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Seismicity anomalies prior to 8 June 2008, M_w=6.4 earthquake in Western Greece

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Abstract. The epicentral area of the M_w=6.4, 8 June 2008 main shock in northwestern Peloponesus, Western Greece, had been forecasted as a candidate for the occurrence of a strong earthquake by independent scientific investigations. This study concerns the seismicity of a large area surrounding the epicenter of the main shock using the seismological data from the monthly bulletins of the Institute of Geodynamics of the National Observatory of Athens. This data set is the most detailed earthquake catalog available for anomalous seismicity pattern investigations in Greece. The results indicate a decrease in seismicity rate seven years prior to the 8 June main shock which constituted a two and a half year long seismic quiescence surrounding the epicentral area. This quiescence anomaly was succeeded by a period of acceleration in seismic activity for five years approximately, until the occurrence of the main shock.

1 Introduction

On 8 June 2008 at 12:25 GMT, a moment magnitude M_w=6.4 earthquake occurred in northwestern Peloponesus, western Greece, between the cities of Patras and Andravida (Fig. 1). The shock was felt in almost all Greece causing 2 deaths, about a hundred injuries and affected roughly 10 000 houses with small to severe damage.

The earthquake parameters of the main shock as determined by the Institute of Geodynamics of the National Observatory of Athens (NOA-IG), provided epicentral coordinates at 37.98° N and 21.51° E, focal depth of 25 km and a moment tensor solution of a strike – slip focal mechanism with a northeast – southwest direction, as also observed from the aftershock distribution in Fig. 1a (http://bbnet.gein.noa.gr/MT.htm, Ganas et al., 2009).

During the first months of 2008, the seismicity rate in Greece increased compared to that of previous years (see later) and the 8 June earthquake in the northwestern Peloponesus was preceded by a few strong shocks that struck the eastern and southwestern parts of the wider region, as shown in Fig. 1b. The earthquake series began on 6 January near the city of Leonidion in eastern Peloponesus (37.10° N–22.82° E) with a main shock of M=6.1 and continued on 14 February near the city of Methoni in southeastern Peloponesus, with two strong shocks of M=6.2 and M=6.1, that occurred within a few hours of each other at 36.41° N–21.64° E and 36.22° N–21.80° E, respectively.

Prior to the 8 June earthquake, precursory anomalous seismicity patterns and anomalous electric field variations, were respectively reported by Papadimitriou (2008) and Sarlis et al. (2008). Both investigations forecasted a large earthquake to occur around the spring of 2008 and interestingly enough the forecasted location of the impending earthquake in both studies included the area of northwestern Peloponesus. In particular, the study of Papadimitriou (2008) concerning the seismicity patterns around western Greece (37.0°–39.5° N and 19.00°–22.00° E) almost a year prior to the 8 June main shock, indicated an elliptical region of anomalous decelerating – accelerating moment release (DAMR) seismicity pattern centered at 38.0° N–20.5° E as the forecasted epicentral region. This elliptical region is found to lie within the wider rectangular region: 37.50°–38.60° N and 20.00°–23.00° E that was indicated by the forecast of Sarlis et al. (2008) as the possible impending earthquake region by the method of "natural time analysis" (Varotsos et al., 2005a) of the on going seismicity (Varotsos et al., 2005b). Both of these studies used the preliminary catalog of NOA-IG with a threshold magnitude of M=3.9 for their respective investigations.

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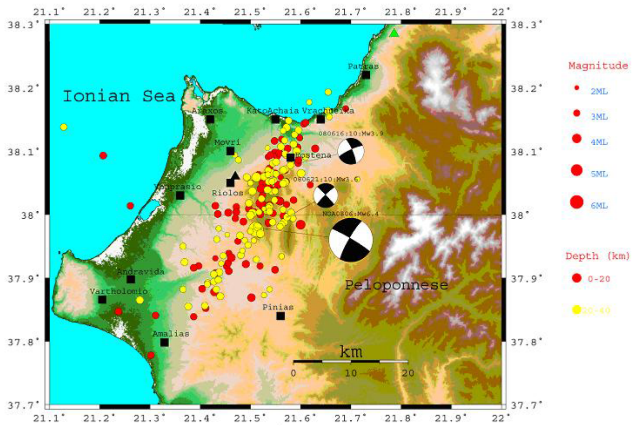

Fig. 1a. Map of the M_w=6.4 earthquake in Western Greece on 8 June 2008 and it's aftershock distribution (after Ganas et al., 2009).

