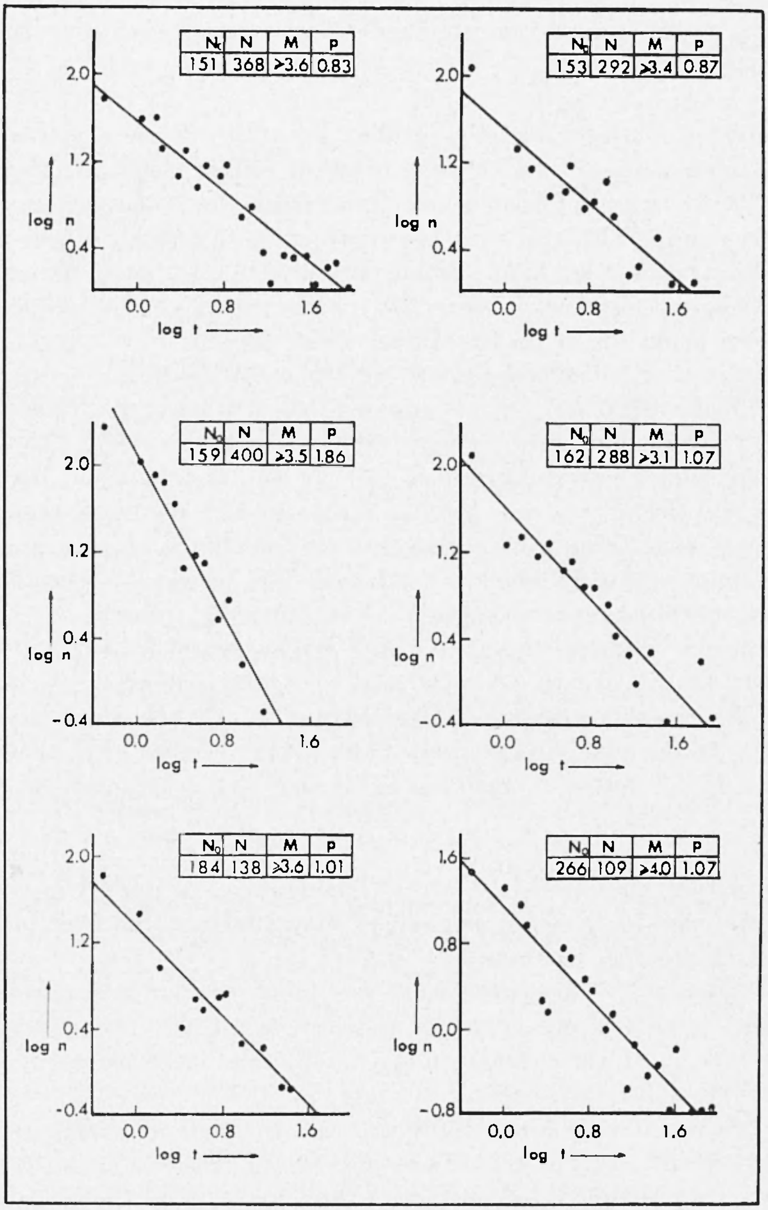

Fig. 3 – The time distribution of aftershocks of six sequences in Greece. The code number, N_0, of each sequence in table II of the publication (12), the total number, N, of aftershocks, the minimum earthquake magnitude, and the value of the decay parameter p are also shown.

TIMES OF OCCURRENCE OF THE LARGEST AFTERSHOCK AND OF THE LARGEST FORESHOCK

The statistical forecasting of the time of occurrence of the largest aftershock is of theoretical and practical significance. When these shocks are large and occur in inhabited areas, they cause considerable damage since the structures have already been shaken by the main shock. On the other hand statistical results on the time of occurrence of the largest foreshock in respect to the main shock can be used to give an idea about the origin time of the main shock.

The time difference T_1 between the main shock and the largest aftershock varies from a few minutes to a few months. To investigate the distribution of T_1 only the largest aftershocks of the main shocks which have magnitudes $M_0 \geqslant 6.0$ and occurred between 1911 and 1973 in this area have been considered. We have taken into account only those shocks because the probability of observational uncertainties is very small in these cases and because only the aftershocks of this range of magnitude can be damaging. This investigation has shown that the cumulative distribution function of T_1 is more satisfactorily fitted by a simple relation than the frequency function.

