Foreshock activity and its probabilistic relation to earthquake occurrence in Albania and the surrounding area

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Abstract

We investigate some characteristics of foreshock activity of moderate and large earthquakes which occurred in the present century in Albania and the surrounding area. Using a prediction algorithm, based on possible foreshocks, we obtained a probabilistic relation between possible foreshocks and mainshocks. From documentary and instrumental data for the period 1901-1994 for the area between 39.0°-43.0°N and 18.5°-21.5°E we evaluated the probability of the occurrence of mainshocks immediately after their possible foreshocks. The result shows that the probability that mainshocks with magnitude $M \geq 6.0$ are preceded by a foreshock with magnitude $M \geq 4.4$, distance ≤ about 50 km and time ≤ 10 days is 38% (6/16). The probability that one earthquake with $M \geq 4.4$ will be followed by a larger earthquake with $M \geq 6.0$ within about 50 km and 10 days is 1.3% (6/468), but the probability increases to 33% (1/3) if 7 earthquakes with $M \geq 4.4$ occur within about 50 km and 10 days. From instrumental data for the period 1971-1994, the probability that mainshocks with $M \geq 5.0$ are preceded by a foreshock with magnitude $M \geq 4.0$ is 33% (5/15). The probability that one earthquake with $M \geq 4.0$ will be followed by a larger earthquake with $M \geq 5.0$ within about 50 km and 10 days is 1.9% (5/262), but the probability increase to 5.6% (1/18) if 3 earthquakes with $M \geq 4.0$ occur within about 50 km and 10 days. We also found a regional variation of foreshock activity with activity decreasing from the Vlora-Elbasani-Dibra transversal seismic belt to the Ionian-Adriatic seismic zone to the interior part of Albania seismic zone.

Key words *probability estimation of foreshock activity*

1. Introduction

Several studies have discussed the possibility of basing earthquake predictions on foreshock activity and seismic swarms (*e.g.*, Mogi, 1968, 1981; Wyss *et al.*, 1983; Jones, 1985; Wyss and Habermann, 1988; Mizoue, 1991; Gupta, 1991; Console *et al.*, 1993). A number of studies on the nature of foreshock activity (Mogi, 1969; Utsu, 1970, 1978; Jones and Molnar, 1979; Yamashina, 1981; Bowman and Kisslinger, 1984; Jones, 1984, 1985; Kagan and Knopoff, 1987; Agnew and Jones, 1991; Console *et al.*, 1993; Imoto, 1993; Maeda, 1993, 1996) show promise that this may be a short term predictor for large earthquakes. However, only rarely are foreshocks recognized before the occurrence of their mainshock, because a decisive definition that distinguishes foreshocks from background sesimicity has not yet been established.

Bowman and Kisslinger (1984) applied a statistical method for estimating foreshock occurrence in the Central Aleutian Island arc and

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found that detectable foreshocks preceded about 6 to 10% of 53 mainshocks of $m_b \geq 4.5$ and 14% of 23 mainshocks of $m_b \geq 5.0$. Jones (1985) investigated the probability that an earthquake in Southern California ($M \geq 3.0$) will be followed by an earthquake of larger magnitude within 5 days and 10 km (*i.e.*, it will be a foreshock) is $6 \pm 0.5\%$. Agnew and Jones (1991) published a detailed study of models for the probability of major earthquake characteristic to a particular fault segment, given the occurrence of a potential foreshock near the fault. They found that the rate of mainshock occurrence after a foreshock decays roughly as t^{-1}, where the foreshock occurs within 10 km of the mainshock. The percentage of mainshocks with foreshocks increases linearly as the magnitude threshold for foreshocks decreases. These results are used routinely by U.S. Geological Survey to issue short-term earthquake warnings after moderate earthquakes (Agnew and Jones, 1991). Console *et al.* (1993) reported that for one of the zones in Central Italy, their method led to the issuing of 63 alarms with an optimal definition of foreshocks as $M \geq 3.0$ after 80 days of quiescence in an area with radius 140 km. The rate of occurrence for mainshocks of $M \geq 4.0$ during the following 48 h, in an area with radius 30 km, is 6 out of 23 events. Maeda (1996) gives optimal values of parameters for possible foreshocks, which provide a prediction algorithm with highest performance, on the basis of Precursor Information Criteria (PIC) (Imoto, 1994). For the Japan and Kuril trenches, estimated values are $M_f \geq 5$, $N_f = 3$, $T_a = 5$ days and $D = 0.5°$ for mainshocks with $M \geq 6.0$, giving 13%, 25%, 617 and 75 for AR, TR, PG and PIC respectively; and $M_f \geq 4.0$, $N_f = 1$, $T_a = 1$ day and $D = 0.25°$ for mainshocks with $M \geq 5.0$, giving 9%, 0.8%, 56 and 220 for corresponding parameter values. These parameters are defined in a later section.

