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Precursory seismic crustal deformation in the area of southern Albanides

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Abstract

On the basis of growing evidence that strong earthquakes are preceded by a period of accelerating seismicity of moderate magnitude earthquakes, an attempt is made to search for such seismicity pattern in NW Aegean area. Accelerating seismic crustal deformation has been identified in the area of southern Albanides mountain range (border region between Greece, former Yugoslavia and Albania). Based on certain properties of this activity and on its similarity with accelerating seismic deformation observed before a strong earthquake which occurred in the same region on 26 May 1960 (M = 6.5), we can conclude that a similar earthquake may be generated in the same region during the next few years. This conclusion is in agreement with independent results which have been derived on the basis of the time predictable model.

Introduction

The Albanides-Hellenides mountain range trends in a N-S direction and a stress field of east-west extension which dominates all along the range has been identified in this region (Figure 1) (Papazachos et al., 1984). The area of southern Albanides has repeatedly been struck by earthquakes with magnitudes up to almost 7.0. Two strong ($M \geq 6.5$) earthquakes occurred there during the present century (18.2.1911 M = 6.7; 26.5.1960 M = 6.5). The last of these earthquakes was preceded by intense accelerating seismic crustal deformation (Papazachos and Papazachos, 2000a).

By searching for accelerating seismic deformation due to the generation of intermediate magnitude earthquakes in the Aegean area it has been observed that the southern Albanides area is one of the regions where accelerating deformation occurs now. Moreover, this deformation is similar to the one which occurred before the generation in the same region of the 1960 earthquake, which is the main reason that motivated this study.

Observations on accelerating intermediate magnitude seismicity have been made for some decades now (Gutenberg and Richter, 1954; Tocher, 1959; Mogi, 1969; Ellsworth et al., 1981; Papadopoulos, 1986; Sykes and Jaume, 1990; Karakaisis et al., 1991; Knopoff et al., 1996; Tzanis et al., 2000). During the last decade various physical mechanisms have been proposed to interpret this phenomenon. In general, the process of generation of these intermediate magnitude shocks (preshocks) has been considered as a critical phenomenon and the large earthquake (mainshock) as a critical point (Sornette and Sornette, 1990; Saleur et al., 1996; Huang et al., 1998; Jaume and Sykes, 1999). The most important consequence of this critical earthquake concept is that the time variations of measures of preshock-mainshock seismic crustal deformation (seismic energy, seismic moment, Benioff strain) follow a power law which has been applied in some attempts to predict earthquakes (Varnes, 1989; Bufe et al., 1994; Sornette and Sammis, 1995).

The goal of the present paper is to investigate in detail the currently observed accelerating crustal seismic deformation in the area of southern Albanides and to compare it with the accelerating seismic deformation observed before the 26.5.1960, M = 6.5 earthquake. Furthermore, an attempt is made to estimate the epicenter, magnitude and origin time of a future mainshock on the basis of these observations and on the hypothesis that the broader southern Albanides region is now at a critical (preshock) state which will

