

Temporal characteristics of some earthquake sequences in Greece

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(Received September 1, 1989; revised version accepted May 30, 1990)

ABSTRACT

Latoussakis, J., Stavrakakis, G., Drakopoulos, J., Papanastassiou, D. and Drakatos, G., 1991. Temporal characteristics of some earthquake sequences in Greece. In: M. Wyss (Editor), *Earthquake Prediction. Tectonophysics*, 193: 299–310.

Temporal features of the aftershock activities following some moderate shallow earthquakes in Greece have been studied by making use of the modified Omori formula and Akaike's Information Criterion (AIC).

Although the main shocks occurred in different seismogenic regions in Greece, the aftershock activities show almost the same anomalous pattern. In most cases, the secondary aftershocks of the aftershock activity of the main event are preceded by seismic quiescence. Also, in some cases, the aftershock activity recovers to a normal level or increases beyond it prior to the occurrence of the large aftershock.

The observed temporal pattern may be useful in predicting a large aftershock which might be as large and destructive as the main shock, if the aftershock activity is monitored immediately after the occurrence of the main shock.

Introduction

Seismicity patterns before large earthquakes have been studied by many investigators in an attempt to understand the physical mechanism of earthquakes and to use them as a tool for earthquake prediction. Especially, a preseismic quiescence of seismic activity in the epicentral area of a large earthquake appears very common (Utsu, 1961, 1969; Inouye, 1965; Mogi, 1968; Ohtake et al., 1977a; Ohtake et al., 1977b; Habermann and Wyss, 1984; Wyss, 1986; Wyss and Habermann, 1988).

However, it is very difficult to recognize seismicity changes as precursors before the earthquake occurs. Furthermore, they show such a wide variation that it is very difficult to represent its temporal features quantitatively, except for the case of aftershock activities.

Aftershock activities have been studied intensively, and it is widely accepted that the occurrence rate of aftershocks $n(t)$ obeys the modified Omori formula (Utsu, 1961):

$$n(t) = \frac{k}{(t+c)^p} \quad (1)$$

where t is the lapse of time from the main shock. Matsu'ura (1986) proposed a method to examine

whether there is any anomalous change in aftershock activity before the occurrence of a large aftershock. If any change is recognized and its common features are known, then it is not only useful for predicting such a large aftershock which might cause additional disaster, but it is also important to identify a possible physical mechanism generating such a large aftershock or an earthquake in general.

In the present study, four earthquake sequences have been studied quantitatively, in order to investigate temporal patterns in aftershock activities prior to large aftershocks which are followed by secondary aftershocks. The main shocks have occurred in different seismogenic regions in Greece with different geophysical and geological properties.

Method

Ogata (1983) proposed the maximum likelihood method to estimate the three parameters K , c , p of the modified Omori formula. Based on this formulation, the likelihood is defined as:

$$L(k, c, p; t_1, t_2, \dots, t_N) = \prod_{i=1}^N n(t_i) \exp\left\{-\int_S^T n(s) ds\right\} \quad (2)$$

were observed from time S to T , and $n(t)$ is the same as (1).

The logarithmic form can be written as follows:

$$\ln L(k, c, p; t) = \sum \ln\{n(t_i)\} - \int_S^T n(s) ds \tag{3}$$

It is useful to plot the cumulative number of aftershocks against the frequency-linearized time r (Ogata and Shimazaki, 1984) in order to check the fit between the modified Omori formula and the temporal pattern of aftershock occurrence. The frequency-linearized time (FLT) is defined as:

$$r = \int_0^t n(s) ds \tag{4}$$

which is equal to the calculated cumulative number of aftershocks using the estimated parameters in equation (1).

Generally, when one aftershock sequence contains some large aftershocks accompanied by their secondary aftershocks, the modified Omori formula is represented by:

$$n(t) = \sum_{i=0}^M H(t - T_i) \cdot \frac{k_i}{(t - T_i + c_i)^p} \tag{5}$$

where $H(t)$ is a unit step function, M is the number of large aftershocks having their own aftershocks, and $T_0(r_0)$ and T_i are the origin time of the main shock and the i th large aftershock, respectively.

The parameters of the modified Omori law have been estimated following Matsu'ura (1986). Once the likelihood is obtained, Akaike's Information Criterion (AIC) (Akaike, 1974) defined by $AIC = -2 \times [\max. \ln(\text{likelihood})] + 2 \times (\text{number of parameters})$, is used to obtain the model which is best fitted to the data.

