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Tectonophysics 420 (2006) 509–517

TECTONOPHYSICS
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Decelerating precursory seismicity in Vrancea

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Received 1 December 2005; received in revised form 20 March 2006; accepted 16 April 2006
Available online 6 June 2006

Abstract

Preshock seismic excitation followed by seismic quiescence has been observed in the seismogenic region of strong shallow mainshocks. The strain released by such preshocks is decelerating with the time to the mainshock and is fitted by a power-law with a power value larger than unit. This model is tested in the present work for the intermediate-depth earthquakes of the Vrancea region, generated in an isolated seismogenic zone proper for such testing. A backward application of this "decelerating preshock strain" model for the case of 4.3.1977 (M=7.5) earthquake, for which reliable data are available, shows a good fit of the power-law pattern to the seismic activity preceding the main shock. The occurrence rate of recent intermediate-depth shocks in Vrancea indicates that this region is currently in a state of decelerating seismic deformation, which may lead to the generation of a strong intermediate-depth mainshock there at about the beginning of the third decade of the present century. The respective uncertainties are unknown due to lack of previous relative studies.

Keywords: Decelerating preshock strain; Intermediate-depth mainshocks; Earthquake prediction; Vrancea region

1. Introduction

Considerable research work has been carried out during the last few decades for intermediate-term earthquake prediction on the basis of several preshock seismicity patterns. Two of these patterns have been observed before many strong earthquakes by several researchers and can be considered as the most significant.

The first of these patterns lasts several years to a few decades and is characterized by accelerating seismicity, expressed by the generation of moderate magnitude earthquakes that occur before a mainshock in a broad region (critical region), which scales with the fault length of the mainshock (Tocher, 1959; Mogi, 1969; Raleigh et al., 1982; Papadopoulos, 1986; Sykes and Jaumé, 1990; Knopoff et al., 1996; Bowman et al., 1998; Brehm and Braile, 1999; Jaumé and Sykes, 1999; Papazachos and Papazachos, 2000; Tzanis et al., 2000; Robinson, 2000; Papazachos and Papazachos, 2001, among many others). The cumulative Benioff strain, S (sum of square root of seismic energy) varies with time, t, to the mainshock according to the following power-law proposed by Bufe and Varnes (1993):

$$S(t) = A + B(t_c - t)^m \tag{1}$$

where, t_c is the origin time of the oncoming mainshock and A, B and m (<1) parameters that can be determined by the available data.

The second pattern concerns the seismic quiescence (mainly expressed by the decrease of the frequency of

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0040-1951/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2006.04.008

small earthquakes) during a time period which lasts several years before the occurrence of the mainshock and occurs in a narrower region (seismogenic region) that includes the fault region and its vicinity (Wyss et al., 1981; Scholz, 1988; Wyss and Habermann, 1988; Wyss, 1997; Chouliaras and Stavrakakis, 2001; Zöller et al., 2002). The decrease of the intermediate-term seismic activity in the seismogenic volume of mainshocks has been also expressed by the time variation of the Benioff strain (Kanamori, 1981; Jaumè, 1992; Bufe et al., 1994; Tzanis and Valianatos, 2003). Preshock seismic quiescence has been mainly attributed to stress relaxation due to preseismic sliding (Wyss et al., 1981; Kato et al., 1997). Association of preshock seismic quiescence in the focal region of a strong earthquake with a preshock seismic excitation in the broader region has been observed by Mogi (1969) who called it a "doughnut pattern."

Papazachos et al. (2004a,b, 2005, in press-a,b) used recent global data to show that strong mainshocks are systematically preceded by a seismicity pattern where accelerating strain in the broader (critical) region, which follows relation (1) with $m<1.0$, is accompanied by decelerating strain in the narrower (seismogenic) region, which also follows relation (1) but with $m>1$. They have further shown that the linear dimension of both regions (critical, seismogenic) scales positively with the mainshock magnitude, M, and negatively with the long-term strain-rate, s (in Joule$^{1/2}$/year 10^4 km^2), of the region. The duration, t_a (in years), of the accelerating preshock sequence in the critical region, as well as the duration, t_d (in years), of the decelerating preshock sequence in the seismogenic region both scale negatively with the long-term strain-rate.