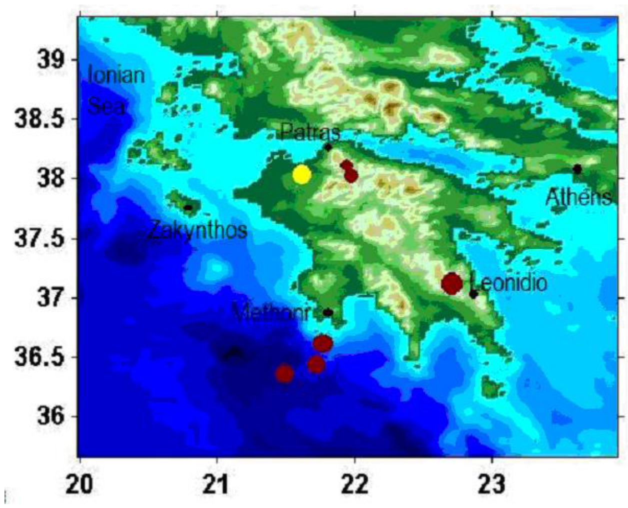

Fig. 1b. Map of the strong earthquakes that struck Peloponesus in 2008.

The spatial and temporal coincidence in the two forecasts motivated this author to study the seismicity patterns of a wider region of interest i.e. 37.00°–39.00° N and 20.00°–23.50° E, considering the preliminary (electronic) Greek earthquake catalog from NOA-IG's web site (http://www.gein.noa.gr/services/cat.html). Using the methodology of Chouliaras and Stavrakakis (2001), he identified an area exhibiting seismic quiescence within the wider forecasted region of the aforementioned studies. The identified area was of 10 km length and a few kilometers width and a NE-SW orientation and located to the southwest of Patras and the northeast of Andravida. This result was communicated by e-mail to P. Varotsos (personal communication, 29 February 2008) and three months later, on 8 June 2008, occurred the M_w=6.4 main shock in the aforementioned area which was indicated. This investigation concerns the more detailed analysis of the seismicity patterns for the region surrounding the epicenter of the M_w=6.4 main shock, using the seismological data from the final monthly bulletins of the Institute of Geodynamics of the National Observatory of Athens (NOA-IG). The data set used is the most detailed earthquake catalog available for anomalous seismicity pattern investigation in Greece.

2 Data analysis and results

The Greek National seismological network is operated by NOA-IG since 1897 and its first instrumental earthquake catalog was published in 1950. In 1964, as the electromagnetic type sensors were introduced and analog registration was started, the practice of a systematic data analysis, bulletin production and routine archiving, common to international seismological observatories, was initiated.

The monthly bulletins of NOA-IG from 1964 to 2000 have been used to compile an electronic earthquake catalog, the most detailed instrumental seismicity catalogue for Greece. The Internet catalogue of NOA-IG contains earthquake data from the monthly bulletins until the year 2000 and from then on the catalog is updated daily with the preliminary bulletins (http://www.gein.noa.gr/services/cat.html). The NOA-IG monthly bulletins for the period 2000 onwards are retrieved either from the ISC or the PDE catalogs.

For the purposes of this study we compiled an earthquake catalog for all of Greece (geographic region 34°–42° N and 19°–29° E) from the data of NOA-IG's monthly bulletins from 1964 until 2007 inclusive and for the year 2008 we used the data from the preliminary Internet catalog. This data set is used as input to the ZMAP software package (Wiemer et al., 1995; Weimer, 2001) which is employed for all subsequent data analysis in this investigation. The seismic quiescence hypothesis of Wyss and Haberman (1988) applies to crustal earthquakes and this investigation mainly concerns earthquakes with depths less than 50 km, in the rectangular region: 37.00°–39.00° N and 20.00°–23.50° E (which will be hereafter called sub-region) to directly compare with the results of the Papadimitriou (2008) and Sarlis et al. (2008).

The time variation of the cumulative seismicity from the NOA – IG earthquake catalog from 1964 till 2008 is shown in Fig. 2. The four curves labeled a to d, show the time variation of the cumulative crustal seismicity for: a) the entire Greek area, b) declustered entire Greek area, c) the sub-region, d) declustered sub-region, respectively.

The entire NOA-IG catalogue for Greece from 1964 till the 8 June 2008 main shock , contains 69958 seismic events and a total of 68 344 seismic events have depths less than 50 kilometers (curve a, Fig. 2). Significant network upgrades and installation of new seismic stations for the NOA-IG seismic network occurred in 1982, 1995, 2000 and 2004 and these periods show apparent accelerated seismicity due to the

