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Stress distribution and seismicity patterns of the 2011 seismic swarm in the Messinia basin, (South-Western Peloponnesus), Greece

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Abstract. In this investigation we examine the local stress field and the seismicity patterns associated with the 2011–2012 seismicity swarm in the Messinia basin, south-western Peloponnesus, Greece, using the seismological data of the National Observatory of Athens (NOA). During this swarm more than 2000 events were recorded in a 12 month period by the Hellenic Unified Seismological Network (HUSN) and also by the additional local installation of four portable broadband seismographic stations by NOA.

The results indicate a Gaussian distribution of swarm activity and the development of a seismicity cluster in a pre-existing seismic gap within the Messinia basin. Centroid Moment Tensor solutions demonstrate a normal fault trending northwest–southeast and dipping to the southwest primarily due to an extensional stress field. During this seismicity swarm an epicentre migration of the three largest shocks is observed, from one end of the rupture zone in the northwestern part of the cluster, towards the other edge of the rupture in the south-eastern part of the cluster. This migration is found to follow the Coulomb failure criterion that predicts the advancement and retardation of the stress field and the patterns of increases and decreases of the seismicity rate (b-value) of the frequency–magnitude relation.

1 Introduction

In June 2011, the Hellenic Unified Seismological Network (HUSN) coordinated by the National Observatory of Athens (NOA), registered an increase of seismic activity at the Messinia basin region, south-western Peloponnesus, Greece (Fig. 1). During the next months a cluster of hundreds of small earthquakes gradually developed and on 14 August 2011 an intermediate magnitude $M_W = 4.8$ event caused moderate structural damages mainly in old buildings and houses. Hereafter, the seismic activity continued to the southeast and two more intermediate magnitude seismic events caused additional damages and alarm amongst the local citizens, on 14 September 2011 with $M_W = 4.6$ and on 10 October 2011 with $M_W = 4.7$.

NOA has the operational responsibility to monitor and assess the seismic hazard for any ongoing seismic activity in Greece and to provide this valuable information to the government and to the citizens. In order to improve the detection for monitoring the 2011 seismic activity and the assessment of the seismic hazard, NOA installed four portable, real-time broad-band seismological stations that encircled the Messinia basin region, on 20 October 2011, to complement the permanent seismological stations of the HUSN.

In Greece, precursory seismicity swarms leading up to large tectonic earthquakes have been identified by Evison and Rhoades (2000) and volcanic seismicity swarms have been observed periodically in the Santorini volcanic island complex (Chouliaras et al., 2012, Fytikas et al., 1990). In addition to these, seismicity swarms that last for many months without a great main shock, have caused cumulative damages (Benetatos et al., 2004; Ganas et al., 2012; Kiratzi et al., 2008; Papazachos and Papazachou, 2003).

Seismicity swarms are characterised by the spatial and temporal clustering of a large number of small earthquakes. These earthquakes are mainly due to small fractures caused by local stress concentration and weakening of the crust by the tectonic stress field which is released gradually and in this way seismicity swarms differ from the traditional foreshock and aftershock sequences that are usually associated with the occurrence of a great main shock (Kanamori, 1972; Mogi, 1963; Scholz, 2002).

The vast majority of seismicity swarms occur in volcanic regions, however they also occur in tectonic boundaries and intracontinental areas. Investigations concerning the driving mechanism of seismicity swarms have shown that they may be attributed to the accumulation of stress in a propagating fracture, the presence and movement of fluids in fault zones and also due to the formation and movement of magma in the dikes of active volcanoes (Contadakis and Asteriadis, 2001; Hainzl and Fischer, 2002; Spicak, 2000; Sykes, 1970; Yamashita, 1999).

It is well known that the b-value of the Gutenberg–Richter law reflects the state of stress and the level of heterogeneity in the Earth's crust (Gutenberg and Richter, 1944; Scholz, 1968; Schorlemmer et al., 2005; Wiemer and Wyss, 1997; Wyss, 1973). Results from the spatial and temporal mapping of the b-values have shown that the b-values of volcanic swarms are rather high, $b > 1$, (Sykes, 1970) while in continental rifts the b-values of the seismic swarms range from 0.8 to 1.0 (Ibs-von Seht et al., 2008).

