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Temporal variation of shear-wave splitting parameters related to Movri Mountain earthquake in northwest Peloponnese (Greece)

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ABSTRACT

On June 8, 2008, at 12:25 GMT, a M_w 6.4 earthquake occurred in the area of northwest Peloponnese, western Greece. The epicenter was located in the municipality of Movri 35km southwest of Patras. In this study, a crustal anisotropy analysis was performed in the epicentral area of Movri Mountain earthquake. Specifically, shear-wave splitting phenomenon and its temporal evolution in relation to the occurrence of Movri Mountain earthquake, was studied using the cross-correlation method. Data analysis revealed the presence of shear-wave splitting in the study area. Both before and after the occurrence of Movri Mountain earthquake, the polarization directions of the fast component of shear waves follow a general NNW-SSE direction. The observed mean fast polarization direction is not consistent with the regional stress field with a general E-W direction of the maximum horizontal compressive stress. The difference between the estimated fast polarization directions and the properties of the regional stress field suggests the presence of a local stress field in the area around the fault. An increase in time delays was observed soon after the occurrence of Movri Mountain earthquake. The average value of delay times before the occurrence of the earthquake was about 18 ±2.6ms, while after the occurrence was about 40 ±4.6ms. The increase in time delays indicates changes in the crustal properties, possibly caused by variation of the pre-existing fluid-saturated micro-crack system characteristics related to the Movri Mountain earthquake occurrence.

