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Seismicity anomalies prior to the 13 December 2008, M_s=5.7 earthquake in Central Greece

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Abstract. This investigation has applied a recent methodology to identify seismic quiescence and seismic acceleration, prior to the occurrence of the 13 December 2008, M_s=5.7 earthquake in Central Greece. Anomalous seismic quiescence is observed around the epicentral area almost twelve years prior to the main shock and it lasted for a period of about four and a half years. After this period an acceleration in seismic activity began and lasted until the main shock. Modeling this seismic sequence with the time-to-failure equation and with a fixed value of the exponent "*m*" equal to 0.32, shows a successful estimation of the occurrence time of the main event within a few days. The physical meaning of this particular choice of the "*m*" value is discussed.

1 Introduction

It was shown recently that anomalous seismic quiescence followed by seismic acceleration preceded the catastrophic 8 June 2008 earthquake in northwestern Peloponesus (Chouliaras, 2009). The region of investigation for that study was the rectangular area: 37.00° to 39.00° N and 19.00° to 23.50° E and an earthquake catalog was compiled from the monthly bulletins of the Institute of Geodynamics of the National Observatory of Athens (NOA-IG), in order to study the anomalous seismicity patterns. The quiescence mapping showed an onset time 8 years prior to the main shock around the epicentral area with a duration of almost 2.5 years. This was followed by seismic acceleration for about 5 years up to the time of the main shock and this acceleration revealed quite a good fitting to the accelerated moment release model (AMR). Prior to the 8 June event, other independent investigations concerning anomalies in the electric field (Sarlis et, al., 2008a) and seismicity patterns (Papadimitriou, 2008 and Sarlis et al., 2008b) had been published.

Almost six months after the catastrophic earthquake of 8 June 2008, i.e. on 24 October 2008, Varotsos et al. (2008a) reported a new anomaly in their electric field measurements at their Patras station and proposed the same region as candidate for the occurrence of a strong main shock. Subsequently, Varotsos et al. (2008b) in an attempt to better identify the time of occurrence of the impending main shock, analyzed in natural time (Varotsos et al., 2005a, b) the seismic events that occurred in the region after the electric signal detection by following the procedure similar to that in Sarlis et al. (2008b). At that time, the analysis of the earthquake catalog for Chouliaras (2009) was under way and it was noticed that the investigated region indicated other areas of quiescence, apart from that of the June 8^{th} event, the most pronounced being in the northeastern part of the region, around Central Greece, i. e., the area of the recent 13 December 2008 main shock with M_s=5.7 (Fig. 1). It is the purpose of this study to present a complete description of the investigation of that seismicity anomaly with respect to the occurrence of the 13 December 2008 main shock.

2 Data analysis and results

On 13 December 2008 at 08:27:20 (GMT), a magnitude M_s=5.7 earthquake occurred near the city of Lamia in Central Greece (Fig. 1). NOA-IG determined the earthquake parameters and provided epicentral coordinates at 38.72° N and 22.57° E and a focal depth of 24 km (http://www.gein.noa.gr/services/Noa_cat/CAT2003.TXT).

For this area in Central Greece, the geological (fault slip) data reported by Roberts and Ganas (2000) indicate a N14° E extension direction and the geodetic data by Clarke et al. (1998) and Briole et al. (2000), a N-S crustal strain.

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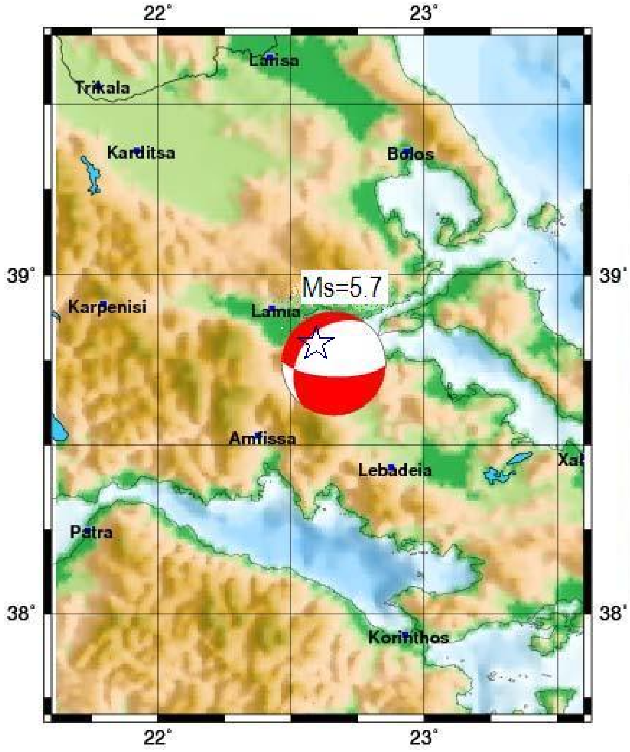

Fig. 1. Location (star) and source mechanism of the M_s=5.7 earthquake in Central Greece on 13 December 2008.