The seismic activity of Vrancea is mainly due to intermediate-depth earthquakes located in an isolated narrow seismogenic region which does not seem to be directly associated with any broader active seismic region. Therefore, only decelerating preshock strain is expected for this region, according to the more general "Decelerating In–Accelerating Out Strain" model suggested by Papazachos and his colleagues. This hypothesis, however, needs careful verification. Thus, the purpose of the present work is to examine the behaviour of the intermediate-depth preshock seismic activity in Vrancea by using the most reliable of the instrumental data available for this region and particularly to test the validity of the "Decelerating Preshock Strain Model."

2. Seismotectonic setting

The Vrancea region is located at the sharp bend of the southeastern Carpathian orogenic belt (Fig. 1) and is characterized by the continental collision between the East European plate and the Intra-Alpine to the north

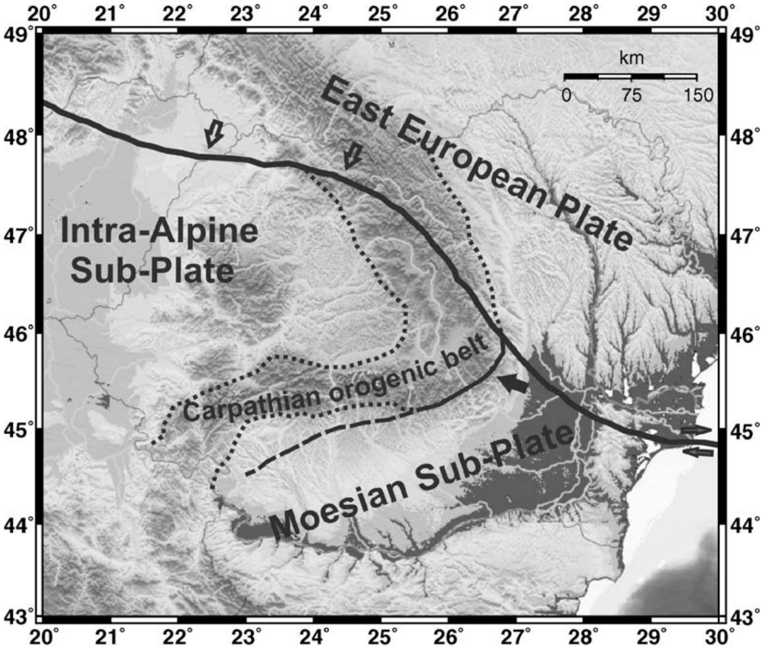

Fig. 1. Continental plates and sub-plates in the area of Carpathians (Constantinescu et al., 1976, modified). Open arrows show the Neogene, already ceased subduction front. Black arrow depicts the active subduction while grey arrows correspond to strike–slip faulting.

and the Moesian subplate to south-west and south-east, respectively (Constantinescu et al., 1976; Cornea and Lazarescu, 1979). This collision process is now in its final stage of evolution (Popescu and Radulian, 2001). The largest earthquakes in this region are of intermediate focal depth (60–170 km) but shallow smaller earthquakes also occur.

A well-defined narrow zone with dimensions of only a few tens of kilometers, close to the contact of the above-mentioned tectonic units is formed by the epicenters of intermediate-depth earthquakes with spatial distribution much denser than that of intermediate-depth earthquakes in other intracontinental regions (Ismail-Zadeh et al., 1999). The shallow seismicity in the Vrancea area (Fig. 3) is moderate ($M<5.7$) and more diffused in comparison with the intermediate-depth seismicity. The foci of these shallow shocks are mainly located between 0 and 40 km depth (Radu, 1974, 1979; Ardeleanu, 1999; Popescu and Radulian, 2001). The corresponding seismogenic volume is about 100 km

