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Short Note

Evaluation of the Results for an Intermediate-Term Prediction of the 8 January 2006 M_w 6.9 Cythera Earthquake in the Southwestern Aegean

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Abstract During the past few decades the critical earthquake model, which is based on observations concerning accelerating seismic deformation and concepts of the critical point dynamics, has been proposed by various seismologists as a useful tool for intermediate-term earthquake prediction. A refined approach of this model has been previously applied to search for preshock (critical) regions in the southern Aegean, using all available data until the middle of 2002. A critical region corresponding to a large mainshock had been identified (Papazachos *et al.*, 2002a,b) in the southwestern part of the Aegean, near the Cythera island. The predicted (in 2002) parameters for this ensuing earthquake are $\varphi = 36.5°$ N, $\lambda = 22.7°$ E for the epicental geographic coordinates (with a model uncertainty of 120 km), focal depth $\leq$100 km, moment magnitude M 6.9 $\pm$ 0.5, and origin time $t_c = 2006.4 \pm 2.0$. The generation of the strong Cythera earthquake on 8 January 2006 with M 6.9, epicenter coordinates $\varphi = 36.2°$ N and $\lambda = 23.4°$ E and a focal depth of $h = 65$ km satisfies this intermediate-term prediction. The region where significant macroseismic effects were anticipated from the predicted mainshock (Cythera, south Peloponnesus, west Crete, and west Cyclades) corresponds to the area where damage by the 8 January 2006 strong earthquake has been observed. The verification of this prediction is strong evidence that the intermediate-term prediction of strong earthquakes is potentially feasible, but additional forward testing of the model is needed to validate this result.

Introduction

Accelerating generation of intermediate (moderate) magnitude preshocks in a relatively broad region around the mainshock fault area is one of the most distinct precursory patterns of strong mainshocks (Tocher, 1959; Mogi, 1969; Sykes and Jaumé, 1990; Knopoff *et al.*, 1996; Jaumé and Sykes, 1999; Robinson, 2000; Tzanis *et al.*, 2000, among others). The generation of these preshocks in this broad (critical) region is often considered as a critical phenomenon culminating in a mainshock considered as a critical point (Sornette and Sornette, 1990; Allégre and Le Mouel, 1994; Sornette and Sammis, 1995; Rundle *et al.*, 1996, 2000).

Bufe and Varnes (1993), based on a damage mechanics model, have proposed the following relation for the time variation of the cumulative Benioff strain, S (in Joule$^{1/2}$), released by preshocks at the time, t:

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

where t_c is the origin time of the mainshock and A, B, and m are model parameters to be determined by the available data. This procedure has also been called the time-to-failure method. The exponent m takes values much smaller than 1 for accelerated moment release (for $B < 0$), whereas values at about $m \sim 1$ correspond to a steady (normal) time variation of the Benioff strain (seismic energy) release. However, results from numerous experimental studies show that m has a mean value of 0.3, which is also the typical value adopted in similar studies (e.g., Zöller and Hainzl, 2002), in agreement with several theoretical considerations and laboratory results (Ben-Zion *et al.*, 1999; Guarino *et al.*, 1999; Rundle *et al.*, 2000; Ben-Zion and Lyakhovsky, 2002).

Bowman *et al.* (1998) suggested the minimization of a curvature parameter, C, which is defined as the ratio of the root-mean-square error of the power-law fit (relation 1) to the corresponding error of the linear fit (steady time variation of the released seismic energy) and used this parameter to identify critical (preshock) regions in various areas. This method has been further developed, and properties of such regions in various seismotectonic regimes (Aegean, Adriatic, Anatolia, Himalaya, Japan, and California) have been determined (Papazachos and Papazachos, 2000, 2001; Scordilis *et al.*, 2004; Papazachos *et al.*, 2005). These properties are expressed by empirical formulas, which relate parameters of a preshock accelerating sequence with the parameters of the ensuing mainshock. Papazachos (2001) has proposed the combination of the minimization of the curvature parameter with these empirical relations and applied an appropriate algorithm to efficiently identify critical (circular or elliptical) regions of strong mainshocks that have already occurred. Moreover, the same approach was applied to identify currently active critical regions and estimate (predict) the parameters of probably ensuing mainshocks associated with these regions.