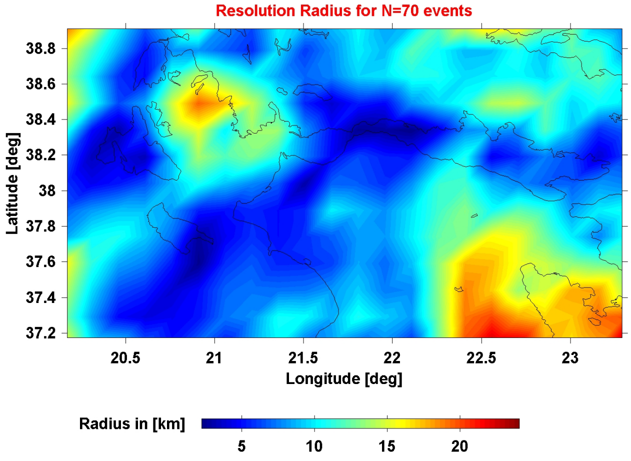

Fig. 2. Map of the investigated region showing the distribution of the radius (of resolution) needed to collect N=70 seismic events using the NOA-IG earthquake catalog.

On average, onshore normal faults strike N290–310° E and dip to the NE (Ganas and Papoulia, 2000; Roberts and Ganas, 2000). The preliminary moment tensor solution in Fig. 1 (http://bbnet.gein.noa.gr/MT.htm) indicates a normal fault with a small sinistral component (strike/dip/rake 92°/69°/−64°). Thus, the 13 December 2008 seismic fault geometry and kinematics is found to be in broad agreement with the regional tectonics and comprises a South-dipping antithetic structure to the main North-dipping faults.

The recently compiled earthquake catalog for the region 37.00° to 39.00° N and 19.00° to 23.50° E from 1964 until 2008 (Chouliaras, 2009) is used throughout this study. Here, we also follow the same methodology as in (Chouliaras, 2009), using the ZMAP software package (Wiemer, 2001) to identify anomalous seismicity patterns.

Seismic quiescence as defined by Wyss and Habermann (1988) may be related to crustal main shocks (Wyss, 1997a, b) and in order to investigate this hypothesis, the gridding method of Wiemer and Wyss (1994) is used to measure the seismicity rate change, namely the Z-value, at the nodes of a grid map. The Z-value is calculated using the equation of Habermann (1983) :

$$Z = (R_1 - R_2)/(\sigma_1^2/n_1 + \sigma_2^2/n_2)^{1/2} \qquad (1)$$

Z measures the significance of the difference between the mean seismicity rate within window R_1, and the background rate R_2, defined as the mean rate outside the window but within the same area. Quantities σ_1 and σ_2 are the variances of the means and n1 and n2 are the corresponding number of bins with a measured seismicity rate.

Changes in the seismicity rate are evaluated as a function of time, at each node of a grid with 0.05° spacing. This grid spacing is related to the accuracy of epicentral determinations of the catalog and also provides a dense coverage in space. At each node of the grid, the nearest N earthquakes are analyzed and a window (Tw=1.5–7 years) is moved through the time series, stepping forward by a one month sampling interval in order to have a continuous and dense coverage in time. The N and T_W values are usually selected accordingly in order to reveal the quiescence signal and this choice does not influence the results in any way. The appropriate value of N may be obtained by investigating the homogeneity, magnitude of completeness (Mc) and density of earthquakes in the investigated region.