Figure 4 shows the cumulative distribution of the relative frequency of T_1. In this plot, N is the probability that the largest aftershock will occur T_1 days after the main shock or later. A relation of the form

$$N(T_1) = c - k \log T_1 \qquad [3]$$

fits well the data as it is shown in this figure. When T_1 is measured in days the values of the parameters, determined by the least squares method, are $c = 0.53$ and $k = 0.23$.

Relation [3] and figure 4 show that in 47 per cent of the cases the largest aftershock occurs in the first day, in 70 per cent in the first ten days, in 81 per cent in the first month, and in 88 per cent in the first two months after the main shock.

Papazachos ([11]) has investigated the time of occurrence of the largest foreshocks which have preceded the main shocks with $M_0 \geqslant 6.0$ in the area of Greece. A relation of the form [3] gives the probability that the largest foreshock will occur T_1 days before the main shock or sooner, with $c = 0.59$ and $k = 0.31$. The similarity between the two relations which describe the time distributions of the largest foreshocks and the largest aftershocks is surprising.

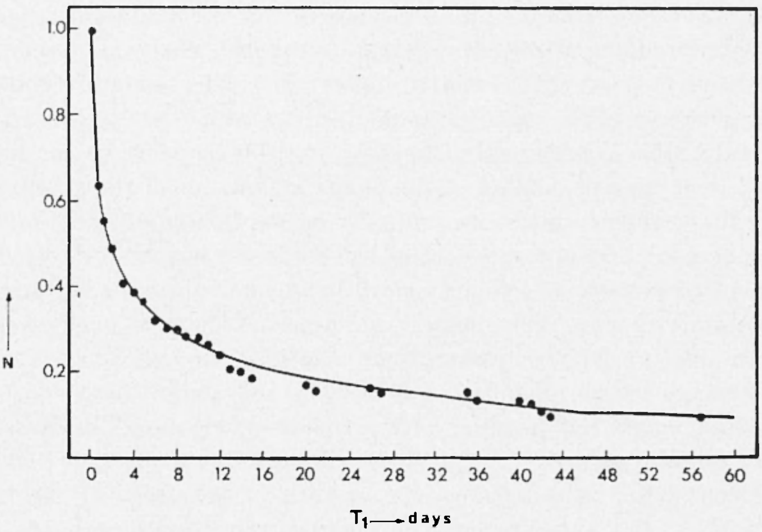

Fig. 4 – The cumulative frequency distribution of the difference between the times of occurrence of the main shock and the largest aftershock.

THE MAGNITUDE DISTRIBUTION LAW AND ITS VALIDITY IN THE AREA OF GREECE

One of the most important statistical laws in Seismology is the well known relation between the frequency n and the magnitude M of the earthquakes, which occur in a certain region and within a certain period of time. Most seismologists today calculate the cumulative distribution N because the errors in the magnitudes are smoothed out. Then the law is expressed by the relation:

$$\log N = a - bM \qquad [4]$$

where N is the number of shocks with magnitude equal to or larger than M and a, b are parameters. This relation, also, holds for seismic sequences. The parameter b is very important as it has some association with several important problems such as the stress and other conditions in the focal regions ([5,17]) and the earthquake prediction problem ([23]).

Ranalli ([16]) has investigated statistically the magnitude distribution of the earthquakes of six seismic sequences in the area of Greece. He has applied Utsu's method and has found that in some cases a considerable percentage of the points in the recurrence curve are outside of the ninety five per cent confidence intervals. This is mainly true for the aftershocks of the earthquake of Karditsa which has code number 153 in the table I of the publication ([12]). For this sequence he has found that a very large percentage of the points are outside of the ninety five per cent confidence intervals. On the basis of these observations he has concluded that in these cases either the law is not valid or the data are poor since they are taken by old instruments. Both his conclusions are only partly true. The anomaly is due to the fact that in these cases the cumulative frequency-magnitude relations are not linear in the whole range of the magnitudes he used to determine these relations.