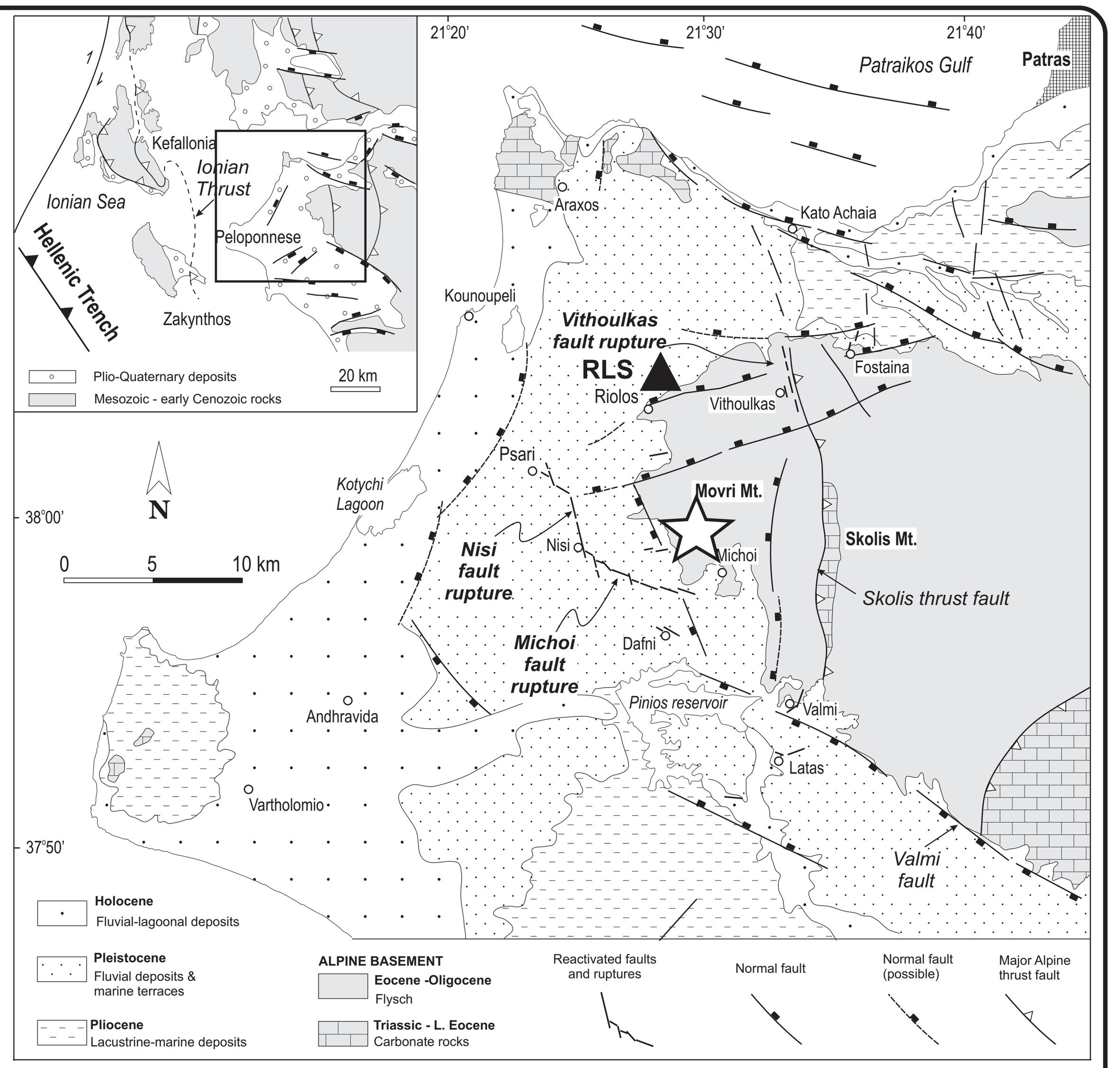


Figure 1. Geological map of northwest Peloponnese showing active faults, the Movri Mountain earthquake epicenter (star), Riolos (RLS) station (triangle) and the reactivated faults during the 2008 Movri Mountain earthquake according to Koukouvelas et al. (2009). Figure modified from Koukouvelas et al. (2009).

INTRODUCTION

Shear-wave splitting is a phenomenon in which shear-waves are separated into two components with different polarization directions and propagation velocities. It occurs during S-wave propagation through an anisotropic medium (Crampin and Chastin, 2003; Crampin and Peacock, 2005). The two splitting parameters that can be measured through the shear-wave data processing are, the polarization direction φ of the fast components of shear waves and the time delay dt between the two components. Parameters φ and dt provide information about the compressive stress direction (Crampin and Peacock, 2005). Several studies on local earthquakes worldwide have revealed the existence of shear-wave splitting in various geological settings indicating anisotropic media (Kaneshima, 1990; Crampin & Lovell, 1991; Gao et al., 1998; Liu et al., 2008). Changes in the parameters of the phenomenon have been observed worldwide in relation to earthquake occurrences. These variations in splitting parameters reflect changes in the anisotropic characteristics of the medium and the stress field (Gao & Crampin, 2004; Crampin & Peacock, 2008; Crampin & Gao, 2012).

Western Greece is characterized by a complex tectonic and geological setting. The tectonic framework of western Greece is dominated by the large dextral strike slip fault off the coasts of Cephalonia island where the change between continent-continent collision in the north and ocean-continent subduction in the south occurs (Underhill, 1989; Sachpazi et al., 2000) (Fig. 1). During the Eocene, north-western Peloponnese was affected by the Alpine collision, which led to the formation of the Hellenic mountain range (Doutsos et al., 1993). Mesozoic and Early Cenozoic carbonate rocks were propagated upward and westward along N-S striking and east dipping thrust faults (Xypolias and Doutsos, 2000). From the early Pliocene up to the present, an extensional stress field has progressively prevailed in the previous compressional tectonic regime in north-western Peloponnese (Doutsos and Kokkalas, 2001).

Movri Mountain earthquake occurred on June 8, 2008, at 15:25 local time (12:25 GMT) in the area of northwest Peloponnese, western Greece. The main shock was accurately located by Konstantinou et al. (2009b), at a hypocentral depth of 18km using a shrinking grid-search relocation algorithm. Various institutes (Institute of Geodynamics of the National Observatory of Athens, Harvard University, United States Geological Survey, Aristotle University of Thessaloniki) provided moment tensor solutions, indicating a dextral strike-slip fault striking NE-SW, with a nearly vertical dip. The event is reported as an earthquake with a mean moment magnitude M_w 6.4 which is the largest instrumentally recorded event in this area (Konstantinou et al., 2009b). The seismogenic fault of Movri Mountain earthquake had no direct surface expression and none of the major surface fault ruptures in the area can fit with a NNE-trending fault at depth (Koukouvelas et al. 2009). Konstantinou et al. (2011) suggest that the presence of over-pressured fluids of deep origin may be responsible for the elevated fluid pressure levels near the hypocenter that led to the reactivation of the fault which generated the event.