Here, for Albania and the surrounding area, we investigated the characteristics of foreshock activity for moderate and large earthquakes of this century. Using a prediction algorithm based on possible foreshocks (Maeda, 1996), we obtained a probabilistic relation between possible foreshocks and mainshocks. We also investigated the regional variation of foreshock activity.

2. Data

The data sources for this work are:

A – The Catalogue of Albania Earthquakes, for the period 1901-1970 for $M \geq 4.1$ (Sulstarova and Koçiaj, 1975).

B – The Catalogue of Earthquakes in Albania and Surrounding Areas, for the period 1971-1990 for $M \geq 4.0$ (Koçiaj *et al.*, 1993). We have improved this catalogue with new information and evaluations.

C – The Monthly Bulletins of Albania Seismological Network for the period 1991-1994.

For the period 1901-1970, in catalogue A, magnitude M_s (surface wave-magnitude) evaluation is made mainly from maximal intensity I_0 (MSK-64) according to the formula (Sulstarova, 1974):

$$M_s = 0.6\,I + 1.0$$

and for the period 1971-1994, we used M_L magnitude values which appear in the catalogues B and C. The investigated area and the seismicity map based on all the data we used are shown in fig. 1. To determine any changes in detection capability, we made several cumulative number of events *versus* magnitude diagrams (with b-value evaluated by Utsu's method (1965)), for different periods (see fig. 2a,b). These and another study (Maeda, 1996) led us to divide the data into three sets.

I - Documentary and instrumental data set for the years 1901-1994, area 39.0°-43.0°N, 18.5°-21.5°E, and depth ≤ 60 km with magnitude $M \geq 4.4$. The b-value is 0.90 (see fig. 2a) for $M \geq 4.4$ in the earlier period of this data set, 1901-1970, and this is close to the previously published value for the Albania area (Sulstarova *et al.*, 1980; Peçi, 1989).

II - Data set for the years 1971-1994 and the same area and depth as data set I, with magnitude $M \geq 4.0$. The b-value (see fig. 2b) is 1.32.

III - Data set having the same data source as data set I but for earthquakes with $M \geq 4.0$. We know that smaller events are not detected and the data set is not complete, especially for the earlier part of the catalogue.

Data set I is suitable for calculating probabilities for $M \geq 6.0$ mainshocks with $M \geq 4.4$

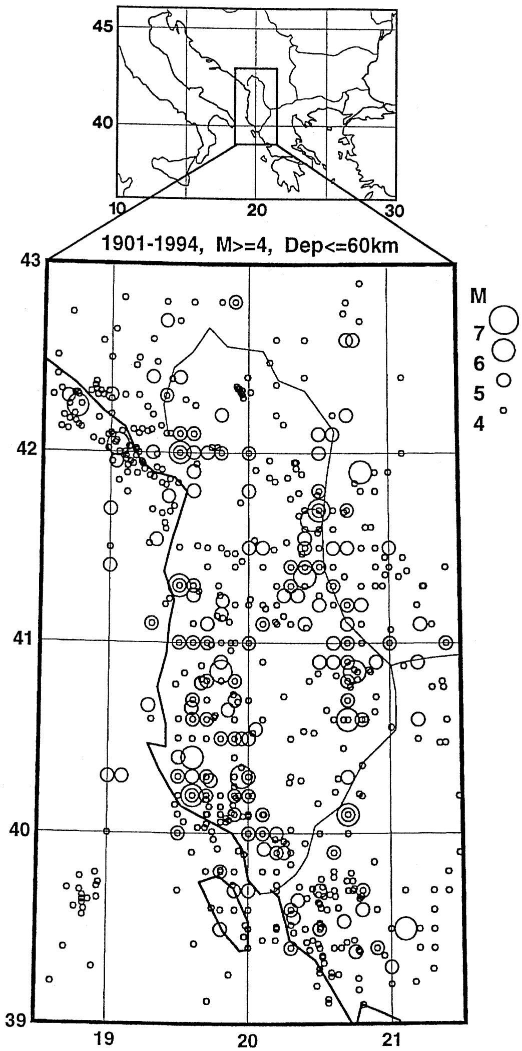

Fig. 1. Epicentral distribution of earthquakes with $M \geq 4.0$ for the period 1901-1994 in Albania and surrounding area.

