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THE CRUSTAL ANISOTROPY PATTERN IN THE EPICENTRAL AREA OF THE 2008 M_W 6.4 EARTHQUAKE IN NORTHWEST PELOPONNESE, GREECE

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Abstract

On June 8, 2008, a M_W 6.4 earthquake occurred on a strike-slip fault in north-west Peloponnese, Greece, 35 km southwest of the city of Patras. We analysed part of the aftershock sequence of the 2008 earthquake, recorded by a portable network of six stations and a permanent station of the Hellenic Unified Seismological Network, in order to perform a shear wave splitting analysis. We determined fast polarization directions φ, and normalized time-delays dt between the fast and slow components. The average value of dt was calculated at 1.7 ±0.5 ms/km, while φ values varied between 155° ±8° and 11° ±9°, with an average of 170° ±9°. The observed φ values at all stations were inconsistent with the regional stress field, which is characterized-by a general E-W orientation of the maximum horizontal compressive stress. On the contrary, the observed fast directions appear to intersect the strike of the causative fault (210°) in smaller angles than the regional principal compressive stress axis. The findings of this work are consistent with those of previous studies in the area, reflecting possibly the presence of a locally rotated principal stress axis to more favorable angles to the strike of the fault of the 2008 strong earthquake.
Keywords: *shear wave splitting, stress field, wave propagation.*

Περίληψη

Στις 8 Ιουνίου 2008, ένας σεισμός μεγέθους M_W 6.4 εκδηλώθηκε στην βορειοδυτική Πελοπόννησο, 35 km νοτιοδυτικά της Πάτρας. Στην παρούσα εργασία, χρησιμοποιήσαμε ένα μέρος της μετασεισμικής ακολουθίας που καταγράφηκε από ένα φορητό δίκτυο έξι σεισμογράφων και έναν μόνιμο σταθμό του Ενιαίου Εθνικού Δικτύου Σεισμογράφων, με σκοπό να πραγματοποιήσουμε μετρήσεις ανισοτροπίας S κυμάτων. Μετρήσαμε διευθύνσεις πόλωσης της ταχείας συνιστώσας των S κυμάτων και χρονικές καθυστερήσεις μεταξύ της βραδείας και της ταχείας συνιστώσας. Η μέση τιμή των κανονικοποιημένων χρονικών καθυστερήσεων υπολογίστηκε στα 1.7 ±0.5 ms/km, ενώ οι διευθύνσεις πόλωσης της ταχείας συνιστώσας κυμάνθηκαν από 155° ±8° έως 11° ±9°, εμφανίζοντας μέση τιμή 170° ±9°. Η υπολογισθείσα μέση διεύθυνση πόλωσης ήταν ασύμφωνη με το πεδίο τάσεων της ευρύτερης περιοχής, το οποίο χαρακτηρίζεται από

μέγιστη οριζόντια συμπιεστική τάση με διεύθυνση σχεδόν Α-Δ. Ωστόσο, η μέση διεύθυνση πόλωσης εμφανίζεται να τέμνει τη διεύθυνση του σεισμογόνου ρήγματος (210°) σε γωνία μικρότερη από αυτή με την οποία το τέμνει ο άξονας της κύριας συμπιεστικής τάσης του πεδίου τάσεων της ευρύτερης περιοχής. Τα αποτελέσματα της παρούσας εργασίας είναι σε συμφωνία με αυτά προηγούμενων εργασιών, υποστηρίζοντας την ύπαρξη ενός τοπικού πεδίου τάσεων, με χαρακτηριστικά διαφορετικά από αυτά της ευρύτερης περιοχής, με τον άξονα της κύριας τάσης να έχει περιστραφεί σε γωνίες ευνοϊκότερες ως προς τη διεύθυνση του σεισμογόνου ρήγματος σε σύγκριση με τη διεύθυνση της κύριας τάσης που επικρατεί στην ευρύτερη περιοχή.
Λέξεις κλειδιά: *Ανισοτροπία S κυμάτων, πεδίο τάσεων, διάδοση κυμάτων.*

1. Introduction

On June 8, 2008, on 12:25 GMT, a strong earthquake occurred in northwest Peloponnese, western Greece. The main shock was accurately located by Konstantinou *et al.* (2009) at a hypocentral depth of 18 km, using a shrinking grid-search relocation algorithm. Several studies have been performed to study the aftershock distribution and the rupture process of this event (Ganas *et al.,* 2009; Gallovič *et al.,* 2009; Konstantinou *et al.,* 2009; Papadopoulos *et al.,* 2010; Feng *et al.,* 2010). Various organizations have provided moment tensor solutions (Institute of Geodynamics of the National Observatory of Athens, Harvard University, United States Geological Survey, Aristotle University of Thessaloniki, National and Kapodistrian University of Athens), which have indicated a nearly vertical dextral strike-slip fault striking NE-SW.