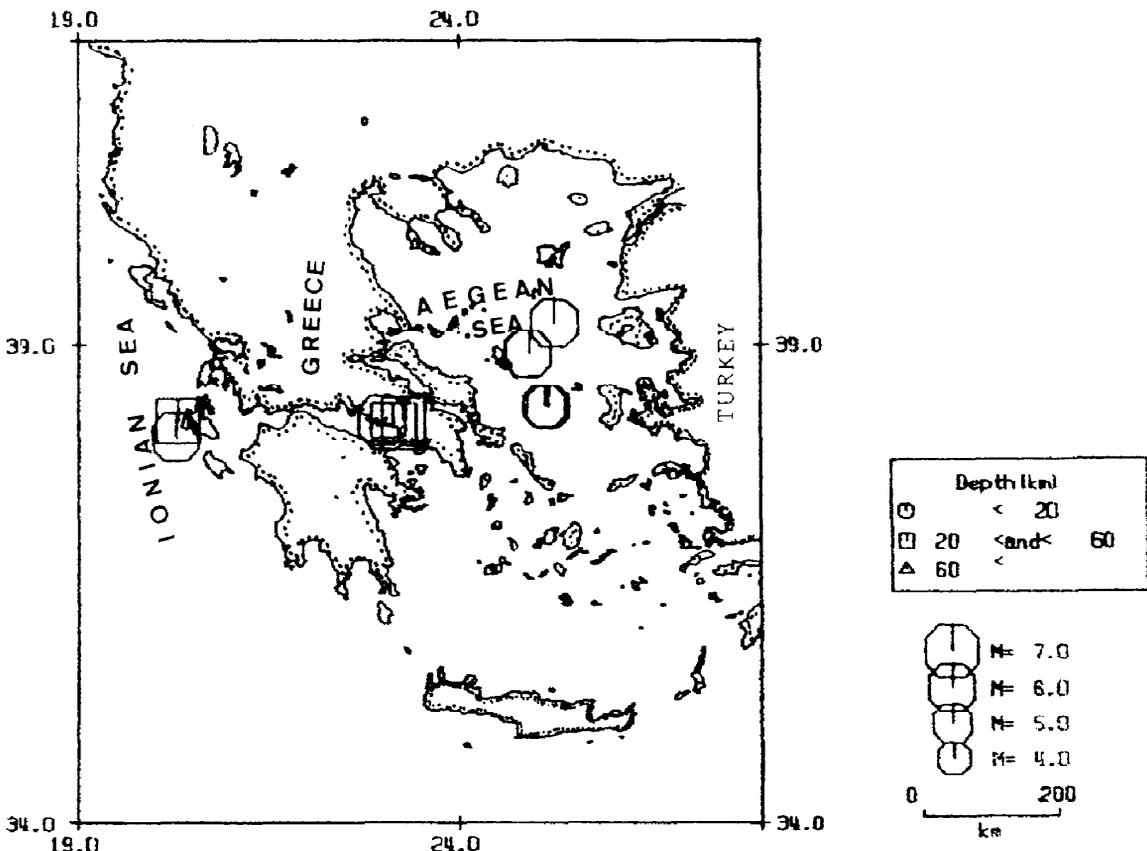


Fig. 1. Epicentre location of the main shocks and their principal aftershocks for some earthquake sequences in Greece.

Data analyses and results

In the present study, four earthquake sequences which occurred in the area of Greece have been analyzed. For studying these sequences, lists of aftershocks have been carefully made from the monthly bulletins of the National Observatory of Athens. Details about the detectability and accuracy of the Greek National Seismological Network are given by Papanastasiou et al. (1989). Table 1 summarizes the parameters of the main shocks and their large aftershocks. The epicentres of the same events are plotted in Fig. 1. In Table 1 the parameters of main shocks and their large aftershocks have been tabulated.

In the following, a detailed analysis of each earthquake sequence is given.

It should be emphasized that, for all the cases, the AIC was first tested for the intervals (0.0– S) and (S – T_{max}), where $S = i/8$ ($i = 1, 2, \dots, 8$) and T_{max} the time period that includes all the data. The smaller AIC, in all cases, was found for the whole interval. Probably this is due to the high threshold magnitude.

The 1981 Gulf of Corinth earthquake sequence (central Greece)

On February 24, 1981 (at 20h53), an offshore earthquake of $M_L = 6.3$ occurred in the eastern part of the Gulf of Corinth. The main shock was followed by two large aftershocks of local magnitude 5.9 on 25 February, (02h35) and 4 March (21h58). This earthquake sequence has been

TABLE 1

Seismological parameters of the main shocks and their principal aftershocks for some earthquake sequences in Greece

Date	h:m	ϕ_N°	λ_E°	Depth (km)	M_L
1981, Feb. 24	20:53	38.23	22.97	17	6.2
1981, Feb. 25	02:35	38.17	23.12	33	5.9
1981, Mar. 4	21:58	38.24	23.26	21	5.8
1981, Dec. 19	14:10	39.22	25.25	16	6.3
1981, Dec. 27	17:39	38.91	24.92	16	6.0
1983, Jan. 17	12:41	38.07	20.25	17	6.2
1983, Mar. 23	23:51	38.23	20.29	23	5.7
1986, Mar. 25	01:41	38.38	25.13	16	5.2
1986, Mar. 26	18:36	38.37	25.18	16	5.3

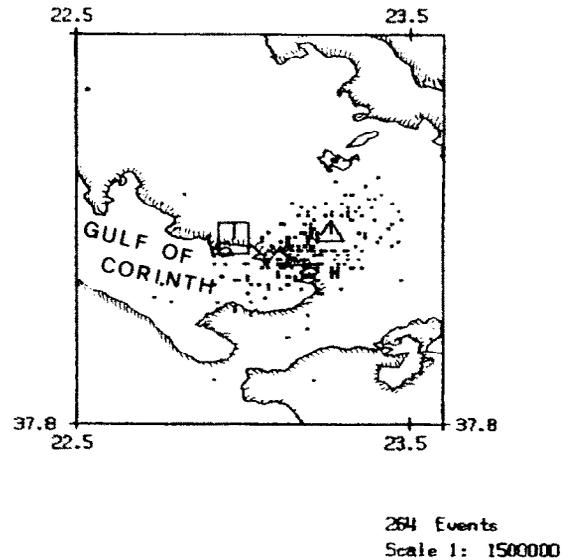


Fig. 2. Aftershock distribution of the 1981 Gulf of Corinth earthquake. The square and triangle show the location of the epicentre of the main shock on February 24 and its large aftershock on March 4, respectively.

studied by many investigators. Jackson et al. (1982) determined the focal mechanism of the main shock and its principal aftershocks from both field mapping and teleseismic observations. Papazachos et al. (1984 a) studied the magnitude, time and space distribution of aftershocks as well as the fault plane solution of the main shock and its largest aftershock. Kim et al. (1984) and Stavrakakis et al. (1986) studied the source process of the same events by using teleseismic waveform modelling.

