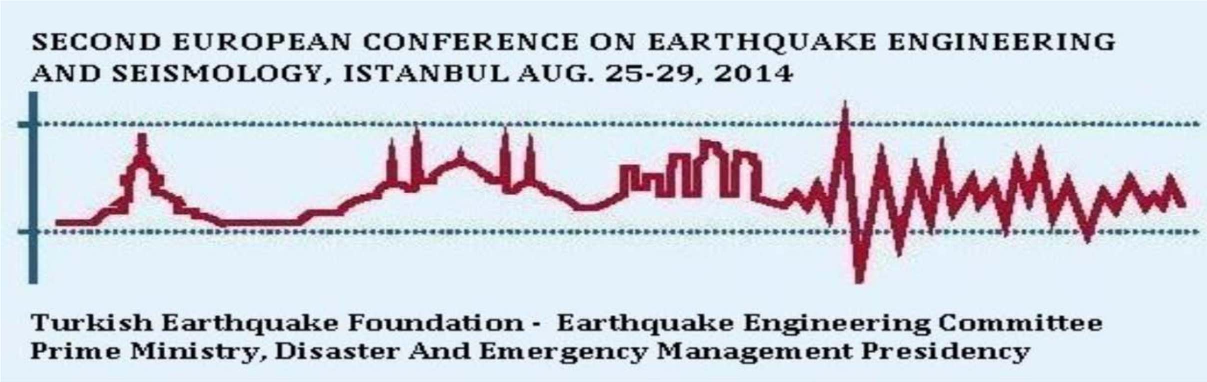

ANISOTROPY STUDY IN VILLIA (E. CORINTH GULF, GREECE)

George KAVIRIS[1], Vasilis KAPETANIDIS[2], Phaedra KRAVVARITI[3], Andreas KARAKONSTANTIS[4], Georgios BOZIONELOS[5], Panayotis PAPADIMITRIOU[6], Nicholas VOULGARIS[7] and Kostas MAKROPOULOS[8]

ABSTRACT

The Gulf of Corinth is considered to be one of the most active tectonic rifts around the world. The high level of seismicity and the quaternary local faulting imply that it is a key place in Europe for the study of various physical processes related to the origin of earthquakes. Mean extension rates of the gulf are significantly high in a NNE-SSW direction (Billiris et al., 1991; Briole et al., 2000). The Gulf of Corinth has experienced several large earthquakes that destroyed some of the ancient cities, such as Heliki, Corinth, Delphi and Patras in historical times (Papazachos and Papazachou, 2003). Since the beginning of instrumental seismology, several earthquakes with M>6 have been located around the Gulf of Corinth (Makropoulos et al., 2012), many of which at its eastern end, close to the city of Corinth. Most focal mechanisms reveal a consistent pattern of E-W trending normal faulting (Hatzfeld et al., 2000).

The station VILL, which belongs to the Seismological Laboratory of the National and Kapodistrian University of Athens, is installed at the eastern Corinth Gulf, in the vicinity of the region where the 1981 Alkyonides earthquake sequence occurred (Jackson et al., 1982). The relatively small distance between the Alkyonides Gulf and Athens makes this area a source of seismic risk for the capital of Greece.

In June 2013, an intense seismic swarm, consisting of more than 400 events was recorded near the station VILL. More specifically, six (6) earthquakes with $3.0 \leq M_L \leq 3.5$ were located in the Porto Germeno area, approximately 8 km west of VILL station, the largest of which occurred on 11 June 2013 (M_L=3.5). In addition, an M_L=4.4 event occurred on 20 September 2013 about 16 km west of the station, which, however, was not followed by a significant aftershock sequence. The events' hypocenters were located using the HYPOINVERSE software (Klein, 1989), incorporating a custom velocity model based on a previous local model for the eastern Corinth Gulf (Kaviris et al., 2007) and manually picked P- and S-wave arrival-time data in station VILL, as well as in other regional stations.