The event was reported as an earthquake with a mean moment magnitude, M_W, of 6.4, which is the largest instrumentally recorded event in this area to date (Konstantinou *et al.,* 2009).The seismogenic fault of the earthquake had no direct surface expression, and none of the major surface-fault traces in the area fit with a NNE-trending fault at depth (Koukouvelas *et al.,* 2009). Konstantinou *et al.,* (2011) suggested that the presence of over-pressured fluids of deep origin might have been responsible for the elevated fluid pressure levels near the hypocenter that led to the reactivation of the unknown fault that generated this event.

One of the frequently used indicators to indentify and measure seismic anisotropy of the Earth is the shear wave splitting (SWS) phenomenon. SWS occurs during S wave propagation through an anisotropic medium as S waves are splitted into two components with perpendicular polarization directions and different propagation velocities (Crampin and Chastin, 2003; Crampin and Peacock, 2005). The two splitting parameters that can be measured through shear wave data processing defining the anisotropy are the polarization direction φ of the fast shear wave component and the time-delay *dt* between the two components. Various models have been proposed to interpret the observed seismic anisotropy in the upper crust. One of the widely accepted physical models, which is known as the extensive dilatancy anisotropy (EDA) model (Crampin, 1978, 1993; Crampin *et al.,* 1984), explains the principal cause of the local SWS phenomenon as S wave propagation through stress-aligned, micro-cracks with orientations parallel/sub-parallel to the direction of the maximum horizontal compressive stress. This model has since been modified, and led to the anisotropic poro-elasticity (APE) model (Crampin and Zatsepin, 1997; Zatsepin and Crampin, 1997), which explains the way in which such fluid-saturated micro-cracks evolve in response to changing conditions in permeable rock. Several studies investigating micro-crack-induced anisotropy have been carried out on various tectonic regimes in Greece. Such cases are, among others, the studies of Kaviris *et al.* (2015, 2014, 2010, 2008); Giannopoulos *et al.* (2015, 2013); Papadimitriou *et al.* (1999, 2010).