To attempt prediction of future strong earthquakes it is clear that seismologists can not rely only on retrospective predictions of past earthquakes and that direct forward testing by specific predictions of future earthquakes is the clearest and most objective way to evaluate the predictive ability of any procedure. Within this framework, Papazachos *et al.* (2002a,b) have identified such regions in the southern Aegean and suggested (predicted) the generation of a strong earthquake ($M \sim 7.0$) in the southwestern part of the Aegean sea. The main purpose of the present work is to show that this test has been successful, because the parameters of a strong earthquake that recently occurred near the island of Cythera (8 January 2006, M 6.9) are within the space, time, and magnitude windows predicted by the critical earthquake model.

Identification of an Active Critical Region and Prediction of the Corresponding Mainshock

Identification of critical regions was originally performed by a procedure based on data from the Aegean area (Papazachos and Papazachos, 2000, 2001). Global data have also been used to further modify and refine this procedure (Papazachos *et al.*, 2005, 2006c), which is described in brief here, without having an important effect on the previously obtained results.

The critical earthquake model is based on relation (1), as this relation is applied to the time variation of the accelerating seismic strain ($m \sim 0.3$), as well as on several empirical relations that have been derived (Papazachos *et al.*, 2006c) on the basis of global observations concerning preshock (critical) regions of strong (M 6.3–8.3) mainshocks. These relations are described by the following equations:

$$\log R = 0.42M - 0.30 \log s_a + 1.25, \quad \sigma = 0.15 \tag{2}$$

$$\log (t_c - t_{sa}) = 4.60 - 0.57 \log s_a, \quad \sigma = 0.10 \tag{3}$$

$$M = M_{13} + 0.60, \quad \sigma = 0.20, \tag{4}$$

where R (in kilometers) is the radius of the circular preshock (critical) region (or the radius of the equivalent circle in the case of elliptical critical region), s_a (in Joule$^{1/2}$/yr$\cdot 10^4$ km^2) is the rate of the long-term seismic deformation per year and 10^4 km^2 in the critical region, t_{sa} (in years) is the start time of the accelerating sequence, t_c is the origin time of the mainshock, M is the magnitude of the mainshock, and M_{13} is the mean magnitude of the three largest preshocks. Whereas equations (2) and (3) define the size of the critical region and the duration of the critical period, respectively, equation (4) correlates the expected mainshock magnitude with the magnitude of its largest preshocks.

To compare the observed R, M, and t_{sa} values estimated for each mainshock with relations (2), (3), and (4), a probability of each parameter was calculated. For this reason each model parameter was estimated with respect to its expected value (from equations 2, 3, and 4), assuming that the deviation of each parameter follows a Gaussian distribution. The average, P_a, of these probabilities is used as a measure of the agreement of the observed parameters with those calculated by these three global relations (Papazachos and Papazachos, 2001). Furthermore, for each point of the investigated area a "quality index", q_a, has been defined (Papazachos *et al.*, 2002b) by the formula:

$$q_a = \frac{P_a}{mC}, \tag{5}$$

where C is the curvature parameter, which expresses the degree of deviation from linearity of the time variation of the cumulative Benioff strain (Bowman *et al.*, 1998) and m is the parameter of relation (1), which expresses the degree of acceleration. On the basis of a large sample of data concerning accelerating preshock sequences of mainshocks that occurred in a variety of seismotectonic regimes and had magnitudes between 5.6 and 8.3 (Papazachos and Papazachos, 2000, 2001; Scordilis *et al.*, 2004; Papazachos *et al.*, 2005, 2006c) the following cutoff values have been determined:

$$C \leq 0.60, \quad P \geq 0.45, \quad m \leq 0.35, \quad q_a \geq 3.0. \tag{6}$$

The geographic point, Q, for which relations (6) are fulfilled and where the quality index q_a obtains its largest value is considered as the geometrical center of the critical region. We should point out that although relation (6) could be alternatively described as a range of values, this is of little practical importance because the corresponding parameters never take in practice their extreme lower (0 for C) or maximum (1 for P and infinity for q_a) theoretical values. Moreover, the magnitude, $M_{\min}$, of the smallest preshock of an accelerating preshock sequence for which relations (6) hold and q_a obtains its largest value (optimum solution) is given by the relation:

$$M_{\min} = 0.46M + 1.91, \qquad (7)$$

where M is the magnitude of the mainshock (Papazachos, 2003; Papazachos *et al.*, 2005). Thus, for mainshock magnitudes 6.0, 7.0, and 8.0 the corresponding minimum magnitudes of accelerating preshock sequences are 4.7, 5.1, and 5.6, respectively.