During the analysis of the data, the existence of the shear-wave splitting phenomenon was observed, which stimulated the conduction of the present anisotropy study for VILL station. All selected events lie within the shear-wave window, having effective angles of incidence smaller than 45° to the vertical. In addition, they have clear and impulsive S wave arrival phases on the horizontal components and the amplitude of the S wave phase on the vertical component is smaller than on the

[1] Lecturer, Department of Geophysics-Geothermics, University of Athens, Greece, gkaviris@geol.uoa.gr
[2] PhD Student, Department of Geophysics-Geothermics, University of Athens, Greece, vkapetan@geol.uoa.gr
[3] Msc Student Department of Geophysics-Geothermics, University of Athens, Greece, fedra-k@hotmail.com
[4] PhD Student, Department of Geophysics-Geothermics, University of Athens, Greece, akarakon@geol.uoa.gr
5 PhD Student, Department of Geophysics-Geothermics, University of Athens, Greece,gbozionelos@geol.uoa.gr
[6] Ass. Professor, Department of Geophysics-Geothermics, University of Athens, Greece, ppapadim@geol.uoa.gr
[7] Ass. Professor, Department of Geophysics-Geothermics, University of Athens, Greece, voulgaris@geol.uoa.gr
[8] Emer. Professor, Department of Geophysics-Geothermics, University of Athens, Greece, kmacrop@geol.uoa.gr

horizontal ones. The methods used for the determination of the splitting parameters are the polarigram (Bernard and Zollo, 1989) and the hodogram. For all events that fulfilled the above-mentioned criteria, the direction of polarization of the medium was calculated, indicating a general NNW-SSE trend. Following, the waveforms were rotated to the fast and slow direction, respectively, and the time delay between the two split shear waves was measured to estimate the magnitude of anisotropy. Finally, the source polarization direction was determined, after removing the time delay. The splitting parameters results are compared to the ones obtained in the framework of a previous anisotropy study in a station located in the same area, approximately 6 km NW of VILL station (Papadimitriou et al., 1999; Kaviris et al., 2008).

In addition, a detailed analysis of the temporal evolution of both the time-delay and anisotropy direction was carried out. In the literature, precursory changes in time-delays have been observed in several cases to seismic stations with epicentral distances up to about 100 km, e.g. before an M=4.9 earthquake that occurred in 2002 offshore northern Iceland (Gao and Crampin, 2006), which makes the analysis of shear-wave splitting parameters an important tool for the assessment of seismic hazard.

INTRODUCTION

The Corinth Gulf is characterized as one of the most active (Makropoulos and Burton, 1984) and rapidly extending regions in Eastern Mediterranean area. Seismological and tectonic studies indicate that the surface morphology of the Gulf of Corinth is mainly due to repeated earthquakes that have generally occurred on 40° to 60° north-dipping normal faults in a mean strike of E-W to ENE-WNW direction. According to GPS measurements, mean extension rates of the Gulf reach 14 mm/yr in the west, 13 mm/yr in the central part and 10 mm/yr in the east, in a mean NNE-SSW direction (Billiris et al., 1991; Briole et al., 2000). These rapid rates of growth are associated with a very young phase of faulting (~ 1 Ma) cutting an older extensional basin (Armijo et al., 1996). The eastward progressive width and depth increase, which coincides with the sediment infill augmentation, suggests that the amount of extension rates across the central-eastern part of the Gulf is greater than at the western boundary (Brooks and Ferentinos, 1984). The faulting geometry at the eastern boundary of the Gulf of Corinth seems to have changed since the initiation of the rifting process.

Concerning the westernmost part of Attica, near the town of Villia, several moderate to large earthquakes have occurred during both the historical and instrumental periods (Fig. 1). In this area, the recorded seismicity is mainly located along E-W to ESE-WNW oriented basin-bounding faults, bringing in contact the Alpine basement of Mesozoic limestone of Sub-Pelagonian geotectonic unit with alluvial and colluvial deposits. The Kaparelli Fault Zone to the north is one of the most active tectonic features of the region, giving rise to an earthquake of Ms=6.4 on 4 March 1981 (Makropoulos et al., 2012). Focal mechanisms of small earthquakes (Ambraseys and Jackson, 1990; Kaviris, 2003; Papazachos and Papazachou, 2003), as well as rose-diagram projections of the local fault system (Poulimenos et al., 1989; Armijo et al., 1996; Maniatis et al., 2003), indicate normal type of rupturing with fault plane striking ESE-WNW and dipping at about 45° at the eastern end of the Gulf of Corinth, including Kaparelli and Alkyonides fault zones to the north and west of the study area respectively.

