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Accelerating seismic crustal deformation before strong mainshocks in Adriatic and its importance for earthquake prediction

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Abstract

Time accelerating Benioff strain release before the mainshock has been observed in all five cases of strong (M > 6.0) shallow mainshocks, which have occurred during the last four decades in the area surrounding the Adriatic Sea. This observation supports the idea that strong mainshocks are preceded by accelerating seismic crustal deformation due to the generation of intermediate magnitude shocks (preshocks). It is further shown that the values of parameters calculated from these data follow appropriately modified relations, which have previously been proposed as additional constraints to the critical earthquake model and to the corresponding method of intermediate term earthquake prediction. Thus, these results show that the identification of regions where time-accelerating Benioff strain follows such constraints may lead to useful information concerning the epicenter, magnitude and origin time of oncoming strong mainshocks in this area. The procedure for identification of the time-acceleration is validated by appropriate application on synthetic but realistic random catalogues. Larger dimension of critical regions in Adriatic compared to such regions in the Aegean is attributed to an order of magnitude smaller seismic deformation of the crust in the former in comparison to the latter.

Introduction

As identification of geophysical precursors has not yet provided a useful tool for short-term earthquake prediction, significant work has been carried out lately towards the target of intermediate term earthquake prediction. It has been shown that strong earthquakes are often preceded by a period of accelerating seismic activity expressed by intermediate magnitude earthquakes, namely ‘preshocks’ (Tocher, 1959; Mogi, 1981, Papadopoulos, 1986; Varnes, 1989; Sykes and Jaume, 1990; Karakaisis et al., 1991; Jaume and Sykes, 1999; Tzanis et al., 2000; Papazachos and Papazachos, 2000, 2001). This preshock period ends with the generation of the mainshock. Statistical physicists’ work suggests that the physical process of such accelerating activity is analogous to a critical phenomenon leading to the critical point, that is, the main shock (Sornette and Sornette, 1990; Rundle et al., 2000). It has been shown that a proper measure of the process, described above, is the Benioff strain even though on theoretical grounds seismic moment is preferred (Varnes, 1989; Bufe and Varnes, 1993; Main, 1999; Veve-Jones et al., 2001).

Sornette and Sammis (1995) attempted a new approach to the earthquake prediction issue, suggesting association of intermediate magnitude earthquakes with the growing correlation length of the regional stress field prior to a large event with the final event in a circle analogous to the critical point of a chemical or magnetic transition. This hypothesis was based on previous work by Varnes (1989) and Bufe et al. (1994) who suggested that the cumulative Benioff strain, S(t), expressed by the relation:

$$S(t) = \sum_{i=1}^{n(t)} \sqrt{E_i(t)} \qquad (1)$$

represents a reliable measure of the preshock seismicity at time t, where E_i is the seismic energy of the i^{th}

preshock and n(t) the number of preshocks occurred within time t. Considering t_c as the origin time of the mainshock, Bufe and Varnes (1993) proposed the following relation that describes the time variation of the cumulative Benioff strain:

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

where, A, B, m are parameters with values calculated by the available data. It should be noted that the choice of S(t) (e.g. Benioff strain, seismic moment, number of events, etc.) is a critical issue, since it is necessary to define a minimum magnitude of preshocks to consider in equation (1) (e.g. Bufe and Varnes, 1993; Jaume and Sykes, 1999) to avoid divergence. Recently, Papazachos (2003) has proposed a linear relation between the mainshock magnitude and the minimum considered preshock and provided a possible physical explanation for this relation. However, the choice of the measure of S(t) needs to also incorporate physical arguments (e.g. Main, 1999) and is still an open question.

Several researchers tried to define areas approaching criticality before the occurrence of strong earthquakes. Bowman et al. (1998) defined circular areas along San Andreas fault, within which cumulative Benioff strain, S(t), showed acceleration before strong ($M \geq 6.5$) earthquakes. They introduced a curvature parameter, C, defined as the ratio of the root mean square error of the power law fit to the corresponding linear fit error. This parameter, which is smaller than one for accelerating or decelerating time variation of seismic energy release and tends to one for a linear (steady-state) time variation, was considered as a reliable measure of the acceleration S(t). The estimations were repeated for several circles centered at a certain mainshock epicenter. The size of these areas found to be depended on the magnitude of an ensuing earthquake. The circle exhibiting the lowest value for parameter C was adopted as defining the critical area. Papazachos and Papazachos (2000, 2001) defined elliptical critical regions of strong earthquakes in the Aegean area and developed further the methodology by determining several relations between the parameters of relation (2) and other independently calculated parameters. These relations that form additional constraints to the accelerating deformation (Benioff strain) model, will be presented below. Furthermore Karakaisis et al. (2001) have observed that the curvature parameter, C, as well as the parameter b of the cumulative frequency distribution of magnitudes of preshocks in the critical region, decreases with time to the mainshock.

The main purpose of the present paper is to identify elliptical critical regions associated with strong ($M > 6.0$) earthquakes in Adriatic Sea and surrounding area (Italy, Former Yugoslavia) and to examine the properties of the accelerating crustal deformation (Benioff strain) in this region. Such work is of theoretical and practical importance because it will show the difference in the behavior of accelerating crustal deformation in this relatively moderate – to low – seismicity area, with respect to such deformation in the high seismicity Aegean area. It is also of practical importance because relations used as constraints in the accelerating deformation model will be tested by data of this area and will be properly calibrated for use in intermediate term prediction of future strong mainshocks.

Basic geotectonic features of the broader Adriatic area are given in Figure 1. Seismicity in this area is due to the existence of the so-called Apoulian (Adriatic) microplate, which rotates counterclockwise. This rotation results in the generation of a compressional field and the generation of earthquakes of thrust faulting along the eastern Adriatic coast (Former Yugoslavia) and a tensional field and the generation of earthquakes on normal faults in Italy (Ritsema, 1974; McKenzie 1972; Mantovani et al., 1996).