Following Chouliaras (2009), we find a lower Mc value in Central Greece compared to a higher value in northwestern Peloponesus, which is undoubtedly due to the density of network stations. To visualize the density of earthquakes in the catalog, we may use the “resolution radius” parameter, defined as the radius needed to collect a statistically significant sample of N seismic events. Figure 2 shows the resolution radii for collecting a sample equal to that in the study of Chouliaras (2009), i.e., N=70 events. One observes that the radii are larger in Central Greece (10.45 km) when compared to northwestern Peloponesus (around 7.7 kilometers) and this choice of N=70 is reasonable for sampling the seismogenic areas that generate large main shocks in Greece (Chouliaras and Stavrakakis, 1997, 2001).

Figure 3 summarizes the Z-value map of the region, with N=70 events and a time window Tw=2.5 years, starting at 2001.3 (see also Fig. 6a in Chouliaras (2009). This map

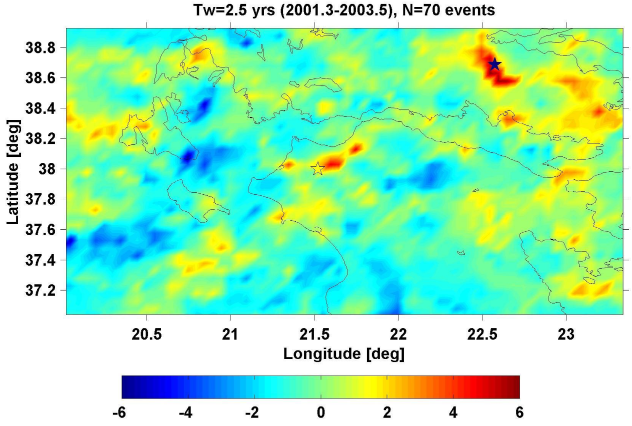

Fig. 3. The Z-value map for the investigated region based on the NOA-IG earthquake catalog starting at the value of 2001.3. Window length Tw=2.5 years, N=70 events and grid spacing=0.05°. The yellow and blue stars indicate the epicenters of the 8 June and 13 December 2008 main shocks, respectively.

clearly reveals the quiescence areas for the 8 June 2008 main shock in northwestern Peloponesus as well as for the 13 December 2008, main shock in Central Greece (Chouliaras, 2009).

The onset and the duration of the quiescence for the 13 December 2008 main shock may be seen in Fig. 4, which depicts the cumulative seismicity at the epicentral area, centered at 38.66° N–22.56° E, and having a radius of 10.45 km in order to accumulate N=70 events. The onset of the quiescence marked by the red arrow is around 1997.8 and the quiescence lasted for more than 4.5 years.

A Z-value map determined in a similar way as in the aforementioned study, for the area surrounding the epicenter of the 13 December 2008 main shock is shown in Fig. 5. To better reveal the quiescence area on the Z-value map, the parameters from the cumulative curve Fig. 4., i.e., the onset time at 1997.8 and Tw=4.5 years are used. One may clearly identify the large area of significant quiescence with a Z-value of 5.3 surrounding the epicenter of the M_s=5.7 main shock. Around this quiescence the seismicity increases and the NW-SE elongated pattern over 30 km in length, resembles a Mogi seismicity anomaly (Mogi, 1985).

A comparison of the cumulative seismicity curves for the main shock in northwestern Peloponesus on 8 June 2008 (blue) and the 13 December 2008 main shock in Central Greece (red) is shown in Fig. 6. The Central Greece quiescence anomaly beginning at around 1997.8 and ending after 2003 with duration of approximately 4.5 years is almost twice that of the anomaly in northwestern Peloponesus that initiated at 2001.3 (blue arrow) and ended after 2003. The radii needed to collect N=70 events are 10.45 and 7.7 km for the Central Greece and the northwestern Peloponesus cases, respectively and this is due to the differences in the density of earthquakes in each area as discussed earlier. It may also

