PREMONITORY CLUSTERING OF SHOCKS IN CRITICAL REGIONS

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ABSTRACT

The spatial distribution of preshocks in the critical (preshock) regions of large main shocks that occurred in the broader Aegean area (34°N-42°N, 19°E-29°E) during the last two decades is investigated. This study is based on the examination of the time variation of the spatial fractal dimension, D_s, of the preshock epicenters that takes values equal to 2, 1 and zero for surface, line and point distribution, respectively. It has been observed that during the last phase of each preshock sequence, epicenters are clustered (D_s<0.8) at the largest activated faults in the critical region. The duration of this clustering, that is, the time difference between the origin time of the mainshock and the drop of D_s from values larger than 1.0 to values smaller than 0.8 lasts up to a few years (2.2±1.1 years). Since this spatial clustering of preshocks has been observed in all cases examined in the present paper, it can be considered as an intermediate term precursory phenomenon and can be used for estimating the origin time of an ensuing mainshock. For this reason the procedure described above has been applied in a region of the southwestern part of the Hellenic arc, which is currently at an accelerating seismic excitation. Such clustering is observed in this region since 2000.4 and therefore it can be considered as further evidence for an ensuing mainshock in this part of the Hellenic arc during the next few years.

INTRODUCTION

Among the seismicity patterns that have been proposed as precursory phenomena of strong earthquakes (mainshocks) the time and space variation of the generation of intermediate magnitude shocks (preshocks) is an impressive and very promising such pattern for intermediate-term earthquake prediction. Measures, s(t), of deformation energy released by preshocks (Benioff strain, seismic moment, etc) are accelerated with time and culminate in the generation of the mainshock (Tocher, 1959; Sykes and Jaume, 1990; Sornette and Sammis, 1995; Huang et al., 1998 and reference therein). It has been shown that the time variation of s(t) can be fitted by a power-law relation and for this reason the generation process of these moderate magnitude preshocks is considered as a critical phenomenon and the mainshock as a critical point (Sornette and Sornette, 1990; Bufe and Varnes, 1993; Jaume and Sykes, 1999). The duration of a preshock sequence is of several years up to a few decades, that is, much longer than the duration of a classical foreshock sequence.

Several studies on the spatial distribution of preshocks have been also carried out (Bowman et al., 1998; Papazachos and Papazachos, 2000). Thus, Bowman and his colleagues considered circular preshock (critical) regions centered at the epicenter of each one of the mainshocks with M≥6.5 that occurred at the San Andreas fault system since 1950. They defined a curvature parameter, C, as the ratio of the root- mean-square error of the power-law fit to its linear fit (it is less than 1 for accelerating or decelerating preshock deformation and almost equal to 1 for more or less linear variation of deformation). Papazachos and Papazachos (2000) defined elliptical preshock regions centered at the epicenters of strong shallow earthquakes in the Aegean area and showed that the dimension of a preshock region is about eight times the dimension of the fault region where classical foreshocks occur. Thus, preshocks generation does not only last much longer than classical foreshocks but their foci are also distributed in a much larger area.

Very recently a systematic investigation of the seismic deformation (Benioff strain) released by intermediate magnitude shocks (preshocks) preceding strong earthquakes (mainshocks) in the Aegean area has shown that in all investigated cases (52 sequences) this preshock deformation is an accelerating function of the time to the mainshock and is very satisfactorily fitted by a power-law relation (Papazachos and Papazachos, 2000; Papazachos and Papazachos 2001). This investigation has led to some relations between the parameters of the power-law and other independently determined parameters and these relations have formed additional constraints to the accelerating seismic deformation model. Parameters of this improved model have been used in an algorithm for intermediate term earthquake prediction (Papazachos 2001). The most important relations in this model are the ones revealing a positive correlation between the dimension of the preshock (critical) region and the magnitude of the ensuing mainshock and, on the other hand, a negative correlation between the duration of the preshock sequence and the long term seismicity level of the preshock region. It has been further shown that the curvature parameter, C, as well as the parameter, b, of the recurrence frequency for preshocks decrease with time to the mainshock (Karakaisis et al., 2002).

