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SHEAR-WAVE SPLITTING AND TEMPORAL VARIATION OF TIME DELAY IN NW PELOPONNESUS (GREECE)

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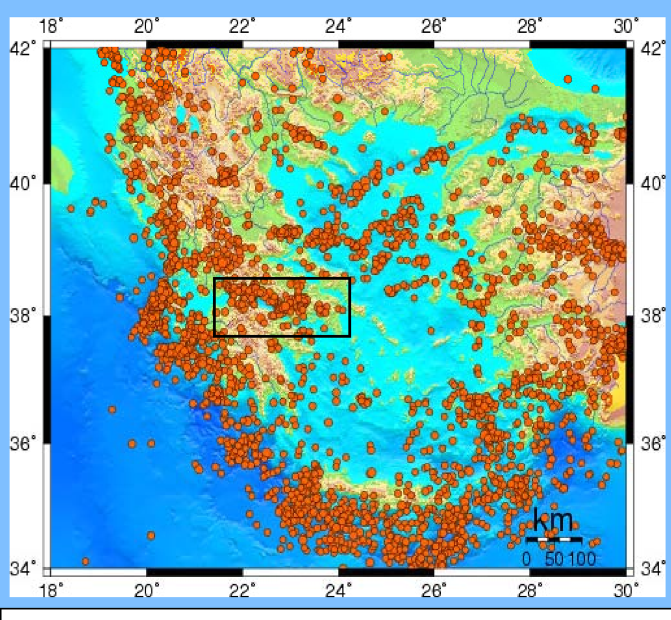
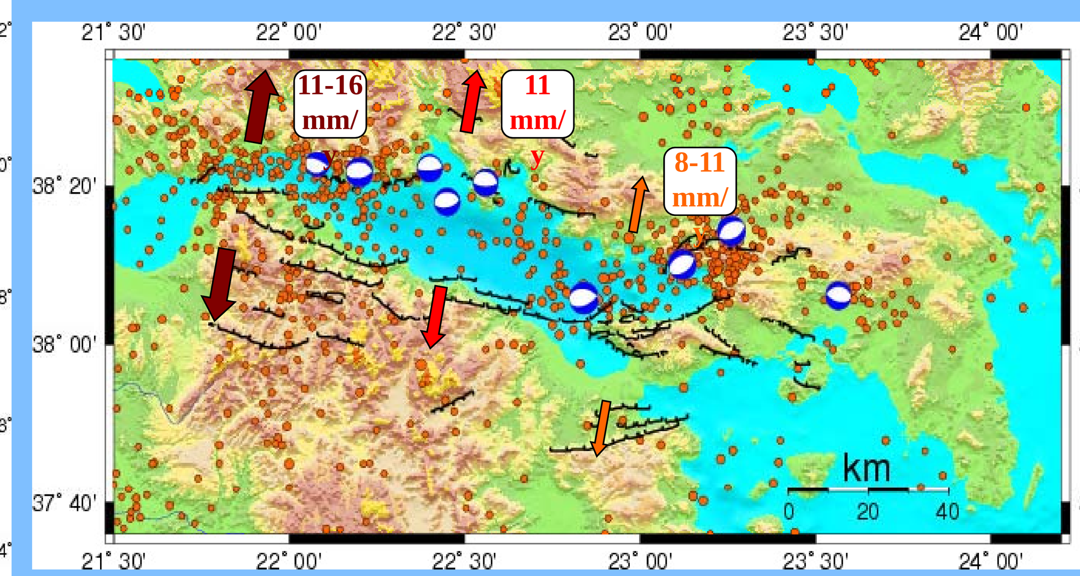
ABSTRACT