foreshocks because it includes many $M \geq 6.0$ earthquakes, but we must allow for the possibility of incompleteness for smaller earthquakes in the earlier part of the catalogue. Data set II is suitable for calculating probabilities for $M \geq 5.0$ mainshocks with $M \geq 4.0$ foreshocks and gives reliable results. From data set III, which contains a large number of data although it is incomplete and inhomogeneous in time, we investigate regional variations of foreshock activity for $M \geq 5.0$ mainshocks.

3. Method

We evaluated the probability of occurrence of moderate and large earthquakes immediately after possible foreshocks by using Maeda's four steps method (1996): a) eliminate small aftershocks; b) segment the region; c) select foreshocks according to the level of clustering, and d) estimate probabilities for the occurrences of mainshocks in an alarm period immediately following possible foreshocks.

The probabilities depend significantly on the parameters used in the selection of possible foreshocks and therefore we estimated the optimal values of those parameters according to the Precursor Information Criteria (PIC) proposed by Imoto (1993, 1994).

The four steps for Maeda's (1996) method were implemented as follows.

a) On the basis of several studies (Utsu, 1969, 1970; Reasenberg and Jones, 1989; Hosono and Yoshida, 1992; Maeda, 1996) we eliminated from the catalogues aftershocks defined as having

$$\log L \leq 0.5\, M_m - 1.8 \tag{3.1}$$

$$t \leq 10^{[0.17 + 0.85(M_m - 4.0)]/1.3} - 0.3 \tag{3.2}$$

and

$$M_a < M_m - M_d : M_d = 1.5 \tag{3.3}$$

where L is epicentral distance from a mainshock; t is time in days from the occurrence of a mainshock; M_m is the magnitude of the mainshock; M_a the magnitude of an aftershock and M_d the magnitude difference between mainshock and aftershock. After removing small aftershocks from the original data, we had 575, 294, and 789 events for data sets I, II and III respectively.

b) To quantify the clustering of earthquakes by counting events in a given space-time window and to define the prospective area where a