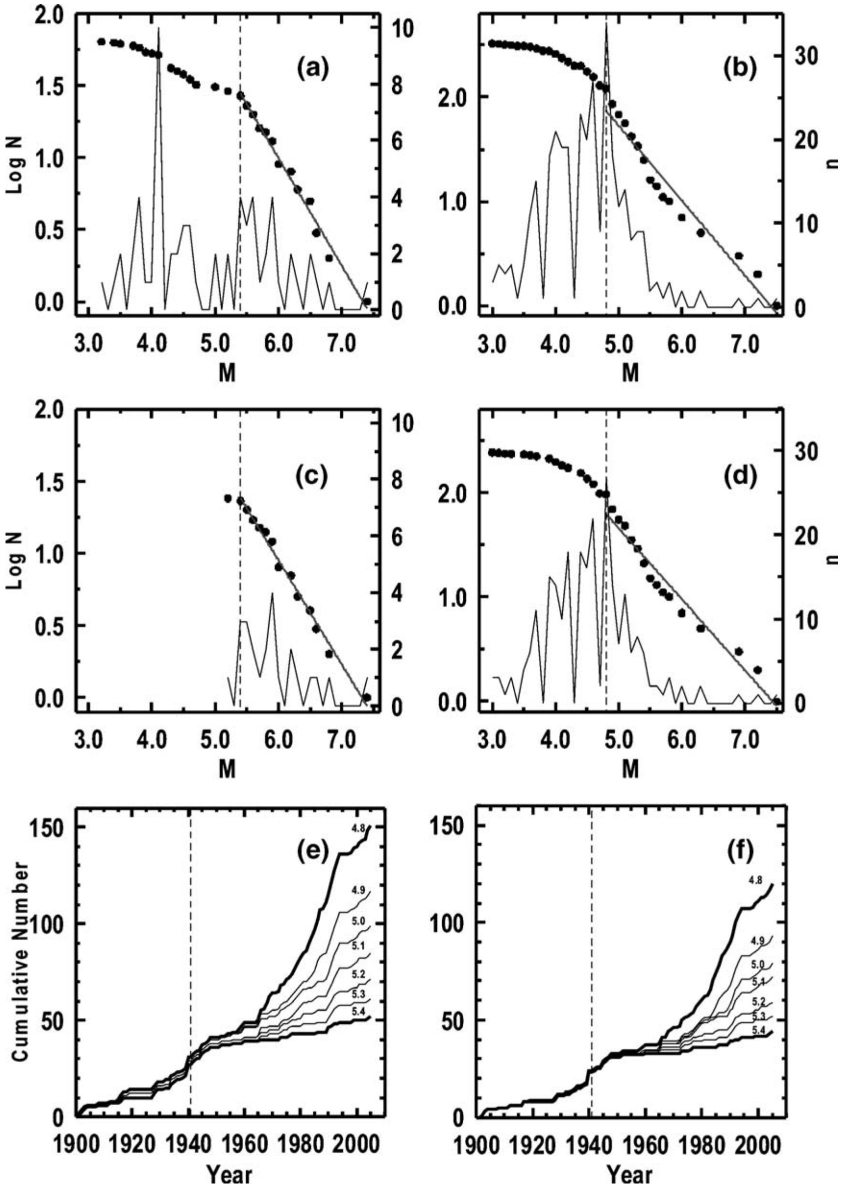

Fig. 2. Frequency (right axis) and cumulative frequency (left axis) magnitude distribution for the periods (a) 1900–1940 and (b) 1941–2005. The figures in (c and d) are the respective plots produced with only the intermediate-depth earthquakes. Plots (e and f) show the seismicity rates (for several magnitude values) corresponding to all and to intermediate-depth earthquakes, respectively.

long, 60 km wide and extends down to a depth of ~170 km (Ismail-Zadeh et al., 1999). On the average five major earthquakes of $M_w \geq 7.0$ with focal depths greater than 60 km occur every century within this seismogenic source (Radu, 1979).