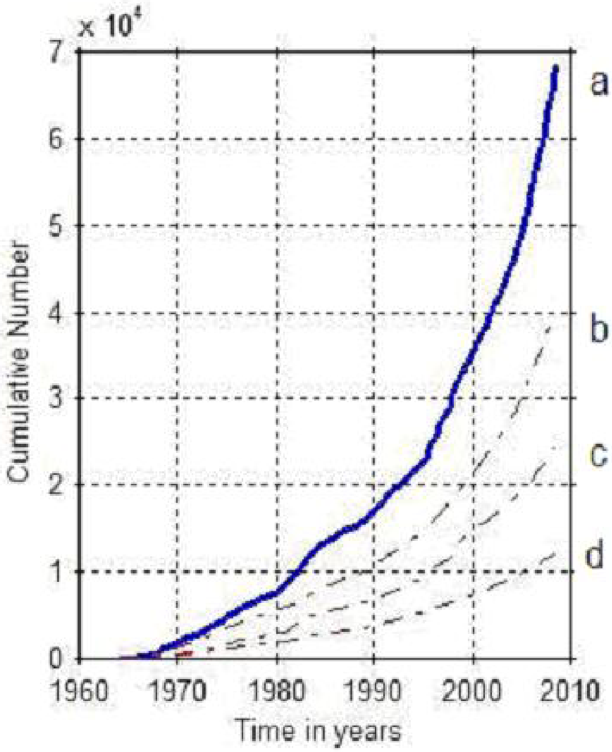

Fig. 2. The time variation of the cumulative seismicity from the NOA-IG earthquake catalog from 1964 till 2008. The four curves labeled (a) to (d), respectively show the time variation of the cumulative crustal seismicity for: **(a)** the entire Greek area, **(b)** declustered entire Greek area, **(c)** the sub-region, **(d)** declustered sub-region.

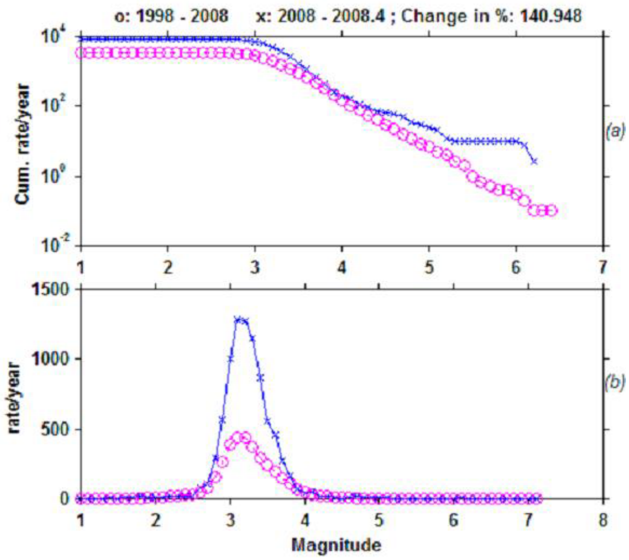

Fig. 3. (a) Plots of cumulative seismicity rate per year versus magnitude for two time periods, in all of Greece. The blue curve is for the period 1998 to 2008 and the red curve for the period 2008 to 2008.4 (main shock), and **(b)** the non cumulative rate per year curves.

improved detectability. This apparent accelerated seismicity is also observed for the sub-region in curve c of Fig. 2 that contains a total of 24 432 crustal events.

On the other hand, increase in seismicity due to the occurrence of large earthquakes and their aftershock sequences (i.e., the Gulf of Corinth earthquake, February 1981, earthquakes in Kozani and Aigio during May–June 1995, Athens earthquake in September 1999) may be eliminated by the declustering algorithm of Reasenbeng (1985). The input parameters of the Reasenberg algorithm, $\mathrm{Tau}_{\max}$ (the maximum look ahead time for clustered events), $\mathrm{X}_{\mathrm{meff}}$ (the effective lower magnitude cut off for the catalogue) and the epicenter and depth errors, have been tested and tuned accordingly for the NOA -IG earthquake catalog, to values of 30 days, 2.0 Richter, and 10 km, respectively. This procedure has sufficiently removed aftershock clusters as shown by the smoothness of the curves b and d in Fig. 2, nevertheless the non-linear behavior of the curve due to NOA-IG's network expansion by the deployment of new seismological stations is persistant and should be seriously considered when investigating precursory accelerating moment release (AMR) models in the Greek earthquake catalog.

As mentioned earlier, large earthquakes struck the eastern and southern coasts of Peloponesus, preceding the 8 June event and a seismicity rate increase is observed in the Greek earthquake catalog during the first five months of 2008 as seen in Fig. 3a and b. In Fig. 3a the cumulative seismicity rate curve in all of Greece for the period of the first 5 months of 2008 (blue curve) shows an increase of around 140% when compared to the cumulative seismicity rate per year for the period covering the previous 10 years (red curve). Figure 3b shows the non-cumulative rate per year curves for the same two periods as in Fig. 3a (blue and red), in this way indicating that the rate increase occurred in the magnitude band M=2.8 to 4.

To the contrary, Fig. 4a and b shows the cumulative and the non-cumulative seismicity rate per year in the rectangular sub-region of investigation, respectively. These results show that the cumulative rate per year in the sub-region has slightly decreased by 9% when compared to the cumulative seismicity rate per year for the previous 10 years (Fig. 4a) mainly in magnitude ranges around M=3 (Fig. 4b), thus justifying the closer investigation of seismic quiescence for this sub-region.