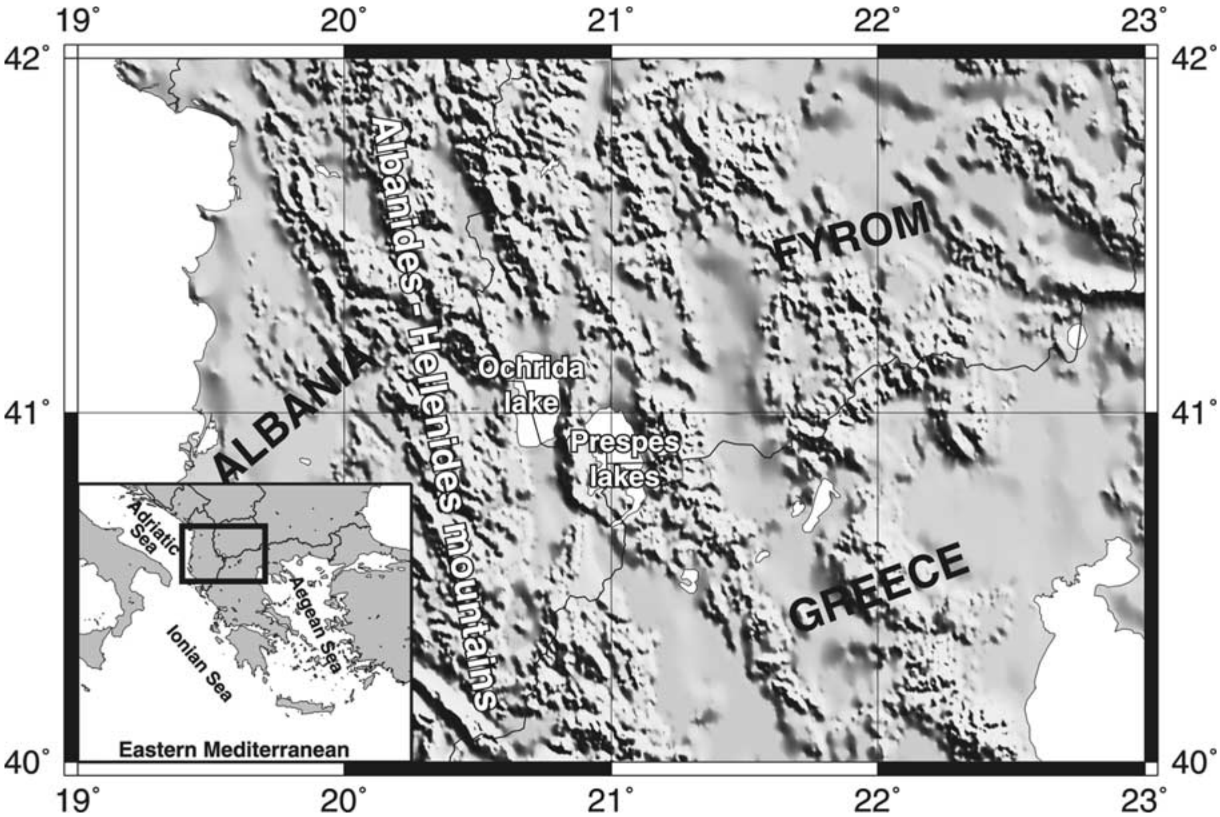

Figure 1. Map of the broader area studied in the present paper. The investigated area is delineated by a rectangle in the inset larger-scale map.

lead to a critical point, that is, to the generation of a mainshock.

Method and data

The method applied in the present paper is based on the time-to-failure power law (Bufe and Varnes, 1993) and the quantification of accelerating Benioff strain by a curvature parameter C (Bowman et al., 1998), as well as on several constraints imposed on the parameters of the critical earthquake model (Papazachos and Papazachos, 2000a, 2001a).

Bufe and Varnes (1993) have used the cumulative seismic energy release (specifically Benioff strain), *S(t)*, as a measure of the preshock seismic deformation at time, t, defined as:

$$S(t) = \sum_{i=1}^{n(t)} E_i(t)^{1/2} \tag{1}$$

where E_i is the seismic energy of the ith preshock and *n(t)* is the number of events at t. To fit the time variation of the cumulative Benioff strain they proposed a relation of the form:

$$S(t) = A + B(t_c - t)^m \tag{2}$$

where t_c is the mainshock origin time and A, B, m, are parameters which can be calculated by the available observations. Seismic energy is calculated from the magnitude of the earthquakes. In the present work we selected to keep the term ‘accelerating seismic crustal deformation’ since we believe that it better reflects the nature of the involved physical process.

Bowman et al. (1998) identified circular regions approaching criticality along the San Andreas fault system since 1950 by minimizing a curvature parameter, C, which quantifies the degree of acceleration of the Benioff strain. This parameter was defined as the ratio of the root mean square error of the power law fit (relation 2) to the corresponding linear fit error:

$$\mathrm{C} = \frac{power - law - mean - square - error}{linear - fit - mean - square - error}$$

C is much smaller than 1 for accelerated or decelerated (seismic quiescence) seismicity and tends to 1 for a linear time variation of seismicity.