For tectonically generated earthquakes the pattern of increases and decreases in seismicity (b-value) are found to follow the Coulomb fracture criterion lobes that indicate the advancement or the retardation of faulting (Stein et al., 1992). A similar result is observed in many seismic swarms whereby the relationship between the seismic energy release and the spatial spreading is found to follow theoretical crack growth models (Hainzl and Fisher, 2002).

In light of the above mentioned theories and observations, we investigate the spatial and temporal patterns of the seismicity in the Messinia basin region, as well as the local stress distribution associated with the 2011 seismic activity, in order to contribute in the assessment of seismicity swarms and their triggering mechanisms in Greece.

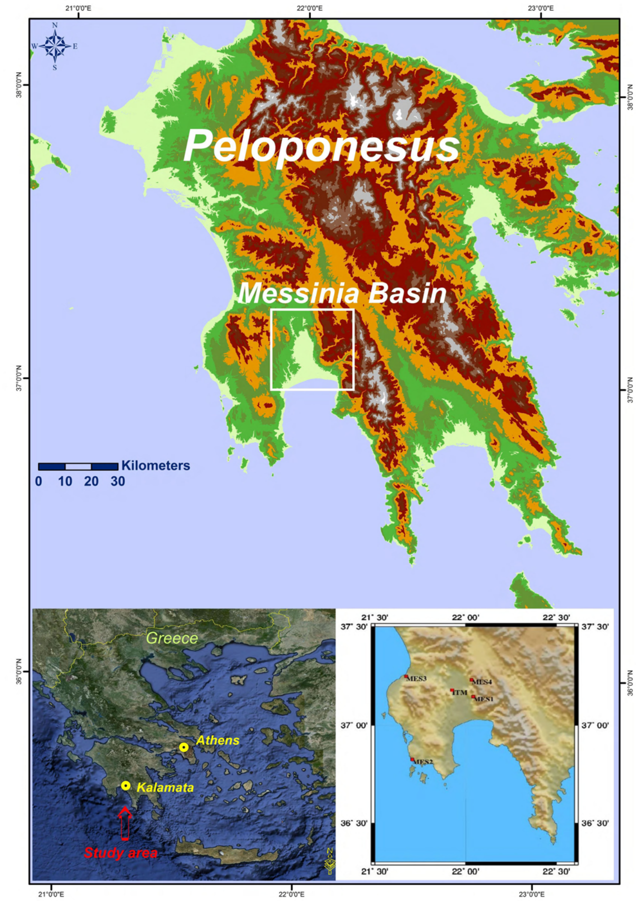

Fig. 1. Maps of Peloponnesus indicating the Messinia basin (upper), the study area (lower left) and the NOA seismological stations (lower right). MES1, MES2, MES3 and MES4 indicate the portable seismological stations and ITM the permanent seismological station belonging to the HUSN.

1.1 Data and results

The area of the 2011–2012 seismic activity in Messinia, south-western Peloponnesus, Greece, is characterized by a northwest–southeast trending basin of Pliocene–Pleistocene marine deposits, bounded by the Taygetos and Kyparisia mountains to the east and west, respectively (Fig. 1). Paleoseismological investigations of the basin have indicated that the seismic activity began close to the Pliocene–Pleistocene boundary and it has continued until the present day (Mariolakos et al., 1997). From the instrumental earthquake catalog of NOA (http://www.gein.noa.gr/) and also from historical earthquake catalogs and relevant studies, it is reported that the region of south-western Peloponnesus has been devastated by large and destructive earthquakes (Makropoulos et al., 2012; Papazachos and Papazachou, 2003; Papoulia et al., 2001). Microseismicity investigations in the Messinia basin by Papoulia and Makris (2004) have revealed the presence of several active minor faults in a northwest–southeast direction and dipping to the southwest with an extensional stress field, in agreement to the results of Papazachos and Delibasis (1969).