The goal of the present paper is to investigate the spatial distribution of preshocks in the critical region, that is, to examine whether preshocks are randomly distributed or are clustered and how this distribution varies with the time to the main shock. Such investigation is of theoretical interest, because it will give information on the physical process in the critical (preshock) region, as well as of practical importance because it can give useful information for the prediction of the main shock. The method applied is based on the fractal theory and the data used concern preshock sequences in the Aegean area for which information on a relatively large number ($n \geq 100$) of preshocks is available.

METHOD AND DATA

Spatial distribution of seismicity is usually investigated qualitatively by plotting epicenters on maps using different symbols to denote different earthquake sizes and different focal depths. The recognition of the fractal structure of the spatial distribution of earthquakes (Kagan and Knopoff, 1980) and of the fractures in rocks (Hirata et al., 1987) formed the basis for a quantitative investigation of the spatial distribution of seismicity. This fractal approach gives the possibility to identify regions where seismicity is randomly distributed or is clustered or has an intermediate character. For this purpose a quantity, called spatial fractal dimension, D_s, is used (Mandelbrot, 1967).

Assuming that the distance, r, between the epicenters of the shocks in a region has a fractal distribution the following relation holds:

$$C(r) = r^{Ds} \quad (1)$$

with D_s=0, D_s=1 and D_s=2, for a distribution at a point, on a line and on a surface, respectively (Grassberger and Procaccia, 1983). Thus, by plotting C(r) as a function of r in a log-log scale we get a straight line with a slope equal to D_s. There is a lower and an upper limit in this curve, which are defined by the minimum and maximum distance among the pairs of epicenters. To get reliable results the lower limit of the distance considered must not be smaller than the location error and its upper limit must be smaller than 30-50% of the maximum distance involved (Dongsheng et al., 1994).

Table 1. *Information on the three past mainshocks (ALK, NAG, CEP) and on the expected mainshock (CYT) as well as on their critical (preshock) elliptical regions. a is the length (in km) of the big axis, z is the azimuth of this axis, e is the ellipticity, t_s is the starting year of the preshock sequence, M_{min}, is the magnitude of the smallest preshock, n is number of preshocks, r_1, r_2 are the smallest and largest considered distance (in km) between the preshock epicenters.*

No	Name	Date	φ^o_N, λ^o_E	M	a	z	e	t_s	M_{min}	n	r_1-r_2
1	ALK	1981, 02, 24	38.2, 22.9	6.7	333	0	0.95	1966	4.3	352	11-208
2	NAG	1981, 12, 19	39.0, 25.3	7.2	280	30	0.80	1951	4.7	205	15-256
3	CEP	1983, 01, 17	38.1, 20.2	7.0	385	60	0.95	1967	4.7	168	13-274
4	CYT	2002.8	36.4, 22.8	6.8	289	70	0.95	1992	4.3	143	26-111