Seismic anisotropy, also called seismic birefringence, is a physical phenomenon that is widely observed in the upper crust since 1980 (Crampin et al., 1980). In the case where shear waves pass through an anisotropic medium, they split into two waves, characterized by almost orthogonal polarizations that propagate with different velocities. Various causes of anisotropy have been reported worldwide, such as crystal alignments (Ribe, 1989), lithologic anisotropy (Crampin et al., 1984), stress-induced effects (Evans, 1984), successive isotropic layers of different thickness (Helbig, 1984) and cracks or microcracks in the vicinity of local faults (Kaneshima, 1990). Nevertheless, most commonly seismic anisotropy is attributed either to the Extensive Dilatancy Anisotropy (EDA) model, related to fluid saturated stress-aligned microcracks (Crampin, 1987), or to the evolution of such microcracks under changing conditions, described by the Anisotropic Poro-Elasticity (APE) model (Crampin and Zatsepin, 1997; Zatsepin and Crampin, 1997). The EDA model satisfactory interprets the apparently stress-aligned polarizations of split shear waves typically observed along most raypaths of seismic shear waves in the Earth's crust. The basic hypothesis of the APE model is that fluid-saturated cracks in the crust are very closely spaced. As a result the cracked rocks are highly compliant critical systems with self-organised criticality.

Temporal variations of time delays between the two split shear waves are indicative of stress-aligned aspect-ratios changes. Increased normalized time delays, lasting from years to hours, indicate stress-accumulation. When deformation caused by such an accumulation in the microcracked rock mass approaches levels of fracture-criticality, time delays abruptly begin to decrease, indicating stress-relaxation (Crampin et al., 2013). Such time delays temporal variations have been monitored in many cases before earthquakes to epicentral distances up to 92 km, for the 2002 M=4.9 event offshore northern Iceland (Gao and Crampin, 2006). A characteristic example is the stress-forecast of an M=5 earthquake in Iceland (Crampin et al., 1999). Another phenomenon, which is mostly observed before volcanic eruptions, is the 90°-flips in anisotropy directions, caused by crack coalescence on impending fault-breaks that concentrates pore-fluid pressures onto fault surfaces until the intermediate horizontal tectonic stress is exceeded and earthquakes occur (Crampin et al., 2004). Such flips, attributed to the APE model, were monitored before the 2001 Mt. Etna eruption (Bianco et al., 2006).

In the framework of the present work, an anisotropy study is performed using data recorded during 2013 by a seismological station installed in the eastern part of the Gulf of Corinth (Greece). The polarigram and the hodogram representations were used to determine the polarization direction of the fast shear-wave, the time-delay between the two split shear-waves and the source polarization direction. Results are compared with the ones obtained by a previous study in the same region. Following, the temporal variation of the splitting parameters is examined to monitor possible stress changes.