The Gulf of Corinth, located in Central Greece, is one of the faster expanding and most seismically active continental rifts around the world and is characterized by normal faulting in an approximate E-W direction. In NW Peloponnesus, in the area between the Corinth Rift and the Hellenic Arc, there is a transition zone characterized by dextral strike-slip faulting. On 4 February 2008 a seismic swarm, including two moderate-size earthquakes (Mw=4.7, 4.5), occurred in this area. The analysis of earthquakes of the sequence revealed the existence of shear-wave splitting, which is related to the existence of anisotropic medium. All the events that were selected for the anisotropy study are located within the shear-wave window, having incident angles smaller than the critical, as well as clear and impulsive S wave arrival phases on the horizontal components. In addition, the amplitude of the S wave phase on the vertical component was smaller than on the horizontal ones. The methods used to determine the splitting parameters, which are the polarization direction of the S_{fast} wave, the time delay between the two split shear waves and the source polarization direction, are the polarigram and the hodogram. The S_{fast} polarization directions of the fast shear wave vary between N81° and N129°. The coherence of the fast shear wave polarizations, irrespective of the azimuth of each event, is consistent with shear-wave splitting due to seismic wave propagation through an anisotropic medium. These observations are consistent with the general NNE-SSW direction of extension in the Gulf of Corinth and, therefore, in agreement with the extensive dilatancy anisotropy (EDA) model. Time delays are sensitive to small changes in microcrack geometry, since changes in shear wave splitting monitor the small-scale stress-induced deformation of micro-cracks throughout the rock mass before a level of microcracking known as fracture criticality is reached when rocks are expected to fracture. Temporal variations in shear-wave time-delays have been observed before several earthquakes worldwide. The obtained values of time delays vary between 0.020sec and 0.090sec. Nevertheless, a decrease of the time delay values was observed after the occurrence of the first moderate earthquake, implying changes of the medium's properties.

Seismicity of Greece



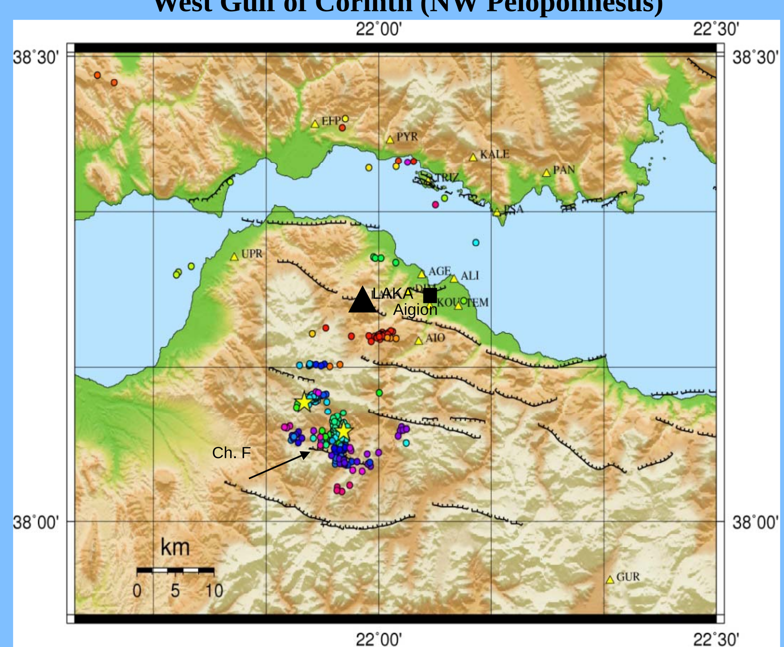
Gulf of Corinth



The Gulf of Corinth is one of the most active tectonic rifts around the world. The high level of seismicity, the quaternary local faulting and the 10 to 15 mm/year approximately N-S extension rate, imply that the Gulf of Corinth is a key place in Europe for the study of various physical processes related to the origin of earthquakes. Several strong historical earthquakes have destroyed cities in the Gulf, such as Heliki in 373 BC. Since 1911, the instrumental seismicity in the Gulf of Corinth is also intense (Makropoulos and Burton, 1981; Ambraseys & Jackson 1990) and includes several large events with M>6 from 1928 (Corinth, Ms 6.3) until 1995 (Aigion, Ms 6.2). In NW Peloponnesus, in the area between the Corinth Rift and Zakynthos island, there is a transition zone characterized by dextral strike-slip faulting.