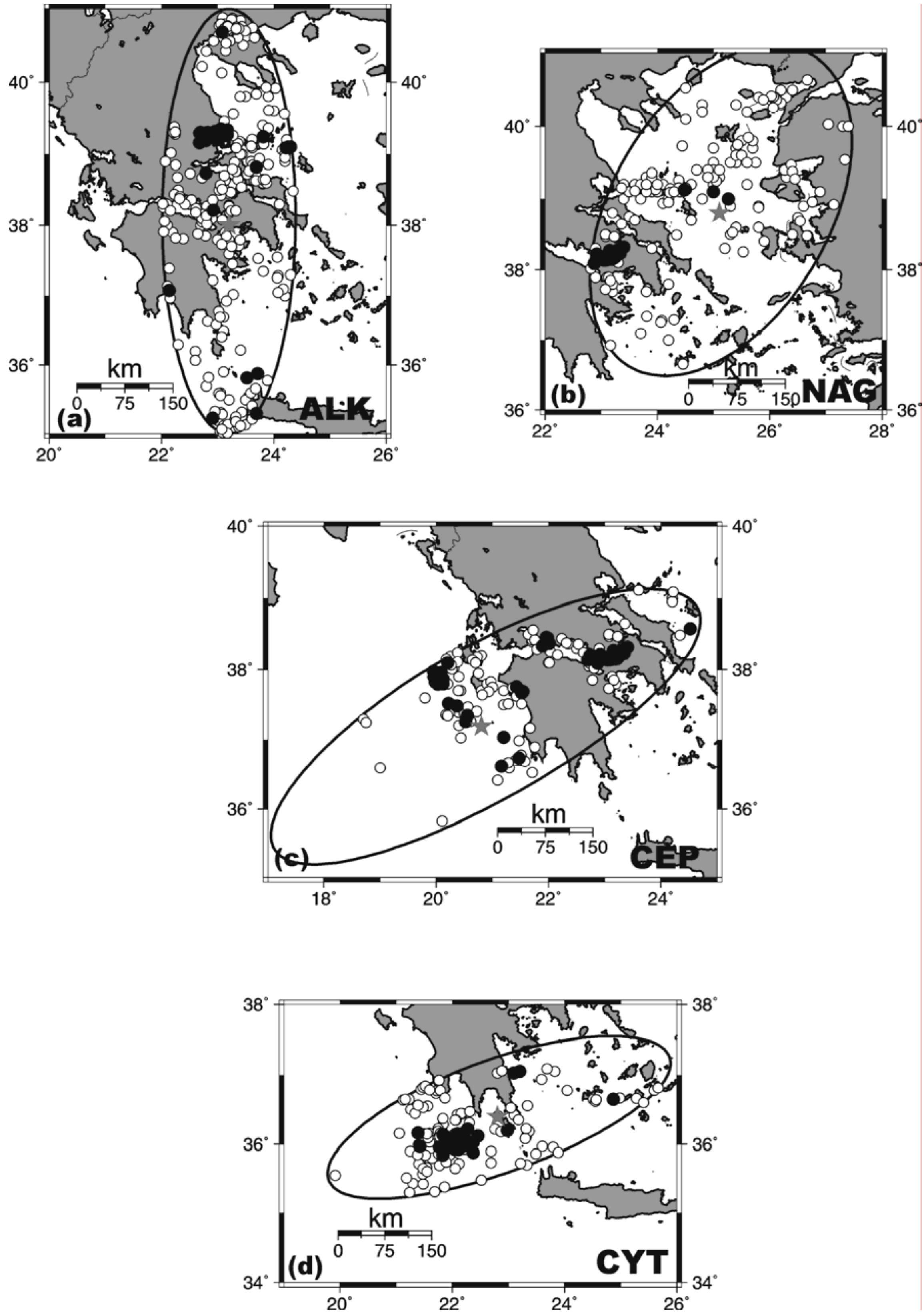

Figure 1. *Elliptical critical regions of the three already occurred mainshocks, (a) ALK, (b) NAG, (c) CEP and for the expected mainshock (d) CYT. The small circles show epicenters of preshocks. Black circles show the epicenters of preshocks, which occurred during the last phase of each preshock sequence. A star denotes the center of each ellipse.*

The basic data set used in the present paper concern preshock sequences of recent (1981-2001) strong ($M \geq 6.7$) main shocks in the Aegean area for which the number of preshocks is sufficiently large ($n>100$). There are three such main shocks for which code symbols (ALK=Alkyonides, NAG=North Aegean, CEP=Cephalonia), dates, epicenter coordinates and magnitudes, M, are given in table (1). In the same table such information is also given for an expected main shock in the southwestern part (CYT=Cythera) of the Hellenic arc (Papazachos et al., 2002). Moreover, information for the four preshock (critical) regions is also given (length, a, and azimuth, z, of the big ellipse axis, the ellipticity, e, the number, n, and the minimum magnitude, M_{min}, of preshocks, the start year, t_s, of the preshock sequence) in the table. Figure (1) shows the 4 elliptical preshock regions and the epicenters of the corresponding preshocks (small circles). The parameters of preshocks (epicenter coordinates, dates, magnitudes) used in the present study have been taken from the catalogue of Papazachos et al. (2000).