In this study we present evidence for shear-wave splitting processes in the epicentral area of Movri Mountain earthquake. Specifically, we detected variations in splitting parameters in relation to the occurrence of Movri Mountain earthquake. We discuss the measured splitting parameters and their variations in comparison with the regional strain and stress field and also with the occurrence of Movri Mountain earthquake.

DATA

For the purpose of this study three-component recordings are needed from stations in continuous operation during the periods before and after the occurrence of the Movri Mountain earthquake. The only station in the study area that satisfied the above criterion was Riolos station (RLS) which is operating since the July of 2001. No other seismological station around the epicenter was equipped with three-component seismometers and operating continuously in the studied time period. The station is part of the seismological network of the Institute of Geodynamics, National Observatory of Athens (GI-NOA) and the Hellenic Unified Seismological Network (HUSN). It is equipped with a three-component, broadband sensor and it is located in Riolos village, about 13km from the epicenter of the Movri Mountain earthquake, in north-western Peloponnese (Fig. 1, 2 &3).

The seismicity studied in this study consists of background earthquakes near to the seismogenic fault and aftershocks of the M_w 6.4 Movri Mountain earthquake. The dataset for the period before the occurrence of the Movri Mountain earthquake was recorded from June, 4[th] 2003 until September, 27[th] 2007 and for the period after the occurrence from June, 10[th] 2008 until July, 13[th] 2008. The local magnitudes vary between 1.3 and 3.9. We used records from 12 events for the first period and records from 207 events for the second one. For the first period of interest we used the events location parameters provided by GI-NOA. Location errors in the horizontal and vertical directions associated with events location by GI-NOA did not exceed 2km. For the second period of interest we used the events location as determined by Konstantinou et al. (2009b). The available seismic events before the Movri Mountain earthquake were much less, since seismicity in the area was low. This explains the small number of the available events of the first period.

S waves have such severe interactions with the free surface that almost all the similarities with the incoming waveform are irretrievably lost when they reach the surface at incidence angles larger than a critical value. The critical value is given by $\sin^{-1}(V_s/V_p)$, where V_s and V_p is the S and P-wave velocities at the source (Booth & Crampin 1985). Using the local 1-D velocity model by Haslinger et al. (1999), the critical angle for our study was estimated at 34.5°. Records of the events within the shear wave window of RLS station have been screened for clean and impulsive S phases on the horizontal components.