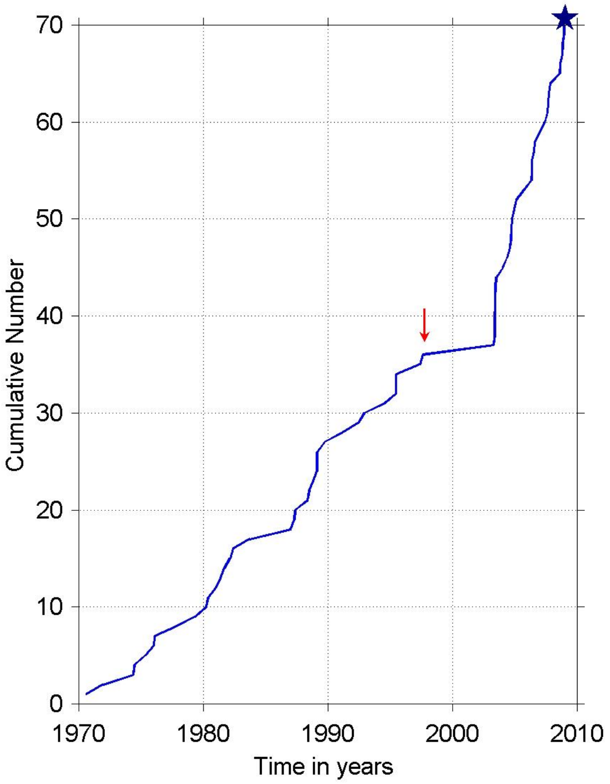

Fig. 4. Cumulative number of earthquakes at the epicentral area of the 8 December 2008 main shock (blue star). The red arrow indicates the initiation of the quiescence period around 1997.8.

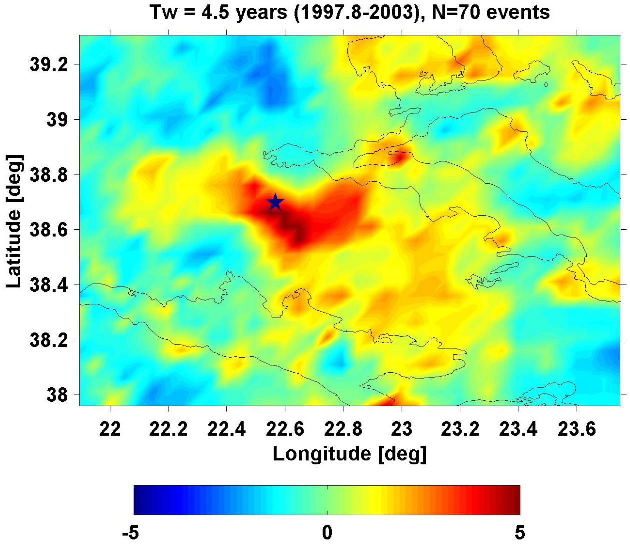

Fig. 5. The Z-value map for the investigated region based on the NOA-IG earthquake catalog starting at the value of 1997.8. Window length Tw=4.5 years, N=70 events and grid spacing=0.05°. The blue star indicates the epicenter of the 13 December 2008 main shock.

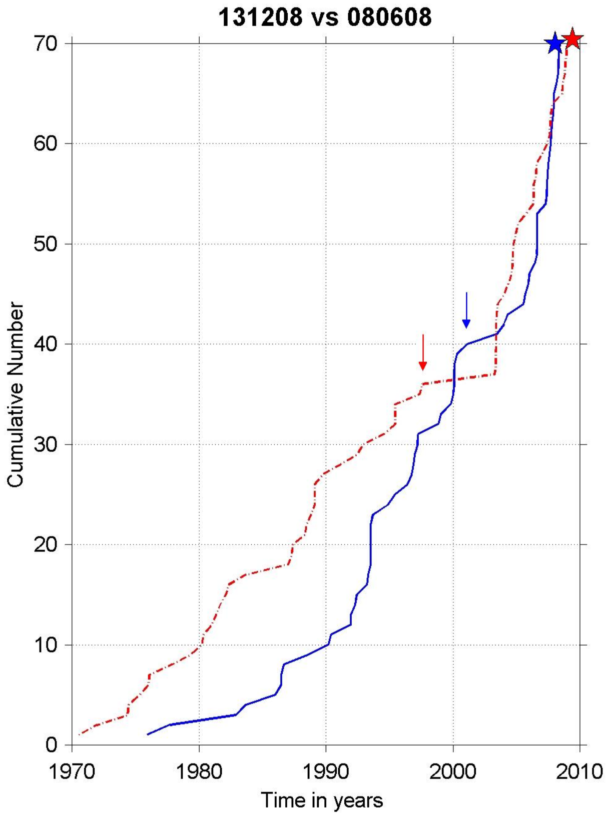

Fig. 6. Cumulative number curves at the epicentral areas of the 8 June (blue) and 13 December (red), 2008 main shocks. The initiation of the quiescence periods is indicated by the arrows at 1997.8 and 2001.3 years, respectively.

be noted that both curves exhibit a common initiation of the accelerated seismicity period after 2003.