Earthquake catalogs are a valuable product of fundamental seismological practice and they form the basis for seismicity, seismotectonic, seismic risk and hazard investigations. The uninterrupted operation and seismological practice at NOA during the last four decades, produces a detailed instrumental seismicity catalog for the Greek area that contains more than 140 000 seismic events from 1964–2013, with a magnitude of completeness $M_c \sim 3.0$ (Chouliaras, 2009). In addition to the routine seismological analysis that involves real-time data from the permanent NOA-HUSN stations, real-time data from any additional portable seismological station installations are also routinely analysed and incorporated in the production of the earthquake catalog. Consequently, we will utilize the NOA catalog in this study to determine and map significant seismicity rate changes associated with the

2011 seismic activity and the on-going tectonic processes for the Messinia basin region.

The seismicity map of the study area for the period 1964–2011 is presented in Fig. 2a. More than 500 earthquakes are mapped and most of these are concentrated in the shallow crust, at depths less than 20 km. The larger seismic events with magnitudes $M > 4$ for the same period are also presented in Fig. 2b where we observe three clusters of seismicity: to the east, the southeast, and the northeast of the basin mainly at shallow hypocentral depths (<10 km). The three largest events in these three regions are the $M = 5.5$ earthquake that occurred to the southeast near the city of Kalamata (37.10° N–22.19° E) on 13 September 1986 (Lyon-Caen et al., 1988, Stavrakakis et al., 1989) and two earthquakes that occurred on 16 September 2001 and 1 March 2004, to the northeast (37.29° N–21.83° E) and to the east (37.19° N–22.14° E) of the Messinia basin with magnitudes $M = 5.2$ and $M = 5.0$, respectively.

The seismicity map of the study area in Fig. 2b also indicates that within the Messinia basin there is an apparent absence of moderate to strong earthquakes from 1964 until 2011. After June 2011, it is this area which becomes activated and an earthquake cluster formation is observed in Fig. 2c. The cluster has a length of ∼20 km, a width of ∼10 km and most of the hypocenters are located in the top 10 km of the crust. As demonstrated, the seismicity cluster has a northwest–southeast orientation in agreement with the orientation of the local basin topography and the seismotectonic structures.

The NOA Centroid Moment Tensor solutions (NOA-CMT) of the 3 larger earthquakes that occurred on 14 August, on 14 September, and on 10 October, with intermediate magnitudes $M_W = 4.8$, $M_W = 4.6$ and $M_W = 4.7$, respectively, are also presented in Fig. 2c. All three NOA-CMT results indicate the rupture of a normal fault with an northeast-southwest strike direction, parallel to the cluster and dipping to the southwest (http://bbnet.gein.noa). In addition to the above results, a migration of the three earthquakes is also observed in Fig. 3c, from the north-western part of the seismic cluster and the epicenter of the 14 August, $M_W = 4.8$ earthquake, towards the other end of the fault and the south-eastern part of the cluster, where the other two earthquakes occurred subsequently on 14 September, $M_W = 4.6$ and on 10 October, $M_W = 4.7$.

More than 2000 shocks with $M > 1$ have been registered in the NOA earthquake catalog for the Messinia basin during the one year period from June 2011–June 2012 as indicated by the power law behaviour of the cumulative seismicity curve of Fig. 3a (blue curve). Apparently, this is a significant seismicity rate increase when compared to the previous 36 yr period (1964–2010) that only contains about one third of the total seismicity. However, a significant part of this rate increase is mainly due to the detection improvement and the increased registration of small magnitude earthquakes ($M < 3$) after the 20 October 2011 installation of the NOA portable network around the seismicity cluster in the basin. We may demonstrate this by comparing the sudden increase in the cumulative seismic activity for earthquakes larger than $M > 1$, after the installation of the portable seismographic network (blue curve) to the cumulative seismicity curve for earthquakes larger than $M_c > 3$ (red curve) which