Method applied

The method applied in the present paper is called 'method of accelerating seismic crustal deformation' and is based on relation (2), on minimizing the curvature parameter C and on several additional constraints expressed by relations between the parameters involved. Thus, Papazachos and Papazachos (2000, 2001) used a sample of data for fifty two preshock sequences in the Aegean area and determined the following relations:

$$\log R = 0.42M - 0.68 \quad \sigma = 0.05 \tag{3}$$

$$M = 0.85M_{13} + 1.52 \quad \sigma = 0.21 \tag{4}$$

$$\log t_p = 5.81 - 0.75 \log s_r \quad \sigma = 0.17 \tag{5}$$

$$\frac{\log \frac{A}{t_p}}{\log S_r} = 1.0 \quad \sigma = 0.04 \tag{6}$$

where M is the magnitude of the mainshock, R (in km) is the radius of the circle with area equal to the area

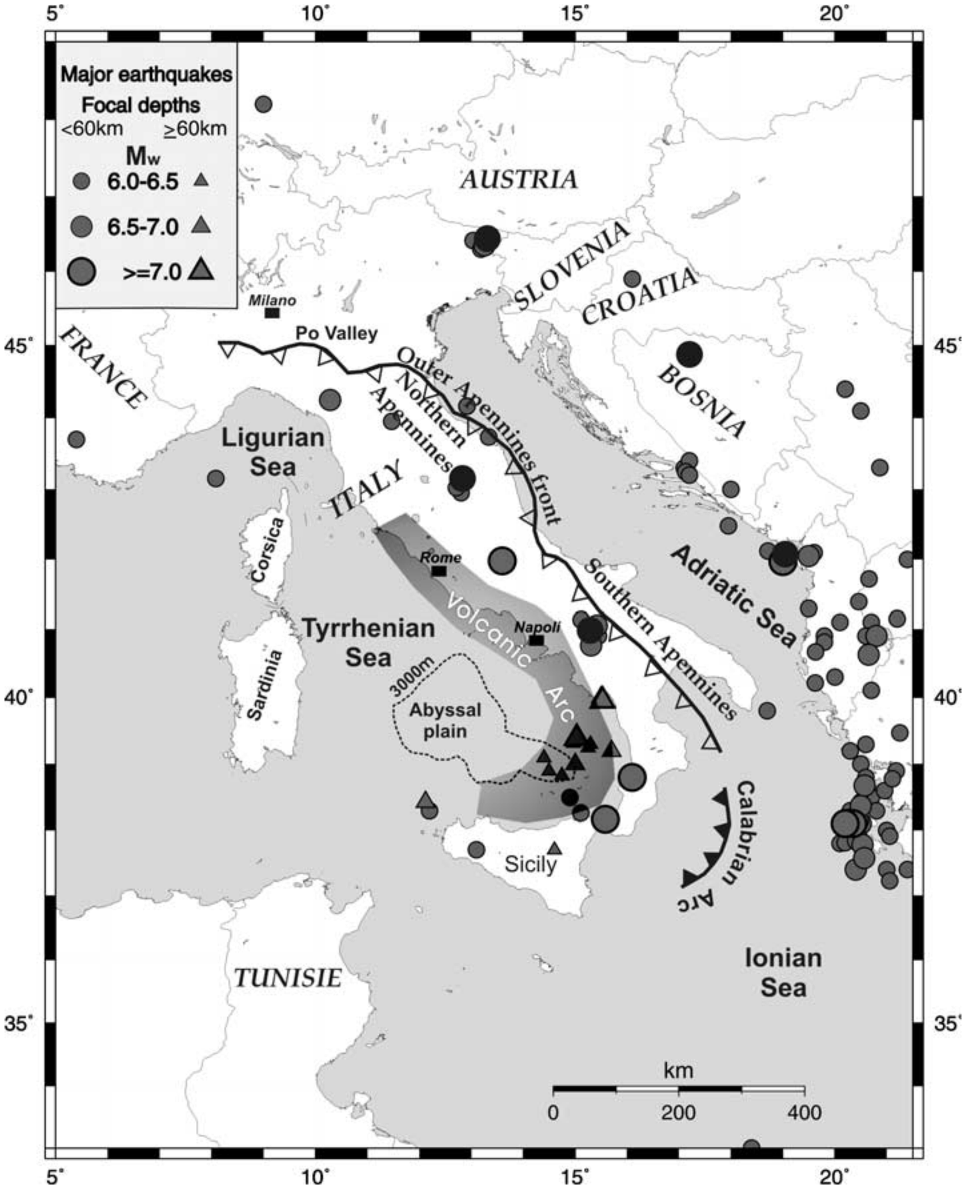

Figure 1. Schematic representation of basic seismotectonic features of the Adriatic area. Black circles show the epicenters of the five mainshocks for which critical regions are investigated in the present paper, while gray circles denote the epicenters of all the shocks with $M_W \geq 6.0$ occurred in the broader Adriatic area since 1900.

of the critical elliptical region (preshock region), A is the parameter of relation (2), M_{13} is the average magnitude of the three largest preshocks, t_p (in yrs) is the duration of the preshock sequence, S_r (in Joule$^{1/2}$/yr) is the long – term Benioff strain rate, expressing the average strain energy release in the examined area, s_r is the same quantity reduced to the area of 10^4 km^2 in order to express the average seismic deformation per unit area, and σ are the corresponding standard deviations. It should be noted that equation (6) is slightly different than the one given by Papazachos and Papazachos (2001), since we found that the values of the ratio of logarithmic rates (A/t_p and s_r) are much better described by a Gaussian distribution. In all calculations the values of the parameters m and C are initially constrained to be smaller than 0.7, that is,

$$m \leq 0.7, \quad C \leq 0.7 \tag{7}$$

According to Papazachos et al. (2001), the accelerating seismic deformation that fulfills relations (7) couldn't be identified until a time, t_i, before the occurrence of the mainshock, which can be described as the identification time for this phenomenon. They also showed that the difference, t_c-t_i, between the identification time and the origin time of the mainshock is given by the relation:

$$\log(t_c - t_i) = 5.04 - 0.75 \log s_r, \quad \sigma = 0.18 \quad (8)$$

Hence, the identification period is larger for low–seismicity areas. From relations (5), (8) it is easily concluded that the difference t_c-t_i is about 17% of the duration, t_p, of the preshock sequence.