Four months before the occurrence of the Mw=6.4 Andravida earthquake (Ganas et al., 2009), on 4 February 2008, a seismic swarm, which could influence the physical properties of the medium in the broader area, burst about 40km NE of the epicenter of this event. It included two moderate-sized earthquakes ~M4.6. A known normal fault in the vicinity of the epicentral area is the Chalandritsa fault (Ch. F.), with an approximate E-W strike. It is interesting that the calculated focal mechanisms of the two main events of this swarm reveal dominant strike-slip (Kapetanidis et al., 2008). This is not in agreement with the well-known normal faults of the area which have a dominant E-W strike, thus it is an interesting case of transition between normal and strike-slip faults.

West Gulf of Corinth (NW Peloponnesus)



LAKA Station – Anisotropy Study

LAKA station is located on the south coast of the Gulf of Corinth, west of the city of Aigion. This station belongs to the ATHENET network, which is the permanent network of the Seismological Laboratory of the University of Athens and part of the Hellenic Unified Seismological Network. The relatively small epicentral distance of this station from the February 4th 2008 seismic swarm permits the detection of many microearthquakes.

The shear-wave splitting phenomenon has been observed during the analysis of this data set. The selected events have clear and impulsive S wave arrival phases on the horizontal components. In addition, the amplitude of the S wave phase on the vertical component is smaller than on the horizontal ones. A visual inspection and a plot of the particle motion in the three planes of projection were used to select the events that match the criteria mentioned above.

The representations used in the present study in order to determine the polarization direction of the S_{fast} wave and the time delay between the two split shear waves are the polarigram (Bernard and Zollo, 1989) and the hodogram.

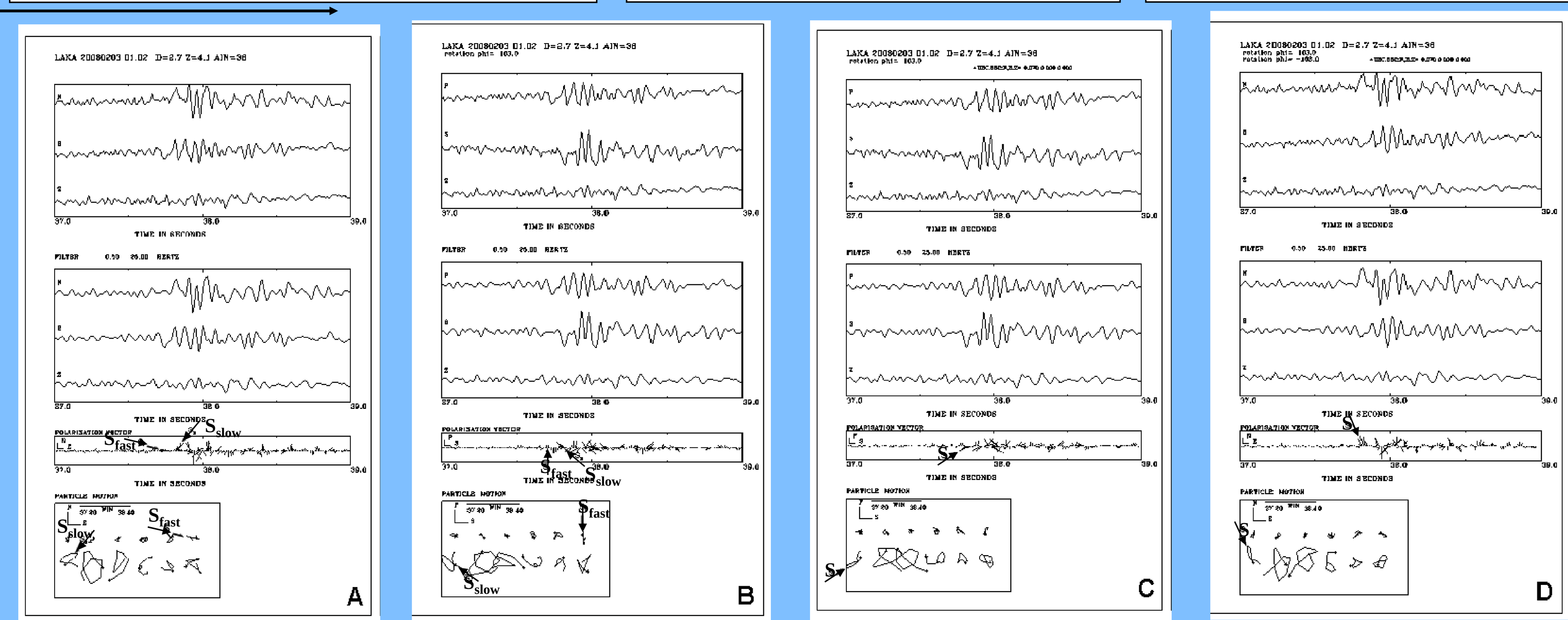
An example of an event that is located close to the LAKA station and fulfils the selection criteria is presented in Figure A. A band-pass filter in the frequency range 0.5-25 Hz was used. The event occurred on 3/2/2008 01:02 GMT, with an azimuth equal to 206° and an angle of incidence equal to 38°, within the shear-wave window.