Real partial non-linearity of the frequency relation has been observed in many cases ([6,13,14,22]). This is mainly due to the fact that the recurrence curve is usually convex upward in the range of the large magnitudes, but this property of the recurrence curve can be only partly responsible for the observed anomaly. The non-completeness of the published data in the range of low magnitudes is the main reason why a considerable percentage of the points are outside of the confidence intervals. To give an example we will examine the aftershock sequence of the Karditsa earthquake [No = 153 in table I of publication ([12])]. For this sequence, Ranalli has used all the data which cover the magnitudes between 3.2 and 5.9 and found that $b = 0.64$ and that 58.3 % of the points are outside of the ninety five per cent confidence intervals. An inspection of the plot of the data shows that this sequence can be considered complete for magnitudes larger than or equal to 3.6. The application of the method used by Ranalli to the data which concern the magnitude range between 3.6 and 5.9 gives very different results. Figure 5 shows the cumulative distribution for this range of magnitudes. The dashed lines show the 95% confidence intervals. Utsu's method give now $b = 1.0$. Only one point out of 18 is outside of the dashed lines which means that only 5.6 % of the points are outside of the 95 % confidence intervals now. This small deviation can probably be attributed to uncertainties in the data. It is worth noted that the b value for this sequence, determined by the least squares method ([6]), is also equal to 1.0.

The criterion put by Ranalli ([16]) has been applied to many complete sequences in this area. It has been found that the percentage of the observations which are outside of the ninety five percent confidence intervals is in most of the cases equal to zero and in the other cases is usually small. Therefore we can conclude that the frequency-magnitude law holds for the seismic sequences in the area of Greece.

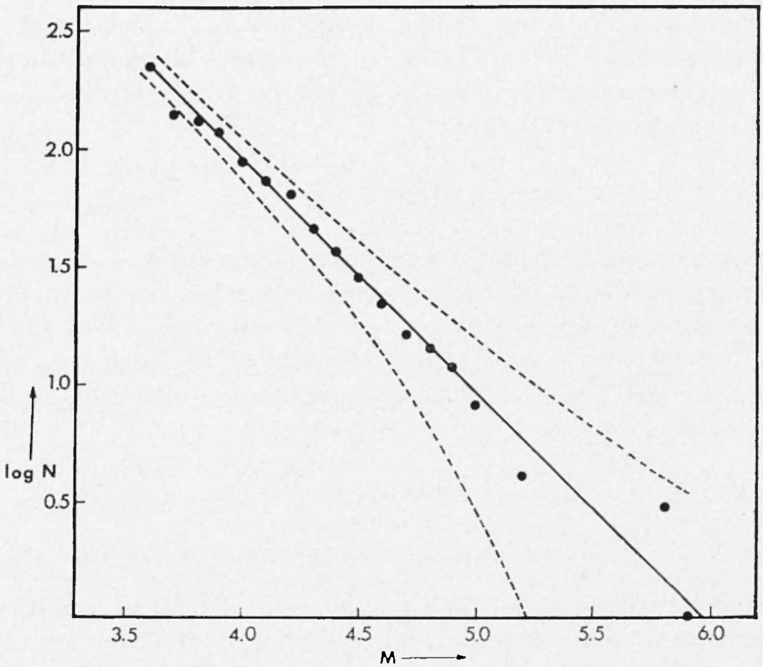

Fig. 5 – The magnitude distribution of aftershocks of the Karditsa earthquake of April 30, 1954.

The parameter b for foreshocks and for the corresponding aftershocks

The parameter b for foreshock sequences is of great importance in Seismology because its small value in relation to the value of this parameter for aftershock sequences and background seismic activity can be considered as a precursor of the main shock ([11,18]). However, some seismologists do not fully agree that the value of foreshock b is always smaller than the value of the corresponding aftershock b. This disagreement is mainly due to the fact that it is difficult to determine this parameter with accuracy since the number of foreshocks is usually small. For this reason it is probably preferable to determine a representative value of the foreshock b in a region, by properly grouping all the foreshock data, and compare this value with the representative value of b of the corresponding aftershocks. In the following a method of grouping is suggested and applied to find such values of b for the foreshocks and the corresponding aftershocks in the area of Greece.