The procedure followed in this paper to calculate D_s and examine its time variation is the one suggested by De Rubeis et al. (1993) and Tosi (1998). The investigated preshock period is separated in windows, each one including 40 events. Calculation of the spatial fractal dimension, D_s, is made by the use of the distance among the epicenters of the forty events of each window and the value is assigned to the occurrence time of the last event.

Figure (2) shows the $\log_2 C(r)$ as a function of $\log_2 r$ for the four cases investigated in the present paper by using the data of the whole preshock period for each case. A straight line is fitted in the linear part of each curve (continuous line in each plot). In table (1) the minimum and maximum distances r_1-r_2 corresponding to this linear part of the curve are given (in km). The smallest distance, r_1, is defined by the location error and the largest distance, r_2, is defined by the corresponding point of the curve where saturation of $\log_2 C(r)$ starts (see fig.2). To calculate the spatial fractal dimension, D_s, for several time windows (with number of observations 40) only distances between r_1 and r_2 shown on table (1) have been used.

RESULTS

Figures (3a, b, c) show the variation of the spatial fractal dimension, D_s, as a function of time, t (in years), to the main shock, for each one of the three preshock sequences which preceded the three already occurred mainshocks. An abrupt drop of D_s from values larger than 1.0 to values smaller than 0.8 is observed in all three cases during the last few years of the preshock period. It indicates a strong spatial clustering of the epicenters of preshocks during the last phase of the critical period.

For the ALK preshock sequence a drop of D_s is also observed in 1978. This is obviously due to the preparation of the generation of another Mainshock, which occurred on 7 July 1980 (M=6.5). Similarly, for the NAG preshock sequence a drop of D_s, which started in 1965, is observed and this is obviously due to the preparation of the generation of the large earthquake, which occurred on 19 February 1968 (M=7.1) in the same area. The time difference between the start of this drop of D_s (dashed arrows in fig. 3) and the occurrence time of the corresponding mainshock varies between 0.6yrs and 1.9yrs. Therefore, this decrease of the value of the spatial fractal dimension in the critical (preshock) region of large main shocks can be considered as an intermediate-term premonitory phenomenon and its start time can be used for estimating the origin time of an ensuing mainshock.

Figure (3d) shows the time variation of the spatial fractal dimension as a function of time in the critical (preshock) region of the expected mainshock in the southwestern part of the Hellenic arc. A clear drop of D_s, which started in 2000.4, is observed for this region too. This is a further support to the results derived by the accelerating precursory crustal deformation method that a large mainshock may occur during the next few years in this part of the Hellenic arc (Papazachos et al., 2002).

In figure (1a, b, c, d) the small black circles show the epicenters of preshocks during the last phase of each preshock sequence when $D_s<1.0$. It is observed that epicenters are really clustered at small areas. These areas coincide with known rupture zones (faults) of strong preshocks. In the case of CEP clustering also occurred in the southwestern part of the Cephalonia Transform Fault (Scordilis et al., 1985) where this mainshock occurred (fig. 1c).