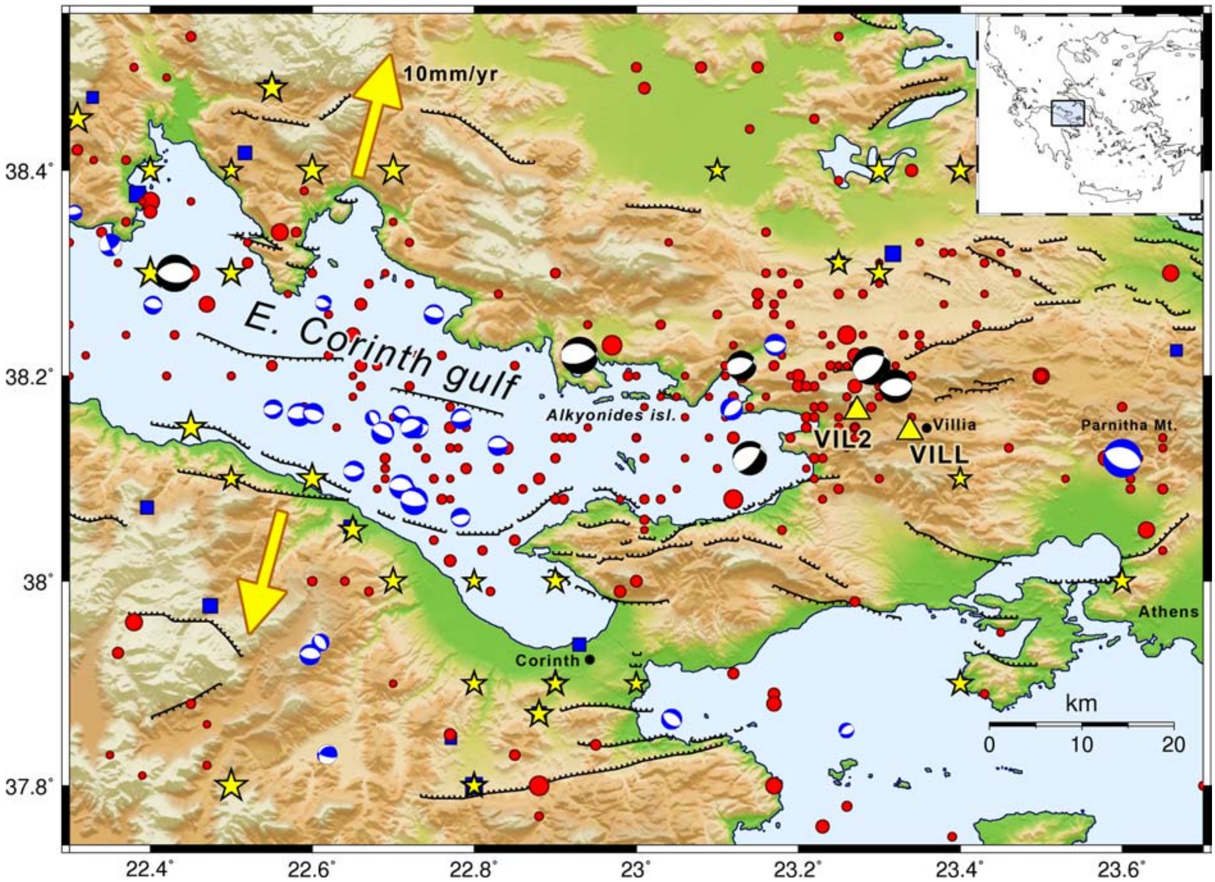

Figure 1. Epicenters of historical (stars: Papazachos and Papazachou, 2003; blue squares: Stucchi et al., 2012) and instrumental (circles: Makropoulos et al., 2012) events and active normal faults of the area. The arrows present the extension of the Gulf of Corinth (Briole et al., 2000). Focal mechanisms of large events are also presented (black: CMT, Ekström et al., 2012; blue: www.geophysics.geol.uoa.gr). The locations of the VILL and VIL2 stations are also indicated.

DATA AND METHOD

Station VILL of the Seismological Laboratory of the National and Kapodistrian University of Athens was installed on 12 October 2009 and belongs to the Hellenic Unified Seismological Network (HUSN). The catalogue data used for the present study were obtained from manually analysed events which were recorded by HUSN during 2013. However, the main focus has been set upon the seismic activity of June 2013, because of the close proximity of its hypocenters to the station VILL, which makes these events probable candidates for anisotropy analysis.

Routine manual analysis was carried out to obtain precise P- and S-wave arrival-times. A preliminary hypocenter location has been performed using the HYPOINVERSE code (Klein, 1989) and as starting 1D velocity model the one determined for the E. Corinth Gulf by Kaviris (2003). A subset of located events with spatial errors less than 2 km and RMS < 0.3 sec was used in order to investigate the average Vp/Vs ratio and the local 1D velocity structure, using the mean travel-time residuals and the location uncertainties (RMS, ERH, ERZ) minimization method (Kissling et al., 1994; Chiarabba and Frepoli, 1997). A 1D velocity model was obtained (Table 1), yielding improved hypocenter solutions for the whole dataset. Magnitudes were determined using coda duration and an empirical relation between duration and epicentral distance (Kaviris et al., 2007; Papadimitriou et al., 2010).

Table 1. 1D velocity models.

	Kaviris, 2003		**This study**	
V_p/V_s ratio	1.79		1.79	
Layer	**P-wave Velocity** (km/s)	**Ceiling Depth** (km)	**P-wave Velocity** (km/s)	**Ceiling Depth** (km)
1	4.5	0.0	4.9	0.0
2	5.5	1.3	5.8	3.2
3	5.7	4.2	6.0	7.0
4	6.1	7.0	6.3	11.0
5	6.3	11.5	7.0	24.0
6	6.5	16.5	7.9	35.0
7	7.0	30.0	8.1	65.0

The calculated median hypocentral location uncertainties, obtained by HYPOINVERSE using the optimum velocity model are ERH = 1.107 km, ERZ = 1.970 km and RMS = 0.190 sec, while the corresponding median error values using the initial, more local model were ERH = 1.127 km, ERZ = 2.190 km and RMS = 0.210 sec, respectively. The Vp/Vs is the same in both models but the one obtained in this study differs in the shallower layers and also includes a higher velocity semi-space at the depth of 65 km to account for HUSN stations in regional epicentral distances. The resulting epicenters also become more concentrated in their corresponding spatial clusters using the custom velocity model.