In a series of papers Papazachos and Papazachos (2000a, b, 2001a) modified the approach of Bowman et al. (1998) using elliptical areas within which the time variation of the Benioff strain is examined, following a procedure which will be described later in the text. As centers of these areas the epicenters of all strong (M = 6.0–7.5) shallow mainshocks which occurred in the Aegean area between 1948–1997 have been considered. They proposed several relations which hold between the main quantities involved in this phenomenon of accelerating seismicity and which can be used to identify regions approaching criticality, that is, to locate critical regions of future earthquakes. These relations hold between the magnitude, M, of the mainshock and: i) the radius, R (in km), of the circle with an area equal to the corresponding ellipse, ii) the parameter, B, of relation (2), and iii) the average magnitude, M_{13}, of the three largest preshocks:

$$\log R = 0.41\,M - 0.64 \quad \sigma = 0.05 \tag{3}$$

$$\log B = 0.64\,M + 3.27 \quad \sigma = 0.16 \tag{4}$$

$$M = 0.85\,M_{13} + 1.52 \quad \sigma = 0.21 \tag{5}$$

They also proposed the following relations which hold between the duration, t_p (in years), of the preshock sequence and the seismic strain rate of the area:

$$\log t_p = 5.04 - 0.75 \log s_r, \quad \sigma = 0.17 \tag{6}$$

$$A = S_r t_p \tag{7}$$

where A is the parameter of relation (2), S_r (in Joule$^{1/2}$/yr) is the long term Benioff strain rate expressing the average strain energy release within the elliptical critical region and s_r is the S_r reduced to 10000 km^2, expressing the average seismicity rate.

The parameters m of relation (2) and C must be smaller than 0.7 because larger values indicate that the power-law fit is practically indistinguishable from the linear fit (similar rms errors for both fits), hence an accelerating activity is difficult to be identified (Bowman et al., 1998; Jaume et al., 2000). The compatibility of the values of the parameters R, B, M_{13}, t_p, A calculated for a certain preshock sequence with those determined by the relations (3), (4), (5), (6), (7) is expressed by a parameter, P (varying between 0 and 1), which is the sum of probabilities calculated for each of the left-side parameters in these equations, assuming that the observed deviations of each parameter follow a Gaussian distribution (Papazachos and Papazachos, 2001a). Thus, for an elliptical area exhibiting accelerated behavior,

$$m<0.7, \; C<0.7 \tag{8}$$

The constraints expressed by equations (3–8) do not allow the identification of accelerated Benioff strain release until a time close to the mainshock origin time, when this behavior is more pronounced. This time, t_i, is termed 'identification time' and is given by the relation (Papazachos et al., 2001):

$$\log(t_c\text{-}t_i) = 4.29 - 0.75 \log s_r \quad \sigma = 0.18 \tag{9}$$

which combined with relation (6) gives:

$$t_c\text{-}t_i = (0.17 \pm 0.05)\, t_p \tag{10}$$

This practically means that the time difference between the mainshock origin time and the identification time is about 17% of the total duration of the preshock sequence, in agreement with recent independent results (Yang et al., 2001).

To define the elliptical preshock region of an impending earthquake, whose epicenter will not necessarily coincide with the center of the elliptical region, Papazachos and Papazachos (2001b) suggested a quality index, q, given by the relation:

$$q = \frac{P}{Cm} \tag{11}$$

This index reaches its peak value at that geographical point which is the center of the elliptical area that corresponds to the best solution, i.e. the solution that better satisfies relations (3–7) and consequently results to high P values, while the data are best fitted by the power-law model (relation 2) than the linear model and exhibit the most pronounced accelerating Benioff strain release (lowest C and m values, respectively). For the strong mainshocks of the Aegean area it was found that, in order to achieve the best solution, these parameters must be:

$$C<0.60, \; m<0.40, \; P>0.40, \; q>3.5 \tag{12}$$

while their average values and the corresponding standard deviations are:

$$\bar{C} = 0.45 \pm 0.08, \; \bar{m} = 0.30 \pm 0.05,$$

$$\bar{P} = 0.56 \pm 0.07, \; \bar{q} = 4.6 \pm 1.5$$

A more accurate estimation of the time of occurrence, t_c, of an ensuing mainshock stems from the observation that the mainshock is usually preceded by a precursory seismic excitation within the critical region, which is related to the time of occurrence of the ensuing mainshock (Papazachos et al., 2001). In these cases, the T_i=f(T_c) graph is formed by two parts separated by a abrupt increase (jump) of T_i (calculated