Let us assume that we know the magnitudes of several complete seismic sequences in a region. The cumulative frequency function for the i sequence can be written.

$$N_i = 10^{mb_i} \qquad [5]$$

where m is equal to the difference between the magnitude M and the largest magnitude M_1 in the sequence, that is $m = M_1 - M$, N_i is the number of earthquakes for which the difference is m or smaller. If we replace each b_i by b so that the sum of the second members should be equal to the sum of the first members and take the logarithms of both sums we find

$$\log N = bm \qquad [6]$$

where $N = \sum_1^k \frac{N_i}{k}$ and k is the number of sequences with $M_1—M$ equal to or larger than m. This relation gives a value of b which can be considered as a representative value of this parameter for all sequences.

There are 47 foreshocks sequences in the table II of the publication ([12]) with two or more foreshocks. These data and the data for 14 foreshock sequences of small earthquakes with epicenters not far from Athens published by Drakopoulos ([2]) have been used to determine b. These 61 foreshock sequences include 290 foreshocks for which $M_1 — M \leqslant 1.5$. The same procedure has been followed for the aftershock sequences which belong to the same main shocks with the 61 foreshock sequences. These aftershock sequences include 790 aftershocks with $M_1—M \leqslant 1.5$. Figure 6 shows the $\log N$ versus $M_1—M$ for foreshocks and aftershocks. It is clear that the b value for foreshocks is smaller than the b value for aftershocks. The two straight lines which fit the data have been determined by the generalized least squares method. Each value of $\log N$ has been weighted according to the value of k. The value of b for foreshocks has been found equal to 0.67 and for the corresponding aftershocks equal to 0.92.

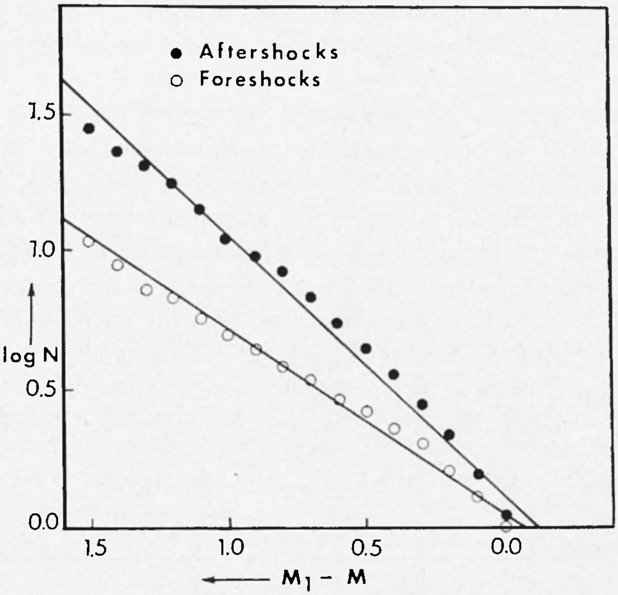

Fig. 6 – The magnitude distribution of the foreshocks and of the corresponding aftershocks.

Magnitudes of the largest aftershock and of the largest foreshock

Several attempts have been made to determine statistical relations between the magnitude, M_0, of the main shock and the magnitude, M_1, of the largest aftershock. According to Bath the relation $M_0 - M_1 = 1.2$ holds. Utsu ([20]) has found the relation $M_0 - M_1 = 5.0 - 0.5 M_0$ for earthquakes in Japan.

To find such a relation the data must be complete. In other words it is necessary to determine the magnitudes of the largest aftershocks of all the main shocks which have magnitudes larger than a certain value and have occurred in a certain region and within a certain period of time. The largest aftershocks of all, but two, the main shocks with $M_0 \geqslant 6.0$ which are listed in the table II of the publication ([12]), fulfill this condition. In other words we know the magnitudes of the largest aftershocks of all the main shallow shocks with $M_0 \geqslant 6.0$ which occurred in the area of Greece between 1911 and 1973 except for two cases in which only the upper limits of the magnitudes of the largest aftershocks are known.