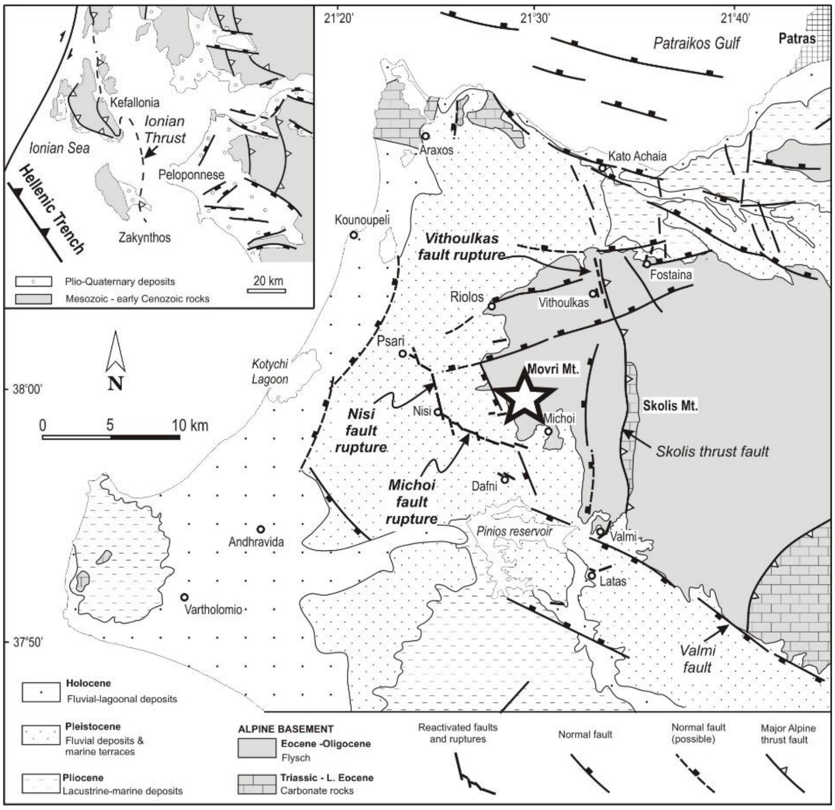

Figure 1 - Geological map of the NW Peloponnese showing the active faults of the study area as well as the reactivated faults during the June 2008 earthquake (star) according to Koukouvelas *et al.* (2009). Figure modified from Koukouvelas *et al.* (2009).

In this work, we first study the existence of S wave anisotropy in the crust around the epicentral area of the 2008 earthquake and then we interpret and discuss the measured splitting parameters in relation with both the local and the regional stress fields, as well as with the occurrence of the 2008 earthquake.

2. Data and Methodology

The French national SISMOB network (https://sismob.resif.fr/) deployed six mobile seismological stations in the study area (see Fig. 2) soon after the occurrence of the 2008 strong earthquake for almost 4 months. The stations were equipped with three-component broad-band seismometers (GURALP-CMG40), high dynamic range at 100Hz (four TAURUS-Nanometrics and two OSIRIS-Agecodagis) and Global Positioning System (GPS) units. The only permanent station (RLS) operated by the Hellenic Unified Seismological Network (HUSN) was also equipped with a three-component broad-band seismometer (Lennartz electronic-Le3D/20).

For the purpose of this study, we used aftershocks recorded between June 14th and September 17th 2008. The hypocentral locations were determined using the HYPOINVERSE software (Klein, 2002). The 1-D crustal velocity model adopted was the one proposed by Tselentis *et al.* (1996) and the magnitudes were computed using the coda duration method (Lee *et al.*, 1972). The hypocentral location process provided a dataset of 78 earthquakes as the input of the splitting analysis, with focal depths ranging from 7km to 25km and magnitudes from 2.3 to 3.4. The calculated mean location uncertainties were, RMS=0.12 s, ERZ=1.27 km and ERH=1.14 km.