Table 1. Epicenter coordinates ($\varphi^\circ{}_N$, $\lambda^\circ{}_E$), magnitude, M, origin time, t_c, and parameters of the best solution for the expected mainshock (first line) and for the *a posteriori* 'predicted' mainshock of 26.5.1960 (second line). The basic focal parameters of this mainshock are given in the third line

No	$\varphi^\circ{}_N, \lambda^\circ{}_E$	M	t_c	C	M	P	q	a(km)	z°	e	t_p	Mmin	n	t_s
1	41.6, 21.1	6.7	2002.5	0.46	0.19	0.53	6.3	222	25	0.95	33.5	5.0	21	1969
2	40.2, 20.5	6.7	1959.9	0.49	0.30	0.86	5.9	181	120	0.80	24.4	5.0	31	1936
3	40.6, 20.7	6.5	1960.5											

identification time) at a certain time, T_c (assumed origin time), which is close to the actual origin time of the main shock ($T_c \approx t_c$). This increase of T_i when this is close to the actual identification time, t_i, is usually associated with changes of other parameters, expected to be affected by seismic excitation. Such changes are the increase of the frequency of the number of preshocks, n, as well as the decrease of the parameters C and m, and the difference, t_{13}, between the mean origin time of the three largest preshocks and the origin time of the mainshock. To incorporate the variations of all the aforementioned parameters, namely, T_i, n, C, m and t_{13}, a preseismic excitation index, *PEI*, was suggested which varies between 0 and 1 in the cases where preseismic excitation is observed. This index can be calculated once the relative rates of change (their ratios r_i, r_n, r_c, r_m, r_t to the maximum absolute values observed during the whole period examined) with time of each one of these five parameters (positive for T_i, n and negative for C, m, t_{13}) have been determined and consists of the average of the five relative values (considering the appropriate signs for the r_c, r_m, r_t ratios).

The data used to calculate the Benioff strain have been taken from the catalogue of Papazachos and his colleagues (2000) and belong to one of the following three complete sets of shocks: 1911–1949 M≥5.0, 1950–1964 M≥4.5, 1965–2000 M≥4.3. The errors in the epicenters are of the order of 15 km for earthquakes that occurred after 1965 (when the first network of seismic stations was established in Greece) and up to 25 km for older earthquakes. All magnitudes are original or equivalent moment magnitudes and their typical error is ≅0.3. The formula:

$$\log E = 1.5\,M + 4.7 \tag{13}$$

derived by Papazachos and Papazachos (2000a), has been used to calculate the seismic energy from the moment magnitude and then the Benioff strain is calculated by relation (1).

Procedure followed and results

To apply this method for identification of preshock (critical) regions, an algorithm developed by Papazachos and Papazachos (2000b) was used. The area between 40°N and 42°N parallels and 19°E and 22°E meridians was separated in small cells (0.25°NS × 0.25°EW). Each point of the grid is assumed to be the epicenter of an impending mainshock and all earthquakes (preshocks) larger than a certain minimum magnitude M_{min}, within the elliptical region centered at this grid point are considered. On the basis of these data the parameters of relation (2) and the curvature parameter C are calculated. The calculations are repeated by applying a systematic search of a large set of values for the azimuth, z, of the large ellipse axis, its length a, ellipticity e, and for the initiation time, t_s (origin time of the 1st preshock), and consequently the duration of the sequence, t_p. Moreover, the calculations are repeated for several magnitudes, M, and origin times of the expected mainshock.

For each grid point the solution exhibiting the largest quality index, q, is chosen. From all these solutions of all grid points, the solution for which the index q has the largest value is considered as the best solution and the corresponding grid point is adopted as tentative epicenter of the expected mainshock. The mainshock origin time is then recalculated more accurately by the use of the preseismic excitation index, *PEI*. Thus, having a more accurate origin time, the whole set of calculations is repeated aiming at a more accurate definition of the epicenter and magnitude of the expected mainshock. The finally adopted magnitude of the expected mainshock is the average value calculated from the relations (3, 4, 5) for the best solution, while its epicenter is in the middle of all grid points which fulfil the relations (12).

