An Overview of Anisotropy Studies in Central Greece using recordings around the Gulf of Corinth (Greece) and aftershocks of the 1999 Athens Earthquake

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Introduction

The Gulf of Corinth is considered as one of the most active tectonic rifts around the world. The high level of seismicity (Makropoulos and Burton, 1984; Ambraseys and Jackson, 1990), the quaternary local faulting and the 10 to 15 mm/year approximately N-S extension rate (Figure 1), 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. Seismological and tectonic studies indicate that the morphology of the Gulf of Corinth is mainly due to repeated earthquakes that have occurred on 40° to 60° north-dipping normal faults. The Gulf is characterized by the long term subsidence of the northern coast and upward displacement of the main footwalls. Several large historical earthquakes have destroyed cities in the Gulf, the most well-known of which is the Heliki earthquake of 373 BC, but only few of them have provided information about the faults that produced them. Recent large events are characterized by normal faulting with an approximately E-W direction, while their focal depths are about 10 km.

In the framework of the present study, analysis of data recorded by the Cornet network and by a temporary seismological network installed in the western part of the Gulf of Corinth revealed the existence of an anisotropic upper crust around both parts of the Gulf. Furthermore, shear wave splitting analysis was performed in the region of Attica using aftershocks of the 1999 Athens earthquake (Mw=6.0) that caused 143 fatalities. The methods used in all the above mentioned regions for the determination of the splitting parameters are the polarigram and the hodogram. For each selected event the direction of polarization of the fast shear wave, the time delay between the two split shear waves and the polarization direction of the source were measured.

Cornet Network – Method used

The Cornet (Figure 2) seismological permanent network (Kaviris et al., 2007) has been installed since 1995 around the eastern Gulf of Corinth (Greece). The shear-wave splitting phenomenon has been observed during the analysis of the Cornet 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.
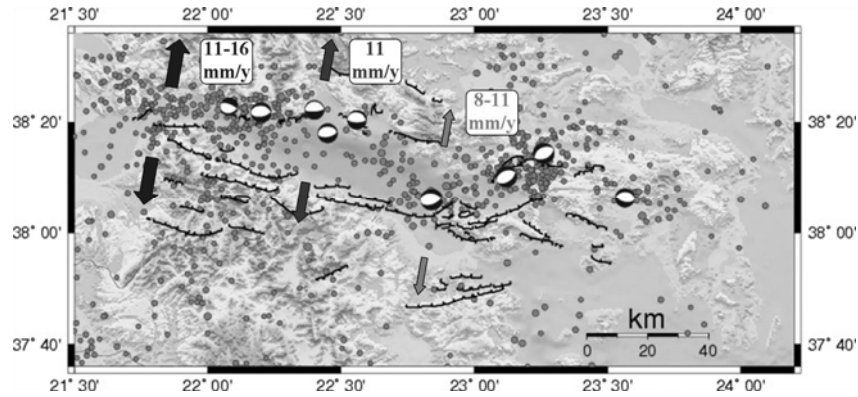

Figure 1. Active normal faults of the area and epicenters located by the Cornet network. The arrows present the extension of the Gulf of Corinth. Focal mechanisms of large events are also presented.
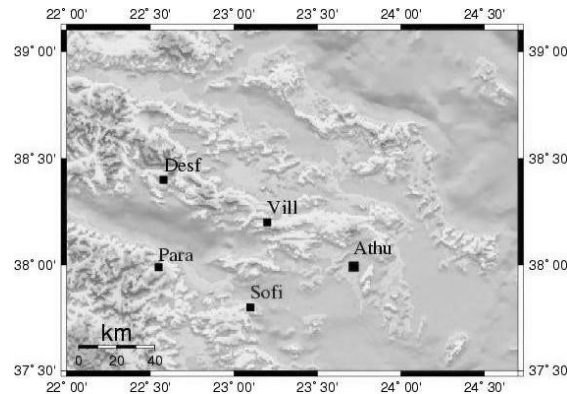

Figure 2. The permanent Cornet Telemetric Network.