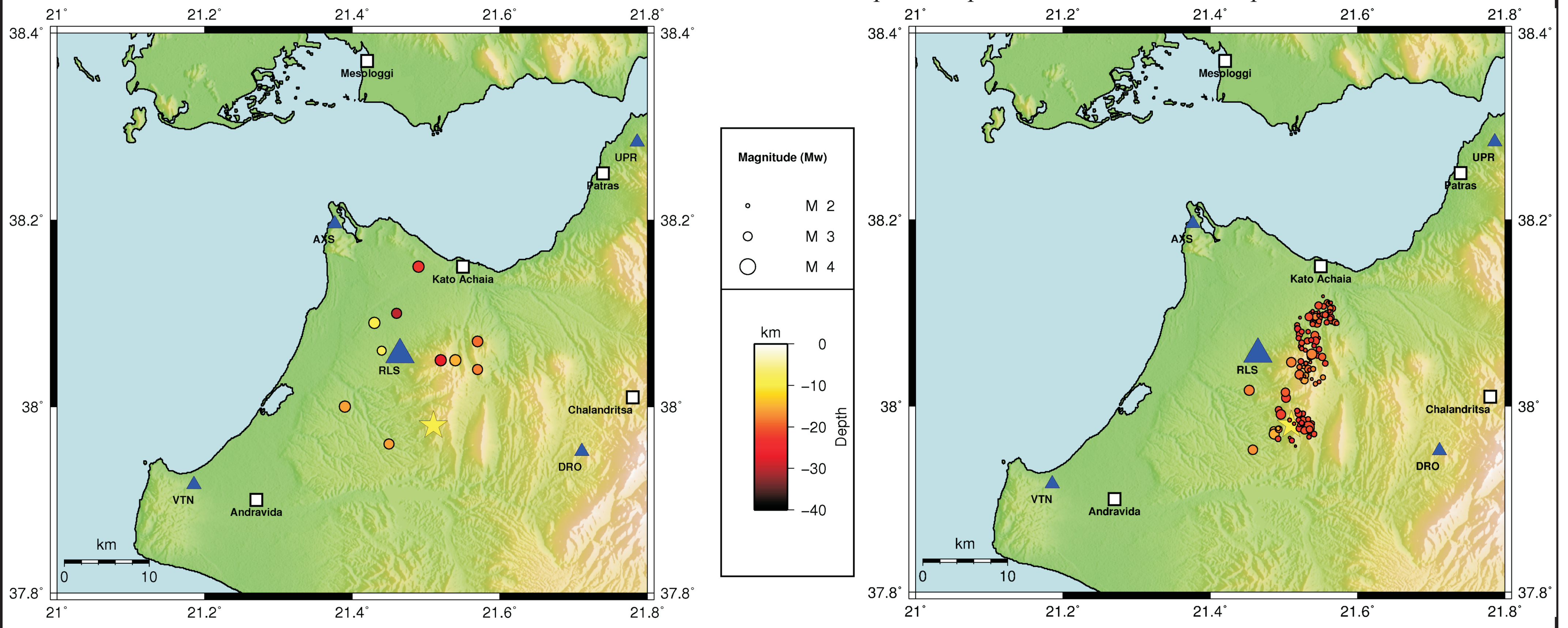


Figure 2 & 3. Maps of NW Peloponnese showing the events from which we obtained valid splitting results for the period before (left figure) and after (right figure) the Movri Mountain earthquake. Also is shown RLS station (triangles), part of the HUSN seismic stations (small triangles), Movri Mountain earthquake (star) and major cities (squares). Hypocenter depths are scaled with color and earthquake magnitudes with diameter of symbol.

METHOD

For estimating the splitting parameters in our dataset we applied the **cross-correlation method** (Ando et al., 1983) as described in Konstantinou et al. (2009a). Before applying the method, we manually picked P and S wave arrival times of our waveform dataset of 219 seismic events recorded by RLS, all within the shear-wave window of the station. The seismograms were interpolated to 200 samples s^{-1}, integrated to displacement and then band-pass filtered with corner frequencies of 1 Hz and 10 Hz. The measurement window for each waveform is defined in the following way as described by Konstantinou et al. (2009a): the start of the window is fixed 0.05s before the S-wave arrival while the endpoint is adjusted each time until the value of cross-correlation coefficient C between the fast and slow components maximizes. The reasoning behind this choice of window measurement is based on the fact that the suitable endpoint may actually vary with different waveform characteristics. According to cross-correlation method, both horizontal seismograms are rotated in the horizontal plane at 1° increment of azimuth a 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 τ 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 uncertainty is estimated using a t-test at a 95% confidence level on the values of C as described by Kuo et al. (1994). Following Liu et al. (2008) and Konstantinou et al. (2009a) we accept 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 3, (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. Applying these criteria, 132 events were selected and splitting parameters for both periods (before and after Movri Mountain earthquake's occurrence) were computed. Two examples of valid splitting measurements are shown in Fig. 4.

RESULTS

After the analysis we obtained valid results (φ, dt) from 10 seismic events for the period before the occurrence of the Movri Mountain earthquake and from 122 seismic events for the period after the earthquake (Fig. 2, 3).

Polarization directions. Before the earthquake, the polarization directions of the fast components vary between 108° and 226° with a mean direction of 166° ±13° (Fig. 5). After the earthquake the polarization directions of the fast components vary between 106° and 231° with a mean direction of 161° ±8° (Fig. 6). Comparing the mean polarization directions that were estimated for both periods and taking also into account the measurement errors, we can claim that the fast polarization directions are following a general NNW-SSE direction in both periods. The occurrence of Movri Mountain earthquake had little or no influence on polarization directions.