The denseness of network stations and the station setting geometry of NOA-IG's seismic network are the determining factor of the detectability of seismic events and the spatial variation of magnitude of completeness (M_c) in Greece (http://www.gein.noa.gr/services/net_figure.gif). Mc is defined as the lowest magnitude of the catalog at which 100% of the events are detected in space and time (Rydelek and Sacks,

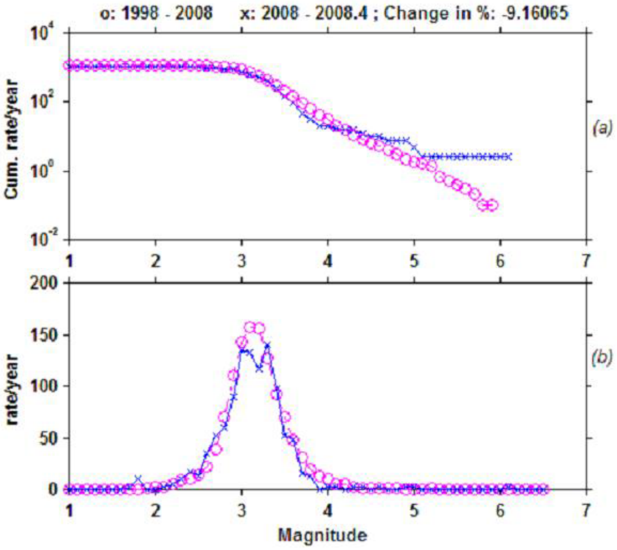

Fig. 4. (a) Plots of cumulative seismicity rate per year versus magnitude for two time periods, in the sub-region. The blue curve is for the period 1998 to 2008 and the red curve for the period 2008 to 2008.4 (main shock), and **(b)** the non cumulative rate per year curves.

1989; Wiemer and Wyss, 2000). The spatial distribution of the Mc of the NOA-IG earthquake catalog for the rectangular sub-region is shown in Fig. 5a. Easily one may distinguish the red areas to the west towards the Eastern Ionian Sea with poor detectability from the dark blue area to the east near Athens of enhanced detectability.

Another method in ZMAP to determine M_c, is based on the assumption that for a given volume a simple power law can approximate the frequency-magnitude distribution (FMD) (Wiemer and Wyss, 2000). The FMD (Gutenberg and Richter, 1944) describes the relationship between the frequency of occurrence and magnitude of earthquakes :

$$\log_{10} N = a - bM \tag{1}$$

Where N is the cumulative number of earthquakes having magnitudes larger than M, and a and b are constants. The procedure to evaluate the goodness of fit is described in detail by Wiemer and Wyss (2000) and basically it computes the absolute difference (R) of the number of events between the observed FMD and a synthetic distribution. Synthetic distributions are calculated using the estimated a- and b- values of the observed dataset for $M \geq M_{co}$, as a function of the cut-off (minimum) magnitude. R defines the fit in percentage to the observed FMD and a model is found at an R-value at which a predefined percentage (90% or 95%) of the observed data set is fit by a straight line. According to that study the 95% level of fit is rarely obtained for real catalogues while the 90% is a compromise.

Figure 5b shows the goodness of the FMD fit to power law for the earthquake data of the sub-region of interest and this

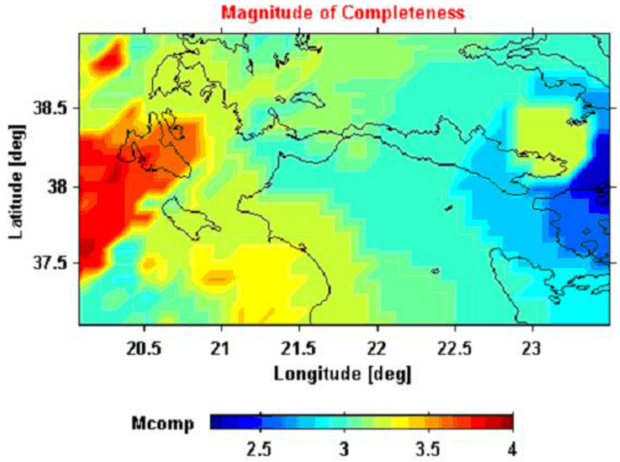

Fig. 5a. The spatial distribution of the magnitude of completeness of the sub-region.

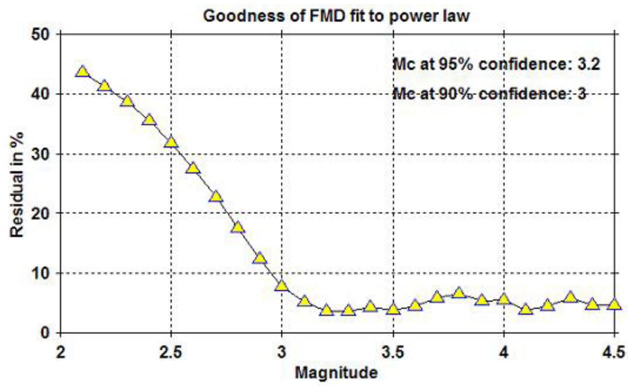

Fig. 5b. The result for the goodness of fit method (Wiemer and Wyss, 2000) to determine the magnitude of completeness (M_c) of the sub-region. The plotted goodness of fit values are the difference between the observed and synthetic Gutenberg-Richter distribution plotted as a function of M_c. The first dashed horizontal line from the bottom indicates M_c around 3 at which 90% the observed data are modeled by a straight line.