Both the polarigram and the hodogram of the N-E plane are presented, where shear-wave splitting is evident. The angle between the north and the fast axis (S_{fast}) is the polarization direction, which is equal to N103°.

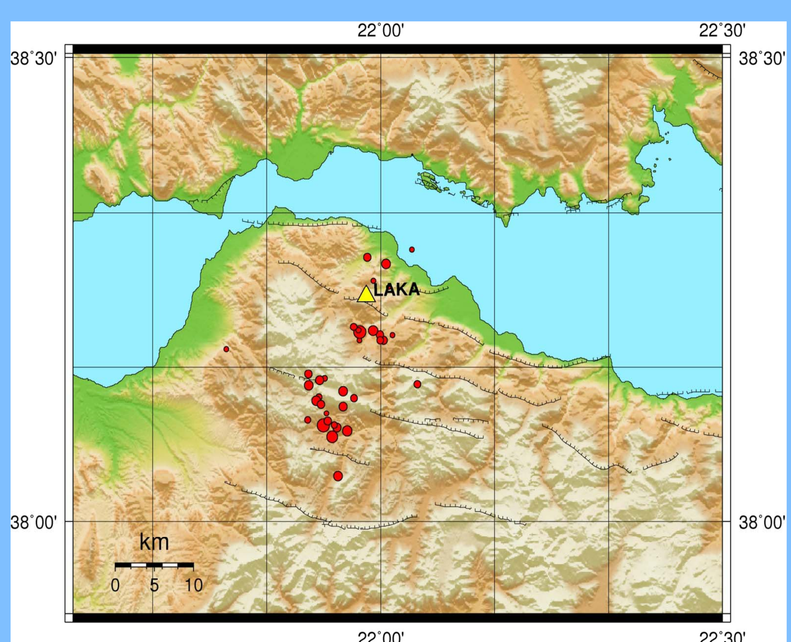
Then, the seismograms are rotated in the fast and slow direction and the obtained polarigram and hodogram are presented in Figure B. In this figure, the obtained polarization vector is oriented almost parallel to the fast component. The measured time delay is equal to 0.070s, represents the magnitude of the anisotropy and is removed in order to obtain the polarization direction of the source.

To measure the polarization direction of the source, the fast component is temporally moved towards the slow one for an interval of time equal to the time delay (0.070 sec) and the obtained waveforms (recorded and filtered) are presented in Figure C. The obtained polarization angle is 57° from the fast axis (F57°). The polarization direction of the source is the sum of this angle and of the polarization direction (N103°) and is equal to N160°.

Following, in Figure D, the horizontal components are rerotated to their initial directions (E-W, N-S, angle of rotation -103°). The obtained waveforms are theoretically those that would be recorded in the case that the medium between the hypocenter and the station (LAKA) was not anisotropic. The polarization direction of the source is directly measured and is found equal to N160°.