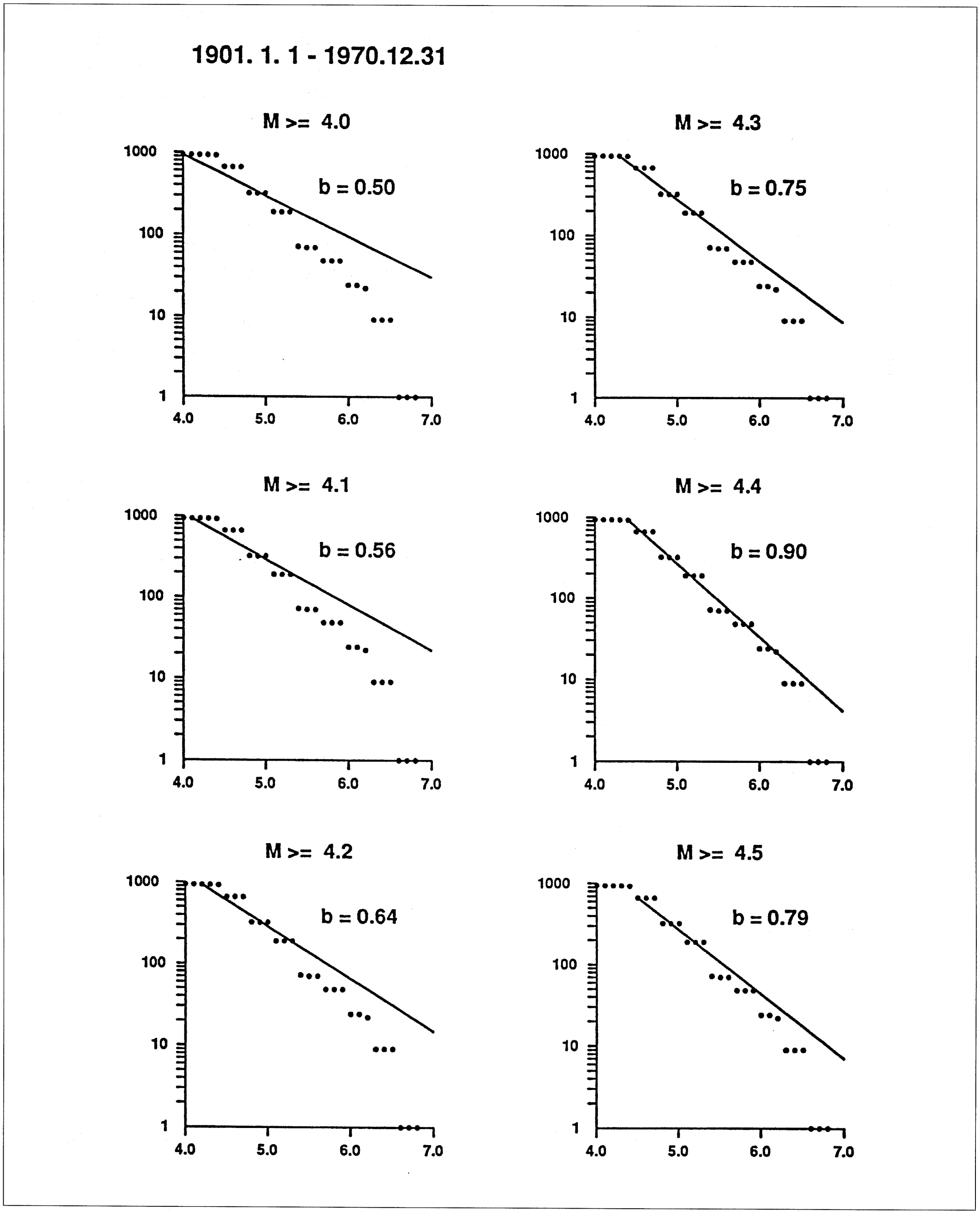

Fig. 2a. Cumulative number-magnitude diagrams and *b*-values for the period 1901-1970 for the different threshold magnitudes.

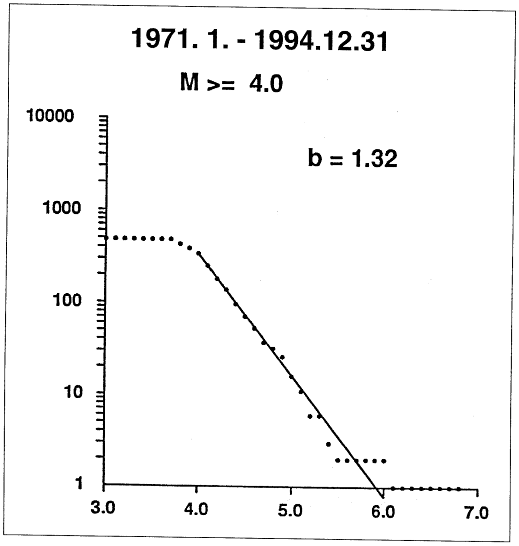

Fig. 2b. Cumulative number-magnitude diagram and b-value for the period 1971-1994 with $M \geq 4.0$.

mainshock is expected to occur, we divided the region into small rectangular segments D degree by D degree with $D = 0.5$. This implies that the distance between a foreshock and a mainshock is less than about 50 km. Segment are spaced at every half of D, that is, they are laid so that they overlap each other by half, because the earthquake which clustered in a marginal zone of a segment should be counted appropriate.

c) The criterion for defining possible foreshocks in each segment is shown in fig. 3. T_f is the time window for selecting possible foreshocks and T_a is the alarm period during which mainshocks are expected to occur. Both T_f and T_a are fixed at 10 days and the magnitude for foreshocks is taken as $M_f \geq 4.4$ for data set I and $M_f \geq 4.0$ for data sets II and III. We give N_f, which defined the number of earthquakes for selecting possible foreshocks, different values to examine its effect on the probability estimation for mainshocks. Every earthquake with magnitude $M \geq 4.4$ in the data set I and $M \geq 4.0$