result shows a 90% fit for M_c=3 and a 95% fit for a M_c=3.2. This result in combination with the spatial variation of M_c in Fig. 5a, makes a choice of M_c=3 as the cut off magnitude for this seismicity study in the sub-region of the 8 June 2008 main shock to ensure homogeneity and completeness of the catalog data.

The Genas procedure (Haberman, 1983) in ZMAP also investigated the changes in the reported seismicity data of the sub-region and no serious artifact exists in the last decade of observations (Note that the installation of the EVR seismic station at 38.92° N–21.81° E, improved the completeness of the catalog and the detectability of the network around 1998).

Since seismic quiescence has shown promising results in identifying precursory anomalies related to crustal main shocks (Wyss, 1997a, b), we map the seismic quiescence in the sub-region, as defined by Wyss and Habermann (1988) using the gridding method of Wiemer and Wyss (1994) and the ZMAP analysis software (Wiemer et al., 1995).

Using ZMAP we measured the changes of seismicity rate at the nodes of a 0.05° grid 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 we took the nearest N earthquakes and searched for rate changes by moving a time window T_W, stepping forward through the time series. The one month time window was selected in order to have a continuous and dense coverage in time. The N and T_W values are usually selected accordingly in order to enhance the quiescence signal and this choice does not influence the results in any way.

N is kept constant in order to investigate the validity of the quiescence hypothesis, which postulates that the quiet area overlaps with the main shock source area. If we take N=70 events, the sample areas will be with radii ranging between 5 and 10 km in the Greek catalog, which are of reasonable dimensions for sampling seismogenetic areas that generate large main shocks in Greece (Chouliaras and Stavrakakis, 1997).

In order to rank the significance of quiescence, we calculated the standard Z values using the LTA(t) function (Wyss and Burford, 1985, 1987; Wiemer and Wyss, 1994)

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

Z measures the significance of the difference between the mean seismicity rate within window R_1, and the backround rate R_2, defined as the mean rate outside the window but within the same area. σ_1 and σ_2 are the variances of the means and n_1 and n_2 are the corresponding number of bins with a measured seismicity rate. Thus at each node a Z value is computed and these Z values are then ranked according to their size.

The computed Z values are then mapped and contoured, revealing the Z value distribution at the beginning of the time window T_W for which they are evaluated, since we want to define the onset of a significant rate change in the seismicity.

Since the length of the quiescence window is unknown for our study we varied the window length from 1.5 to 7 years to reveal the possible quiescence anomalies. Other studies have reported a range of T_W=1.5–7 yrs for seismic quiescence prior to crustal main shocks (Wyss, 1997a, b) and also that the duration of quiescence as well as the rate of earthquake production depends on the size of the sampled area for the Greek earthquake catalog (Chouliaras and Stavrakakis, 2001).

The Z value map for the rectangular sub-region with a time window of T_W=2.5 yrs starting at the value of 2001.3 is presented in Fig. 6a. Easily one observes the quiescence anomaly related to the epicenter of the 8 June main shock as well as more distant anomalies to the eastern part of the investigated region. In this section we will focus on the anomaly in the northwestern part of Peloponesus while comments on the other anomalies will be made in the discussion section.

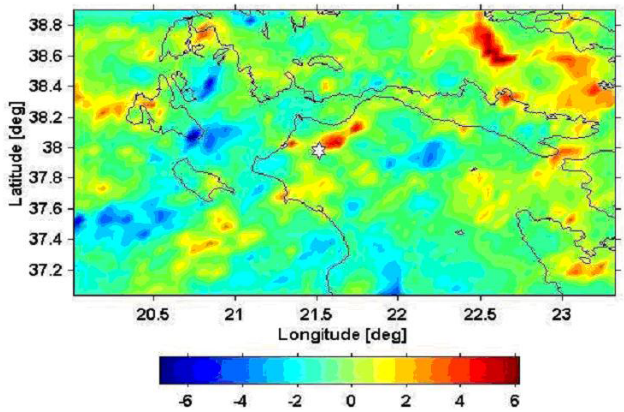

Fig. 6a. The Z value map for the rectangular sub-region based on the NOA-IG bulletin catalog starting at the value of 2001.3. The chosen window length is T_W=2.5 years, N=70 events and grid spacing=0.05°.