For studying this sequence a list of aftershocks has been carefully made. In order to ensure the homogeneity of the data a threshold magnitude equal to 3.5 is chosen. The cut-off magnitude is $M_L = 2.5$. It is very difficult to examine the case of the largest aftershock because of the very high number of aftershocks immediately after the main shock. In Fig. 2 the epicentres of the sequence are plotted.

Omori's law for the interval 0.0 to 9.0 days is written as follows:

$$n(t) = \frac{28.25}{(t + 0.005)^{0.410}} \quad 0 \leq t \leq 9.0 \quad (6)$$

and is plotted in Fig. 3(A).

Top and middle figures show the cumulative number of aftershocks against ordinary time and FLT, respectively. The calculated cumulative

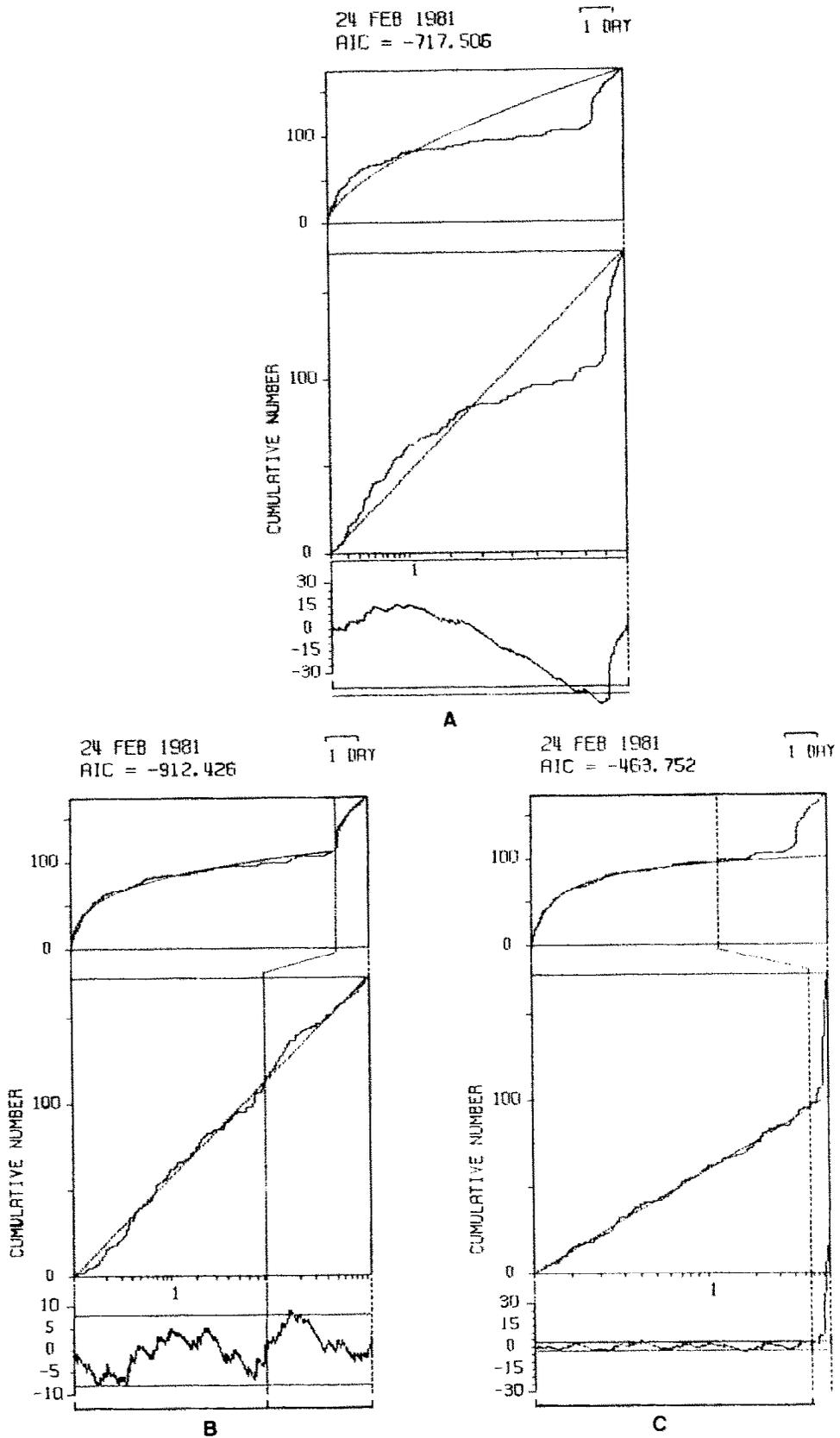


Fig. 3. Top and middle figures show the cumulative number of aftershocks against ordinary time and FLT, respectively. The bottom of the figure magnifies the difference of the observed cumulative number from the calculated one on the same time scale as the middle. (Further explanations are given in the text.) (A) The frequency-linearized time from all data. (B) The best fitted model from