An example of an event located close to the Sofiko station is presented (Figure 3a), where the polarigrams in the E-Z and N-Z planes are plotted. The polarization vector is oriented almost parallel to the horizontal component, showing that the vertical component has smaller amplitudes than the horizontal ones. This fact indicates that the shear waves are propagating approximately vertically through the anisotropic media. In the same figure, the polarigram of the N-E plane is also presented, where shear-wave splitting is evident. The angle between the north and the fast axis is the polarization direction, which is equal to N120°. Then the seismograms are rotated in the fast and slow directions and the obtained polarigram is presented in Figure 3 (b). In this figure the obtained polarization vector is oriented almost parallel to the fast component. The measured time delay is equal to 0.040 sec, represents the magnitude of anisotropy and is removed in order to obtain the polarization direction of the source.

To measure the polarization of the source, the fast component is temporally moved towards the slow one for an interval of time equal to the time delay (0.040 sec) and the obtained waveforms are presented in Figure 4 (a). The obtained polarization angle is F5°. The polarization direction of the source is the sum of this angle and of the polarization direction (N120°) and is equal to N125°. Following (Figure 4(b)), the horizontal components are rerotated to their initial directions (E-W, N-S, angle of rotation -120°). The obtained waveforms

are theoretically those that would be recorded in the case that the medium between the hypocenter and the station (Sofi) was not anisotropic. The polarization direction of the source is directly measured and is found equal to N125°.

Results of the Anisotropy Study - Cornet Network

The S_{fast} polarization directions for each Cornet station are presented on equal-area projections of the upper hemisphere in Figure 5. The outer circle defines the S-wave window and represents an angle of incidence of 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 for the 75 events analyzed at Sofiko station vary between 0.024sec and 0.160sec, while the polarization directions of the fast shear wave vary between N78° and N126°. The coherence of the fast shear wave polarizations at Sofiko station, irrespective of the azimuth of each event, is consistent with shear-wave splitting due to the seismic wave propagation through an anisotropic medium. The same observation is evident for the Paradeisi and Villia stations. The values of the time delays at Paradeisi station, where 47 events were analyzed, vary between 0.024sec and 0.128sec, while at Villia station (57 analyzed events) between 0.040sec and 0.184sec. The polarization directions of the fast shear wave at Paradeisi station vary between N125° and N165°, while at Villia station between N125° and N163°. For Desfina station the 101 events that were analyzed present more complicated results as the shear wave polarizations present two different and quasi-perpendicular main directions. The values of the time delays at Desfina station vary between 0.016sec and 0.096sec, while the polarization directions of the fast shear wave vary between N16° and N160°. Comparing the calculated time delays, we observe that they have higher values in the stations situated in the eastern part of the Gulf (Sofiko and Villia).
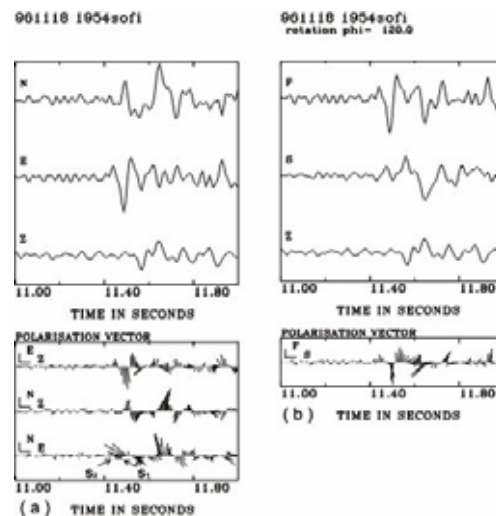

Figure 3. (a) Earthquake recorded at Sofiko station. Original traces are presented at the top. At the bottom the polarization vector is presented in the E–Z, N-Z and N–E planes. In the north-east plane the polarization directions of the fast (S_1) and the slow (S_2) shear waves are indicated. (b) Seismograms are rotated parallel and orthogonal to the polarization direction of the fast shear waves and the waveforms are presented at the top. At the bottom the polarization vector is presented in the fast-slow plane where the time delay is measured.