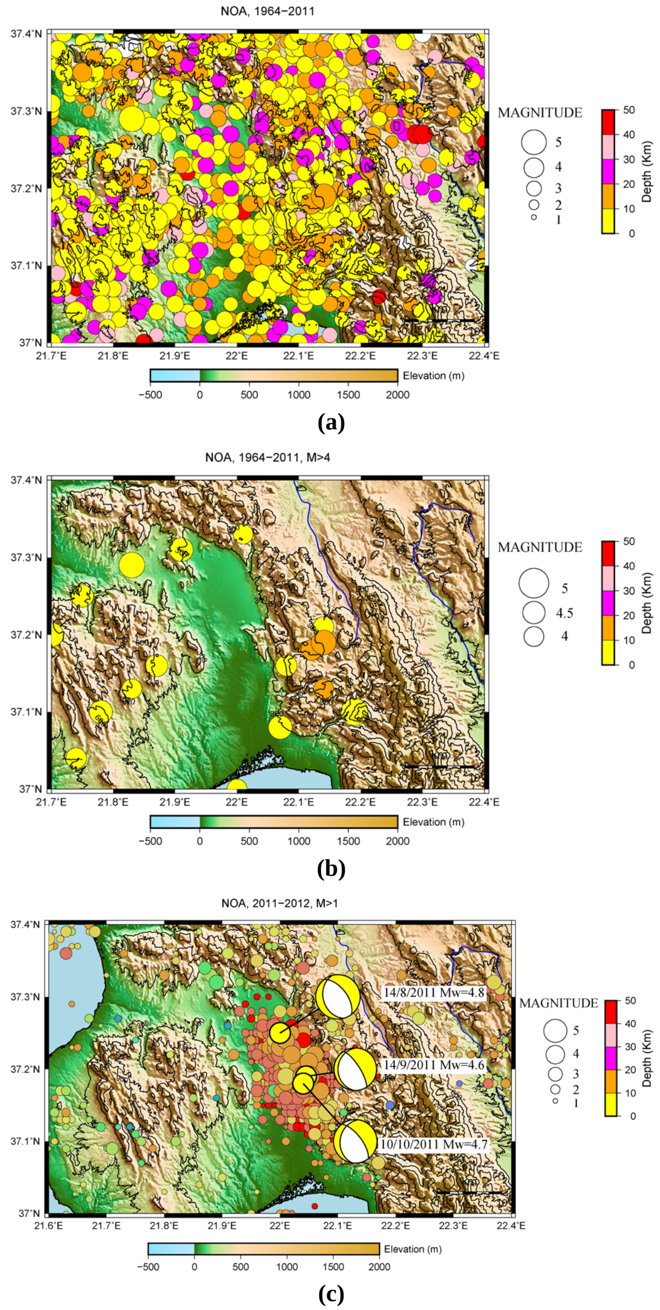

Fig. 2. Seismicity maps of the Messinia basin for **(a)** the instrumental period 1964–2011, **(b)** the large seismic events with $M > 4$ from 1964–2011, **(c)** the 2011 seismic swarm cluster for the period June 2011–June 2012. Beach balls indicate the NOA-CMT solutions for the three largest events.