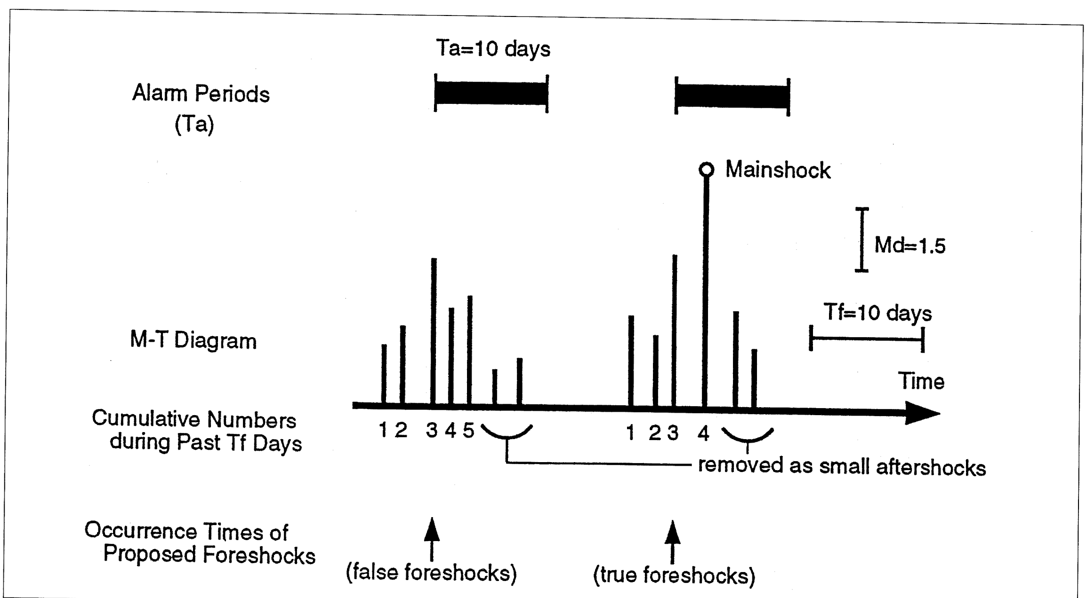

Fig. 3. Schematic diagram showing alarm criterion for each segment for the case of $T_f = 10$ days, $N_f = 3$, and $T_a = 10$ days, where T_f is the time window in which the number of earthquakes should be counted with $M_f \geq 4.4$ or $M_f \geq 4.0$; N_f is the cumulative number of earthquakes during past T_f days for defining possible foreshocks; and T_a is the alarm period during which the mainshock is expected to occur.

in the data set II and III is checked to see if it satisfies the condition of clustering for possible foreshocks.

d) The probability estimation is expressed in terms of the factors: Alarm Rate (AR), Truth Rate (TR) (Utsu, 1977) and Probability Gain (PG) (Aki, 1981; Kagan and Knopoff, 1977).

AR is the ratio of the number of mainshocks occurring in the expected space-time to the total number of mainshocks. TR is the ratio of the number of cases of possible foreshocks followed by a mainshock in the expected space-time to the total number of cases of occurrence of possible foreshocks.

PG is the ratio of occurrence rate of mainshocks in the expected space-time from the prediction algorithm to the background occurrence rate, and is a good index for evaluating the relation between possible foreshocks and mainshocks.

The characteristic for AR indicates that mainshocks preceded by foreshocks become rarer as the number of foreshocks becomes larger. The fact that TR and PG have maximum values at some value of N_f means that such a grade of clustering earthquakes are most likely to be true foreshocks.

Since AR and PG vary differently with changes in parameters for possible foreshocks, we used the PIC criterion (Imoto, 1993, 1994; Maeda and Imoto, 1995) to estimate the optimal value of N_f for a prediction algorithm. PIC can be expressed as:

$$\mathrm{PIC} = 2\, n_0\, \mathrm{AR} \log_e \mathrm{PG} + \\ + 2n_0\,(1-\mathrm{AR})\log_e\{(1-\mathrm{AR})/(1-\mathrm{AR}/\mathrm{PG})\} - 2 \tag{3.4}$$

where n_0 represents the total number of mainshocks. Here we omit from the original formula the term related to the number of parameters, because we dealt only with relative values of PIC by changing the value of N_f. PIC includes not only mainshocks successfully alarmed, which are related to the first term of the formula (3.4), but also mainshocks with alarm (second term). The larger the value of PIC, the higher the total performance of the prediction algorithm.

Using data sets I and II, we evaluate the probability of occurrence of mainshocks immediately after possible foreshocks. We use different values of N_f, that is, different levels of clustering earthquakes as possible foreshock, to evaluate AR, TR, PG and PIC and select the optimal value on the basis of PIC.

4. Result and discussion

4.1. *Evaluation of probabilities*

Using data sets I and II, we evaluated the probability of occurrence of mainshocks immediately after possible foreshocks. We used different values of N_f, that is, different levels of clustering earthquakes as possible foreshock, to evaluate AR, TR, PG, and PIC and selected the optimal value on the basis of PIC.