This intermediate-depth seismic activity is a result of the subduction of the northern part of the Moesian sub-plate (considered as the continuation of the Black Sea sub-plate) under the Intra-Alpine sub-plate (Fig. 1) with an angle of 60° (Constantinescu et al., 1973) or almost vertically (Roman, 1970). The Carpathian orogenic belt (Fig. 1) is originated by the northwestern sub-plate which overrides the subducting one (Riznichenko et al., 1980). According to McKenzie (1970), the large events in the Vrancea region occur in a vertical relic slab sinking within the mantle and now overlain by continental crust. Fuchs et al. (1979) and Khain and Lobkovsky (1994) likewise suggest that intermediate-depth seismicity in the Vrancea region is a result of a SE–NW paleo-subduction, the southeastern margin of which is now decoupled from the crust and continues sinking gravitationally. The active subduction of this slab ceased about 10 Ma ago and since then only slight horizontal shortening is observed in the sedimentary cover (Wenzel, 1997).

3. The data

To carry out this study, it is necessary to compile a catalog of earthquakes which occurred in the broader area of Vrancea. This catalog must be homogeneous and complete above specific magnitude values over certain time periods. The data sources we use are the bulletins of the International Seismological Center (ISC, 2005) and the National Earthquake Information Center (NEIC, 2005) of the USGS, the online CMT catalog of Harvard (2005) and the catalog of European earthquakes of Karnik (1996). The compiled catalog concerns a broad area bounded by the coordinates 43–49°N, 20–30°E and covers the time interval 1900–October 2005. To ensure the homogeneity of the catalog with respect to the magnitude, the moment magnitude scale was selected as the most reliable one. Proper relations converting magnitudes of other scales (estimated by several seismological centers) to equivalent moment magnitudes were used (Baba et al., 2000; Scordilis, in press). The finally adopted magnitude for each earthquake is either the original moment magnitude (published by Harvard or USGS) or the equivalent moment magnitude estimated as the weighted mean of the converted magnitude values, by weighting of each participating magnitude with the inverse standard deviation of the respective relation applied. The compiled catalog includes information on 792 earthquakes with equivalent moment magnitudes between 3.0 and 7.5 for the period 1900–2005.

The completeness of the catalog for the area bounded by the coordinates 43.5–48.5°N, 22.0–30.0°E has been checked for several time periods and cut-off magnitudes. Apart from the variations of frequency and cumulative frequency of magnitudes (Gutenberg–Richter cumulative frequency–magnitude relation) for several time periods, the temporal variations of the seismicity rate for certain magnitude values have been also considered (Fig. 2). It has been found that the catalog is complete for the following periods and corresponding magnitudes:

$$\begin{array}{ll} 1900-1940 & M \geq 5.4 \\ 1941-2005 & M \geq 4.8 \end{array} \qquad (2)$$

Individual tests for the intermediate-depth earthquakes ($h \geq 60$ km) showed that the above completeness criteria also hold for such earthquakes (Fig. 2). Fig. 3 shows a map with the epicenters of all known earthquakes which occurred in the area during the time interval 1900–2005 and comply with the above completeness criteria.

4. Method applied

The spatial distribution of earthquakes (Fig. 3) shows that the Vrancea region can be considered as an isolated area not related with neighboring seismic centers which could play a role in a mainshock preparation process. Several efforts, attempted in the present study, to define wider regions that have been under seismic acceleration before the strong intermediate-depth mainshocks of Vrancea showed that such regions could not be identified. This was expected for two main reasons: (a) the shallow seismicity in the broader area is poor with magnitudes not exceeding the $M = 5.7$ and (b) the intermediate-depth seismic activity is associated to a gravitational sinking decoupled from the crust (e.g., McKenzie, 1970; Fuchs et al., 1979; Khain and Lobkovsky, 1994) which results in activity concentrated in a narrow area that could not be affected by the minor shallow activity of its broader neighbor. On the contrary, decelerating patterns (excitations followed by periods of quiescence) are obviously observed (shaded parts) in the plot of the cumulative Benioff strain as a function of time during the period 1941–2005 (Fig. 4). This plot was derived using the