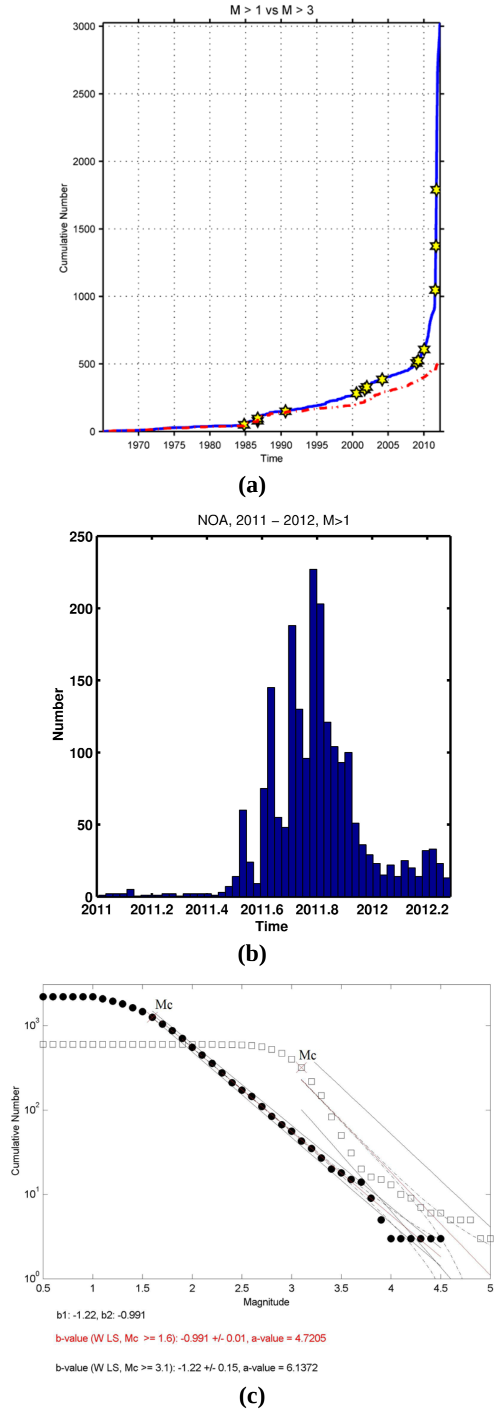

Fig. 3. (a) Cumulative seismicity of the Messinia basin area for the period 1964–2012. The blue curve includes all earthquakes with $M > 1$ and the red curve all earthquakes with $M > 3$. Yellow stars indicate events with $M > 4$. **(b)** Time histogram for the 2011 seismic swarm indicating a bell-shaped, Gaussian distribution. **(c)** Comparison of the FMD for two time periods. Open circles indicate the period before the 2011 swarm (1964–2011) and dark circles a one year period after the initiation of the swarm (June 2011–June 2012).

indicates a more constrained rate increase to be associated with the tectonic process.

The histogram of the 2011 seismic activity in the Messinia basin in Fig. 3b exhibits a bell-shaped Gaussian distribution, typical of swarm activity without the presence of a strong earthquake. As indicated by the normal distribution of the histogram, the seismic activity begins in June 2011 increasing with time and reaches peaks in the period of August to October due to the occurrence of the three larger earthquakes. After these peaks the activity decays, however more small magnitude events are registered in the catalog due to the installation of the local seismographic network.

Temporal variations of the frequency–magnitude distribution (FMD) of the Gutenberg–Richter (1944) law may be effectively used to study the seismicity rate changes due to the 2011 seismic activity. We therefore determine the frequency–magnitude distribution (FMD) for the first period prior to the seismic activity (1964–2011) and compare this to the FMD for the second period that includes the seismic activity (1964–2012) following Chouliaras (2009) and Chouliaras et al. (2012). The slopes of the FMD curves are determined with the weighted least-squares (WLS) method and these define the b-value of the Gutenberg–Richter (1944) relationship as presented in Fig. 3c. In this case we notice a decrease of the determined b-value from ∼1.2 before the seismic activity increase in 2011, to a value of ∼1 after the initiation of the seismic activity in June 2011. This rate change is also found to accompany a shift of the two FMD curves from $M_c \sim 3.1$ before 2011 to a value of $M_c \sim 1.6$ after 2011, due to the aforementioned detection improvement.

In order to map the spatial variation of the rate change associated with the stress field distribution due to the 2011–2012 seismic activity in the Messinia basin, we used the gridding method of Wiemer (2001) to determine and map the b-values, with a sample of $N = 70$ events per node and a grid spacing of 0.02°, for two periods i.e. before and after 2011, as presented in Fig. 4a and b, respectively.

A direct comparison of the two b-value maps indicates that the 2011–2012 seismic cluster ruptured a zone of progressively decreasing b-values and increasing stress. This area as outlined in Fig. 4b from the north-western part of the cluster and the epicentre of the first of the larger events of the 2011 seismicity swarm, towards the south-eastern part of the cluster at the other end of the fault, where the epicenters of the other two larger earthquakes are located.

The results thus far indicate for a northwest–southeast migration mechanism of the three larger events of the 2011 seismic activity towards a region of higher stress and lower b-values. To further validate these results, we also study the possible stress transfer mechanism of the 2011 seismic activity by determining the Coulomb stress change as a result of the occurrence of the first of the three largest events. Following Okada (1992), we adopt the NOA focal mechanism CMT solution and the Coulomb 3.2 software, using the projected normal fault centre, at a depth of 6.6 km with a