For data set I (see fig. 4a), maishocks with magnitude $M_m \geq 6.0$ are preceded by a foreshock with magnitude $M_f \geq 4.4$, distance ≤ about 50 km and time ≤ 10 days with AR of 38% (6/16) and TR of 1.3% (6/468); PG and PIC are 68, 39 respectively. But the TR value increases to 33% (1/3) and PG becomes about 2170 if 7 earthquakes with magnitude $M_f \geq 4.4$ occur within about 50 km and 10 days.

For data set II (see fig. 4b), mainshocks with magnitude $M_m \geq 5.0$ are preceded by a foreshock with magnitude $M_f \geq 4.0$, distance ≤ about 50 km and time ≤ 10 days with AR of 33% (5/15) and TR of 1.9% (5/262); PG and PIC are 27 and 23. The value of TR increases to 5.6% (1/18) and PG becomes about 119 if 3 earthquakes with magnitude $M_f \geq 4.0$ occur within about 50 km and 10 days.

The PIC has a maximal value for both data sets I and II for $N_f = 1$; *i.e.* $N_f = 1$ is the optimal value and results in the highest performance for the prediction algorithm.

The values of AR for $N_f = 1$ are apparently similar to the result of Jones (1984), *i.e.* 35% of mainshocks with $M_m \geq 5.0$ are preceded by foreshocks with $M_f \geq 2.0$ within 1 day and 5 km. However, we cannot easily compare the results of different studies because the definitions for foreshocks are not the same. Imoto (1994) pointed out that one possible way of comparing the effectiveness of different prediction algorithms is to use the value of PIC divided by the total

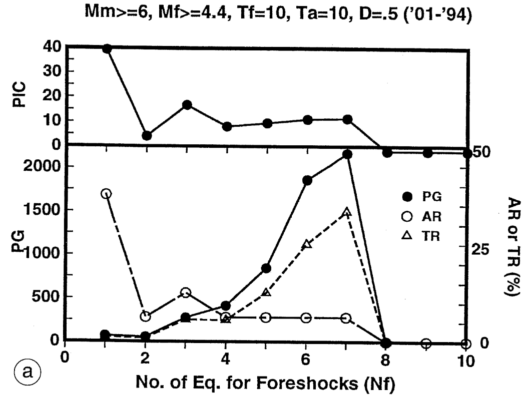

Fig. 4a. Variation of AR, TR, PG and PIC with N_f for data set I, for the case of $M_m \geq 6.0$, $M_f \geq 4.4$, $T_a = 10$ days and $D = 0.5$.

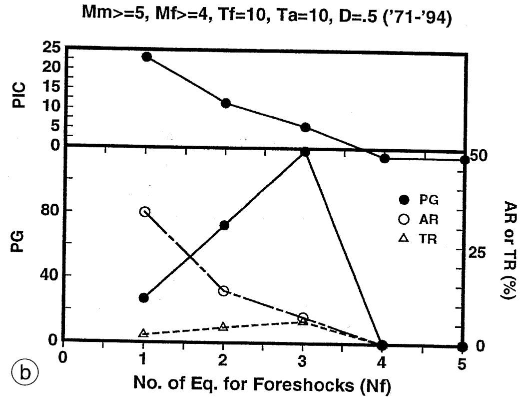

Fig. 4b. Variation of AR, TR, PG and PIC with N_f for data set II, for the case of $M_m \geq 5.0$, $M_f \geq 4.0$, $T_a = 10$ days and $D = 0.5$.