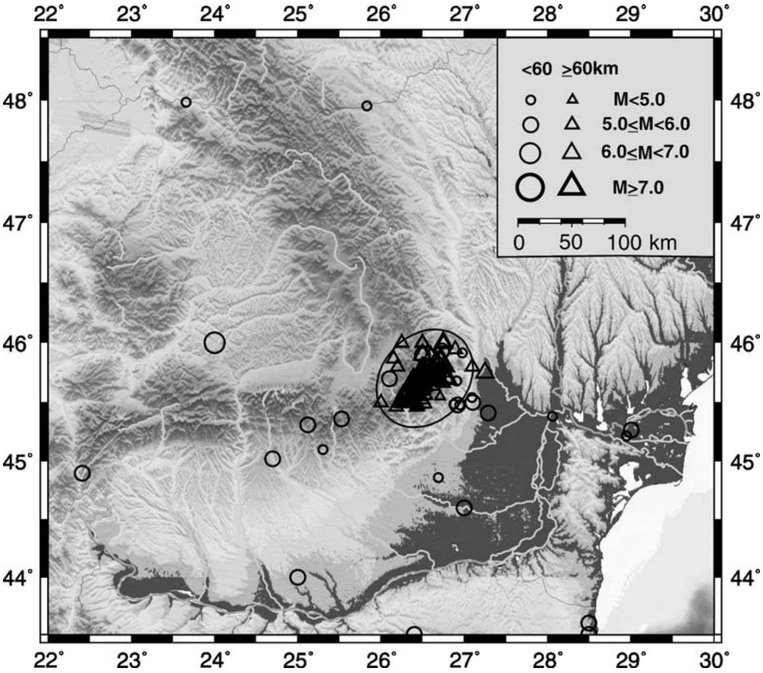

Fig. 3. Map with the epicenters of all known earthquakes which occurred in the broader area of Vrancea since 1900 and follow the completeness criteria defined in the present work. The black elliptical frame delimits the area where intermediate-depth seismicity occurs and which was tested for decelerating preshock strain.

intermediate-depth earthquakes that follow the completeness criteria (relation (2)).

Papazachos et al. (2004b, 2005, in press-a,b) studied strong mainshocks which occurred in different seismotectonic environments during the last few decades and showed that decelerating seismic strain (Benioff strain) released by intermediate magnitude preshocks in a seismogenic region follows power-law relation (1) with $m>1$, as well as the relations:

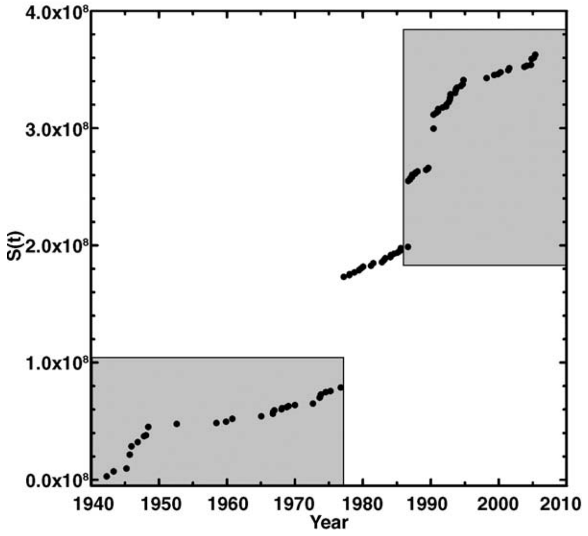

Fig. 4. Time variation of the cumulative Benioff strain (in joules$^{1/2}$) released by intermediate-depth earthquakes in Vrancea ($M \geq 4.8$) for the period 1941–2005. The shaded parts denote periods of decelerating seismicity.