The S_{fast} polarization directions at each Cornet station are presented in Figure 6 using equal-area rose diagrams. The mean direction at Sofiko station is N106⁰ ± 13⁰. At Paradeisi station we observe two directions of anisotropy with a mean value equal to N142 ⁰ ± 13°, while at Villia station there are three directions with a mean value equal to N142° ± 10°. Finally, at Desfina station various directions of anisotropy are observed (Papadimitriou et al., 1999). However, two main directions are distinguished, approximately N55° and N143°.
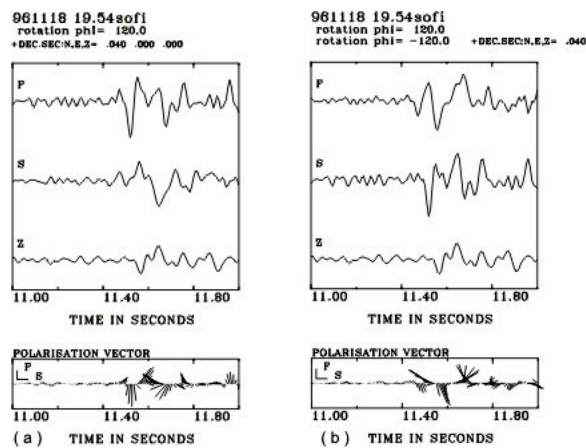
Figure 4. (a) Measurement of the time delay for the event presented in Figure 3. (b) Measurement of the polarization direction of the source on waveforms rerotated in the initial direction after time correction.
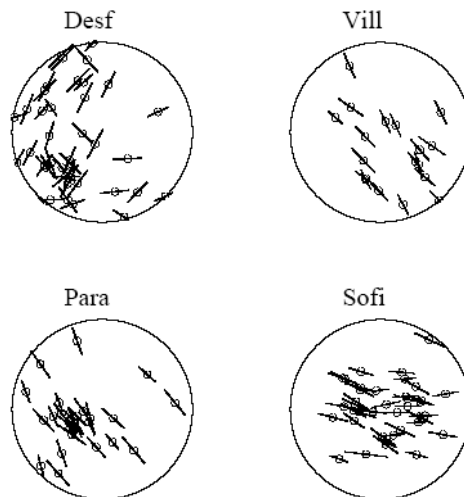

Figure 5. Polar equal-area projections on the upper hemisphere of the fast shear wave polarizations measured at each Cornet station.
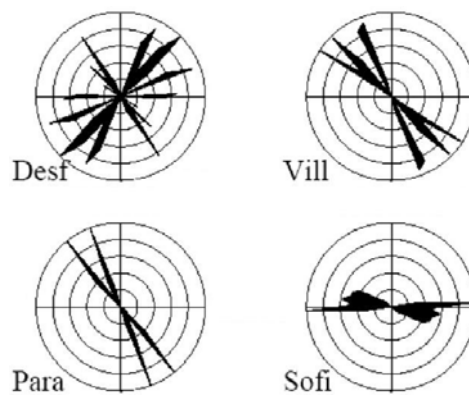

Figure 6. Rose diagrams of the fast shear wave polarization directions at all Cornet stations.

Results of the Anisotropy Study - CORSEIS Network

The CORSEIS seismological network (Figure 7) that consists of nine seismological stations has been installed at the western part of the Corinth Gulf, around the city of Aigion, and at the northern coast of the Gulf, around the Trizonia islands, on April 2000.

The seismological station Psar is located on the south edge of the Psaromita peninsula (northern part of the Gulf of Corinth). The azimuthal distribution of the events that were selected for the anisotropy study is very satisfactory.