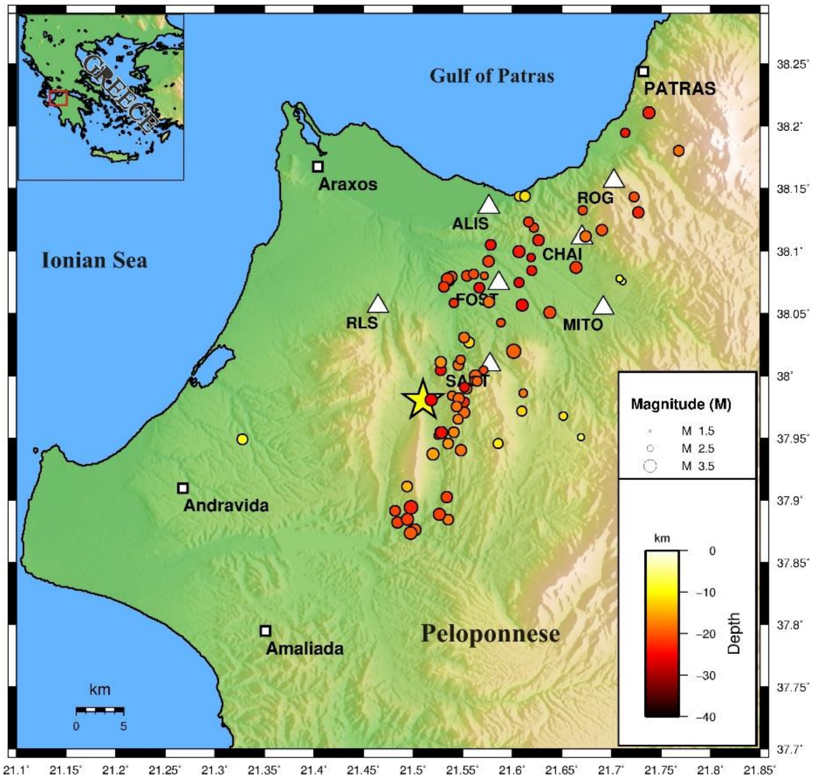

Figure 2 - Map of the study area in NW Peloponnese. Seismic stations used for the shear wave splitting measurements are shown as triangles. ALIS, FOST, ROG, CHAI, MITO and SANT stations deployed by the French national SISMOB network. RLS station is a permanent station operated under the framework of the Hellenic Unified Seismological Network. The seismic events (colored circles) from which the valid seismic results were obtained, the June 2008 main shock (star) and major cities (squares) are also shown. The depths of the events are color coded according to the color scale (bottom-right). The diameters of the circles are proportional to the magnitudes.

For the estimation of the splitting parameters we applied the cross-correlation method proposed by Ando *et al.* (1983). The seismograms were interpolated to 200 samples s^{-1}, integrated to displacement and then band-pass filtered between 1 Hz and 10 Hz. The measurement window for each waveform was defined in the following way: the start of the window was fixed 0.05 s before the S-wave arrival while the endpoint was adjusted until the value of cross-correlation coefficient C between the fast and slow components was maximized.

According to the cross-correlation method, both horizontal seismograms are rotated in the horizontal plane at 1° increment of azimuth from -90° to 90°. Then, for each azimuth, the cross-correlation coefficient C is calculated between the two orthogonal seismograms, for a range of time-delays in a selected time window. When the absolute value of C reaches a maximum, the corresponding values of azimuth and time are chosen as the fast polarization direction and the time-delay between the separated shear waves, respectively. The measurement's uncertainty is estimated using a t-test at a 95% confidence level on the values of C as described by Kuo *et al.* (1994).

We accepted as valid the splitting measurements which conform to the following criteria: (a) the C value is larger than 0.80, (b) the signal-to-noise ratio is larger than 2.5, (c) the change of the measured *dt* is less than 0.02 s when the window size is varied by ±0.02 s and (d) the change of the measured φ is less than 10° when the window size is varied by ±0.02 s. An example of a valid splitting measurement is shown in Fig. 3. The recordings, from which we calculated the splitting parameters are derived from seismic events located within the effective shear-wave window (Crampin and Gao, 2006) of every station (incidence angle ≤45°).