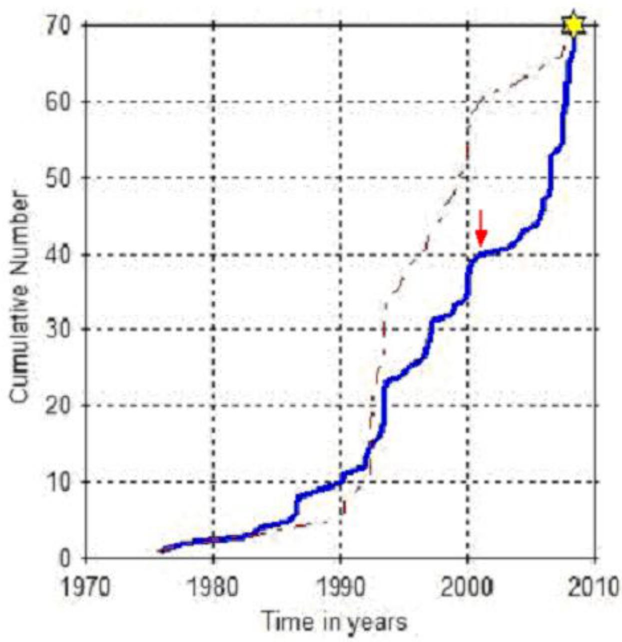

Fig. 6b. The cumulative seismicity of two areas within the quiescence anomaly as a function of time. The top curve (red) is centered at 38.03° N and 21.44° E lying just to the northwest of the main shock and the bottom curve (blue) is centered at 38.03° N and 21.55° lying just to the northeast. The red arrow indicates the time value of 2001.3.

The elongated lobe shaped quiescence anomaly with a Z value around 6 in Fig. 6a, includes the epicenter of the main shock and a large part of its aftershock area (Fig. 1a). The anomaly extends to the northeast of the epicenter almost parallel to the aftershock distribution almost up to the nearby coastline while vanishes to the northwest of the epicenter. Around the quiescence anomaly the seismicity increases and the pattern resembles the Mogi seismicity anomaly (Mogi, 1985). Figure 6b shows the cumulative seismicity of the two areas mentioned above plotted as a function of time. The top curve (red) is centered at 38.03° N and 21.44° E lying just to the northwest of the main shock and the bottom curve (blue) is centered at 38.03° N and 21.55° lying just to the northeast. Comparing the two curves one notices differences in the earthquake production of the two sampled areas having approximate radii of 8.3 and 7.7 km, respectively, in order to produce N=70 events. In both curves the quiescence anomaly is clearly observed to begin around the value of 2001.3 and has a duration of approximately 2.5 years.

After around 2004, both curves show accelerated seismicity prior to the main shock. The accelerated seismicity after the quiescence may be analyzed with the accelerated moment release (AMR) hypothesis using the empirical predictive technique called time-to-failure analysis (Varnes, 1989; Bufe and Varnes, 1993; Bufe et al., 1994).

The time-to-failure analysis tool in ZMAP assumes the rate of seismic release to be proportional to an inverse power of the remaining time to failure and in this way one may test this hypothesis and predict the time and magnitude of a future event. According to Varnes (1989) the time-to-failure equation is:

$$\sum \Omega(t) = K + (k/(n-1))(t_f - t)^m \tag{3}$$

where Ω is a measure of seismic energy release, c, K, k and n are constants, m=1−n (n≠1) and t_f is the time-to-failure (main shock). This implies that the knowledge of Ω at four values of t is the minimum information required for computing t_f and the constants m, k and K. For this study the seismic release may include any quantity determined from the earthquake magnitude using the expression:

$$\log_{10} \Omega = cM + d \tag{4}$$

where M is the earthquake magnitude and c and d are constants. The coefficient c is normally 1.5 for moment or energy, 0.75 for Benioff strain release and zero for event count. In this investigation event counts are used and an unconstrained best fit of the foreshock data is attempted (free t_f and m) simply to show a power law distribution in time for the analyzed foreshocks. A more detailed investigation of the time-to-failure hypothesis and Greek earthquakes will be presented in a separate study.

Figure 7a shows the power law fit to the cumulative seismicity curve of the (blue curve of Fig. 6b) for five years before the main shock and Fig. 7b for the time period a few months prior to the main shock. The power law of the time to failure model is fitting closely both to the long term and the short term foreshock activity, respectively.

For comparison purposes, we show the Z value map for the declustered catalog near the epicentral region in Fig. 8a, using the same time window as in the clustered case of Fig. 6a. Easily one observes the quiescence anomaly to persist in the declustered catalogue in the same area and of the same geometrical distribution as in the clustered data. Figure 8b confirms the existence of the quiescence anomaly in the cumulative curve of the area centered just to the northeast of the main shock, at the same location as the blue curve of Fig. 6b, although only 50 events are produced from the same area because of the declustering procedure. Again one notices evident similarities in the two cases, the presence of a quiescent period followed by a period of accelerated seismicity prior to the occurrence of the main shock.