An event is analyzed (Figure 8) using the polarigram, as well as the hodogram representation. The linearity of the particle motion is clear, as well as its deviation caused by the arrival of the slow shear wave. The measured S_{fast} polarization direction of this event is equal to N105° (Fig. 8a). The time delay, measured after rotating the waveforms to the S_{fast} polarization direction, is equal to 0.056s (Fig. 8b). The polarization of the source is measured after the correction of the time delay (Fig. 8c) and is equal to N130° (Fig. 8d).
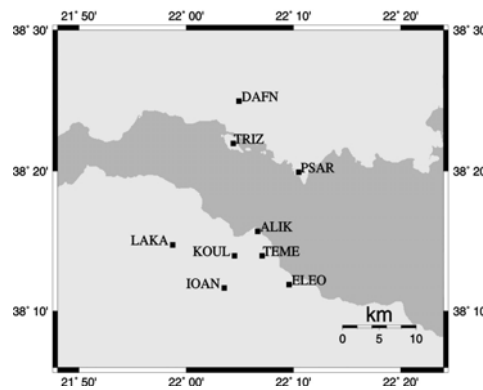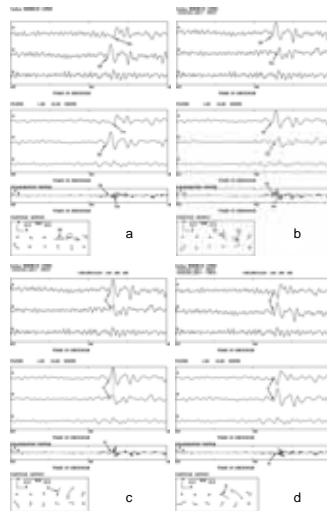

Figure 7. The CORSEIS Seismological network.

Figure 8. (a) Original traces of an earthquake recorded at Psar station, filtered traces, polarigram and hodogram in the N-E plane. (b) Traces rotated parallel and orthogonal to the polarization direction of the fast shear waves, filtered waveforms of the rotated traces, polarization vector and hodogram in the fast-slow plane. (c) Traces rotated parallel and orthogonal to the polarization direction of the fast shear waves after the correction of the time delay, filtered waveforms, polarigram and hodogram. (d) Traces rerotated to the North and East directions, filtered waveforms of the rerotated traces, polarization vector and hodogram.

Anisotropy study was performed on 5 stations of the CORSEIS Network, 3 of which are located on the northern part of the Gulf (Dafn, Psar and Triz), while 2 on the southern part (Alik and Laka).

Figure 9 presents the S_{fast} polarization directions on equal-area projections of the upper hemisphere for the CORSEIS stations. The values of the time delays at Dafnochori station vary between 0.016sec and 0.120sec, while the polarization directions of the fast shear wave vary between N57° and N113°. The polarization directions of the fast shear wave at Trizonia station vary between N88° and N138° whereas, the time delays range between 0.016sec and 0.128sec. The values of the time delays at Psaromita station vary between 0.016sec and 0.128sec, while the polarization directions of the fast shear wave vary between N78° and N140°. Concerning Laka station, the values of the time delays vary between 0.024sec and 0.104sec, while the S_{fast} polarization directions vary between N72° and N150°. Finally, the values of the time delays at Aliki station vary between 0.032sec and 0.128sec, with their majority between 0.064sec and 0.096sec. This station presents the highest time delay values. A possible explanation is that Aliki is the only CORSEIS station that is situated on sediments, while the others are situated on rock. Anisotropy directions for Aliki station vary between N75° and N130°.
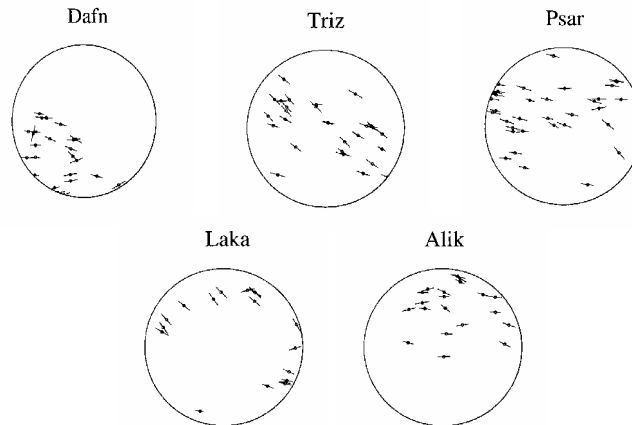

Figure 9. Polar equal-area projections on the upper hemisphere of the fast shear wave polarizations measured at CORSEIS stations.