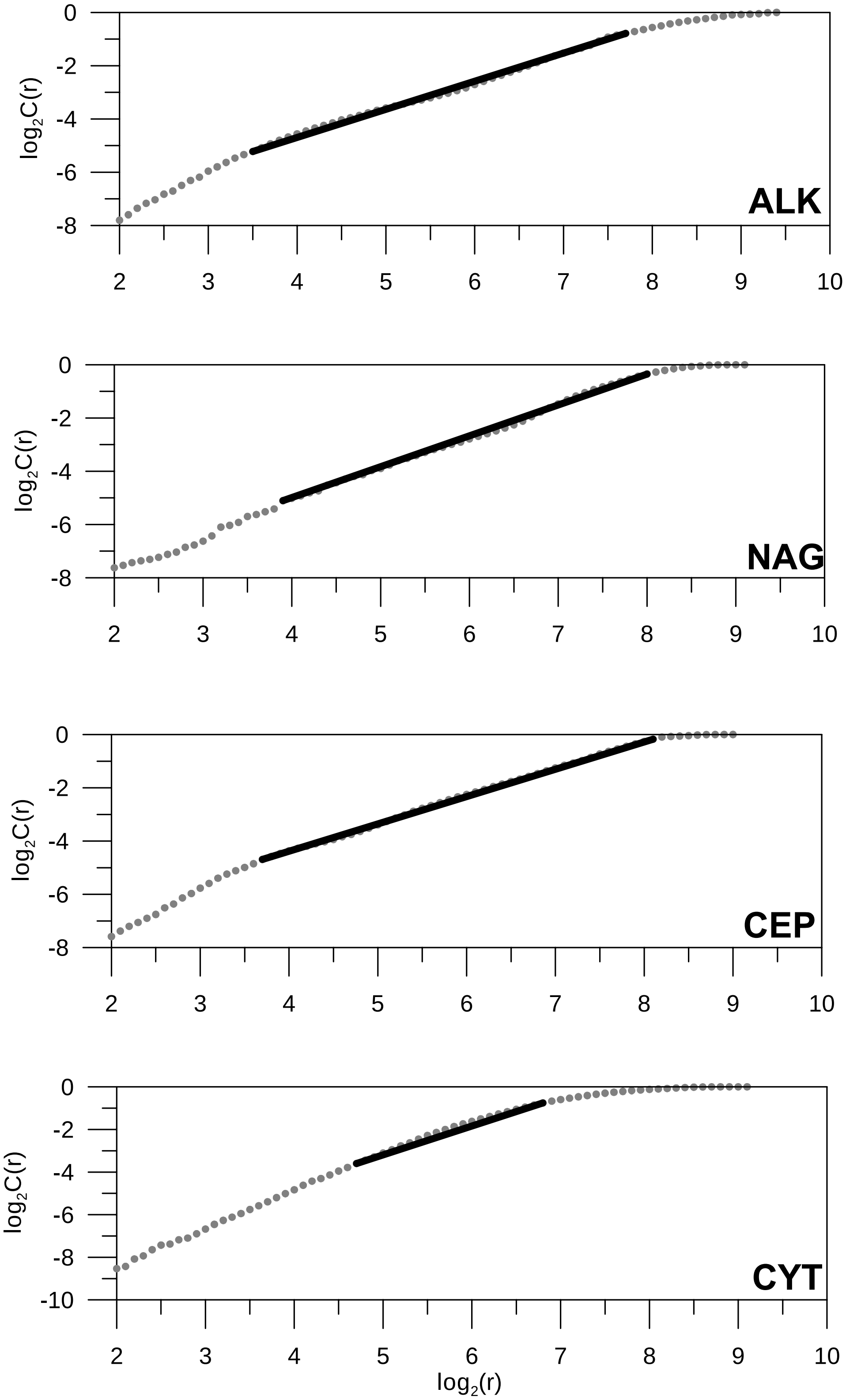

Figure 2. *Log-log plots of C(r) versus the distance r (in km) between the epicenters of the preshocks in the critical regions of the Alkyonides (ALK), Northern Aegean (NAG), Cephalonia (CEP) mainshocks and for the expected mainshock (CYT). The continuous line segment shows the linear section of the curve.*