number represented by dashed lines (see Fig. 3) is calculated using Omori's parameters which are obtained by the maximum-likelihood method from data in the range designated by a horizontal bracket at the right top. Figures on the FLT axis show lapse of time in days from the left end. The bottom of Fig. 3 illustrates the difference of the observed cumulative number from the calculated one on the same time scale as the middle. The double standard deviation of the difference in the designated range is also shown by the two parallel lines. In order to investigate the seismic patterns of the sequence various models have been tested in terms of AIC. The model which best fits the data, corresponds to an AIC equal to -912.426 . The modified Omori formula is given by the relationship:

$$n(t) = \begin{cases} \frac{21.62}{(t + 0.027)^{0.806}} & \text{for } 0 \leq t \leq 8.0447 \text{ days} \\ \frac{22.33}{(t + 0.027)^{0.806}} & \text{for } 8.0447 \leq t \leq 9.0 \text{ days} \end{cases} \quad (7)$$

and is plotted in Fig. 3(B).

Based on both figures, it is evident that a short quiescence is observed which is followed by a foreshock—like high activity before the occurrence of the second principal aftershock on March 4 (2.7–8.0 days). Figure 3(C) illustrates the practical meaning of the current analysis for earthquake prediction purposes. Suppose that the aftershock activity were observed in real time and the cumulative number as well as the difference ΔN of the observed cumulative number from the calculated one were also plotted in real time. Then, from Fig. 3(C) one would observe that ΔN varies between -5 and 5 until $t = 5.68$ days. After that period a remarkable increase would be observed which could be considered as an anomalous pattern of the sequence. Actually, this pattern was followed by the second significant aftershock of $M_L = 5.8$ on March 4, 1981.

The 1981 North Aegean earthquake sequence

On December 19, 1981 (at 14h10), a strong earthquake of local magnitude $M_L = 6.3$ occurred in the northern Aegean Sea. This shock was followed by a considerable number of aftershocks.

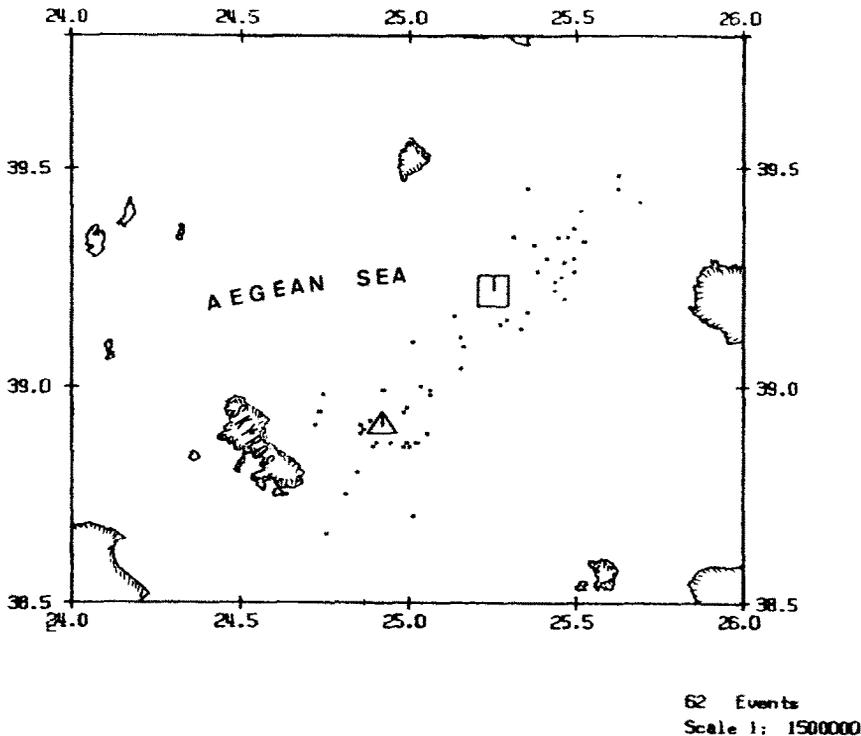


Fig. 4. Aftershock distribution of the 1981 North Aegean earthquake. The square and triangle show the location of the epicentre of the main shock on December 19 and its large aftershock on December 27, 1981, respectively.

On December 27, its largest aftershock of $M_L = 6.0$ occurred in the southwesternmost part of the aftershock area. Details of the seismic sequence as

well as of the focal mechanism of the main event and its largest aftershock are given by Papazachos et al. (1984b). Figure 4 shows the epicentre distri-