In the first line of Table (1) the parameters of the expected earthquake by the above described procedure are presented, that is, the epicenter coordinates ($\varphi^\circ{}_N$,

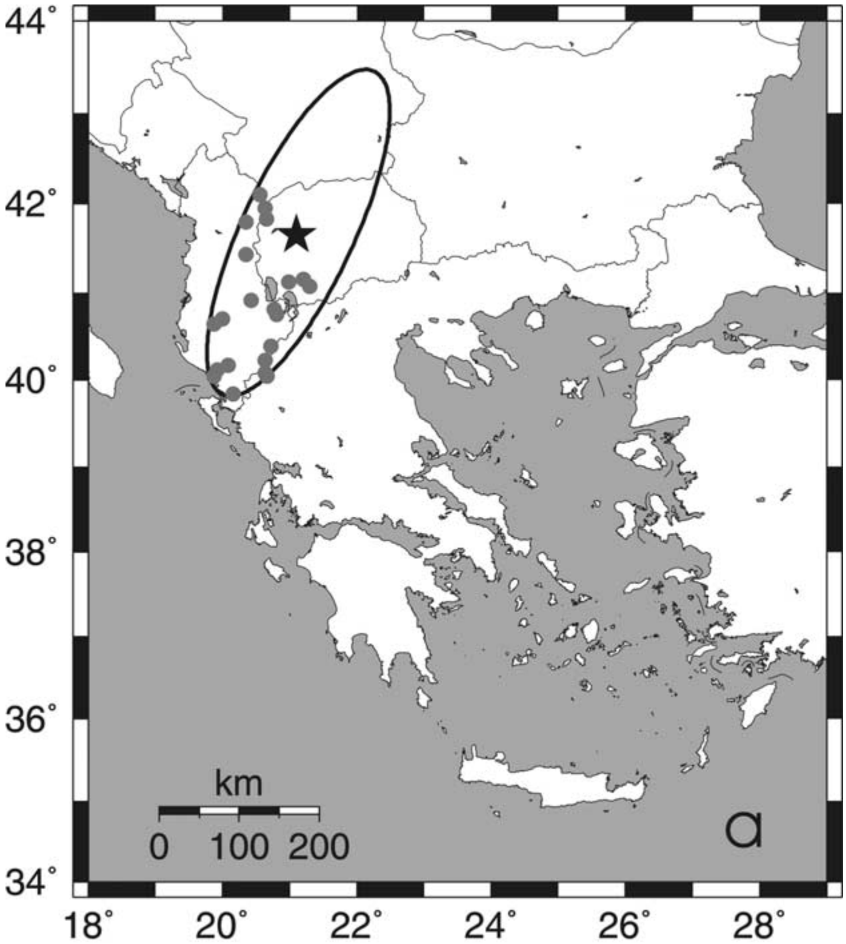

Figure 2. (a) The elliptical critical region where accelerating seismicity is currently observed and the epicenters of the corresponding shocks (preshocks). The epicenter of the expected earthquake is denoted by a star. (b) The elliptical critical region and the preshocks of the 1960 mainshock. The star denotes the epicenter of the 'predicted' event while the diamont corresponds to the actual epicenter of the 1960 mainshock.

$\lambda°_E$) of the expected mainshock, its magnitude M, its estimated origin time t_c, the curvature parameter C, the parameter m, the compatibility parameter P, the quality index q, the length a (in km), of the large axis of the elliptical region, the azimuth z (measured clockwise from north), of its principal axis, the ellipticity e, of this region, the duration t_p (in years), of the preshock sequence, the minimum magnitude of the preshocks M_{min}, the number n, of observations used (number of preshocks plus the expected mainshock) and the year t_s, when the accelerating preshock deformation started. An attempt was made to apply this method in order to 'predict' *a posteriori* the mainshock which occurred in this area on 26 May 1960; the results are shown in the second line of Table 1. The basic focal parameters of this mainshock are listed in the third line of this table.

As can be derived from Table 1, although the critical region where accelerating deformation currently takes place does not coincide with the preshock region of the 26.5.1960 earthquake, the quality parameters q has similar values in both cases.