Rose diagrams for the CORSEIS stations are presented in Figure 10. Concerning the Dafnochori station, the main S_{fast} polarization direction is N93°, while a secondary one equal to N110° is also observed. The rose diagram for Trizonia station reveals that the main S_{fast} polarization direction is about N130°, while a secondary one equal to N110° is also observed. The main S_{fast} polarization direction for Psaromita station is N105°, which is the best defined for all the stations used in the anisotropy study for CORSEIS network, since no secondary direction is observed. For Laka station the main S_{fast} polarization direction is N123°, while a secondary one equal to N100° is also observed. Finally, the main S_{fast} polarization direction for Aliki station is N90°, with a secondary one equal to N110°.
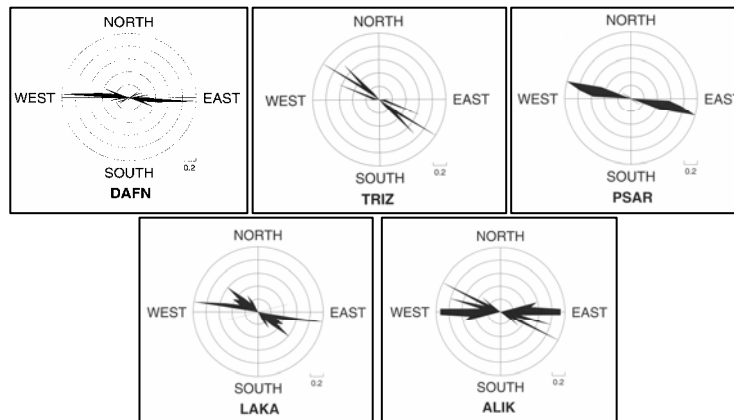
Figure 10. Rose diagrams of the fast shear wave polarization directions at CORSEIS stations.

Results of the Anisotropy Study using aftershocks of the 1999 Athens Earthquake

On 7 September 1999, an earthquake (Mw=6.0) occurred northwestern of Athens, the capital of Greece (Papadimitriou et al., 2002). A temporary seismological network (Figure 11) was installed in Western Attica, very close to the main fault one day after the main shock and a large number of aftershocks were recorded. During the analysis of these aftershocks the existence of shear-wave splitting was revealed.

An example of an earthquake recorded by the Zofr station is presented using the polarigram representation in the three planes of projection (Fig. 12a). Inspecting the projection on the E-Z and the N-Z planes, it is evident that the direction of polarization is almost parallel to the horizontal component. The polarigram on the N-E plane reveals that the motion of the fast shear-wave is linear with a polarization direction equal to N113°. The original waveforms are rotated to the fast and slow direction to measure the time delay (Fig. 12b). The polarization vector of the fast shear wave is oriented almost parallel to the fast direction, which means that the measurement of this direction is correctly performed. The time interval between the two shear wave arrivals is the time delay, which is equal to 0.030 sec. The measured time delay is then corrected and the seismograms are rerotated to their original directions. The obtained polarisation vector, which is equal to N317°, is the polarization of the source.
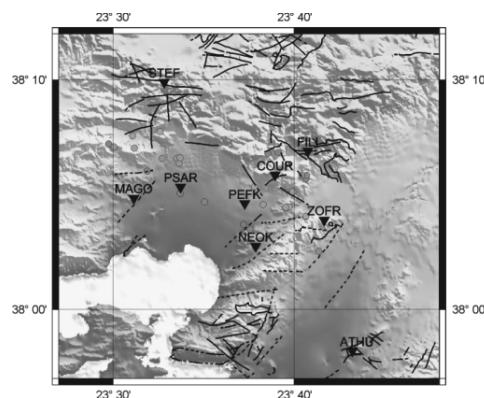

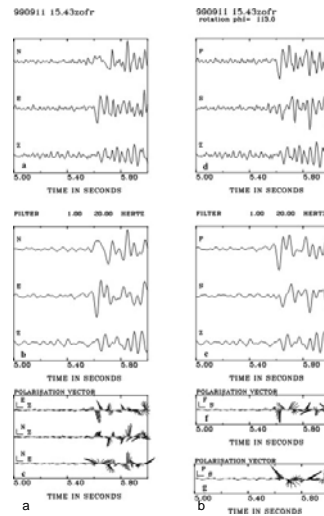Figure 11. Seismological Network in Western Attica.