$$\log a = 0.23M - 0.14\log s_{\mathrm{d}} + 1.40, \quad \sigma = 0.15 \tag{3}$$

$$\log(t_{\mathrm{c}} - t_{\mathrm{sd}}) = 2.95 - 0.31\log s_{\mathrm{d}}, \quad \sigma = 0.12 \tag{4}$$

where, α (in kilometers) is the major axis of the elliptical seismogenic region (or the radius of a circular seismogenic region), M is the magnitude of the mainshock, s_{d} (in joules$^{1/2}$/year$\cdot 10^4$ km^2) is the long-term seismicity of the seismogenic region expressed by the annual Benioff strain rate, t_{c} is the origin time of the ensuing mainshock and t_{sd} (in years) is the starting time of the decelerating preshock sequence. The same authors introduced a quality index, q_{d}, defined by the relation

$$q_{\mathrm{d}} = \frac{P \cdot m}{C} \tag{5}$$

where P is the probability that the parameters which are calculated for the candidate seismogenic region are compatible with relations (1), (3) and (4) and C is the curvature parameter defined by Bowman et al. (1998) as the ratio of the root mean square error of the power-law fit (relation (1)) to the corresponding linear fit error, quantifying the deviation of the released Benioff strain from linearity. The cut-off values determined (Papazachos et al., in press-b) for parameters C, m, P and q_d are

$$C \leq 0.60, \quad 2.5 \leq m \leq 3.5, \quad P \geq 0.45, \quad q_d \geq 3.0 \tag{6}$$

with a typical value for $m = 3.0$.