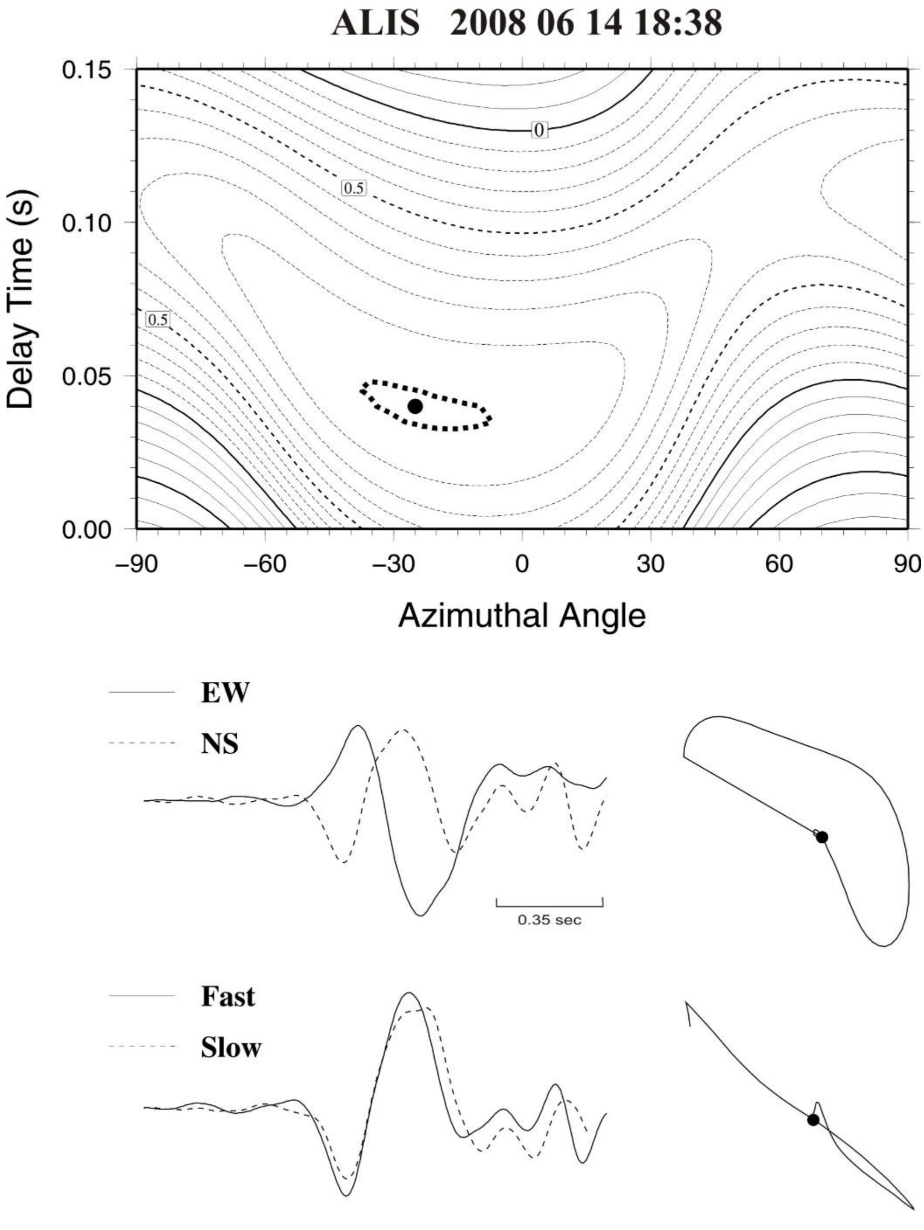

Figure 3 - An example of a valid splitting measurement of the shear waves recorded at the ALIS station for an event that occurred in June 14, 2008. Upper panel: Contour diagram of the cross-correlation coefficient in the (φ, dt) space. The preferred solution of (φ, dt) corresponding to the maximum value (dot) is shown within the 95% confidence region (dotted line). Lower panel: Superposition of the horizontal components (upper traces), and the corrected fast and slow components (lower traces) once the splitting effects have been removed. Particle motions are shown to the right of each subpanel.

3. Results

After the shear wave analysis we obtained 200 valid splitting measurements derived from 78 seismic events. Specifically, we obtained 28 valid measurements from ALIS station, 33 from CHAI, 28 from FOST, 38 from MITO, 24 from RLS, 20 from ROG and 29 measurements from SANT station. A first overview of the results shows the following: the time-delays, which were normalized according to the hypocentral distances, varied between 1.1 ±0.5 ms/km at MITO station, and 2.6 ±0.6 ms/km at FOST station, with a mean value of 1.7 ±0.5 ms/km. The fast polarization directions varied between an average NNW-SSE direction at RLS station and an average of a NNE-SSW direction at CHAI station, exhibiting a mean of 170º ±9º (~N-S). Table 1 gives a summary of the average values of the splitting parameters measured per seismic station.

Table 1 - Summary of the average values of the splitting parameters per seismic station.

Station	Nobs	φ (º)	dt (ms km^{-1})
ALIS	28	8 ±10	1.9 ±0.6
CHAI	33	11 ±9	1.3 ±0.4
FOST	28	159 ±6	2.6 ±0.6
MITO	38	179 ±8	1.1 ±0.5
RLS	24	155 ±8	1.3 ±0.3
ROG	20	161 ±10	1.2 ±0.4
SANT	29	159 ±9	2.5 ±0.6

Note: Nobs denote the number of observations per station, ϕ is the mean of the fast polarization directions based on directional statistics (Trauth, 2010), *dt* is the average time delays normalized according to the hypocentral distance.

4. Interpretation and Discussion

The June 2008 earthquake in northwest Peloponnese occurred on a pre-existing dextral strike slip fault formed during past tectonic processes that affected the area. The strike of the fault is 210o as determined by seismological means (Konstantinou *et al*., 2009). Konstantinou *et al.* (2011) performed a stress inversion of all available focal mechanisms in the area and estimated that the principal compressive stress axis of the regional stress field has an azimuth of ~273o (see Fig.4). The angle between the strike of the fault and the σ1 of the regional stress field shows that the fault is severely misoriented compared to the regional prevailing stress field. This means that the 2008 earthquake occurred within an unfavorable stress regime.