Figure 2a shows, on a map of the broader Aegean area, the elliptical critical region and the epicenters of the shocks (preshocks) for which Benioff strain was calculated. The star at the center of the ellipse shows the epicenter of the expected mainshock. Figure 2b shows the elliptical critical region for the mainshock which was 'predicted' to occur in this area by the end of 1959 (star) and its preshocks, while the diamont denotes the actual epicenter of the 26.5.1960 mainshock

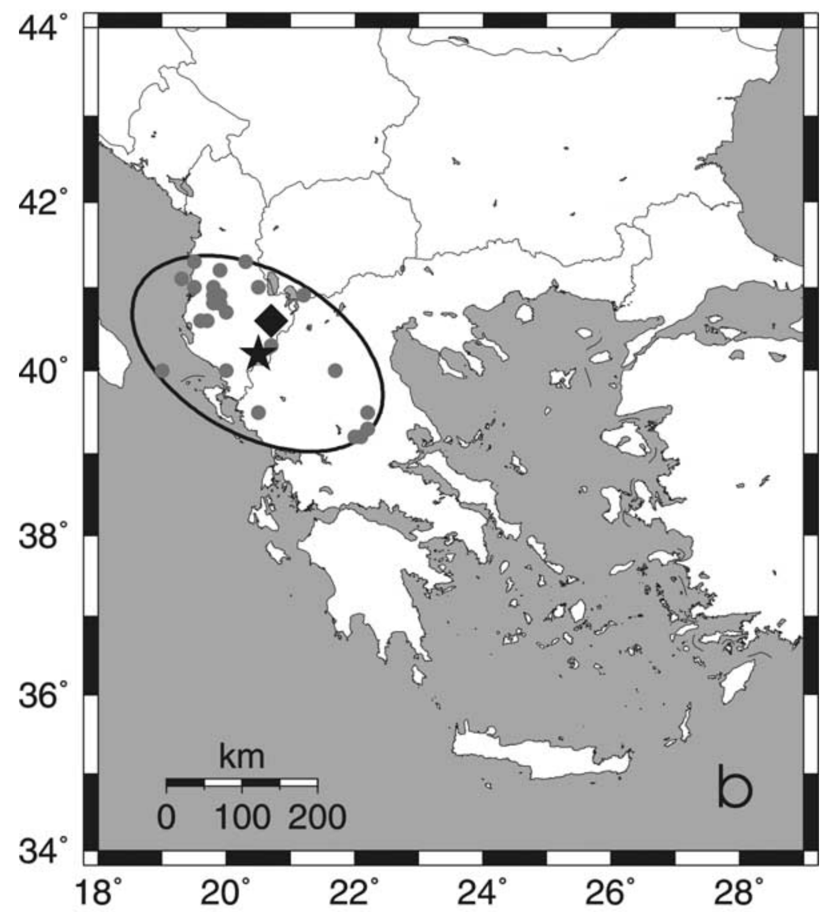

Figure 2. Continued.

(M = 6.5). Figure 3 shows the time variation of the cumulative Benioff strain, *S(t)*, for the expected mainshock (a) and for the mainshock which occurred in 1960 (b), as it has been calculated by using preshocks with $M \geq 5.0$.

Figure 4 shows the time variation of the parameter *C*, calculated without considering the mainshock, for the case of the expected earthquake; the first 6 preshocks were taken and fitted by both the power-law and linear fit. The resulted *C* value is plotted against the occurrence time of the last (6^{th}) event. Then, the next preshock is included in the sample and calculations are repeated for the seven preshocks with the resulting *C* value being plotted against the occurrence time of the 7^{th} preshock, etc. It is observed that *C* decreases as the origin time of the mainshock is approached. Similar decrease of *C* with time has been observed by Karakaisis et al. (2000) for several preshock sequences in the Aegean area.