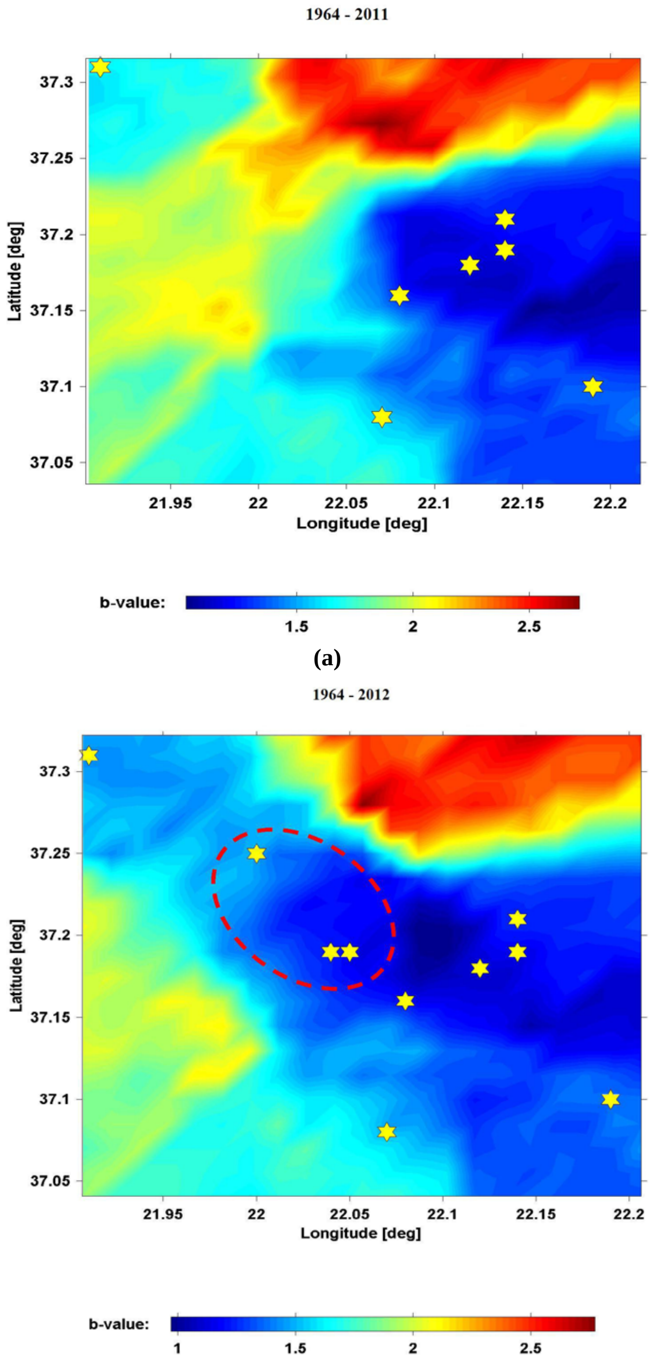

Fig. 4. B-value maps for the Messinia basin **(a)** prior to the 2011 seismic swarm, from 1964–2011 and **(b)** b-value map including the seismicity of the 2011 swarm. The yellow stars indicate the larger seismic events with $M > 4$ and the red ellipse shows the 2011 seismicity swarm cluster containing the three largest earthquakes.

strike/dip/rake of $165°/34°/-71°$ and a coefficient of friction $\mu = 0.4$, in an elastic half space with uniform isotropic elastic properties (Lin and Stein, 2004; Toda et al., 2005). In this procedure the Wells and Coppersmith (1994) empirical magnitude–area relations were employed in order to determine the corresponding fault length and width.