To quantify the compatibility of the values of the parameters R, M, t_p and A calculated for a seismic sequence with those determined by relations (3), (4), (5) and (6), a parameter P was defined (Papazachos and Papazachos, 2001), which is the average value of the probabilities that each of these five parameters attains, a value close to its expected one from these relations, assuming that the observed deviations of each parameter follow a Gaussian distribution. Furthermore, Papazachos et al. (2002c) have chosen a quality measure for each solution, q, defined by the relation:

$$q = \frac{P}{m \cdot C} \quad (9)$$

in an attempt to simultaneously evaluate: the compatibility of an accelerated seismic deformation with the behavior of past preshock sequences (large P), the deviation of seismic deformation from linearity (small C) and the degree of acceleration of the seismic deformation (small m). By using data of the Aegean area they determined the following cut off values:

$$C \leq 0.70, \quad m \leq 0.35, \quad P \geq 0.45 \quad q \geq 3.0 \quad (10)$$

To apply this method for the identification of a preshock (critical) region and to predict the corresponding mainshock, Papazachos (2001) developed an algorithm. According to this algorithm, shocks (preshocks) with epicenters in an elliptical region centered at a certain geographical point (assumed epicenter of the mainshock) are considered and the parameters of relation (2) as well as the curvature parameter, C, are calculated. 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 the time, t_s, since when accelerating seismic deformation started, for the magnitude, M, and the origin time, t_c, of the mainshock. These computations are repeated for a grid of points in which the investigated area is separated with the desired density (e.g. 0.2°NS, 0.2°EW). From all solutions obtained the one that fulfills relations (10) and has the largest q parameter is considered as the best solution. The geographical point which corresponds to the best solution is considered as the epicenter of the mainshock and the average magnitude calculated by relations (3), (4) for this solution is considered as the magnitude of the mainshock. The origin time, t_c, corresponding to the best solution is considered as the origin time of the mainshock. Because this is a very rough approximation, an alternative technique has been proposed and tested for the determination of the origin time.

This technique for estimation of the origin time, t_c, of an oncoming mainshock is based on a precursory seismic excitation (swarm of shocks, etc) which has been observed to occur in the critical region before the generation of the mainshock (Papazachos et al., 2001). This excitation is recognized and used to predict t_c from an abrupt increase (jump) in the relation $T_i = f(T_c)$ between assumed values, T_c, of the origin time and the corresponding calculated values, T_i, of the identification time. The increase (jump) occurs at a time T_c =,T_{pr} which is approximately equal to the real origin time (T_{pr},$\cong$,t_c). This excitation is also associated to an increase in the frequency, n, of preshocks, a decrease of the parameters C and m (due to additional deviation of S(t) from linearity) and decrease of the difference, t_{13}, between the mean origin time of the three largest preshocks and the origin time of the mainshock (due to the occurrence of at least one of the three largest preshocks during this excitation). Papazachos et al. (2001) considered the ratio of the rate of each of the five parameters with respect to the maximum rate observed during the examined period (r_i, r_n, r_c, r_m, r_t) as a normalized value and the average of these normalized values as the Preshock Excitation Indicator (PEI). This indicator varies between 0 and 1 for relative increase of seismic activity (seismic excitation) with respect to the activity predicted by relation (2) and between –1 and 0 for relative decrease of seismic activity (seismic quiescence). Thus, in the plot of PEI as a function of T_c, the value of $T_c(=T_{pr})$ for which PEI has its maximum (positive) value is about equal to the origin time of the oncoming mainshock.

Papazachos et al. (2002b) applied the method described above, to retrospectively predict the epicenter, the magnitude and the origin time of eighteen strong mainshocks ($M \geq 6.0$), which occurred in the Aegean area since 1980. From the comparison of the predicted with the observed parameters they concluded that the uncertainties in the predicted epicenter is about 120 km, in the magnitude ±0.5 and in the origin time ±1.5 years with high confidence (>90%), which suggests that the proposed technique can be applied as an intermediate term earthquake prediction method.

The data

Only instrumental data are used in the present study, that is, epicenters and magnitudes of shallow earthquakes which occurred in Adriatic Sea and surrounding areas (33°N–50°N, 05°E–21°E) since 1900. There are several sources of such data (bulletins, catalogues, etc) where magnitudes of the earthquakes are in several scales (moment magnitude, M_w, surface wave magnitude, M_s, body wave magnitude, m_b, local magnitude, M_L). It is, therefore, necessary to make an homogeneous earthquake catalogue for this area, that is, a catalogue where all magnitudes are in the same scale and as such scale the moment magnitude scale, M_w, is selected. For that purpose formulas that relate the moment magnitude with each one of the other magnitude scales have been used.

The sources of data used in the present paper are:
a) the Italian catalogue for the earthquakes of the period 1900–1980 (Postpischl, 1985) and a continuation of this catalogue up to the end of 1998, made available to us by the Istituto Nationale di Geofisica, Roma (ING). The magnitudes of this catalogue are in a local magnitude scale, called M_{ITL} for the purpose of the present study, and are magnitudes based on amplitudes or signal durations (Giardini et al., 1997).
b) The catalogue published by Karnik (1969) for the period 1900–1955 and its continuation up to 1990 (Karnik, 1996) where magnitudes are in M_s scale.
c) The catalogue of Papazachos et al. (2000) where magnitudes are originally reported, or equivalent to, moment magnitudes.
d) The bulletins of the Geophysical Laboratory of the University of Thessaloniki and the bulletins of the Geodynamic Institute of the National Observatory of Athens where magnitudes are in a local scale called M_{LGR} scale.
e) The bulletins of ISC (International Seismological Center, 2002) and other international centers (NEIC, Harvard) where M_w, M_s, m_b magnitudes are given. The following relations have been used to transform magnitudes from other scales to equivalent moment magnitudes, M_w*:

$$M_w^* = M_{ITL}+0.42, \quad M_{ITL} \geq 3.2 \quad \sigma = 0.34 \tag{11}$$

$$M_w^* = M_{LGR}+0.5, \quad 3.6 \leq M_{LGR} \leq 6.5 \quad \sigma = 0.21 \tag{12}$$

$$M_w^* = 1.28m_b - 1.12, \quad 4.8 \leq m_b \leq 6.0 \quad \sigma = 0.36 \tag{13}$$

$$M_w^* = M_s, \quad 6.0 \leq M_s \leq 8.0 \quad \sigma = 0.28 \tag{14}$$

$$M_w^* = 0.69M_s + 1.83, \quad 4.2 \leq M_s < 6.0 \quad \sigma = 0.30 \tag{15}$$

where σ is the standard deviation. Relations (12), (13), (14) and (15) have been proposed by Papazachos et al. (1997, 2002a) and relation (11) has been derived for the purposes of the present study by comparing M_{ITL} with original M_w or with the average magnitude M_w* calculated by the other formulas when no M_w was available.