To estimate (predict) the parameters of an oncoming mainshock using this model, we have separated the broad region into a dense grid (e.g., with spacing 0.25° × 0.25°). The geographic point of the grid that fulfills relations (6) with the highest value of q_a is the geometrical center, Q, of the critical region and the corresponding solution (M, t_{sa}, s_a) is the optimal solution. The point Q is considered as the epicenter, $E(\varphi, \lambda)$, of the oncoming mainshock and the magnitude, M, of the best solution as its magnitude. The origin time, t_c, can be calculated by the use of relation (3), as the starting time, t_{sa}, of the accelerating sequence is defined during the optimization process.

Intermediate-Term Prediction of the Cythera Earthquake

The initial identification of the accelerated (critical) region in the southwestern part of the Aegean area with this procedure was performed using data up to 1 July 2000 and resulted in the estimation of epicenter parameters $\varphi = 36.4°$ N, $\lambda = 23.0°$ E, M 6.8 and a predicted time window 2001.3 − 2004.3 (Papazachos *et al.*, 2002b). Estimation was repeated by the use of additional data collected during the next two years and the prediction for the southwestern part of the Aegean area based on data up to 1 July 2002 (Papazachos *et al.*, 2002a) were $\varphi = 36.5°$ N, $\lambda = 22.7°$ E (epicentral error ≤120km), M 6.9 (±0.5), origin time $t_c = 2006.4$ (±2.0 yr) and focal depth $h \leq 100$ km. Figure 1 shows (a) the elliptical (critical) region where the intermediate-magnitude shocks (preshocks) had been in an accelerated mode and (b) the corresponding time variation of the cumulative Benioff strain, $S(t)$, before the mainshock (Papazachos *et al.*, 2002a).

The parameters of the 8 January 2006 Cythera earthquake are 36.2° N, 23.4° E, M 6.9 and $h = 65$ km, hence it can be considered that the specific intermediate-term earthquake prediction was successful, as these parameters are within the predicted (in 2002) space, time, and magnitude windows. We have estimated the corresponding probability, within these time-space-magnitude windows, for random occurrence of this earthquake, on the basis of the Gutenberg–Richter magnitude distribution and a Poisson time probability distribution. For this purpose we have tested the use of various parts of the available seismological catalog, such as the post-1911 (instrumental period) data for the Aegean area (complete for $M \geq 5.2$), the post-1845 (instrumental and recent historical) data (complete for $M \geq 6.5$), etc., using the completeness proposed by Papazachos and Papazachou (2003) for the examined region. In all examined cases, using the upper $+2\sigma$ level (95%) of the Gutenberg–Richter curve, the corresponding probabilities for random occurrence are quite low (3–4%), suggesting a high-reliability level of corresponding prediction.

Papazachos *et al.* (2002b) have also predefined the area where macroseismic effects due to this ensuing mainshock were most probably expected (Cythera, southern Peloponnesus, western Crete, and western Cyclades). This assessment was mainly based on historical and instrumental information from similar intermediate-depth earthquakes in the study area (broader Cythera region). Note that the large earthquake of 8 January 2006 caused damage in Cythera, southeast Peloponnesus, and western Crete. Moreover, the typical fault-plane parameters for the intermediate-focal-depth earthquakes in the Cythera region (Papazachos and Papazachou, 2003) are strike = 61°, dip = 70°, rake = 144° (strike-slip fault with significant thrust component), in good agreement with the published Harvard CMT solution of the Cythera 2006 earthquake (strike = 69°, dip = 58°, rake = 122°).

The intermediate-term prediction of the Cythera earthquake has already found a practical *a priori* application: The Institute of Engineering Seismology and Earthquake Engineering (ITSAK), after evaluating the possibility of the generation of a large earthquake in this region, had installed a dense strong-motion network of accelerographs in the broader area of the expected earthquake. As a result, the intermediate-depth Cythera earthquake was recorded at a wide distance range by several strong-motion instruments, and the corresponding records are the first accelerograms available for a large intermediate-depth earthquake in the Hellenic Arc and, hence, are very valuable for engineering purposes.