An additional indication that the approach to a critical point (occurrence of the ensuing mainshock) is associated with identifiable non-normal behavior of seismic activity comes from observations from a small number of natural cases and from experiments on cellular automaton models (Smith, 1998; Jaume and Sykes, 1999; Jaume et al., 2000). In these studies it was found that the *b* value of the Gutenberg and Richter (1944) recurrence law decreases prior to the generation of the oncoming mainshock and that this could be due to either an overall increase in event size or an overall increase in the rate of occurrence. Figure 5 shows the time variation of the parameter *b*, calculated for a moving window of at least 40 preshocks, with a step of one preshock, under the constraint that the magnitude range, ΔM (denoted by the dashed line)

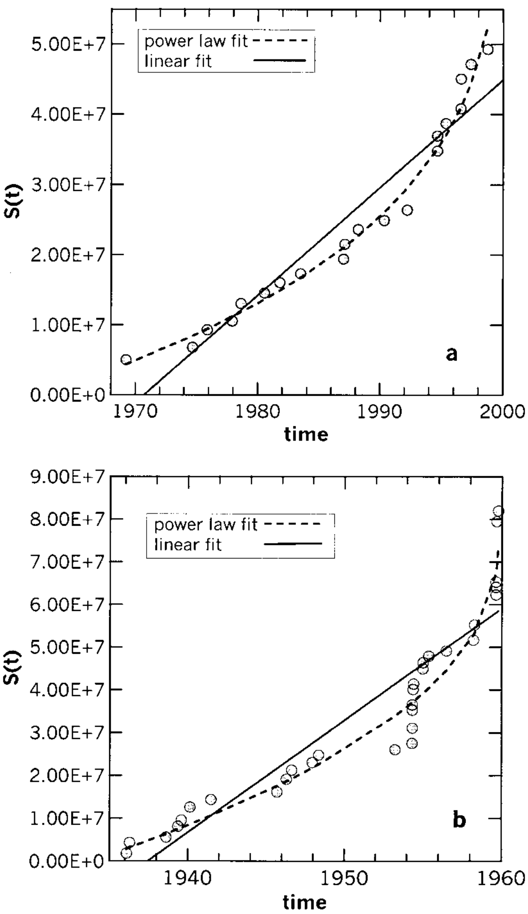

Figure 3. Time variation of the cumulative Benioff strain, *S(t)*, for the present seismic activity (a) and for the sequence which preceded the 26.5.1960 earthquake (b). he solid curves are the fits of relation (2) and the dashed lines are the linear fits.

is at least 1.5 (Papazachos, 1974). *b*-values are plotted against the middle of the time interval they span. In order to have a relatively large and complete data set, all earthquakes with M$\geq$4.3 which occurred in the preshock region since 1969 have been considered. A decrease of the *b* values is observed, in agreement with the results concerning other preshock sequences in the Aegean sea (Karakaisis et al., 2000).

The determination of the uncertainties in the parameters (epicenter, magnitude, origin time) of the ensuing mainshock is a difficult task. Papazachos and Papazachos (2000b) applied the same methodology in an attempt to make retrospective prediction for eighteen mainshocks which have already occurred and compared the obtained predictions with the observed parameters. Based on their results we can conclude

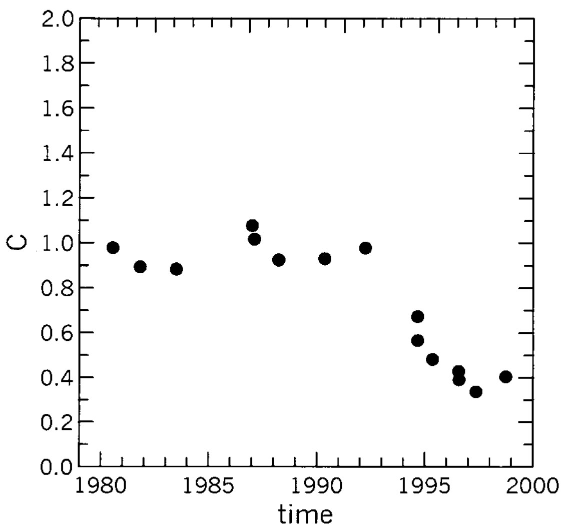

Figure 4. Time variation of the *C* value for the present seismic activity.

that there is a high probability (90% confidence) for the epicenter of the ensuing mainshock to be within a distance of $\leq$100 km from the epicenter proposed in Table 1, for its magnitude to be within $\pm$0.4 from the proposed magnitude and for the origin time to be within $\pm$1.5 years from the proposed origin time.