The finally adopted magnitude, M_w*, for each earthquake is the weighted mean of the values calculated by relations (11), (12), (13), (14) and (15) by taking as weight the inverse of the standard deviation, σ, for the corresponding magnitude scale. Figure 2 shows a plot of the adopted magnitude, M_w*, as a function of the original moment magnitude, M_w (calculated from seismic moment), for 119 earthquakes for which both magnitudes were available. Individual M_w* values for these events derived by each initial magnitude using relations (11), (12), (13), (14) and (15) are also denoted. The correlation is very good with a mean difference equal to –0.10 and a standard deviation equal to 0.28. The epicenters given by ING were adopted in the present study and when these were not available the geometrical means of the epicenters determined by the other seismological centers were used. The catalogue finally compiled includes information for 17,999 earthquakes with equivalent moment magnitudes between 3.6 and 7.2 for the period 1900–2001. The completeness of the catalogue was checked using both the Gutenberg-Richter cumulative frequency – magnitude relation (Figure 3) and time variations of the cumulative number of shocks with a certain magnitude cut off. It has been shown that the data are complete for the following periods and corresponding magnitudes:

$$\begin{array}{ll} 1900-2001 & M \geq 4.7 \\ 1971-2001 & M \geq 4.2 \\ 1991-2001 & M \geq 3.6 \end{array} \tag{16}$$

The errors in the epicenters and the magnitudes are of the order of 20km and 0.3, respectively.

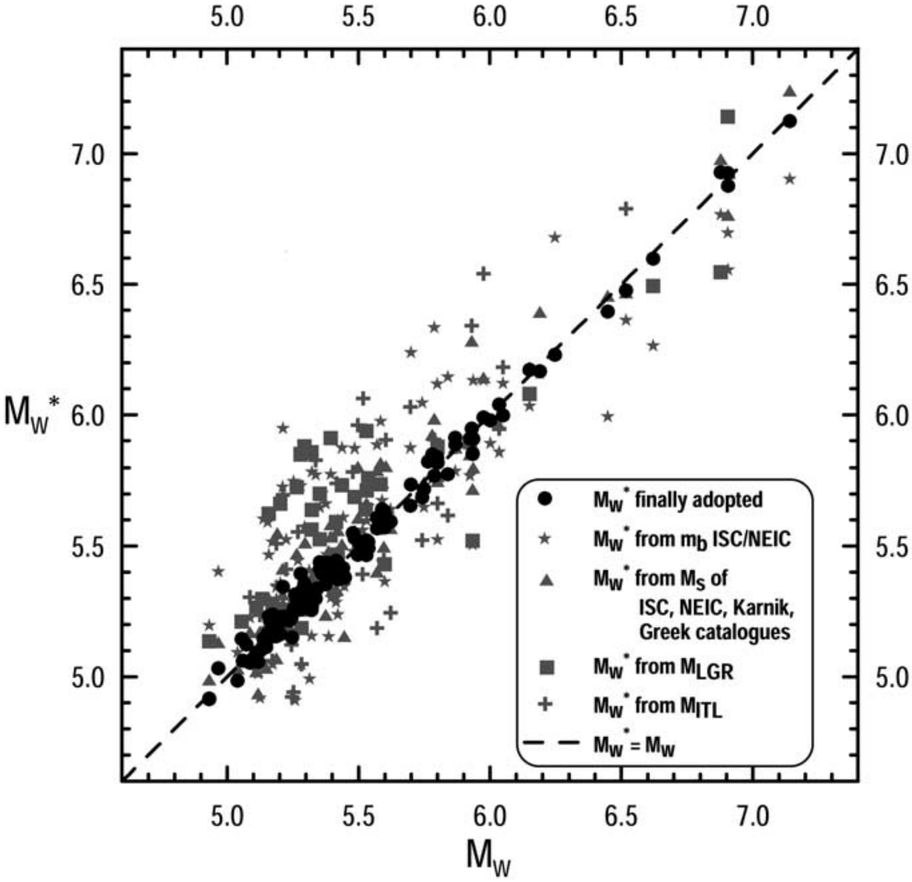

Figure 2. Equivalent moment magnitudes, M_W*, calculated from measured magnitudes in other scales (M_{ITL}, M_{LGR}, M_b, M_s, see relations 11, 12, 13, 14 and 15) against original moment magnitude, M_W, calculated from measured seismic moment for 119 earthquakes located in the Adriatic area.

To define the mainshocks for which critical (preshock) regions can be determined by the available data, certain conditions must be fulfilled. Firstly, each mainshock must be preceded by a period of a few decades for which a complete set of data is available because preshock sequences in critical regions last for a few decades (Papazachos and Papazachos, 2001). Secondly, the difference in magnitude between the mainshock and the smallest preshock must be at least 1.7 for mainshock magnitudes $M \leq 7.0$ and at least to 1.9 for $M \geq 7.1$ (Papazachos, 2003). Thirdly, the area where epicenters of mainshocks are located must be smaller than the area covered by the available complete data so that the critical region of each mainshock is within the area with complete data. Based on these conditions and on relations (16), the following two complete samples of mainshocks with epicenters in the area 35.0°N–48.0°N, 7.0°E–19.1°E have been considered:

$$\begin{aligned} &1965 - 2001 \quad M \geq 6.2 \\ &1981 - 2001 \quad M > 6.0 \end{aligned} \qquad (17)$$

These are five mainshocks, which are listed on Table 1. The date, epicenter coordinates (φ, λ) and moment magnitude, M, are given in the second, third and fourth columns of this table for each one of these five mainshocks. The epicenters of earthquakes with $M \geq 6.0$, occurred in Adriatic since 1900, are shown on the map of Figure 1.