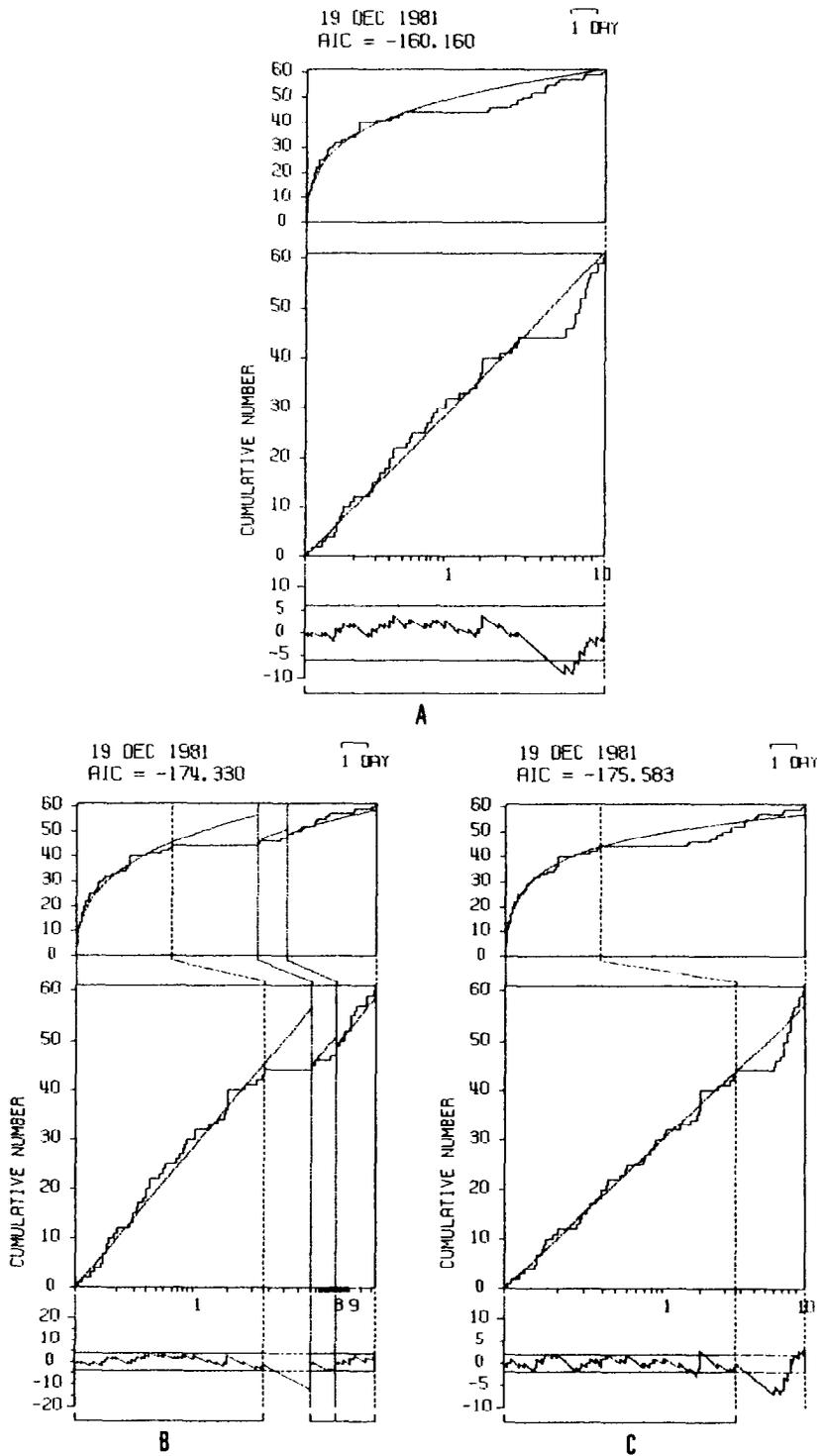


Fig. 5. Aftershock sequence of the 1981 North Aegean earthquake. (Further explanations are given in the text.) (A) The frequency-linearized time from all data. (B) The best fitted model from all data. (C) FLT from data until $t = 3.69$ days.

bution of the aftershocks with $M_L = 3.5$, as well as the location of the main shock and its large aftershock. The cut-off magnitude was chosen to be equal to 3.0.

For the time interval 0–11.53, which includes the large aftershock and part of its secondary aftershock sequence, the modified Omori formula (AIC = -160.16) is represented by the relationship:

$$n(t) = \frac{10.48}{(t + 0.028)^{0.8}} \quad \text{for } 0 \leq t \leq 11.53 \text{ days} \tag{8}$$

and is shown in Fig. 5(A), which corresponds to all data. Figure 5(B) illustrates the best fitted model including also all data. This model corresponds to AIC = -174.330, and the modified Omori formula is expressed by the relationship:

$$n(t) = \begin{cases} \frac{11.02}{(t + 0.013)^{0.73}} & \text{for } 0. \leq t \leq 3.69 \text{ days} \\ \frac{1.14}{(t + 0.013)^{0.73}} & \text{for } 7.0 \leq t \leq 8.145 \text{ days} \\ \frac{0.10}{(t + 0.013)^{0.73}} & \text{for } 8.145 \leq t \leq 11.53 \text{ days} \end{cases} \tag{9}$$

Based on this relationship, the following patterns are recognized. During the time interval $0. \leq t \leq 3.69$ days, aftershock activity of the main shock is observed which is followed by a quiescence in the time period $3.69 \leq t \leq 7.0$ days, and by a recovery to the normal stage in the time interval $7.0 \leq t \leq 8.145$ days. Finally, an aftershock activity of the largest aftershock is observed during the time $8.145 \leq t \leq 11.53$ days.

Figure 5(C) illustrates the case in which the cumulative number and the difference ΔN were observed in real time. It is evident that ΔN varies from 2.5 to -2.5 until $t = 3.69$ days. After that time period, a remarkable decrease was observed which could be considered as an anomalous pattern. Also in this case, this pattern was followed by the large aftershock on December 27 in the southwestern part of the aftershock area.