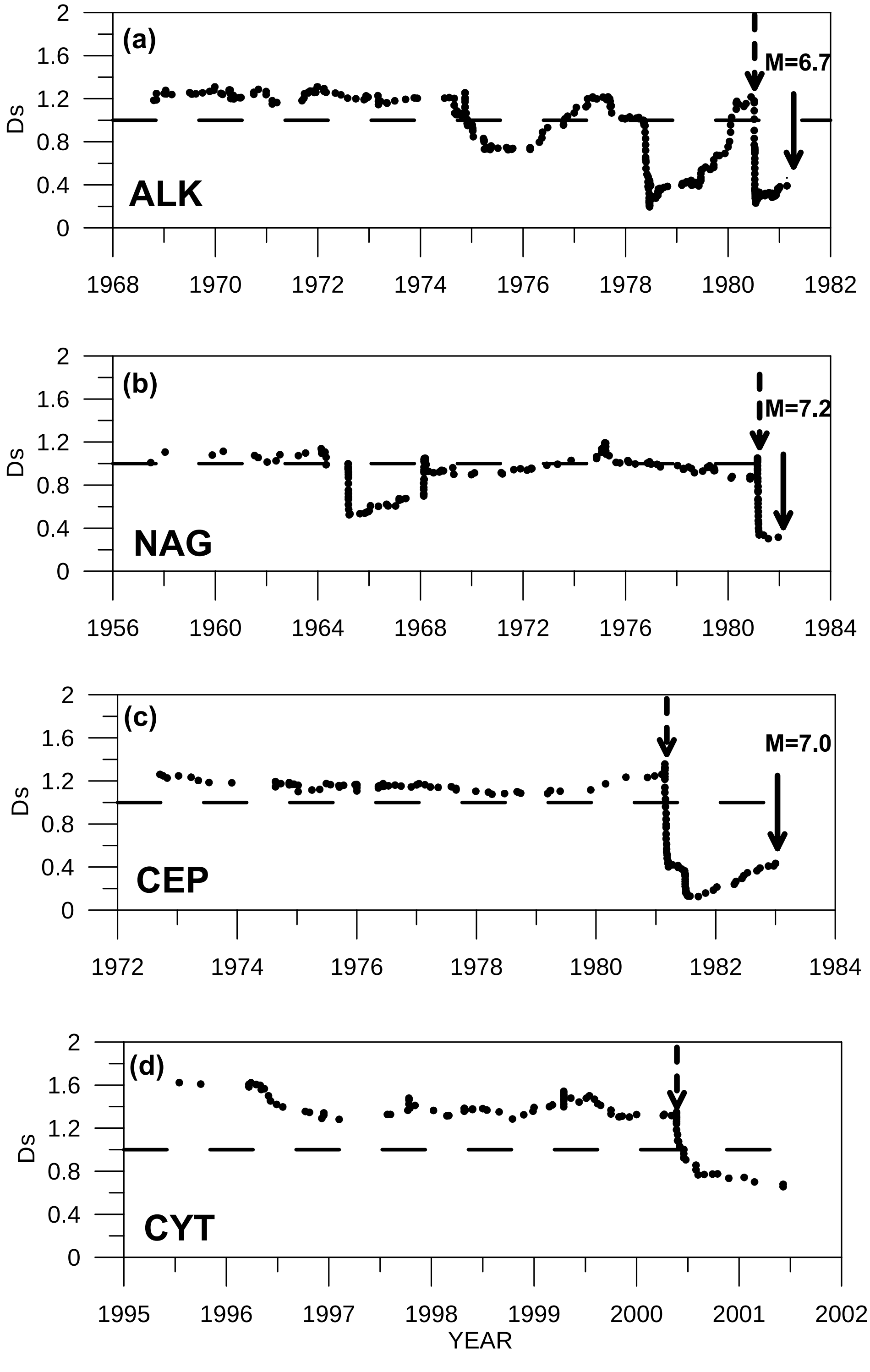

Figure 3. *Time variation of the spatial fractal dimension, D_S, for the distribution of the epicenters of preshocks in the critical regions of the, (a) Alkyonides (ALK), (b) Northern Aegean (NAG), (c) Cephalonia (CEP) mainshocks and (d) for the expected mainshock (CYT). Dashed arrows show the time when start of the drop in D_s occurs. The continuous line arrows show the time of the mainshock. The magnitude of the mainshock is also given.*

Hence we can suggest that intense spatial clustering of seismic activity (D_s<1.0), which occurs in the critical (preshock) region of an oncoming mainshock during the last phase of the preshock period, is usually located on the largest faults of the preshock region or in the rupture zone of the mainshock.