It would be interesting to examine also smaller magnitude mainshocks ($M \simeq 5.5$). However, this is practically not possible for two reasons: a) to examine such events we would need a minimum cut-off magnitude of ~3.5 (Papazachos, 2003) that is possible only after 1991 for the examined area (see equation 16), implying that we do not have enough data to study

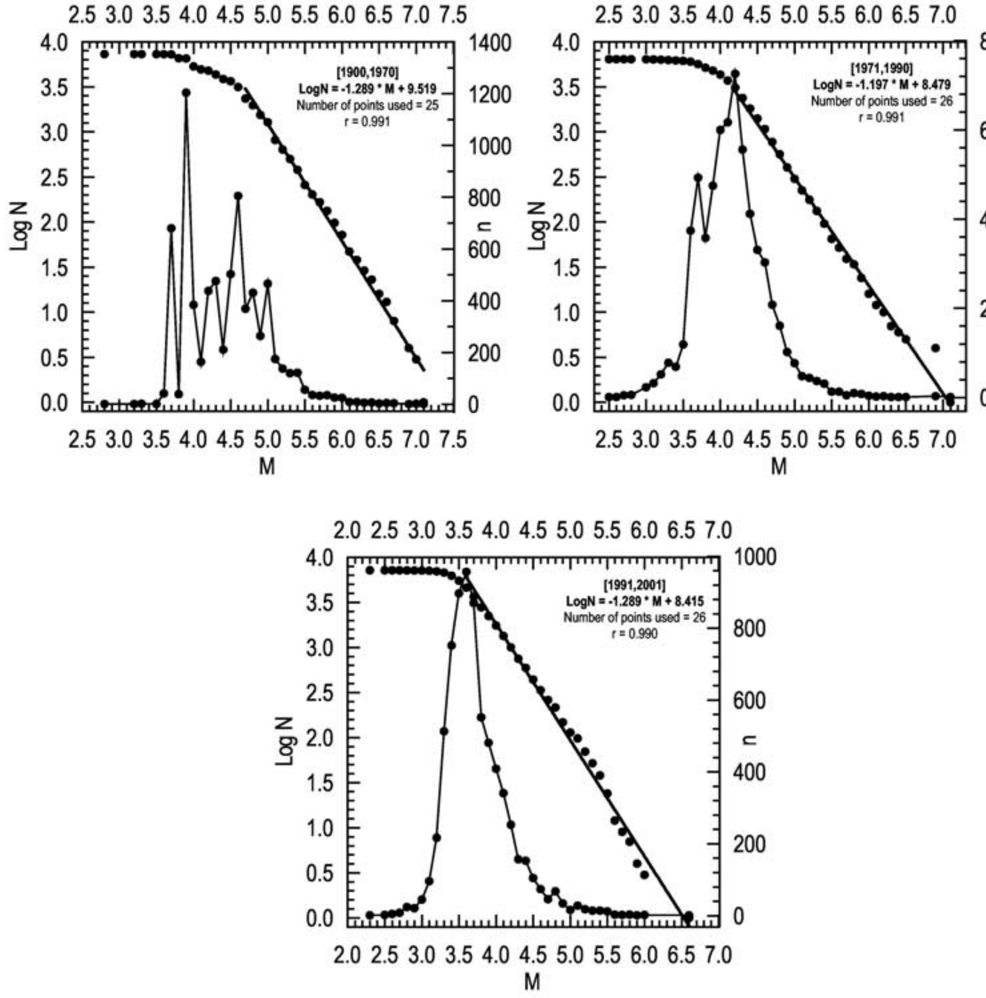

Figure 3. Magnitude distribution of the earthquakes used in the present study. Both, cumulative-frequency and frequency distribution have been used to determine the cut-off magnitude for several time periods.

Table 1. Information on the parameters of the five mainshocks (date, epicenter, magnitude) and on the parameters of the model used for the five sequences. A (in 10^9 Joule$^{1/2}$), B (in 10^8 Joule$^{1/2}$/yr) are the parameters of relation (2). R (in km) is the radius of the circle which has an area equal to the area of the corresponding ellipse, M_{13} is the mean magnitude of the three largest preshocks, S_r (in Joule$^{1/2}$/yr) is the Benioff strain rate in each elliptical region, s_r (in Joule$^{1/2}$ per year and per 1000 km^2) is the Benioff strain rate per unit area and t_p (in years) is the duration of the preshock sequence

N	Date	φ, λ	M	A	R	M_{13}	$LogS_r$	$Logs_r$	t_p
1	1969, 10, 27	44.8, 17.2	6.2	0.06	186	5.7	6.24	5.16	30.2
2	1976, 05, 06	46.4, 13.3	6.5	0.19	297	5.9	6.68	5.24	37.3
3	1979, 04, 15	42.0, 19.1	7.1	0.52	364	6.5	7.18	5.57	42.3
4	1980, 11, 23	40.8, 15.3	6.9	0.14	286	5.9	6.93	5.52	17.9
5	1997, 09, 26	43.0, 12.9	6.1	0.16	200	5.7	6.68	5.58	33.7

Table 2. Retrospectively predicted parameters of the five mainshocks (φ^*, λ^*, M^*, t_c^*). C is the curvature parameter, m is the parameter of relation (2), P is the compatibility measure, q is the quality measure, a (in km) is the length of the major semi-axis of the elliptical region having azimuth z (in degrees), e is the ellipticity of the critical region, M_{min}, is the minimum magnitude of preshocks, n is the number of preshocks and t_s is the start year of each sequence

N	φ^*,λ^*	M*	t_c*	C	m	P	q	a	z	e	M_{min}	n	t_s
1	44.8, 17.6	6.3	1970.8	0.31	0.29	0.58	6.6	253	90	0.80	4.7	22	1937
2	46.2, 13.7	6.5	1976.4	0.39	0.29	0.47	4.2	352	90	0.70	4.8	58	1939
3	43.2, 19.4	7.0	1979.8	0.35	0.29	0.76	7.4	651	120	0.95	5.2	88	1937
4	41.0, 15.5	6.7	1981.4	0.27	0.29	0.45	5.8	512	120	0.95	4.9	49	1963
5	43.4, 13.4	6.4	1997.0	0.54	0.29	0.76	4.5	303	90	0.90	4.8	45	1964

a complete preshock period which is of the order of 20–40 years and, b) the preshock acceleration of such small-magnitude mainshocks is usually ‘masked’ by the much broader areas of larger ($M \geq 6.0$) events, hence it is difficult to identify them. Therefore, we limited ourselves to the five cases complying with equation (17), which correspond to relatively large mainshocks ($M > 6.0$).

Results

Table 1 shows for the best solution the values of the parameter A of relation (2), the radius, R (in km) of the circle with area equal to the elliptical critical region, the average magnitude, M_{13}, of the three largest preshocks, the logarithms of the strain rate, S_r, s_r, and the duration, t_p (in yrs), of the preshock sequence for each of the five examined cases. The values of M_{13}, t_p, S_r in Table 1 fulfill relations (4), (5), (6), that is, these values are well within the $\pm 2\sigma$ of these relations. Therefore, these three relations, derived from a large set of data (Aegean area), also hold for the Adriatic area. The values listed in this table for R, however, are much higher than those expected by relation (3) (higher than $\pm 2\sigma$). Fixing the gradient of the two relations, which are calculated for the Aegean area from a large set of data using the values of R and M listed on Table 1 we find the relation:

$$\log R = 0.42M - 0.32 \tag{18}$$

for Adriatic. Relation (18) shows that the areas of the critical regions for Adriatic are much larger than the corresponding areas (for the same magnitude values) for the Aegean. A physical explanation of this observation is attempted in the discussion. Table 1 also shows that the duration, t_p, of the preshock sequences in Adriatic varies between 18 yrs and 42 yrs with an average of 33 yrs.