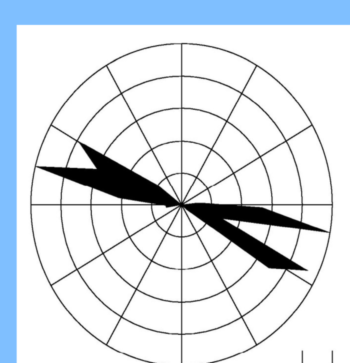
Results of the Anisotropy Study



The polarization directions of the fast shear wave are presented on equal-area projections of the upper hemisphere. The outer circle defines the shear wave window and represents an angle of incidence equal to 45°. The length of the bars is proportional to the time delay between the fast and slow shear waves. The values of the time delays at LAKA station vary between 0.020s and 0.090s, while the S_{fast} polarization directions of the fast shear wave vary between N81° and N129°. The coherence of the fast shear wave polarizations at LAKA station, irrespective of the azimuth of each event, is consistent with shear-wave splitting due to the seismic wave propagation through an anisotropic medium.

During the analysis of the events of the 4 February 2008 sequence in NW Peloponnesus that were recorded by the LAKA station, 36 were selected for the anisotropy study. The angles of incidence of the selected events vary between 14° and 44°. The back azimuth range of the selected epicenters is quite satisfactory, varying between 2° and 318° with two gaps, the first between 64° and 142° and the second between 251° and 318°. Furthermore, the back-azimuths of the 83% of the selected events vary between 142° and 232°.

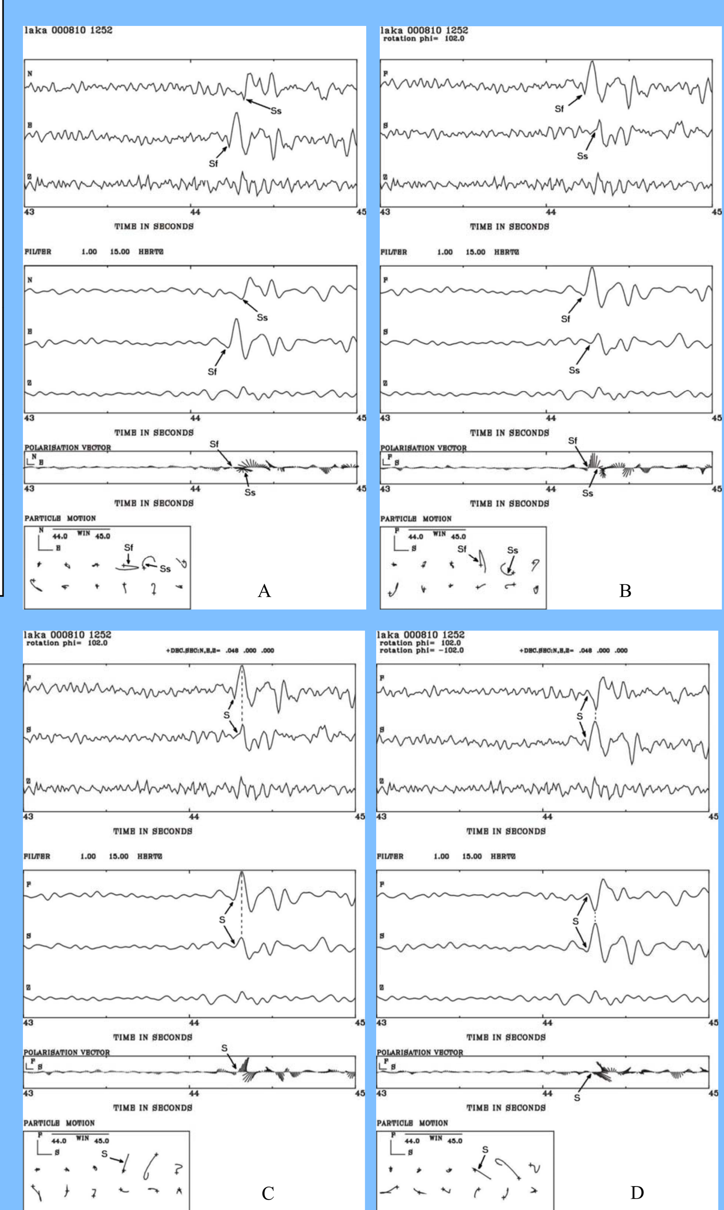
The rose diagram of the S_{fast} polarization directions for all the selected events at LAKA station is presented. Two main S_{fast} polarization directions of about N100° and N120° are observed, with a mean value equal to N110° ±2°.