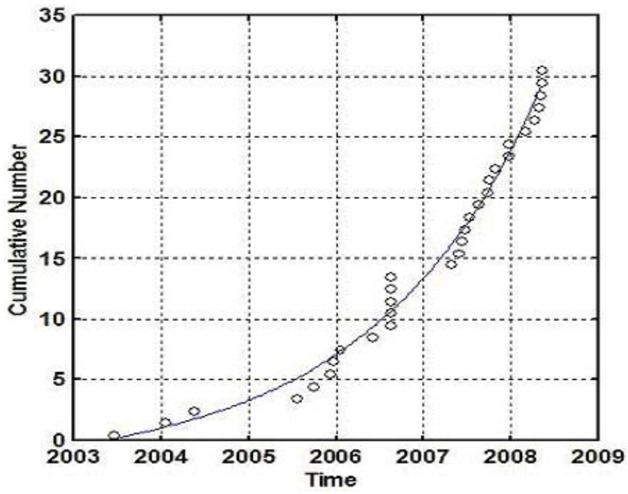

Fig. 7a. Fit of the power law time-to-failure equation to the cumulative seismicity 5 years prior to the 8 June 2008 main shock.

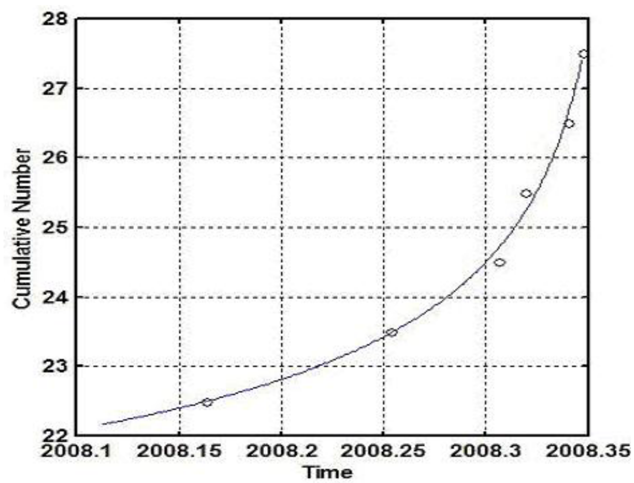

Fig. 7b. Fit of the power law time-to-failure equation to the cumulative seismicity 5 months prior to the 8 June 2008 main shock.

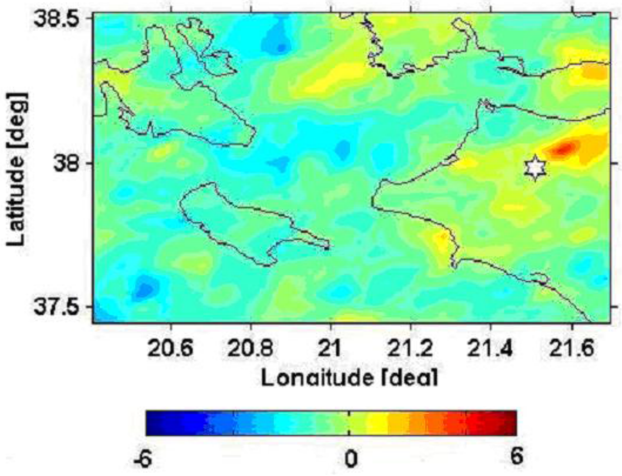

Fig. 8a. The Z value map near the epicentral region based on the declustered catalog and starting at the value of 2001.3. The chosen window length is T_W=2.5 years, N=50 events and grid spacing=0.05°.

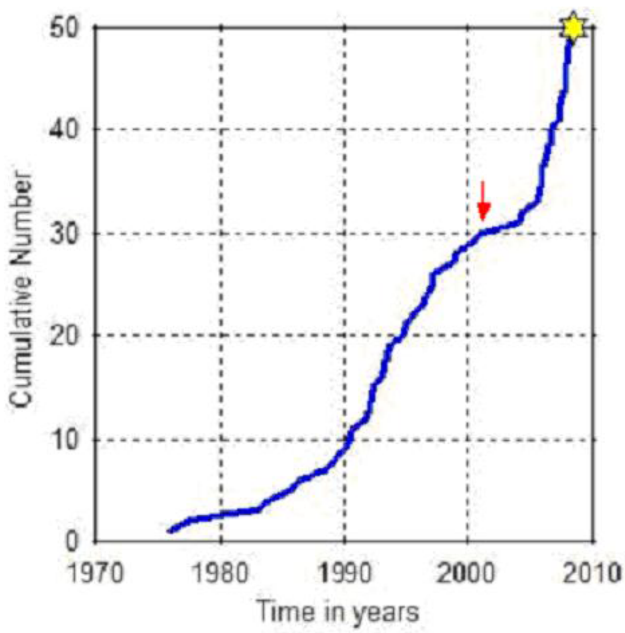

Fig. 8b. The existence of the quiescence anomaly in the cumulative curve of the declustered catalog for the area centered at 38.03° N and 21.55° just to the northeast of the main shock, (at the same location as the blue curve of Fig. 6b). The red arrow indicates the time value of 2001.3.