Table 2 gives the values of the parameters for the best solution of each of the five sequences. In all calculations the value of parameter m was kept constant, since both observations (Papazachos et al., 2002b) and theoretical considerations (Rundl et al., 2000) show that its value is equal to 0.29. The coordinates (φ^*, λ^*) of the geographical point, the magnitude, M*, and the time, t_c* (in years), which correspond to the best solution and are listed on Table 2 can be considered as the retrospectively predicted parameters (epicenter, magnitude, origin time) of the corresponding mainshock. Comparison of these retrospectively predicted parameters (listed on Table 2) with the corresponding observed parameters of the five mainshocks (listed on Table 1) shows that: the distance between observed and predicted epicenter varies between 29 km and 136 km with an average equal to 61 ± 39 km, the difference, M – M*, between the observed and predicted magnitude varies between –0.3 and 0.2 with an average equal to 0.0 ± 0.2, and the difference between the observed and predicted origin time varies between –1.0 years and 0.7 years with an average of –0.3 ± 0.7. This is in agreement with the results obtained independently for the Aegean area by Papazachos et al. (2002b).

Figure 4 shows the five elliptical critical regions for the corresponding best solutions. The star in each case indicates the center of the ellipse, which is considered as the predicted epicenter, while the black circle corresponds to the observed epicenter. The epicenters of the preshocks are shown with gray circles.

Figure 5 shows the corresponding plots of the cumulative Benioff strain, S, as a function of time. The dashed line is the power law (relation 2) fit to the data and the full line is the linear fit. It is clear that

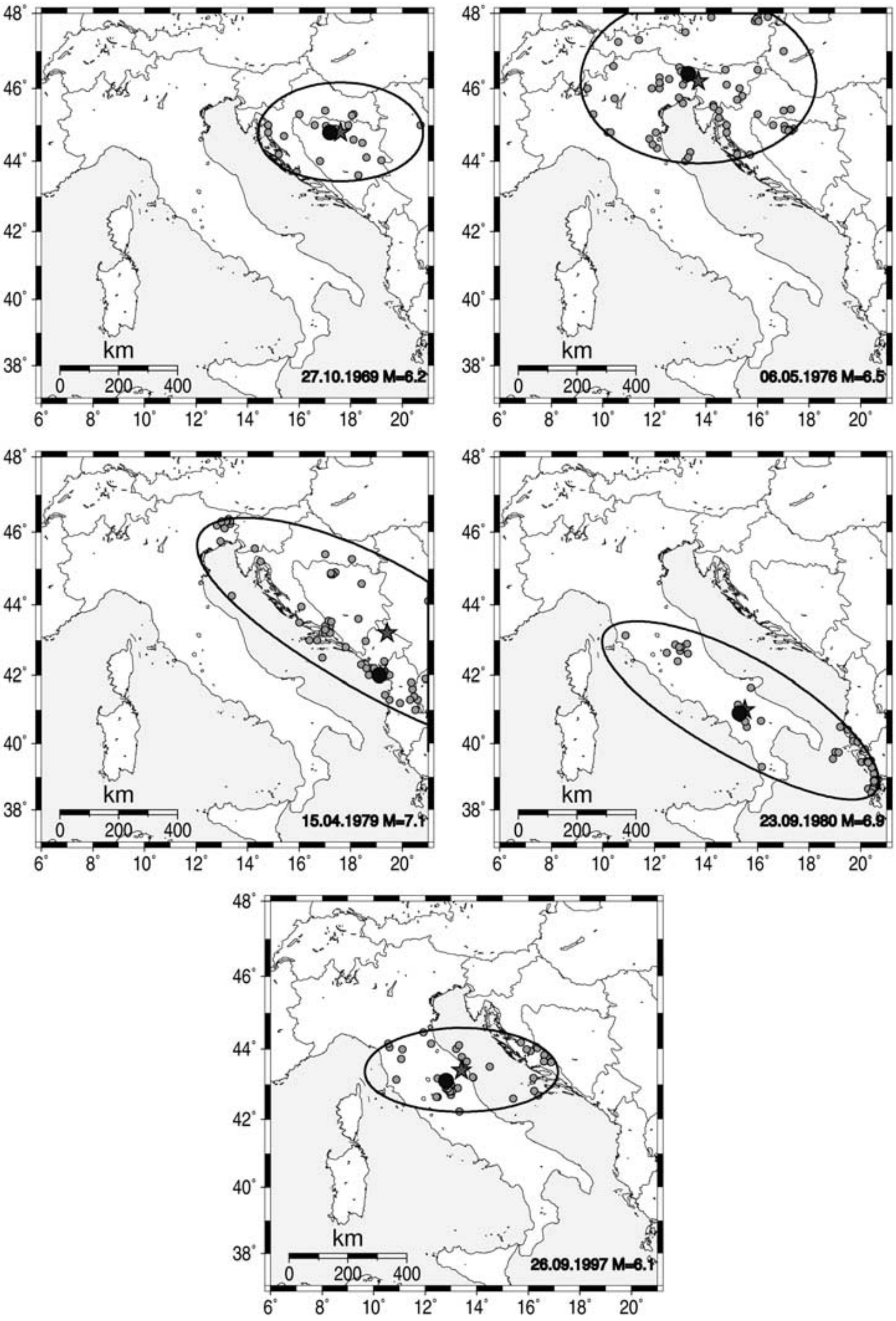

Figure 4. The five elliptical critical regions studied in the present work. Stars correspond to the center of each ellipse (or the retrospectively predicted epicenter), black circles are the observed epicenters and gray circles the epicenters of the preshocks.