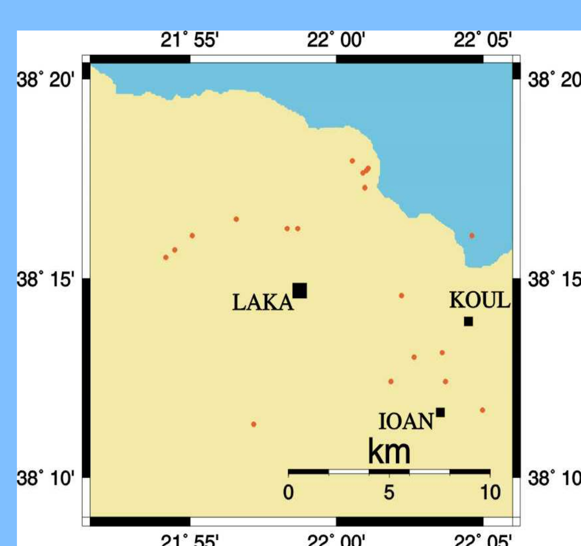


LAKA Station – Previous Study

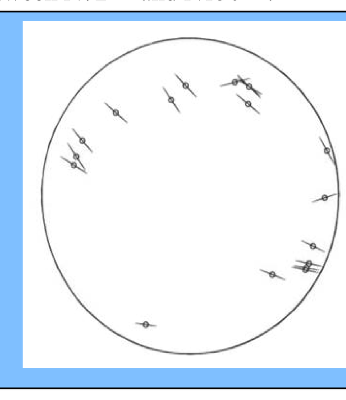
It is worth noticing that a previous anisotropy study was also performed for the LAKA station during the year 2000 (Kaviris et al., 2008). The smallest angle of incidence of the selected events that were processed was ih=31°, while a lack of epicenters was observed for the azimuthal range 140° -270° within which only one selected event was located.

The polarigram and the hodogram representation were also used for an event recorded by the LAKA station, where a band-pass filter in the frequency range 1-15 Hz was used. This local earthquake took place on 10/8/2000 12:52 GMT, with a backazimuth equal to 118° and an angle of incidence equal to 35°, within the shear-wave window. The S_{fast} polarization direction was N102° (Fig. A) and the time delay was found equal to 0.048s (Fig. B). After correcting the time delay (Fig. C), the seismograms are rotated to the original directions and the polarization of the source is equal to N120° (Fig. D).



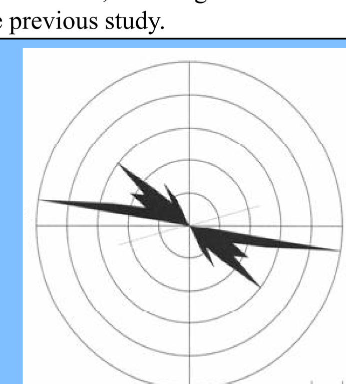


The S_{fast} polarization directions for the selected events regarding LAKA station are presented using equal-area projections of the upper hemisphere. The values of the time delays for the year 2000 varied between 0.024sec and 0.104sec, while the polarization directions of the fast shear wave between N72° and N150°.



The rose diagram for all the selected events at the LAKA station (previous study, 2000) are also presented. The main S_{fast} polarization direction was N123°, while a secondary one equal to N100° was also observed.

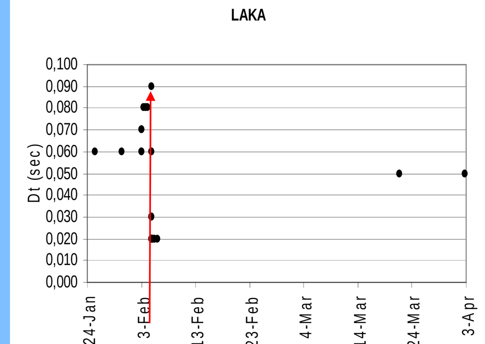
It is obvious that in both studies similar main polarization directions are obtained, with higher variation in the previous study.