Papazachos *et al.* (2006c) investigated the time variation of the quality index, q_a, for 46 accelerating preshock sequences of several mainshocks that occurred in different seismotectonic regimes (Mediterranean, Japan, California). Note that they observed that this index, which expresses the predicting ability of the critical earthquake model, increases with time and obtains its largest value a few years before the mainshock and then decreases up to the time of the mainshock. Figure 2 shows the time variation of the quality index, q_a, for the Cythera 2006 earthquake. A similar pattern is observed (Fig. 2), indicating that the precursory accelerating strain has been practically identifiable since 1996 for this mainshock. This observed pattern indicates a temporal variation of the precursory physical process in the critical region, which can be also useful for future predictions.

Discussion

The intermediate-term prediction of the Cythera 2006 earthquake presented in the present work is based on a modified approach of the accelerating Benioff-strain model (Papazachos and Papazachos, 2000, 2001; Papazachos *et al.*, 2002b). This model has recently been refined (Papazachos

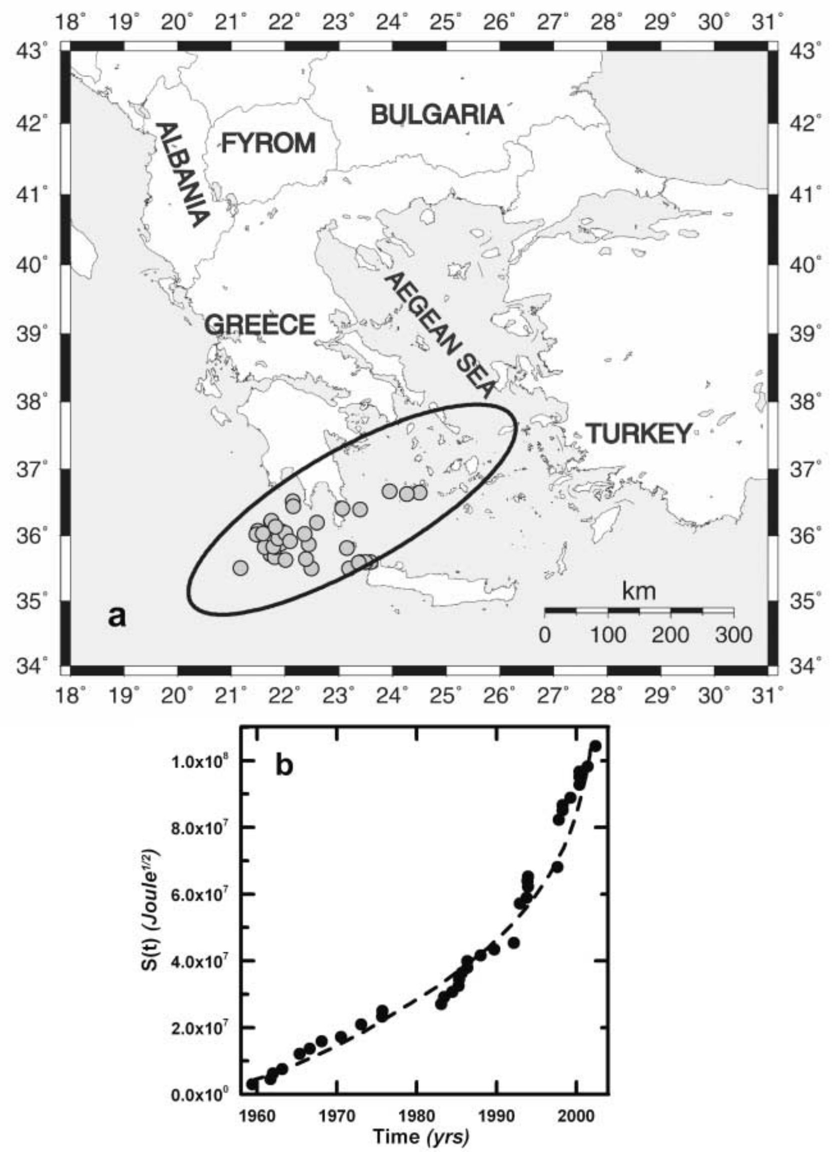

Figure 1. (a) The elliptical region in the southwestern part of the Hellenic Arc where accelerating seismicity of intermediate-magnitude ($M \geq 5.1$) shocks (preshocks) has been observed and the epicenters (small circles) of the shocks. (b) Time variation of the Benioff strain, $S(t)$, released by these shocks until 1 July 2002 and fit (dashed line) by a power-law [$S(t) = A + B\,(t_c - t)^m$] relation (Papazachos *et al.*, 2002a).

et al., 2005, 2006c); hence, it can be expected to be more efficient for prediction of future earthquakes. An additional encouraging fact is that the Cythera earthquake was also independently predicted by Tzanis and Vallianatos (2003), using a similar method, who also suggested that the expected rupture would most likely occur on a strike-slip fault.