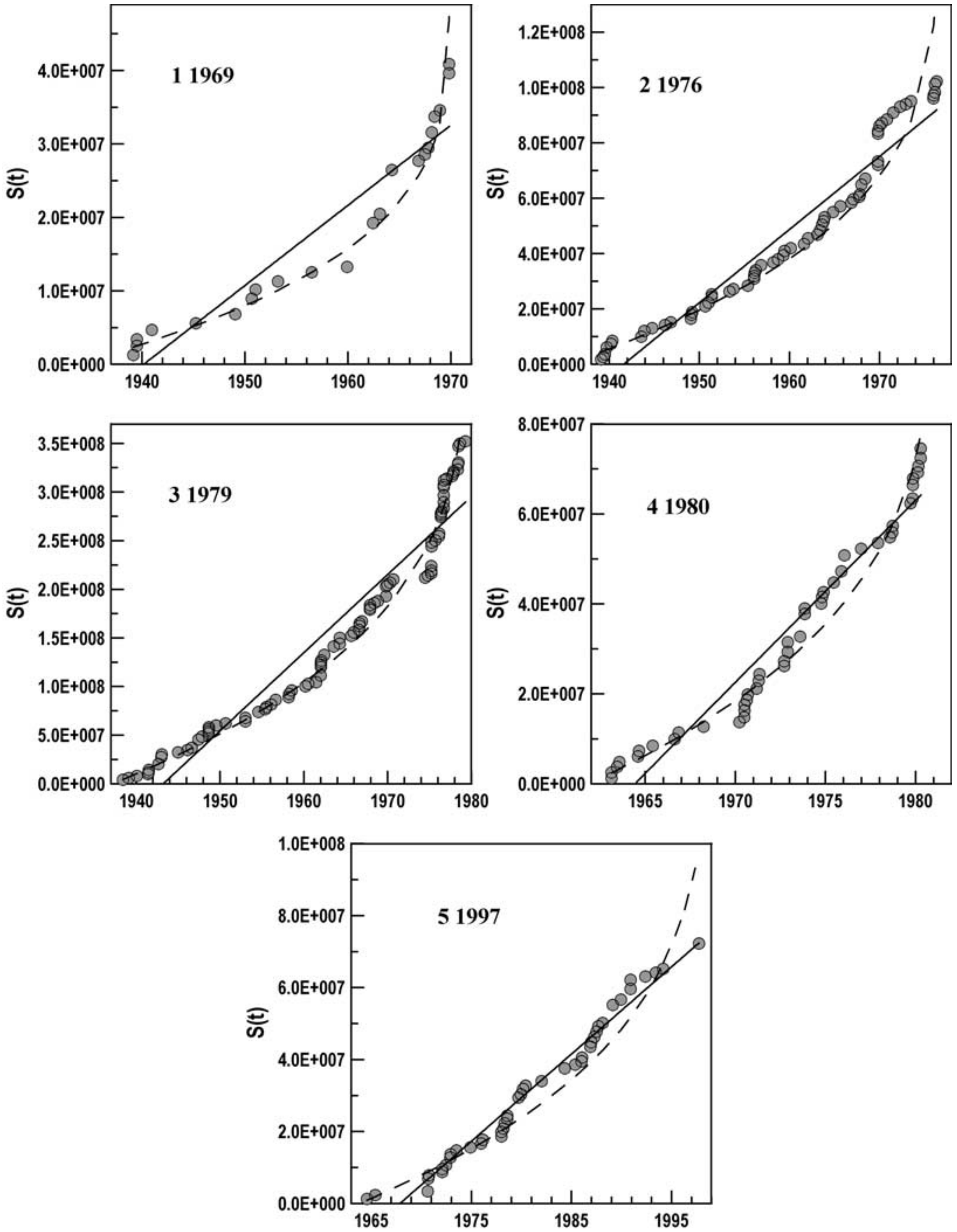

Figure 5. The Benioff strain, S(t), as a function of time for the five cases. Numbers correspond to code numbers of Tables 1 and 2.

the power law fits the data better than the linear relation (see values of the curvature parameter varying between 0.27 and 0.54 in Table 2). Therefore accelerated seismic crustal deformation (Benioff strain) due to the generation of intermediate magnitude earthquakes clearly occurred before all five mainshocks investigated in this study.

Tests using random catalogues

The retrospective analysis performed in the previous section has to be checked against the possibility that the identified accelerated seismic deformation pattern could have randomly occurred. This test can be easily applied using synthetic random catalogues (e.g. Bowman et al., 1998; Zoller et al., 2001; Papazachos et al., 2002c) in order to examine if the observed results are obtained due to the data randomness and the large parametric space examined for the critical area (various values of ellipticity, azimuth, size, duration of preshock period, etc.).

In order to create realistic synthetic random catalogues, we followed the procedure of Papapazachos et al. (2002c), which is a modified version of the approach proposed by Zoller et al. (2001). In brief, the procedure involves: a) foreshock-aftershock declustering, b) estimation of seismicity (Gutenberg-Richter relation) parameters and use of random (Poisson) time-distribution for the occurrence times and the Gutenberg-Richter relation for the magnitude distribution of each seismogenic zone to estimate the corresponding random epicenter distributions in space and time, which are in this way fit (equivalent) to the declustered catalogue and, c) addition of foreshocks-aftershocks to calculate the final synthetic catalogues.

Twenty-five (25) random catalogues were compiled for the broader Italy area using the previous procedure for the five examined earthquakes. For the zonation we used the zones proposed by Baba (2003), which are based on the zones defined for Italy by Meletti et al. (2000), the SESAME group (Jimenez et al., 2001) for the Adriatic area and Papaioannou and Papazachos (2000) for the western Aegean area (Ionian islands, etc.). Appropriate Gutenberg-Richter relation parameters were estimated using the compiled catalogue. Using the random catalogues we have applied the same procedure for the identification of accelerated deformation patterns, using exactly the same criteria used for the five earthquakes. The results obtained for the synthetic random catalogues showed that in 40% of the examined cases no (false) accelerated deformation could be identified. However, in the remaining cases the examined data-sets exhibited accelerated seismicity patterns in accordance with the criteria defined by relations (3), (4), (5), (6), and (10). Hence it is possible to identify areas, which falsely appear to be under a state of accelerated deformation, even when the underlying seismicity distribution is random in time and space.