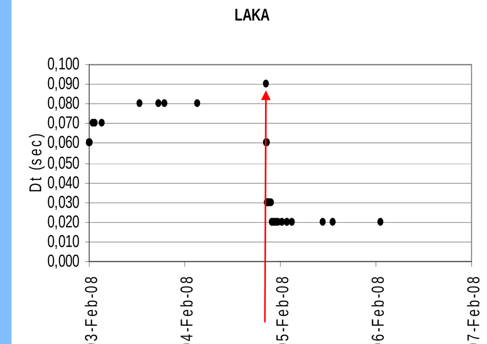
Temporal Variation of time delay

One of the splitting parameters measured in the present study is the time delay between the two split shear waves. Time delays are sensitive to small changes in microcrack geometry, since changes in shear wave splitting monitor the small-scale stress-induced deformation of microcracks throughout the rock mass before a level of microcracking known as fracture criticality is reached when rocks are expected to fracture . Temporal variations in shear-wave time-delays have been observed before several earthquakes with magnitudes M 1.7 to M 7.7 (Crampin and Peacock, 2008). These observations have been performed in different regions, worldwide, such as Iceland, China, U.S.A. and Taiwan. Whenever there are adequate data, these characteristic patterns of temporal variation are seen before all larger earthquakes and earthquakes can be stress-forecasted (Crampin et al., 1999). A necessary condition for fracturing is that cracks are so closely-spaced that shear-strength is lost and rocks fracture whenever there is any disturbance.

As it is already mentioned in the previous section, the obtained values of the time delays at LAKA station vary between 0.020sec and 0.090sec. The first major event of February 4th 2008 occurred at 20:25GMT. It is important to notice that the time delays before the occurrence of this shock vary between 0.060 and 0.090 sec, while afterwards between 0.020 and 0.060 sec (Figs. A, B). This decrease clearly indicates a change of the medium's properties after the occurrence of the first major event. Various anisotropy studies are performed in Greece, but this is the first time that temporal variation of the time delay is observed before the occurrence of an earthquake.



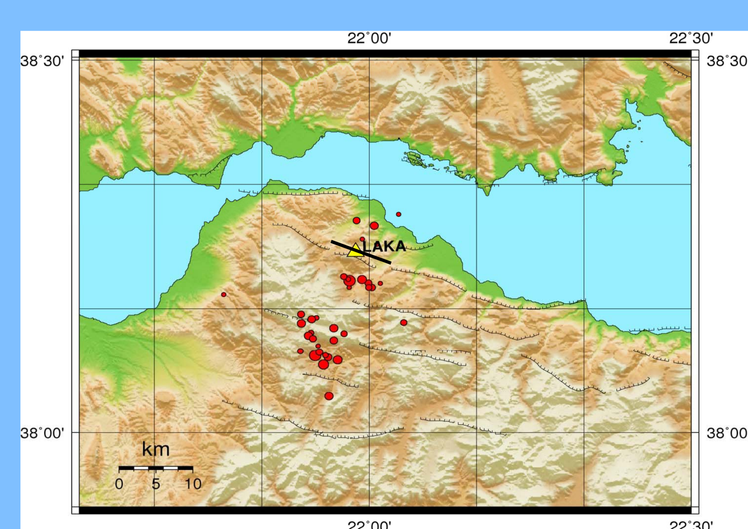
(A) 25 January to 2 April 2008



(B) 3 to 6 February 2008

The arrows indicate the time of the first major event.

Conclusions



Conclusions

On 4 February 2008, two moderate earthquakes ~M4.6 triggered a seismic swarm in NW Peloponnesus. Analysis of the data revealed the existence of an anisotropic upper crust around LAKA station and an anisotropy study was performed. Using the appropriate selection criteria, a dataset comprising of 36 events was obtained. Scattered and converted phases that could lead to false identification of the split shear waves were identified and rejected.

Almost linear polarization was observed, with a mean direction equal to N110°. The uniformity of the fast shear wave polarizations, irrespective of the azimuth of each event, is consistent with what is expected for shear-wave splitting due to propagation through an anisotropic medium. These observations are consistent with the general NNE-SSW direction of extension in the Gulf of Corinth and, therefore, in agreement with the extensive dilatancy anisotropy (EDA) model.

Finally, it is worth mentioning that an important reduction of time delay values was observed immediately after the occurrence of the first major event, implying changes of the medium's properties.

Acknowledgements

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