The 1983 Cephalonia Island earthquake sequence

On January 17, 1983 (at 12h41), a strong earthquake of local magnitude 6.2 occurred in the northwesternmost part of the Hellenic arc. This shock was followed by numerous aftershocks, the largest of which occurred on March 23 (23h51) and had a local magnitude equal to 5.7. Scordilis et al. (1985), based on the fault plane solution of the main shock and its largest aftershock, on the distribution of the aftershocks as well as on geomorphological information, proposed the existence, west of the Cephalonia and Zante islands, of a strike-slip dextral fault with a thrust component which strikes in an about NE-SW direction and dips to SE. Using this fault plane solution, Stavrakakis et al. (1989) studied the rupture process of the main shock by inversion of teleseismic P-waves.

In Fig. 6 the epicentral distribution of the aftershocks is shown as well as the location of the main shock and its largest aftershock. A threshold magnitude of 3.7 was chosen with cut-off magnitude 2.4.

For the time interval 0.0 to 65.3 days, which also includes the large aftershock and part of its

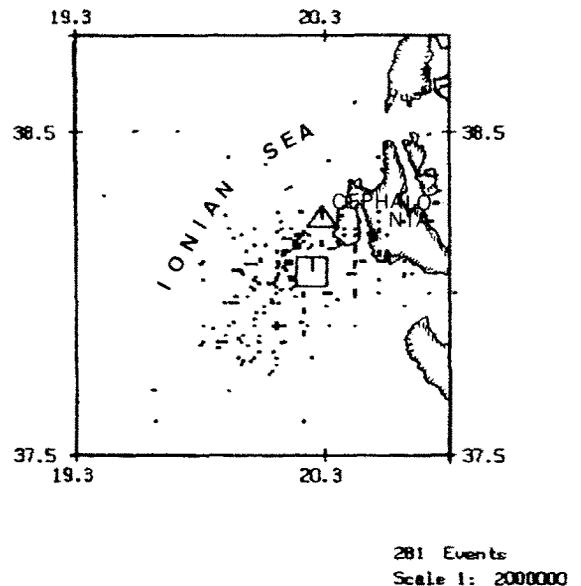


Fig. 6. Aftershock distribution of the 1983 Cephalonia Island earthquake. The square and triangle show the location of the epicentre of the main shock on January '17 and its largest aftershock on March 23, 1983, respectively.