In addition to the proposed accelerating seismicity model, a decelerating seismicity pattern in the immediate fault vicinity has recently been proposed (Papazachos *et al.*, 2006c), which is also of importance for intermediate-term earthquake prediction. This model of decelerating seismicity had not been applied in the published results of the Cythera earthquake because it was not known at that time (2002). Decelerating seismicity has also been used for other future earthquakes combined with the accelerating seismicity model (Papazachos *et al.*, 2006a,b). It must be mentioned that the accelerating and decelerating preshocks associated with a strong mainshock ($M \geq 6.0$) are of intermediate magnitude ($M \geq 4.0$) and, at least in part, cover different space, time, and magnitude windows (Papazachos *et al.*, 2006b,c). A similar power-law relation (1) can also be applied for decelerating preshocks with $m > 1.0$ ($m \sim 3.0$).

We have attempted to perform a backward test of the decelerating seismicity model for the Cythera earthquake and have found a satisfactory optimum solution ($C = 0.35$, $q_d = 6.6$) corresponding to a mainshock with magnitude M 6.8, a geometrical center, F (36.1° N, 23.5° E), which is very close to the epicenter of the Cythera 2006 earthquake and a radius $r = 126$ km for a circular decelerating preshock region. The time variation of the quality index, q_d, for the Cythera decelerating preshock sequence is very similar to the time variation of the accelerating index presented in Figure 2. Therefore, the successful intermediate-term prediction of the intermediate-depth Cythera earthquake by the use of the accelerating deformation model and the solution obtained here for the decelerating strain model by

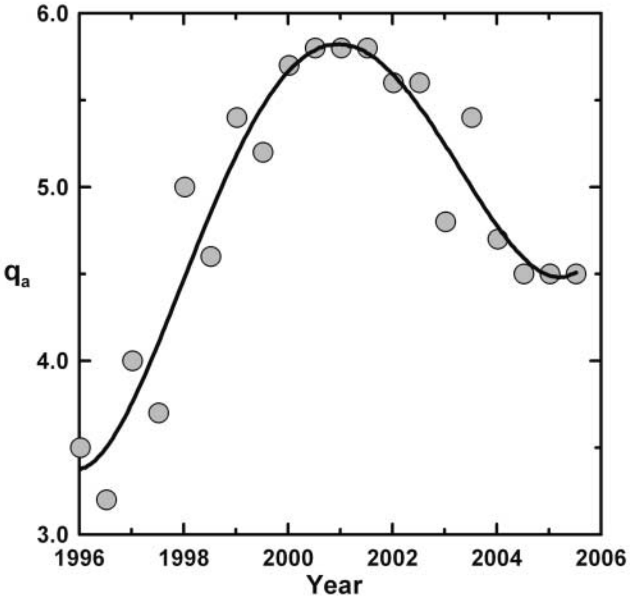

Figure 2. Time variation of the quality index, q_a (relation 5), for accelerating Benioff strain in the critical (preshock) region of the Cythera 2006 strong earthquake.

a backward procedure indicate that these two patterns are also applicable for intermediate-depth strong earthquakes. However, additional tests need to be performed for future predictions to further validate this suggestion.

An additional accelerating pattern had been also observed in the southeastern part of the Aegean by using data up to 1 July 2000 but with low q_a values. For this reason a careful monitoring and re-estimation of the model parameters was suggested to verify and evaluate the time-evolution of accelerated seismic energy release in the eastern part of the southern Aegean area (Papazachos *et al.*, 2002b). Recent re-estimation of the seismic accelerating and decelerating seismic energy release in this area by using data until 31 October 2005 indicates the possible generation of an oncoming mainshock with epicenter coordinates E (37.2° N, 26.7° E with epicentral error <150 km), origin time $t_c = 2009.6 \pm 2.5$ yr, moment magnitude M 6.6 ± 0.4 and focal depth $h \leq 100$ km (Papazachos *et al.*, 2006a).

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