Figure 12. (a) Original traces of an event recorded at Zofr station, filtered traces, polarigrams in the three planes of projection. (b) Traces rotated parallel and orthogonal to the polarization direction of the fast shear waves, filtered waveforms of the rotated traces, polarization vector in the fast-slow plane and polarigram from which the polarization of the source is estimated.

The polarization directions of the analyzed events are presented using equal-area rose diagrams (Figure 13). The S_{fast} polarization directions for the Neok station vary between N78° and N114°, while the time delays vary between 0.025 sec and 0.060 sec. The polarization directions of the fast shear wave for the Mago station vary between N77° and N113°, while the time delays between 0.055 sec and 0.060 sec. The time delays of the Fili station vary between 0.025 sec and 0.075 sec and the polarization directions of the fast shear wave between N85° and N113°. The values of the S_{fast} polarization directions for the Psar station vary between N80° and N114°, while the time delays between 0.025 sec and 0.100 sec. Finally, the polarization directions of the fast shear wave for the Zofr station vary between N74° and N113°, while the time delays between 0.030 sec and 0.085 sec.

Discussion

Analysis of the data revealed the existence of an anisotropic upper crust around the Gulf of Corinth. The large number of events that were processed ensures the detailed study of anisotropy, as well as the validity of the conclusions. Using the appropriate selection criteria, a dataset of events was winnowed. For instance, scattered and converted phases that could lead to false identification of the split shear waves were identified and rejected.
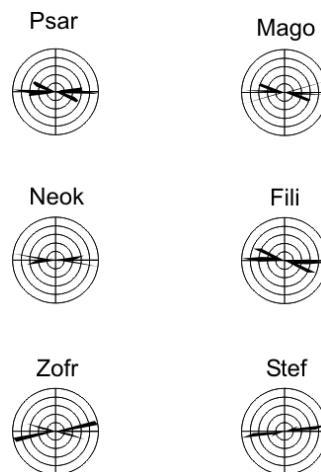

Figure 13. Rose diagrams of the fast shear wave polarization directions.

All Cornet stations presented almost linear polarization with mean values of anisotropy (Fig. 14a) N106° (Sofi), N142° (Para), N142° (Desf, main direction) and N142° (Vill). Mean polarization directions at Para, Desf and Vill stations coincide, while the mean polarization direction at Sofi station is closer to E-W. Mean values of the anisotropy direction of the CORSEIS stations vary between N90° and N120° and are presented in Figure 14b.

The uniformity of the fast shear wave polarizations at each station around the Gulf of Corinth (Cornet and CORSEIS networks), 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 and, therefore, in agreement with the extensive dilatancy anisotropy (EDA) model.
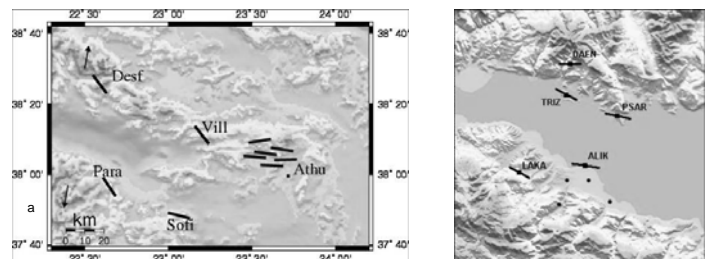

Figure 14. Mean S_{fast} polarization directions for (a) Cornet Network and temporary network installed in Western Attica and (b) CORSEIS Network.

An anisotropy study was also performed at Western Attica using aftershocks of the 7th September 1999 Athens earthquake. Mean anisotropy directions (Fig. 14a) at all stations are almost parallel, varying between N87° and N99°. The only exception was the mean direction calculated at Stef station (N81°). Mean directions are almost parallel to the azimuth of the main fault. The observed anisotropy is in agreement with the stress field of Western Attica and can be explained by the extensive dilatancy anisotropy (EDA) model.

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