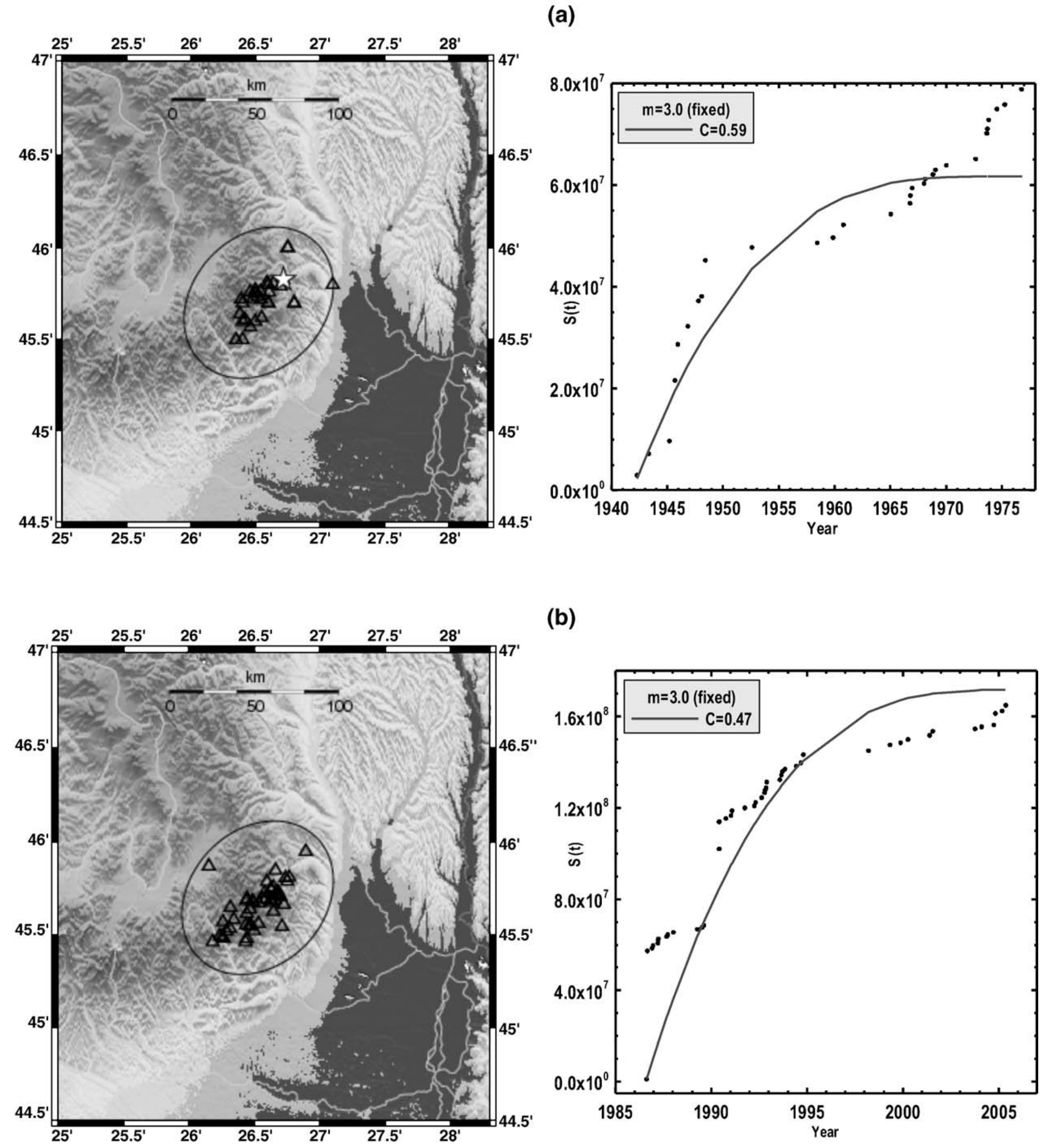

Fig. 5. (a) Elliptical (seismogenic) region and epicenters of decelerating preshocks of the 4.3.1977 mainshock (denoted with a star). (b) Elliptical region where decelerating strain is currently observed. The respective time variation of the cumulative Benioff strain, $S(t)$ (in joules$^{1/2}$), is shown on the right of each figure.

5. Backward testing of the model

The largest earthquakes in Vrancea which occurred during the instrumental period are of intermediate focal depth (~100 km) and have magnitudes of about 7.5. Two such earthquakes occurred after 1900, the first on 10.11.1940 (M=7.4) and the second on 4.3.1977 (M=7.5). We can, therefore, consider this as the magnitude of the characteristic earthquake for the Vrancea region, the time period between two such mainshocks as a full inter-event time and apply the testing procedure for the shock of 1977. On the other hand, the data of this period (1941–1977) are accurate enough and complete for shocks with $M \geq 4.8$ in this region (see relations (2)). At the same time, it is meaningless to test relation (3) because the area where intermediate-depth earthquakes occur is well defined by the spatial distribution of their epicenters. For these reasons, data of this period have been used to backward test the validity of the “Decelerating Preshock Strain Model” as this model is quantitatively expressed by relations (1) and (4).

The elliptical region (major axis with length of 50 km and azimuth 40°, ellipticity 0.6) which delimits the intermediate-depth seismicity (Figs. 3 and 5a) was considered for testing the decelerating preshock model (validity of relations (1) and (4)) for a mainshock with M=7.5 and origin time 4.3.1977. After trying several values of the power parameter, m, of relation (1), it is shown that the strain released by preshocks of the 1977 mainshock is decelerating with the time to the mainshock according to power-law relation (1) with a power parameter m=3.0. Fig. 5a shows a map with the epicenters of the complete preshocks (open triangles) in the elliptical seismogenic region of the 1977 mainshock (white star) and the associated decelerating Benioff strain release, next to this map.

Keeping the scaling coefficient (−0.31) of relation (4) and using the value $\log s_d$=6.96 calculated for the intermediate-depth earthquakes of the Vrancea region, we find the following relation between the duration, t_c-t_{sd}, of the decelerating preshock sequence and the strain rate, s_d, in the region:

$$\log(t_c - t_{sd}) = 3.70 - 0.31 \log s_d \qquad (7)$$

This relation indicates that the duration of the preshock sequences for intermediate-depth mainshocks in Vrancea is longer than that specific for regions of shallow seismicity with similar mean seismicity rate, s_d.