In order to further evaluate the obtained results, we have examined the distribution of the determined C and q values of the observed and synthetic catalogue results. The histograms of the C and q values obtained for 60% of cases where false accelerated deformation solutions were obtained for random catalogues are presented together with the corresponding values for the five examined events in Figure 6. Therefore, Figure 6 suggests that using a synthetic random catalogue it is possible to misidentify false strong accelerated deformation behaviour (small C values) which are compatible with the strict constrains set by relations (3), (4), (5), (6) and (10) describing this accelerated pattern behaviour. However, these results also clearly show that although it is possible to obtain a few solutions with high q and low C solutions from random catalogues, the corresponding probability for obtaining values similar to those of the five events is quite low. Moreover, comparison for the five events showed relatively low probabilities of 10–22% using the q values and 15–40% using the C values for observing the specific C and q values from random catalogues. The worst values (22% for q and 40% for C) are obtained for the last event (event 5 in Table 1), which is in agreement with its relatively high C value (see Table 1) and the not very clear accelerated deformation pattern seen in Figure 5 for this event. However, for the remaining events, the average probability of observing an accelerated pattern out of random chance (as quantified by the tests on random catalogues) is quite low ($\sim$15%), similar to the results obtained by Papazachos et al. (2002c) for the southern Aegean area.

Discussion and Conclusions

Application of an algorithm for the identification of accelerating Benioff strain before five strong earthquakes in the area around Adriatic Sea shows that such accelerating strain due to the generation of intermediate magnitude shocks (preshocks) has been clearly observed in all five cases. These observations fur-

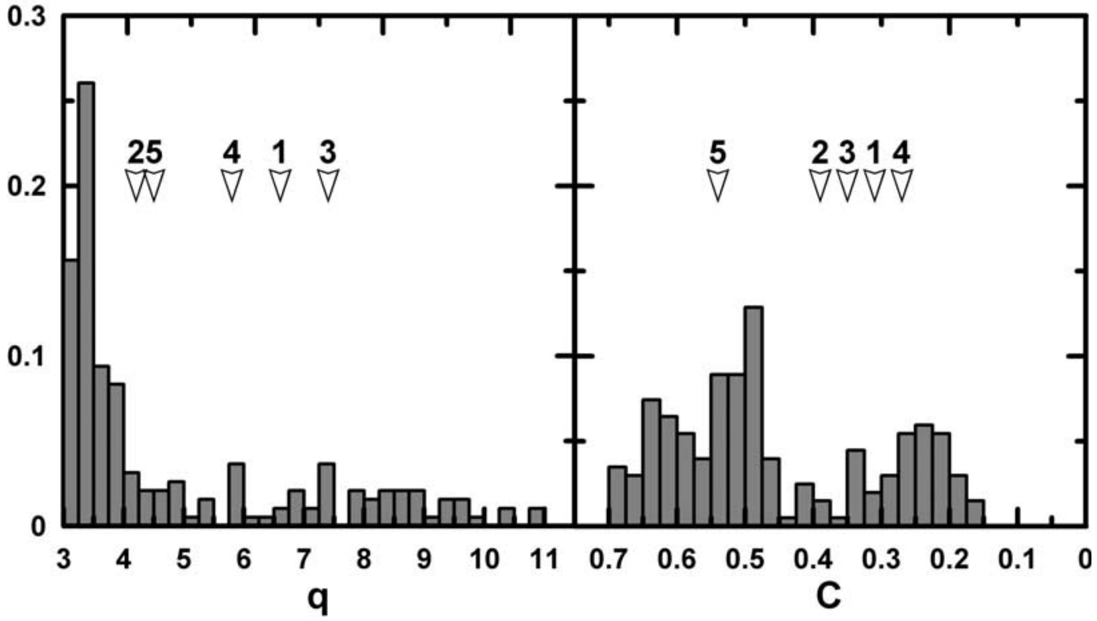

Figure 6. Frequency histograms of the C and q values obtained from the cases where accelerated deformation pattern is falsely identified using random catalogues. The corresponding values for the five events determined in the present work are also shown for comparison.

ther support the idea that accelerating seismic crustal deformation precedes strong mainshocks.

It has further been shown that empirical relations between the parameters of the accelerating deformation model, derived for Aegean, also hold for Adriatic. The areas, however, of the preshock (critical) regions in Adriatic are clearly larger than those defined for equal magnitudes of the mainshocks in Aegean. A preliminary explanation for this difference can be given using the results of Dobrovolsky et al. (1979) who considered the model of a 'soft' elastic inclusion in a more solid elastic half-space in order to model the earthquake preparation region and the related precursory phenomena. Examination of this model showed that the radius of the preparation region, *r*, scales with the magnitude of the expected mainshock, *M* and the maximum stress level, ε, using the relation:

$$\log r = 0.43M - 0.33 \log \varepsilon - 2.73 \qquad (19)$$

for $M \geq 5.0$ and $\log \varepsilon \geq -8$. It is interesting to notice the almost identical behavior of equations (3) and (18) with equation (19) concerning the magnitude dependence of the preparation region. This coincidence of magnitude dependence suggests that the two radii (*R* and *r*) can be considered as similarly defining the extent of the accelerated deformation-earthquake preparation region. Therefore, the different seismicity and deformation levels between the Aegean and the Adriatic, expressed through the much lower s_r values in the Adriatic regions compared to the values presented by Papazachos and Papazachos (2000) for the Aegean area, should also have an effect on the preparation region radius, as can be seen from equation (19), which also predicts larger *r* values for lower seismicity (smaller ε values) areas, such as the Adriatic.

An attempt to retrospectively predict these five mainshocks by this method of accelerating crustal deformation has shown that the uncertainties in these predictions can be up to 136 km for the epicenter of the expected mainshock, ±0.2 for its magnitude and ±1.0 year for the time. The robustness of the obtained results has been further demonstrated by the use of synthetic but realistic random catalogues. Application of the proposed method on several such catalogues has shown an average probability of 15% of obtaining false accelerated deformation patterns. Although such probability should be always taken into account, it suggests a very small probability ($\sim 0.15^5 \simeq 7*10^{-5}$) that the identified acceleration for all five events is random.

It is clear that the information presented in the present paper concerns only the identification of accelerated deformation patterns and the assessment of its use and robustness (using random catalogues) for the *a posteriori* prediction of the specific five examined events. Therefore, we have not attempted to determine a complete strategy to use the proposed method in a systematic way to *a posteriori* predict all past events in the Adriatic region and assess 'false alarms', etc., which is the subject of an ongoing research. However, the observations presented in the present work suggest that a continuous monitoring of the study area and a systematic search for identification of regions where accelerating deformation takes place may provide a method to obtain valuable information concerning the basic parameters (epicenter coordinates, magnitude, origin time) of oncoming strong mainshocks in the area around Adriatic Sea.

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