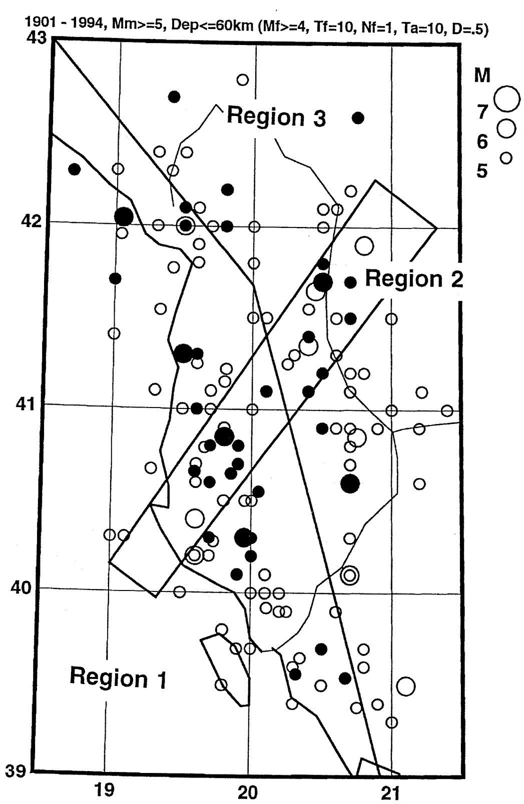

Fig. 5. The distribution map of earthquakes with $M \geq 5.0$ preceded by foreshock(s) with $M \geq 4.0$ within about 50 km and 10 days (solid circles) and those preceded by no foreshocks within the same range of distance and time (open circles), for the period 1901-1994. Seismic region are also shown.

number of mainshocks, N_m. If we so compare the result for mainshocks with $M_m \geq 5.0$ for the Japan and Kuril trench region (PIC is 220 for 397 mainshocks (Maeda, 1996)) with that of this study (PIC is 23 for 15 mainshocks) on the basis of Imoto's criterion, we can say that the foreshock activity in Albania and surrounding area (PIC/N_m = 1.5) is more effective in predicting mainshocks with $M_m = 5.0$ than for the Japan and Kuril trench region (PIC/N_m = .55).

4.2. *Region variation of foreshock activity*

We also evaluated the probabilities according to regional variation of seismicity in the area. Several studies of seismicity in the Aegean area show that the seismic activity is concentrat-

Table I. List of mainshocks with $M_m \geq 5.0$ preceded by foreshock(s) with $M_f \geq 4.0$ within about 50 km and 10 days on the basis of data set III for the period 1901 through 1994.

Year	Month	Day	h:min	Lat.	Long.	Depth	Magnitude
1905	6	1	21:47	42°12.0′	19°48.0′	31	5.3
1905	8	4	09:14	41°42.0′	19°00.0′	16	5.9
1905	8	12	21:26	42°00.0′	19°30.0′	13	5.3
1907	8	16	13:15	41°06.0′	20°06.0′	13	5.6
1920	11	26	08:50	40°18.0′	19°57.0′	7	6.5
1920	11	29	15:48	40°39.0′	19°51.0′	18	5.3
1921	3	30	15:05	41°42.0′	20°30.0′	17	6.2
1922	6	9	16:13	41°48.0′	20°30.0′	15	5.3
1922	12	7	16:37	41°42.0′	20°42.0′	14	5.4
1923	1	7	12:27	41°06.0′	20°06.0′	17	5.0
1926	12	17	06:17	41°18.0′	19°36.0′	20	5.0
1926	12	17	06:20	41°18.0′	19°30.0′	20	5.0
1926	12	17	06:31	41°18.0′	19°30.0′	20	5.6
1926	12	17	11:39	41°18.0′	19°30.0′	11	6.5
1927	8	14	00:00	42°06.0′	19°30.0′	17	5.0
1930	7	16	16:00	40°18.0′	20°00.0′	11	5.3
1931	1	28	05:55	40°36.0′	20°42.0′	10	6.2
1931	8	13	06:21	40°18.0′	19°42.0′	7	5.3
1931	9	20	03:30	40°36.0′	19°42.0′	13	5.0
1932	12	11	21:46	42°42.0′	19°24.0′	22	5.0
1935	3	31	03:44	41°06.0′	20°24.0′	18	5.0
1935	4	3	21:44	41°12.0′	20°30.0′	11	5.0
1946	4	16	11:43	40°48.0′	19°54.0′	27	5.0
1947	2	5	15:33	42°36.0′	20°45.0′	11	5.4
1948	8	27	11:24	42°00.0′	19°48.0′	17	5.6
1959	8	17	04:29	40°48.0′	19°42.0′	20	5.0
1959	9	1	11:37	40°51.0′	19°48.0′	18	6.2
1959	10	7	08:30	41°00.0′	19°36.0′	25	5.6
1960	5	26	05:10	40°36.0′	20°42.0′	7	6.2
1963	2	22	14:12	40°12.0′	20°00.0′	17	5.3
1964	12	9	19:06	40°54.0′	20°30.0′	17	5.0
1966	8	16	03:53	40°06.0′	19°54.0′	6	5.3
1967	7	20	19:03	40°42.0′	19°54.0′	6	5.3
1967	12	4	00:48	41°30.0′	20°42.0′	5	5.3
1968	2	24	12:55	41°24.0′	20°24.0′	5	5.0
1969	4	8	15:48	40°33.0′	20°03.0′	17	5.0
1969	10	13	01:02	39°42.0′	20°30.0′	15	5.6
1976	3	2	19:41	40°39.6′	19°35.4′	11	5.0
1979	4	15	06:19	42°02.4′	19°03.0′	4	6.8
1979	4	15	14:43	42°17.4′	18°40.8′	7	5.0
1979	11	6	05:26	39°33.6′	20°19.2′	26	5.1
1981	7	3	21:42	39°32.4′	20°40.2′	41	5.0