Discussion

It has not been shown that accelerating seismic crustal deformation always leads to the generation of a mainshock. For this reason, we cannot exclude the possibility that the accelerating Benioff strain currently observed in the area of southern Albanides may stop after some time without the generation of a strong earthquake there. On the other hand, several cases have been reported in which no identifiable accelerating seismic activity was observed to precede certain mainshocks (Bufe et al., 1994). However, recent relevant work for the Aegean area (Papazachos and Papazachos, 2000a, 2001a) shows that all strong recent earthquakes for which reliable data are available were preceded by accelerating deformation. Moreover, the currently observed preshock sequence and the precursory sequence of the 26.5.1960 earthquake have similar acceleration patterns (similar *C*, *q*). These similarities also favor the hypothesis that the present sequence is also a precursory one and a mainshock will follow.

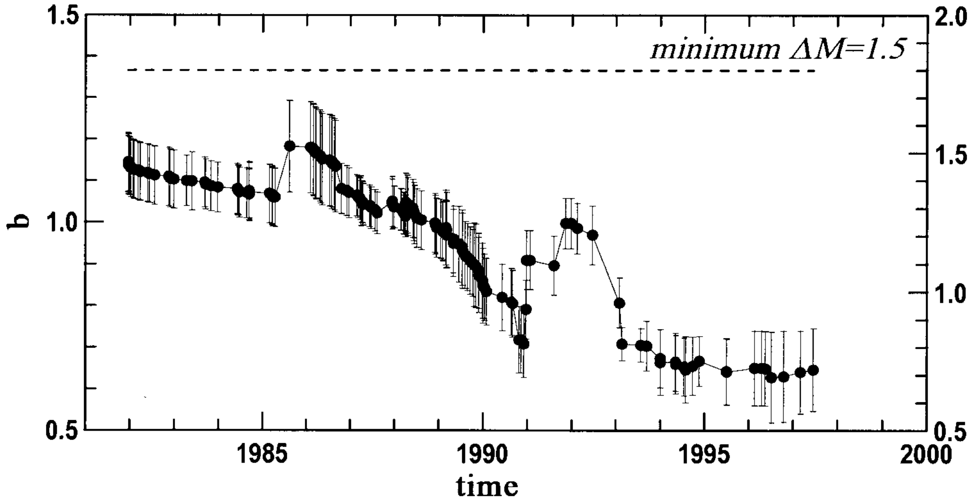

Figure 5. Time variation of the *b* value (error bars are also shown). The dashed line shows the magnitude range, ΔM, which holds for the calculations (see text for explanation).

An additional evidence which might strengthen our hypothesis stems from recent time-dependent seismicity studies for the broader Aegean area. During the present century two very strong earthquakes occurred in the area of southern Albanides; the larger (M = 6.7) occurred on 21 February 1911 and the smaller (M = 6.5) on 26 May 1960. According to the regional time predictable model (Papazachos, 1989; Papazachos and Papaioannou, 1993), the larger the magnitude of a mainshock in a region, the longer the time till the next mainshock. Thus, since the interevent time which followed the M = 6.7 mainshock in the area studied is about 49 years (Papazachos and Papaioannou, 1993), the interevent time which will follow the M = 6.5 earthquake can possibly be of the same order or smaller, as it is predicted by the method applied in the present work. Therefore, the generation of a strong earthquake during the next few years in this region is also in agreement with the regional time predictable model.

In order to summarise: we presented evidence that the evolution of the currently observed accelerating seismic deformation in the area of southern Albanides (border region of Albania, Greece and former Yugoslavia) may culminate in the generation of a strong earthquake in the area. This scenario must be taken into serious consideration because past earthquakes of similar magnitudes (1911 M = 6.7, 1960 M = 6.5) caused serious damage and loss of life in this region (Papazachos and Papazachou, 1997). Furthermore, a possible manifestation of the observational fact that the aforementioned area is now in a seismically active state may be the occurrence of moderately strong (M = 5.0–6.0) mainshocks, such as the 9 April 2001 (M = 5.7) event that occurred within the elliptical critical area (with epicentral coordinates 40.09°N–20.53°E), which may also cause damage in the area studied.

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