The accelerated seismicity may be analyzed with the accelerated moment release (AMR) hypothesis according to which the rate of seismic moment release is proportional to an inverse power of the remaining time-to-failure (Varnes, 1989; Bufe and Varnes, 1993; Bufe et al., 1994). The so called time-to-failure analysis is an empirical technique based on the equation (Varnes, 1989):

$$\sum \Omega(t) = K + (k/(n-1))(t_f - t)^m \tag{2}$$

where Ω is a measure of seismic energy release, K, k and n are constants, m=1−n ($n \neq 1$) and t_f is the time-to-failure (main shock). The "seismic release" as defined by Bufe and Varnes (1993) is determined from the earthquake magnitude using the expression:

$$\log_{10} \Omega = cM + d \tag{3}$$

where M is the earthquake magnitude and c and d are constants. The coefficient c is 1.5 for moment or energy, 0.75 for Benioff strain release and zero for event counts (Kanamori, 1977).

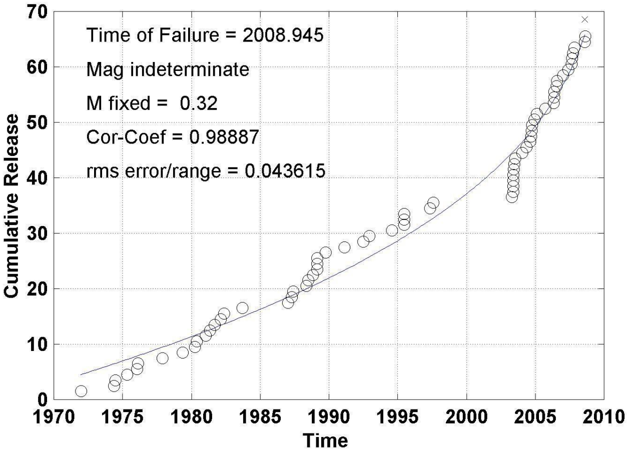

Fig. 7a. The cumulative release of earthquakes (from 1970 onwards) at the epicentral area of the 13 December 2008 main shock, fitted to the time-to-failure equation. The determined parameters and constants are discussed in the text.

Chouliaras (2009) used event counts instead of the seismic energy (which is frequently used) and an unconstrained best fit of the foreshock data (free t_f and m) simply to show a power law distribution in time for the analyzed foreshocks. That study showed that both long (5 year) and short (5 months) term earthquake activities in the foreshock sequence well fit to the time-to-failure equation, in general agreement with the discussion of Bufe and Varnes (1993) concerning the pattern of long and short cyclic earthquake activity based on the pioneering work on "seismic cycles" by Fedotov (1976).

The aforementioned method is applied to the case of the 13 December 2008 main shock in this study, however, for the first time we fix the value of the exponent "m" to the value of 0.32. If this choice of m-value is appropriate, it should enable us to search for the value of time-to-failure t_f. The validity of the m=0.32 choice will be discussed in detail later and here we just point out that Bufe and Varnes (1993) have already shown empirically that in actual earthquake sequences the value of m=0.32 provides actual times of seismic events.

Figure 7a shows the best fit solution of the time-to-failure equation to the cumulative curve for the entire period of the NOA-IG earthquake catalogue, at the epicenter of the main shock by fixing the value of m=0.32. This result indicates a good correlation at t_f=2008.945. Similarly we investigate the short term foreshock behavior and Fig. 7b shows a short term (about one year prior to the main shock) behavior fitted once again with a fixed m=0.32. A good correlation is seen in this case for t_f=2008.949. The t_f value range 2008.945 to 2008.949 corresponds to the date range 11–14 December, which agrees remarkably well with the actual occurrence of the earthquake on 13 December 2008.

3 Discussion

This investigation has applied the recent methodology developed by Chouliaras (2009) to identify seismic quiescence and acceleration before the occurrence of the M_s=5.7 earthquake that took place in Central Greece on 13 December 2008. The earthquake catalog of the region of investigation compiled from the monthly bulletins of NOA-IG has been used as database. The homogeneity and completeness of the catalog has been evaluated in this and in the aforementioned study in detail. This study goes further on to test the time-to-failure hypothesis by fixing the value of exponent "m" in Eq. (2) to m=0.32. In doing this, we succeeded in estimating the time of occurrence of the 13 December 2008 main shock to the accuracy of a few days.