Delay times. Before the earthquake, raw delay times values vary between 5ms and 50ms with an average value of 18 ±2.8m (median value 10ms) (Fig. 5). After the earthquake the raw time delays vary between 5ms and 115ms with an average value of 40 ±4.6ms (median value 43ms) (Fig. 6). Time delays were normalized by hypocentral distances showing an average value of 4ms/km in the first period and 11ms/km in the second one. This parameter is very sensitive to small changes in the geometry of the micro-fractures/micro-cracks system of the crust. Especially in cases of earthquake occurrences, there are noticeable variation in time delays values that can be ascribed to stress changes (Crampin and Lovell, 1991).

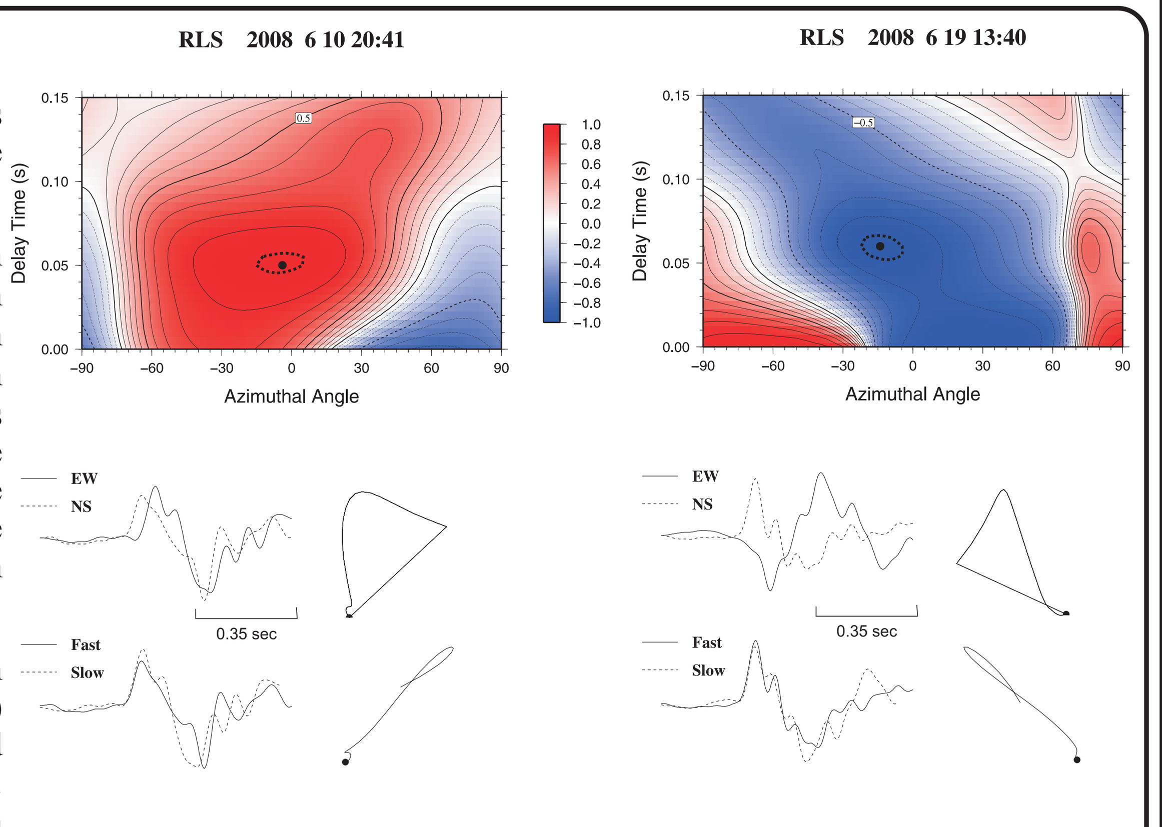


Figure 4. Valid splitting measurements of S-waves recorded at RLS station for two events that occurred in June 10, 2011 and June 19, 2011. Upper panel: Distribution diagrams of the cross-correlation coefficients in φ-dt space. The preferred solutions (φ, dt) corresponding to the maximum absolute values (dot) are shown within the 95% confidence region (dotted line). Lower panel: upper traces are the superposition of E-W and N-S components. The lower traces are the corrected fast and slow components. Particle motions are shown to the right of each sub-panel.