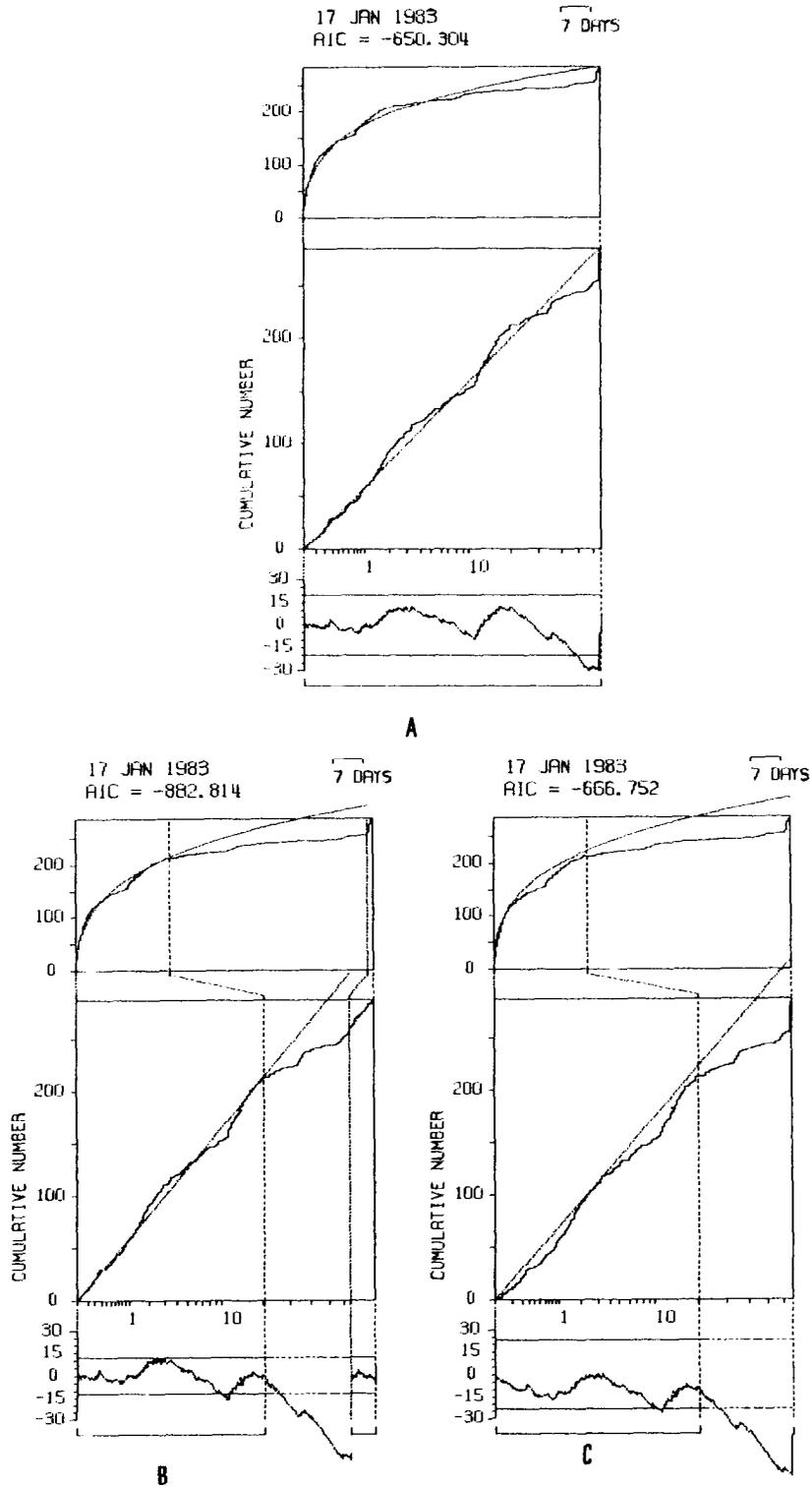


Fig. 7. Aftershock sequence of the 1983 Cephalonia Island earthquake. (Further explanations are given in the text.) (A) The frequency-linearized time from all data. (B) The best fitted model from all data. (C) FLT from data until $t = 20.4$ days.

sequence, the modified Omori formula is represented by the relationship (AIC = -650.304):

$$n(t) = \frac{36.81}{(t + 0.19)^{0.81}} \quad \text{for } 0 \leq t \leq 65.3 \text{ days} \quad (10)$$

as shown in Fig. 7(A). On the other hand, the best fitted model corresponds to AIC = -882.814 and is plotted in Fig. 7(B). Based on this figure, the following patterns are recognized. During the time period $0 \leq t \leq 20.4$ days, an aftershock activity of the main shock of January 17 is observed, which is followed by a quiescence during the time $20.4 \leq t \leq 64.4$ days. Finally, the quiescence is followed by a recovered aftershock activity in the time period $64.4 \leq t \leq 65.3$ days. In this case, the modified Omori formula is written as:

$$n(t) = \begin{cases} \frac{36.6}{(t + 0.18)^{0.76}} & \text{for } 0 \leq t \leq 20.4 \text{ days} \\ \frac{17.8}{(t + 0.18)^{0.76}} & \text{for } 64.465 \leq t \leq 65.31 \text{ days} \end{cases} \quad (11)$$

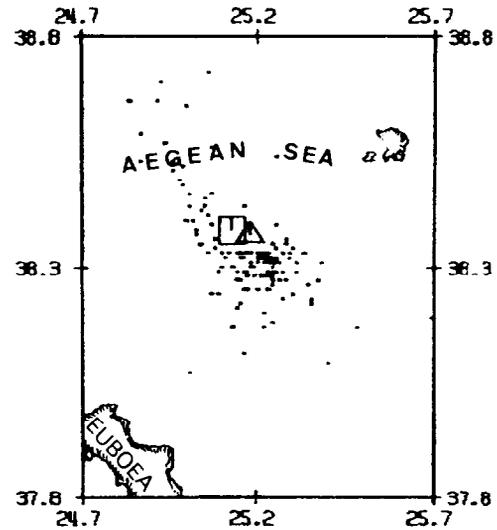
Figure 7(C) illustrates also the case in which the seismic activity was watched in real time. It is evident that the difference ΔN varies between 2.5 and -2.5 until $t = 20.4$ days. After that period, a remarkable decrease was observed which could be considered as an anomalous pattern. Also in this case, the decrease of ΔN was followed by the occurrence of the largest aftershock on March 23.

The 1986 Central Aegean earthquake doublets

On March 25, 1986, a moderate earthquake of local magnitude 5.2 occurred in the central Aegean Sea. After four days, on March 29 a second event of local magnitude 5.3 took place in the same focal region.

Figure 8 shows the aftershock distribution as well as the location of the two large events. A threshold magnitude equal to 3.1 with a cut-off magnitude equal to 2.5 is chosen.

For the time period 0-4.95 days, which also includes the second event and part of its aftershock



92 Events
Scale 1: 1500000

Fig. 8. Aftershock sequence of the 1986 Central Aegean doublets. The square and triangle show the location of the epicentre of the first event on March 25 and the second one on March 29, 1986, respectively.

sequence, the modified Omori formula (AIC = 200.06) is represented by the relationship:

$$n(t) = \frac{14.5}{(t + 0.0004)^{0.197}} \quad \text{for } 0 \leq t \leq 4.95 \text{ days} \quad (12)$$

which is plotted in Fig. 9(A). The best fitted model is illustrated in Fig. 9(B) corresponding to an AIC = -293.312. In this case, the modified Omori formula is represented by the relationship:

$$n(t) = \begin{cases} \frac{10.3}{(t + 0.022)^{0.64}} & \text{for } 0 \leq t \leq 2.02 \text{ days} \\ \frac{4.3}{(t + 0.022)^{0.64}} & \text{for } 3.8 \leq t \leq 4.7 \text{ days} \\ \frac{19.7}{(t + 0.022)^{0.64}} & \text{for } 4.7 \leq t \leq 4.95 \text{ days} \end{cases} \quad (13)$$

Based on this relationship, the following patterns are recognized. During the time period $0 \leq t \leq 2.02$ days, an aftershock activity of the first event of March 25 is observed, which is followed by a quiescence in the time interval $2.02 \leq t \leq 3.80$ days,