It is worth to notice the declination of the decelerating curve, observed during the last 6 years before the generation of the mainshock (Fig. 5a). This short-term excitation signs the end of the quiescence period and indicates that the oncoming mainshock is near. This has been also observed by Papazachos et al. (in press-a) and is supported by simulation models (Hainzl et al., 2000).

6. A forward test

Data on shocks in the same elliptical region have been used for a forward test. In this case, however, the origin time, t_c, and the magnitude, M, are not known, because they concern a future mainshock which must be predicted. In other words, this is a test for the ability of the method to predict future mainshocks in Vrancea.

Fig. 5(b) shows a map with the elliptical seismogenic region of the probably ensuing mainshock and the epicenters of decelerating preshocks (open triangles) that follow the completeness criteria. Next to this map there is a plot of the time variation of the cumulative Benioff strain, $S(t)$, as it is indicated by the data available up to now (1.1.1986–31.10.2005) and the fit to these data (solid line) by power-law relation (1), with m=3.0. It is of interest to note the excellent fit of the data available up to now by a power-law, as this is inferred by the small value of the curvature parameter (C=0.47) and the very similar properties of the current seismic activity in Vrancea since 1986 with the seismic activity before the 1977 mainshock.

It must be noticed that even though the previous mainshock occurred at 1977, the period which reveals the current deceleration starts at 1986. The reason is that in order to observe deceleration a prior excitation is required (Papazachos et al., in press-b). Such an excitation has predictive properties (Evison and Rhoades, 1997; Evison, 2001). In the case of Vrancea, this excitation is signaled with the strong shocks of 1986 (M=7.2) and 1990 (M=6.9).

The magnitude, M=7.5, which is the maximum observed magnitude in the Vrancea region, is also assumed for the probably oncoming mainshock in this region. From relation (7) and for t_{sd}=1986.6, we find an origin time $t_c \sim 2021$ for the expected mainshock. The uncertainties involved in these parameters (predicted magnitude and origin time) cannot be estimated because very limited information is available for intermediate-depth earthquakes. The corresponding uncertainties for shallow earthquakes are ±0.4 for the magnitude and ±2.5 years for the origin time with a probability of 75% (Papazachos et al., 2005). In the lack of other information, we may assume (just indicatively) that uncertainties on the basic focal parameters of predicted intermediate focal depth earthquakes are expected to be of the same order.

7. Conclusions

The “Decelerating Preshock Strain” model has been tested by using data of intermediate-depth earthquakes of the Vrancea region. A backward test of the model was performed by considering the intermediate-depth earthquake of 4.3.1977 ($M=7.5$) as the mainshock at which the decelerating preshock generation culminates. Preshock activity fits well power-law relation (1) with an m value (=3.0) identical to that estimated by Papazachos et al. (in press-b) for shallow preshocks in different seismotectonic environments. The duration of the intermediate-depth preshock sequences in Vrancea is longer than other regions (with shallow earthquakes) of similar mean seismicity rate, s_d (see relations (4) and (7)).

The forward test of the model shows a very good fit of the data (from 1986 up to now) by power-law relation (1). This led to the conclusion that the next maximum earthquake ($M \sim 7.5$) in Vrancea is expected in the beginning of the third decade of the present century ($t_c \sim 2021$). This estimated origin time of the probably ensuing mainshock is in good agreement with results of studies on earthquake risk in Romania (Wenzel and Lungu, 2000) where it is concluded that the recurrence time for intermediate-depth strong earthquakes in this region with $M \geq 7.4$ is about 50 years.

Acknowledgements

The author thanks B. Papazachos for his substantial help and stimulating discussions during all stages of this work as well as G. Karakaisis and C. Papazachos for critically reading the manuscript. Thanks are also due to the two anonymous reviewers and the editor for their apposite remarks and suggestions that helped to improve the quality of the manuscript. The maps have been produced using the GMT software (Wessel and Smith, 1995).

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