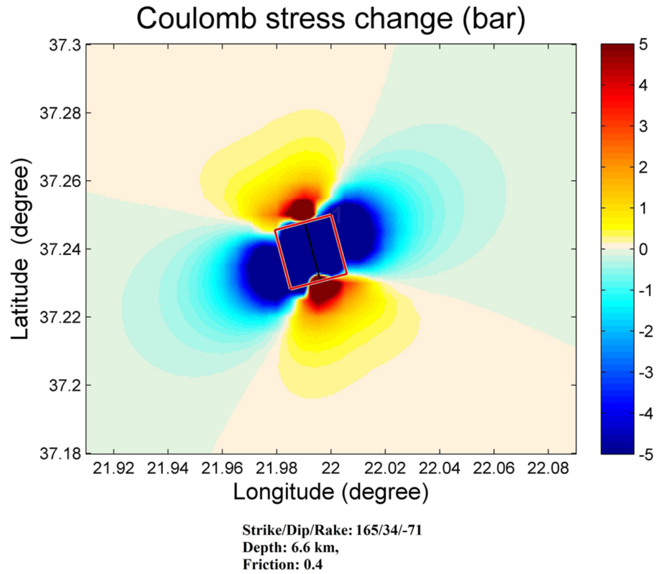

Fig. 5. Coulomb stress distribution due to the occurrence of the first largest event of the 2011 seismicity swarm on the 14 August 2011 with $M_W = 4.8$. Red lobes indicates positive stress and blue lobes negative stress.

The spatial distribution of the Coulomb stress change due to the occurrence of the first intermediate magnitude earthquake of the 2011 seismic activity with $M_W = 4.8$ on 14 August 2011 is presented in Fig. 5. Stress increase areas close to failure are represented by the red lobes and in our case a northwest–southeast direction of positive stress is found. This direction is coincident to the principle faulting direction, the orientation of the seismic cluster, the orientation of the low b-value zones and also with the direction of the successive occurrence of two more intermediate magnitude earthquakes that occurred on the opposite end of the fault to the southeast.

2 Summary and conclusions

Seismicity swarms that involve the spatial and temporal clustering of small earthquakes are a usual phenomenon in Greece and it is important to identify and distinguish these swarms from the usual ongoing tectonic activity.

The Messinia basin seismic activity that begun in June 2011, is analysed in this study with respect to its spatial and temporal seismicity patterns and the local stress field. A Gaussian distribution of the reported seismicity characterizes this swarm, with peaks in activity due to three intermediate magnitude earthquakes that occurred successively in August, September and October 2011. The seismic activity during a one year period from June 2011–June 2012 formed a cluster in a pre-existing seismic gap within the basin. The epicenters are orientated in a northwest–southeast direction parallel to the principle faulting of the region and the NOA-CMT solutions of the three largest events further confirm a northwest–southeast striking normal fault that dips to the southwest.

During the 2011 seismic activity in the Messinia basin, an epicentre migration is also observed for the 3 larger magnitude earthquakes. The spatial and temporal distribution of these events demonstrates that the master event of the Messinia 2011 seismic swarm was succeeded by two other equivalent earthquakes at the other edge of the rupture area rather than within the rupture area. This migration appears to follow a direction of progressively decreasing b-values and increasing stress, from the north-western part of the swarm cluster, towards the south-eastern part. In agreement with these results is also the Coulomb stress redistribution due to the occurrence of the first of the three larger events, that shows a maximum stress transfer from the northwest, towards the epicentres of the next two larger shocks that occurred subsequently in the south-eastern part of the cluster.

The triggering of tectonic earthquakes by the transferring static or dynamic stresses from previous earthquakes and the seismicity rate changes due to the local stress triggering are well predicted by the Coulomb fracture criterion (Schorlemmer and Wiemer, 2005; Stein et al., 1992; Stein, 1999; Wyss and Weimer, 2000; Westerhaus et al., 2002; Freed, 2005; Parsons et al., 2006). Additionally, swarm earthquakes are found to trigger shocks near the extreme borders of the rupture area and this process may be modeled by an increase of stress and pore pressure on the front of a progressively growing fracture (Hainzl and Fisher, 2002). In the case of self-triggering swarm due to stress redistribution and the subsequent induction of fluid flow it is expected that most of the earthquake ruptures will be initiated at the edge of the previous rupture and in this way the cluster of the seismic swarm will grow proportionally with each event. On the other hand, it is well known that fault zones are characterized by high permeability and lower strength therefore fluids can migrate more easily than in compact rock. In this case of fluid diffusion, the spatial growth of the swarm cluster will be proportional to time.

Based on the results presented in this study, we further encourage a more detailed study of the spatial and temporal evolution of the 2011 seismic swarm cluster in the Messinia basin. A relocation of the seismic events using a local velocity model will certainly improve the accuracy of the spatial and temporal evolution of the swarm and provide valuable insight into the triggering mechanism.

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