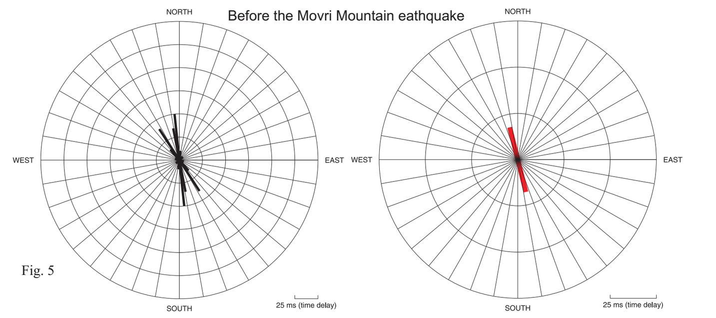
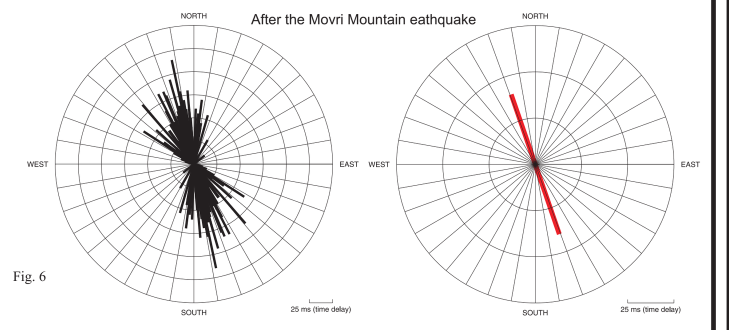


Figure 5 & 6. Rose diagrams of the fast polarization directions as a function of delay times and mean polarization directions as a function of the average delay time. The left and right diagrams correspond to the results for the period before and after the Movri Mountain earthquake, respectively.



DISCUSSION & CONCLUSIONS

Konstantinou et al. (2011) estimated that the principal compressive stress axis of the regional stress field has an azimuth of ~273° forming with the strike of the fault (210°) an angle of ~63°. The angle between the strike of the fault and the σ_1 of the regional stress field implies that the fault is severely misoriented compared to the regional prevailing stress field. This means that the Movri Mountain 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 σ_1, is needed. Konstantinou et al. (2011) suggest that the presence of fluids may be responsible for the elevated fluid pressure levels that led the fault to reactivate. Fluids allowed the fault to slip by rotating the principal stress axis locally around the fault to more favorable angles. Fluids are lower crust or upper mantle sourced and possibly the relatively permeable and fractured fault zone acted as passage way (Konstantinou et al., 2011).

The fast polarization directions are usually parallel or sub-parallel to the present-day direction of the maximum compressive stress throughout at least the uppermost 20km of the crust (Crampin and Lovell, 1991). The mean fast polarization orientation, using the complete dataset of the present study, was measured at ~164° ±10°, 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 existence of a local rotated 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 and the mean fast polarization direction, we infer that the angle between the strike of the fault and the rotated principal local stress axis is equal to 46° ±10°. It seems that the local σ_1 is rotated towards lower angles to fault's reactivation compared to regional σ_1. This supports the suggestion of Konstantinou et al. (2011), according to which σ_1 had to form locally lower angles in relation to the strike of the fault in order for Movri Mountain earthquake to occur.

According to our results we suggest that shear-wave splitting in the epicentral area of Movri Mountain earthquake was most probably caused by fluid-saturated micro-cracks, oriented parallel or sub-parallel to the maximum compressive stress axis of a local stress field in the vicinity of the fault. The earthquake occurrence caused a change in the deformation level of the crust and micro-crack system geometry (including crack density and aspect ratio). The observed average increase in time delays values on the one hand and the maintenance of the same mean fast polarization direction after the Movri Mountain earthquake on the other hand, suggests that the cause of the observed variation in splitting parameters was a possible over-pressured fluids migration through the pre-fractured damage zone of the fault.

Shear wave splitting analysis results presented in this study, can be summarized as follows:

A) Disagreement between the fast polarization directions and the orientation of the regional stress field was observed
B) Fast polarization directions did not change after the occurrence of Movri Mountain earthquake
C) Time delays increased soon after the event's occurrence
D) The above results could support the increased effect of fluids in the Movri mountain earthquake occurrence