According to Sibson (1990) for seismogenic fault reactivation to occur, a favorable orientation between the strike of the fault and σ1, is needed. Konstantinou *et al*. (2011) suggested that the presence of fluids may have facilitated the reactivation of the fault causing the 2008 event. Fluids could have allowed the fault to slip by rotating the principal stress axis locally around the fault to more favorable angles.

Recent studies have confirmed the existence of fluids in the study area. For instance, Konstantinou *et al.* (2011) made use of a database of helium isotope measurements around Greece and surroundi ng areas compiled by Pik and Marty, (2009). One such measurement taken at a location about 20 k m away from the earthquake's epicentre, shows a significant percentage (7%) of mantle helium. Fu rthermore, tomographic imaging of Pn velocities performed by Al-Lazki *et al.* (2004), indicate abn ormal low values beneath northwest Peloponnese. These low Pn velocities may represent molten ar eas in the upper mantle that can be considered as possible sources of degassing fluids. Fluids are lo wer crust or upper mantle sourced and possibly the relatively permeable and fractured fault zone ac ted as passage way (Konstantinou *et al*., 2011).

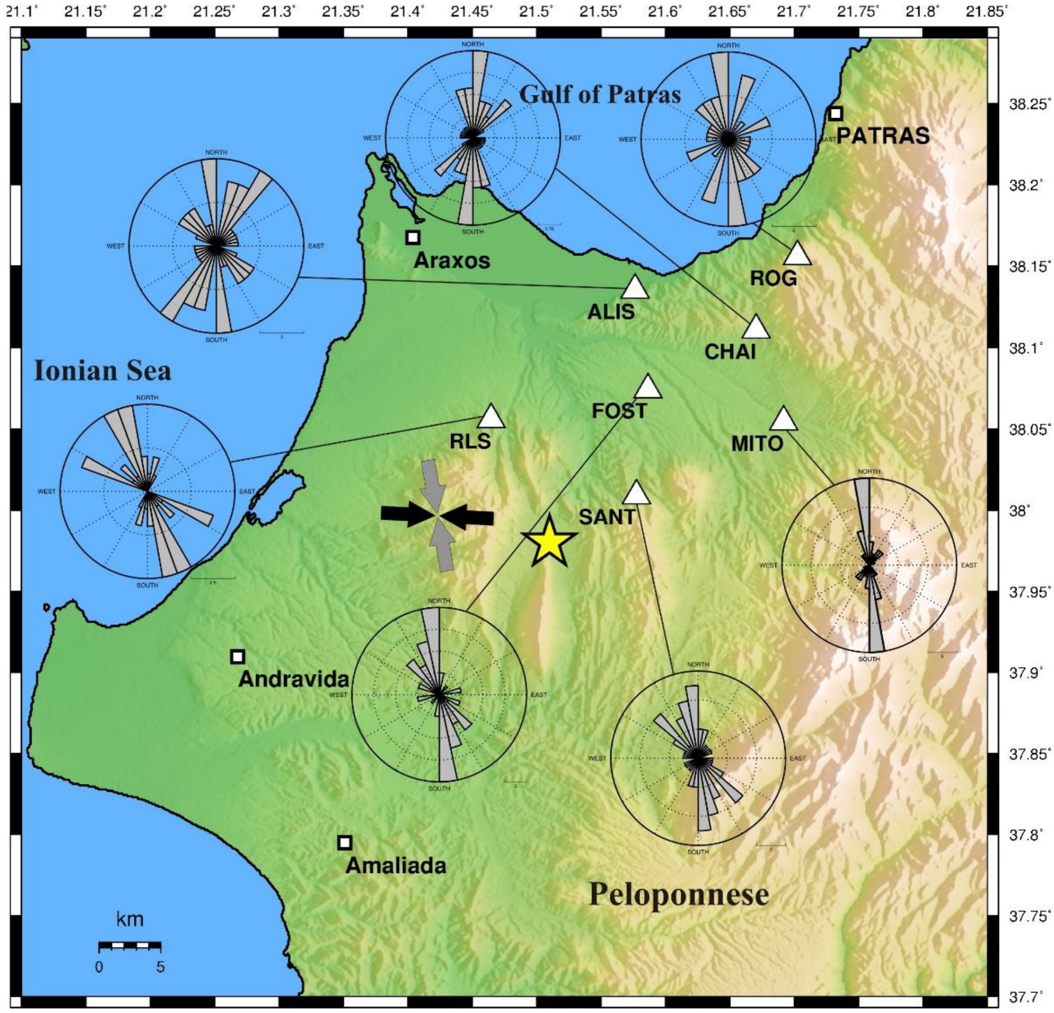

Figure 4 - Map of the study area showing rose diagrams of the measured fast shear wave polarization directions.The direction of the principal compressive stress axis (σ_1) of the regional stress field (Konstantinou *et al.,* 2011) and the proposed direction of the local rotated σ_1 axis are presented with black and gray arrows, respectively. Seismic stations, the 2008 main shock and major cities are also presented as in Fig. 2.

The fast polarization directions are usually parallel or sub-parallel to the present-day direction of the maximum compressive stress throughout the crust (Crampin and Lovell, 1991). The mean fast polariz ation orientation, using the complete dataset of the present study, was measured at 170^o ±9^o. Thus, we can claim that the direction of the maximum horizontal compressive stress at the study area is almost parallel to this value. Consequently, this indicates the presence of a local stress field in the vicinity of the fault with different characteristics from those of the prevailing regional stress field.

Comparing the strike of the fault (210^o) and the mean fast polarization direction (170^o ±9^o), we infe r that the angle between the strike of the fault and the rotated principal local stress axis is about 40 ^{o}. It seems that the local σ_1 is rotated towards lower angles to fault compared to the regional σ_1. Thi s supports the suggestion of Konstantinou *et al.