We also attempted to estimate an optimum value for the magnitude, M_{min}, of the smallest preshock, that is, if there is a value of M_{min} for which the precursory phenomenon is more pronounced. We found that the precursory spatial cluster of preshocks is more pronounced when the difference between the magnitude of the main shock and the magnitude of the smallest preshock is 2.4±0.2.

DISCUSSION

As can be concluded from figures (1) and (3), epicenters of preshocks which occur up to a certain time are almost randomly distributed in the preshock (critical) region (D_s>1.0), while during the last phase of the preshock period the preshock epicenters are clustered (D_s<0.8) in the rupture zones of the largest preshocks. Thus, we can separate the preshock period into two phases: the first, which is long (several years or decades) and a second one (a few years). During the first phase, ruptures take place in relatively small faults distributed all over the preshock region, while during the second (last) phase ruptures occur mainly in certain large faults of this region.

To further test the hypothesis that an abrupt decrease of the spatial fractal dimension, D_s, from more than 1.0 to less than 0.8 occurs in the last phase of the preshock sequence we examined the time variation of D_s for all other (four) main shocks with M≥6.4 which occurred in this area since 1981 and for which less than 100 events were available (05.07.1983 M=6.4, 13.05.1995 M=6.6, 15.06.1995 M=6.4, 13.10.1997 M=6.4, 18.11.1997 M=6.6) as well as for two strong main shocks which occurred before 1981 (19.02.1968 M=7.1, 28.03.1970 M=7.0). This change of D_s was also observed in all these cases but it was not always so pronounced as in the cases of the large (M≥6.7) main shocks shown in figure (3) for which the available data formed a larger data sample (n>100). The precursory time for all nine cases examined varies between 0.6yrs and 4.2yrs with an average equal to 2.2yrs and a standard deviation equal to 1.1. It means that when this precursory phenomenon is observed the origin time of the ensuing main shock can be estimated with an uncertainty of ±2.0yrs with a high confidence (~90%). It is of interest to note that this value is almost equal to the uncertainty of this estimation when the alternative method of preshock excitation is applied (Papazachos et al., 2001).

We should point out that the result presented in the current work and the sudden D_s decrease seen in figure (3) should only be considered in the framework of the accelerated seismicity model, as this has been applied for the broader Aegean area (Papazachos and Papazachos 1999, 2000). Therefore, the observed D_s decrease can be used as a precursory indicator only for areas exhibiting an accelerated deformation pattern and not as an isolated phenomenon. For this reason and in order to test the significance of our result we have used the results of Papazachos et al. (2002) who have showed that it is possible to identify false accelerated seismicity behavior in realistic random catalogues with a probability of ~15%. Using such false accelerated seismicity patterns we found that in 15-20% of the examined cases a similar decrease of D_s as the one seen in figure (3), was “falsely” identified. Therefore, we should expect that the decrease of D_s in areas of observed accelerated seismicity may also randomly occur, with a probability of ~15-20%.

The precursory spatial clustering of preshocks is more pronounced when the difference between the magnitude of the mainshock and the magnitude of the smallest preshock is 2.4±0.2. This is very helpful from practical point of view because we save significant time in the search for identification of this precursory phenomenon. It is also of theoretical importance because it indicates that the phenomenon is observed when preshocks have magnitudes larger than a certain value, that is, for intermediate magnitude preshocks. Similar results have been recently reported by Vinciguerra (2000) who found that the small magnitude seismicity that preceded the 1989 eruption of Mt Etna, exhibited an abrupt decrease of the time fractal dimension, D.

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