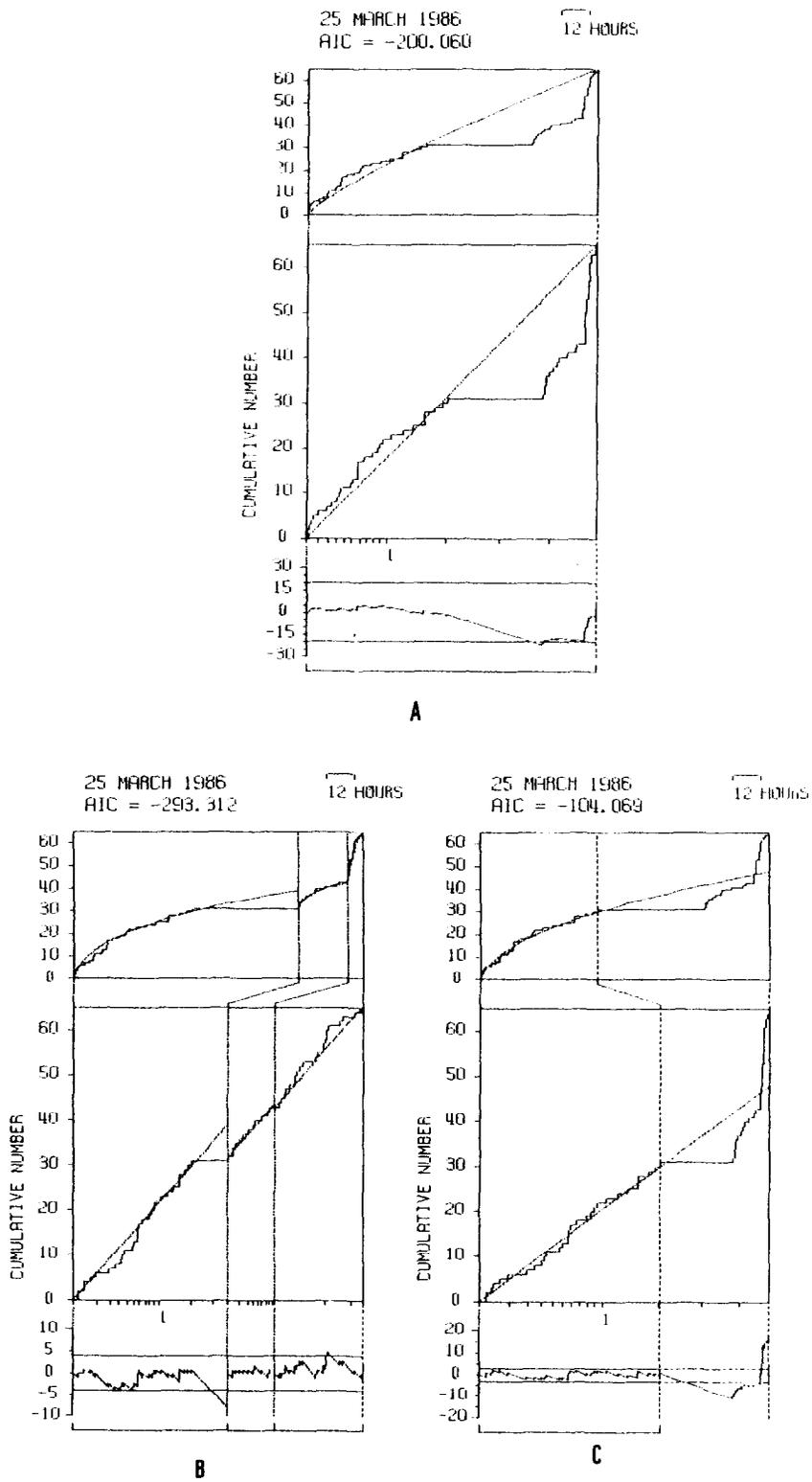


Fig. 9. Aftershock sequence of the 1986 Central Aegean doublets. (Further explanations are given in the text.) (A) The frequency-linearized time from all data. (B) The best fitted model from all data. (c) FLT from data until $t = 2.02$ days.

which is also followed by a recovered aftershock activity in the time of 3.8–4.7 days. At the final stage, and during the time interval 4.7–4.95 days, an aftershock activity of the second event of March 29 is observed.

Figure 9(C) illustrates the case in which the seismic activity was monitored in real time. The difference ΔN varies between 5 and -5 until $t = 2.02$ days. After that time period, a decrease was observed which could also be considered as an anomalous pattern. Actually, this pattern was followed by the second large event in the same focal region.

Discussion and conclusions

In the present study, four earthquake sequences in Greece have been analyzed to seek any anomalous change in aftershock activities of the main shock before the occurrence of large aftershocks.

It has been recognized that, before the occurrence of such large aftershocks, the whole aftershock area of the main shock becomes quiescent. Then the aftershock activity recovers to the normal level or increases beyond the normal level prior to the large aftershock.

Although the earthquake sequences occurred in different seismotectonic regions of Greece with different geological and geophysical properties, almost the same seismic patterns before the occurrence of large aftershocks have been observed. However, more data are needed to verify this conclusion. If the same temporal characteristics were observed, then this method could be used for earthquake prediction purposes. Especially, if quiescence and recovery were observed in the real time check, then one could expect soon a significant aftershock. The rough location of this aftershock can be estimated by checking the location of the aftershocks during the recovered stage. However, the precise magnitude and time of occurrence of the significant aftershock cannot be predicted using this method.

Acknowledgements

We thank R.S. Matsu'ura for providing us the subroutines used in the present study. Two anonymous

reviewers read the manuscript and made constructive comments. We thank both of them.

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