* (2011), according to which σ_1 had to form locally s maller and more favorable angles in relation to the strike of the fault in order for the 2008 earthqua ke to occur. The findings of the present work, as well as the suggestion of fluid involvement, is sup ported by a recent shear wave anisotropy analysis that was carried out by Giannopoulos *et al.* (201 3) at the same area. Giannopoulos *et al.* (2013) measured shear wave splitting parameters by analy zing foreshocks and aftershocks of the 2008 earthquake recorded at RLS station. The results of the previous work revealed fast polarization directions of 164º ±10º, indicating the observed disagreem ent between the calculated orientation and the regional principal stress axis.

In conclusion, our observations can be explain by the EDA and APE models (Crampin, 1978; Zatsepin and Crampin, 1997), highlighting a key role for over-pressured fluids in the splitting parameters. We suggest that shear-wave splitting in the epicentral area of the 2008 ear thquake was most probably caused by fluid-saturated micro-cracks, oriented parallel or sub-paralle l to the maximum compressive stress axis of a local stress field in the vicinity of the fault. We sugg est that the cause of the observed differences between the fast polarization directions and their mea n directions was a possible migration of fluids through the fractured damage zone which allowed lo cal rotations of the stress field. This suggestion could also explain to some extent, the differences b etween the average normalized time-delay values per station (see Table 1). These differences possi bly reflect parts of the crust with different level of deformation and micro-crack systems with diffe rent geometry (crack density and aspect ratio) and level of saturation.

5. Conclusions

The results of the shear wave splitting analysis are summarized as follows:

(i) the data analysis revealed the existence of an anisotropic crust around the epicentral area of the 2008 earthquake in north-western Peloponnese, as shear wave splitting processes were observed in all stations

(ii) fast polarization directions presented a general N-S orientation (170º ±9º), which is in disagreement with the orientation of the regional stress field.

(iii) S-wave anisotropy at the study area was most probably caused by micro-cracks and micro-fractures that were oriented parallel or sub-parallel to the maximum compressive stress axis of a local stress field in the vicinity of the seismogenic fault.

(iv) the results of this work support in some extent the suggestion of a rotated local stress field to more favorable angles to the strike of the seismogenic fault of the 2008 earthquake.

6. Acknowledgments

The figures were created using the Generic Mapping Tool software (Wessel and Smith, 1998) (http://www.soset.hawaii.edu/gmt/). Data analysis performed using the Seismic Analysis Code software that was developed at Lawrence Livermore National Laboratory, CA, USA.

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