The total number of the shallow main shocks with $M_0 \geqslant 6.0$ in that table is 89. If we assume a linear correlation between M_0 and M_1 a correlation coefficient equal to 0.50 is found by these data. The slope of the line which fits these data is not much different from unit, which means that the difference $M_0—M_1$ is independent of M_0. This difference has been found equal to 1.13 for the 89 cases with $M_0 \geqslant 6.0$.

For 23 out of 219 sequences in the table II of the publication ([12]), the magnitudes of the largest aftershocks are not known but only the probable upper limits of these magnitudes. If these upper limits are taken as the magnitudes of the largerst aftershocks in these 23 cases,

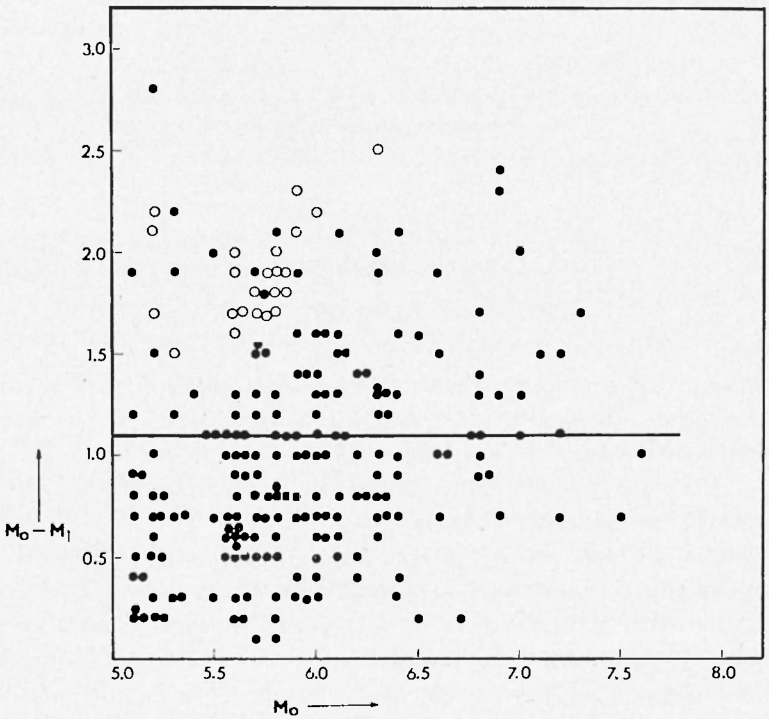

Fig. 7 - Plot of the difference in magnitude between the main shock and the largest aftershock versus the magnitude of the main shock.

the relation $M_0 - M_1 = 1.07$ will be found to hold for the 219 sequences in this area. We can therefore safely conclude that the relation:

$$M_0 - M_1 = 1.1 \qquad [7]$$

holds for the mean difference between the magnitude of the main shock and the magnitude of the largest aftershock in the area of Greece, at least when $M_0 \geqslant 5.1$. This relation is almost identical with Bath's relation.

Figure 7 shows the plot of $M_0 - M_1$ versus M_0. The dots show the cases for which the magnitudes of the largest aftershocks are known and the open circles the cases for which the magnitudes of the largest aftershocks are assumed to be equal to their probable upper limits. The large scattering shows that the value of M_1 depends on other parameters too. Purcaru ([15]) has shown that the difference $M_0 - M_1$ is a linear function of the parameter b.

The author of the paper ([11]) has used the homogeneous data for 39 recent foreshock sequences of main shocks with $M_0 \geqslant 5.5$ and has found a linear correlation between the magnitude M_{-1} of the largest foreshock and the magnitude of the main shock, with a correlation coefficient equal to 0.54. The slope of the regression line has been found almost equal to one. The relation:

$$M_0 - M_{-1} = 1.9 \qquad [8]$$

holds on an average.

Relations [7] and [8] and the finding that the b value for foreshocks is smaller than the b value for aftershocks fully justify the observation that the number of foreshocks is usually much smaller than the number of aftershocks of a main shock.

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