The motivation of selecting the value of m=0.32 may be understood in the following framework: Varotsos and Alexopoulos (1984) found that, for a given measuring station and a given epicentral area, the amplitude E of the Seismic Electric Signal (SES) preceding rupture is interrelated with the magnitude M of the impending earthquake through the relation:

$$\mathrm{Log}_{10} E = aM + b \tag{4}$$

where a and b are constants. Interestingly the value of the constant "a" was found to lie in the narrow range a=0.31 to 0.35 (see page 92 of Varotsos and Alexopoulos, 1984) and remains the same for all the measured stations and epicentral areas. In other words, "a" seems to be a universal constant originating from the fractal properties of the emitting source. This is so because SES may be emitted when the source enters the critical regime (Varotsos et al., 1982) which is inherently associated with fractality (see 270–272 of Varotsos, 2005). In fact, the following physical mechanism has been proposed for the emission of SES (Varotsos and Alexopoulos, 1984): When the stress increases in the focal region of a future earthquake, it will affect physical properties of the crust including a decrease of e.g. the dielectric constant (Varotsos, 1978). Among others, the following may also happen: the relaxation time of the atomic scale electric dipoles (e.g., see Varotsos and Alexopoulos, 1980, 1981) that inherently exist in it may decrease. When the stress reaches a critical value, the relaxation time becomes very short and the electric dipoles exhibit a cooperative orientation, which results in an emission of a transient electric current (this constitutes the SES). Since this emission is associated with the approach to criticality, it is intuitively expected that a power-law relation may exist between the amplitude of the electric signal and the earthquake magnitude M. Hence, Eq. (4), which can be alternatively written as a power-law relation between E and M, reveals that the quantity "a" may be interpreted as a critical exponent characterizing the approach to failure.

Since the value of "a" has been well established by the field SES experiments and in view of the fact that the SES detection occurs during the acceleration period of seismicity, it may be reasonable to assume that the value for "m" in Eq. (2) is comparable to the value of "a" i.e., $m \approx a \approx 0.31$–0.35. The present discussion may shed light on the earlier study (Bufe and Varnes, 1993) which empirically found that the time-to-failure equation gives satisfactory results when the "m" value is 0.32.

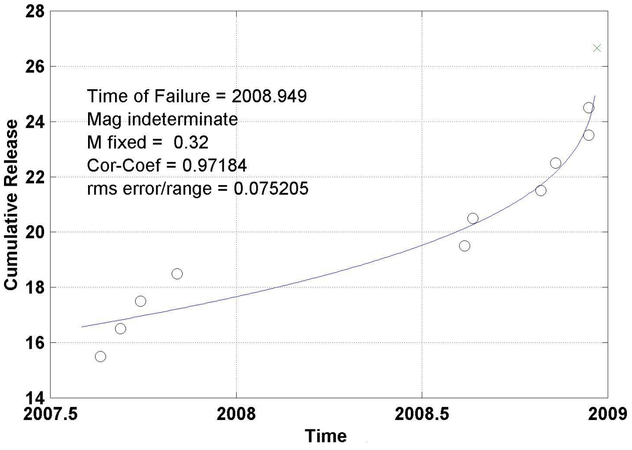

Fig. 7b. The cumulative release of earthquakes (from 2007.5 onwards) at the epicentral area of the 8 December 2008 main shock, fitted to the time-to-failure equation. The determined parameters and constants are discussed in the text.

4 Conclusions

1. The results of the quiescence investigation of the 13 December 2008 main shock show that the quiescence period began almost 12 years before and had a duration of approximately 4.5 years. The spatial extent of this quiescence covers more than 30 km around the epicentral area in a NW-SE direction, conforming with the local seismotectonic observations and having the shape of a Mogi seismicity anomaly.

2. Following the quiescence which ended around 2003, an acceleration period began and lasted until the occurrence of the main shock. This acceleration period is modeled in this investigation using the time-to-failure empirical technique that hypothesizes that the rate of earthquake energy release is proportional to the inverse power of the remaining time to failure. The time-to-failure equation was applied to the cumulative event curve that surrounds the epicentral area for a radius of 10.45 km in Central Greece by fixing the value of m=0.32. The result is a successful estimation of the occurrence time of the 8 December 2008 main shock within a few days. The origin of this success is attributed to the proper selection of the "m" value, the physical meaning of which is discussed.

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