3 Discussion and conclusions

The 8 June 2008 earthquake in northwestern Peloponesus in Greece came after a period of increased seismic activity that included the occurrence of a few strong earthquakes in the perimeter of eastern and southwestern Peloponesus in the previous five months. Prior to this event, two independent scientific investigations had forecasted the occurrence of a strong earthquake in a region which included the actual epicenter and in an anticipated time window that included the main shock (Papadimitriou, 2008; Sarlis et al., 2008). In addition to these, a preliminary investigation by this author, three month's before the main shock, narrowed down an elliptical area of seismic quiescence to just a few kilometers to the southeast of the actual epicenter (P. Varotsos, personal communication, 2008).

For a more detailed investigation of the seismicity prior to the 8 June 2008 main shock, an earthquake catalog of Greece from 1964 till 2008 was compiled from the final monthly bulletins of NOA-IG. A total of 69 958 events comprise the entire catalogue up to the 8 June main shock and 64 344 of these earthquakes have depths less than 50 km and are considered in this investigation. The catalog data prior to the 8 June main shock indicate that the seismicity rate in all of Greece for the first five months of 2008 showed an increase by 140% compared to the rate of the previous ten years. However, the seismicity rate in the sub-region (37.00°–39.00° N and 20.00°–23.50° E) containing the epicenter of the main shock showed a 9% decrease for the same time period.

A detailed analysis concerning the homogeneity and completeness of the catalog for the sub-region indicates a magnitude of completeness of $M>3$ as a lower magnitude threshold in order to closely investigate the seismic quiescence hypothesis prior to the 8 June main shock (Wyss and Habermann, 1988). The methodology of mapping seismic quiescence for crustal earthquakes in Greece (Chouliaras and Stavrakakis, 2001) is applied to the earthquake catalogue of NOA-IG for the same sub-region that includes the regions investigated by Papadimitriou (2008) and Varotsos et al. (2008). The result indicates an area of seismic quiescence adjacent to the epicentral and aftershock area of the main shock and this anomaly is persistent regardless of the declustering procedure. This quiescence began almost seven years prior to the main shock around the value of 2001.3 and lasted for roughly 2.5 years. The geometrical distribution of the quiescence found to surround the epicenter of the main shock resembled a Mogi seismicity anomaly with three quiescence lobes covering most of the aftershock area.

Following the period of quiescence, a period of activation exists and a power law time-to-failure model seems to describe the evolution of the seismicity until the occurrence of the main shock. The duration of this activation period was of the order of 4.5 years approximately twice as long as the quiescence period and there existed a second sub period just a few months prior to the earthquake in which the time-to-failure model is found to approximate the local foreshock activity.

These activation phenomena have been also observed in the seismicity pattern investigation of Papadimitriou (2008). In that investigation the preliminary catalog of NOA-IG was used and the threshold magnitude of the investigation was

$M>3.9$ with a region of 90 km radius centered around the main shock with a data set of only 776 events from 1999 till 2007.1.

Evidently sudden rate changes such as quiescence are easier to map in the Greek earthquake catalog than accelerated seismicity phenomena that are inherently contaminated with apparent seismicity increase due, for instance, to increased reporting of earthquakes by occasional network upgrades and expansions. Such artifacts in the Greek catalog data may lead to erroneous interpretations regarding accelerating seismicity patterns and accelerated moment release (AMR) as discussed recently by Hardenbeck et al. (2008).

On the other hand, Sarlis et al. (2008) investigated the evolution of the seismicity in the “natural time” concept, that is the seismicity that evolves in a rectangular region surrounding the epicenter from the time of occurrence of an electrical precursor signal on 9 February 2008 prior to the 8 June main shock. In this particular seismicity study. they also used the events (20 in total until the main shock) with $M>3.9$ from the preliminary NOA-IG earthquake catalog and concluded that the criticality stage was reached on 27 May, just a couple of days prior to the main shock. It appears that the data, results and methodology in their study enabled to map, with a reasonable accuracy, the precursory seismicity patterns associated with the 8 June 2008 main shock.

Recently Uyeda and Kamogawa (2008) reported on the success of associating the pre-seismic electric anomalies with the “natural time” analysis of the on going seismicity as a new tool in evaluating the occurrence of the impending main shock (Varotsos et al., 2008). The coincident reporting of successful forecast concerning the 8 June 2008 earthquake by independent investigators that employed different methodologies seems to encourage further cooperative multidisciplinary investigations for earthquake prediction research in Greece.

At the time of preparation of this manuscript a strong seismic event with M_s=5.7 occurred on 13 December 2008 at 08:27 UTC with epicenter at 38.72° N and 22.57° E. This seismic event may be related to the prominent Z value quiescence anomaly on the northeastern part of the region mapped in Fig. 6a and that will be presented in detail in a separate study.

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