ed along major seismic fracture zones (Papazachos, 1980; Papazachos *et al.*, 1984; etc.). Papazachos *et al.* (1987) divided the Aegean and surrounding area into 17 fracture zones of shallow earthquakes ($h \leq 70$ km) on the basis not only of the seismicity but also of the tectonic features of the region. Some of these zones include part of Albania. Detailed features of the geology, tectonics and seismicity in Albania have been reported (Aliaj, 1983,1988; Sulstarova, 1986; Sulstarova *et al.*, 1980; Muço, 1994).

For this study, on the basis of these studies and focal mechanism solutions for some earthquakes (Muço, 1994), we divided the area into three regions (see fig. 5):

Region 1: The Ionian-Adriatic seismic zone is the western part of the area excluding part of region 2 and has a southeastern extent of several hundred kilometers from the Dalmatian coast, continuing to Greece. Compressional stress is dominant with orientation almost perpendicular to the shoreline.

Region 2: The Vlora-Elbasani-Dibra transversal seismic belt is a transversal fault zone with ENE extension and dislocates the Albanides along their width. Extensional stress is dominant (Aliaj, 1983; Sulstarova, 1986).

Region 3: The interior part of Albanide seismic zone includes the eastern part of the area excluding part of region 2 and has predominately extensional stress in the NW-SE direction.

Figure 5 shows the distribution map of earthquakes for $M_m \geq 5.0$ preceded by foreshock(s) with $M_f \geq 4.0$ within about 50 km and 10 days (solid circles) and those preceded by no foreshocks within the same range of distance and time (open circles) on the basis of data set III for the period 1901 through 1994. The seismic zones and the seismic belt mentioned above are also indicated. The total number of mainshocks preceded by foreshock(s) is 42 and they are listed in table. I. For Region 1 (see fig. 5) the ratio of mainshocks which are preceded by foreshocks to all mainshocks for $M_m \geq 5.0$ is 23% (19/83). This value corresponds to the Alarm Rate (AR). For Region 2 the value of AR is 33% (16/49) which gives similar values to those in the dominantly transverse faulting region of California (Jones, 1985) and also to those (Savage and de Polo, 1993) found in the more extensional Eastern California and basin and range. For region 3 the value of AR is 15% (7/47).

From these values we see that there is regional variation of foreshock activity decreasing from Region 2 to 1 to 3. According to the interpretation that foreshocks or some kind of swarm activity could be related to the degrees of heterogeneity in structure (Mogi, 1963), this result suggests that Regions 2, 1 and 3 would be fractured or have small-scale heterogeneity in that order.

5. Conclusions

We evaluated the probabilities of occurrence of mainshocks immediately after possible foreshocks for the Albanian and surrounding area and obtained:

1) The optimal value of $N_f = 1$ with the conditions of $M_f \geq 4.4$, $T_a = 10$ days and $D = 0.5°$ for $M_m \geq 6.0$ mainshocks, giving 38% (6/16), 1.3% (6/468), 68 and 39 for AR, TR, PG and PIC respectively. But the TR and PG values increase to 33% (1/3) and 2170 for $N_f = 7$.

2) The optimal value of N_f for possible foreshocks for the data set II is also $N_f = 1$ for $M_f \geq 4.0$, $T_a = 10$ days and $D = 0.5°$ for $M_m \geq 5.0$ mainshocks, giving 33% (5/15), 1.9% (5/262), 27 and 23 for AR, TR, PG and PIC. But the TR and PG values increase to 5.6% (1/18) and 119 respectively for $N_f = 3$.

3) There is regional variation of foreshock activity on the basis of data set III; Region 2, 1 and 3 exhibit decreasing activity of foreshocks in that order.

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