The present anisotropy study was performed after applying selection criteria to reect scattered and converted phases. More specifically, all chosen events are located close to the VILL station (Fig. 2), within the shear-wave window, having incident angles smaller than the critical which is taken equal to 45°. In addition, they have clear and impulsive S wave arrival phases on the horizontal components, while the amplitude of the S wave phase on the vertical component is smaller than on the horizontal ones. The shallow focal depths of the located events, relative to their corresponding epicentral distance from the station VILL, cause the effective angle of incidence for most events to be greater than 45° to the vertical, leading to their rejection.

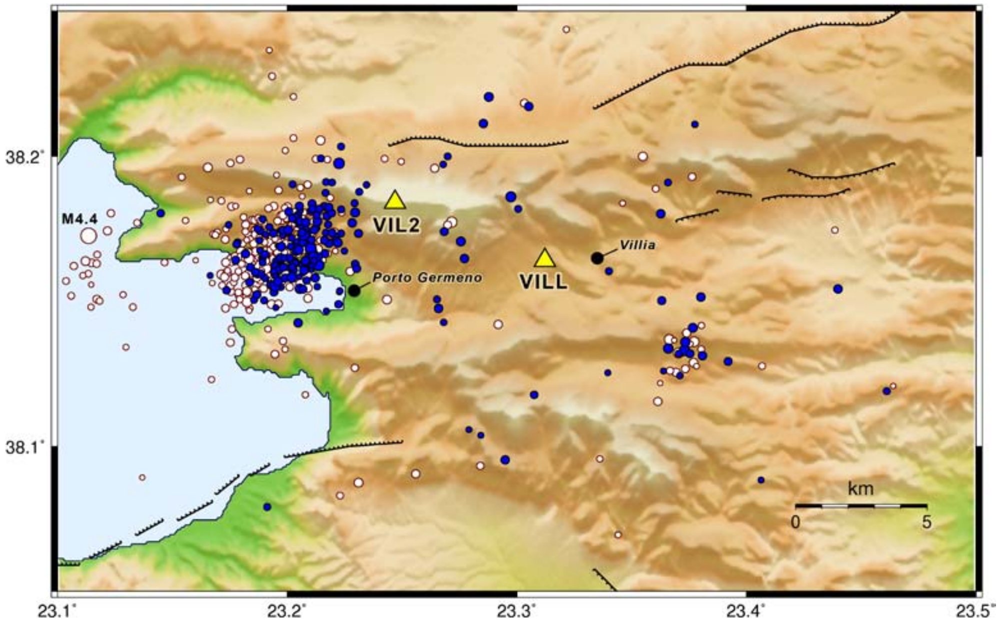

Figure 2. Epicenters of earthquakes that have occurred in the vicinity of station VILL during 2013. Events used in the framework of the anisotropy study are represented with blue colour. The location of station VIL2 is also indicated in the map. The major M_L=4.4 event which occurred on 20 September 2013 is also marked at the western part of the map.

The splitting parameters determined in the framework of the present study are the polarization direction of the fast shear wave, the time delay between the two split shear waves and the source polarization direction. Visual inspection, including both polarigrams (Bernard and Zollo, 1989) and hodograms, is applied. This procedure is time consuming but ensures the validity of the results on typical records, whereas automatic methods are usually effective for noise-free recordings. The above-mentioned representations have successfully been applied in several anisotropy studies performed in the Greek territory (Papadimitriou et al., 1999, 2010; Kaviris et al., 2008, 2010).

The applied methodology is described by presenting as an example an event that occurred on 16 June 2013, during the burst of the seismic activity in the vicinity of the VILL station. The recorded and the filtered waveforms, the polarigram and the hodogram in the N-E plane are displayed in Fig. 3a. The S_{fast} polarization direction is the angle between the north and the fast axis, being equal to N165°. Then, the seismograms of the horizontal components are rotated parallel and orthogonal to the polarization direction of the fast shear wave and are presented in Fig. 3b, along with the respective polarigram and hodogram. It is observed that both the polarization vector and the particle motion are oriented almost parallel to the fast direction, verifying the value determined during the first step. In addition, the time delay between the two split shear waves, which in the present case is 0.100 sec, is measured.

Following, the calculated time delay is removed by temporally shifting the fast component towards the slow one, according to the obtained time delay, while the corresponding angle, measured from the fast axis, is F150°. The source polarization direction, used for the determination of focal mechanisms (Musumeci et al., 2005), is the sum of the latter angle and the S_{fast} polarization direction, being equal to N135° (Fig. 3c). This value is verified by re-rotating (angle -165°) the horizontal components to their initial directions (N-S and E-W), as presented in Fig. 3d. In this case the polarization of the source can directly be measured, also N135°, given that the waveforms are theoretically those that would be recorded in the case of an isotropic medium.

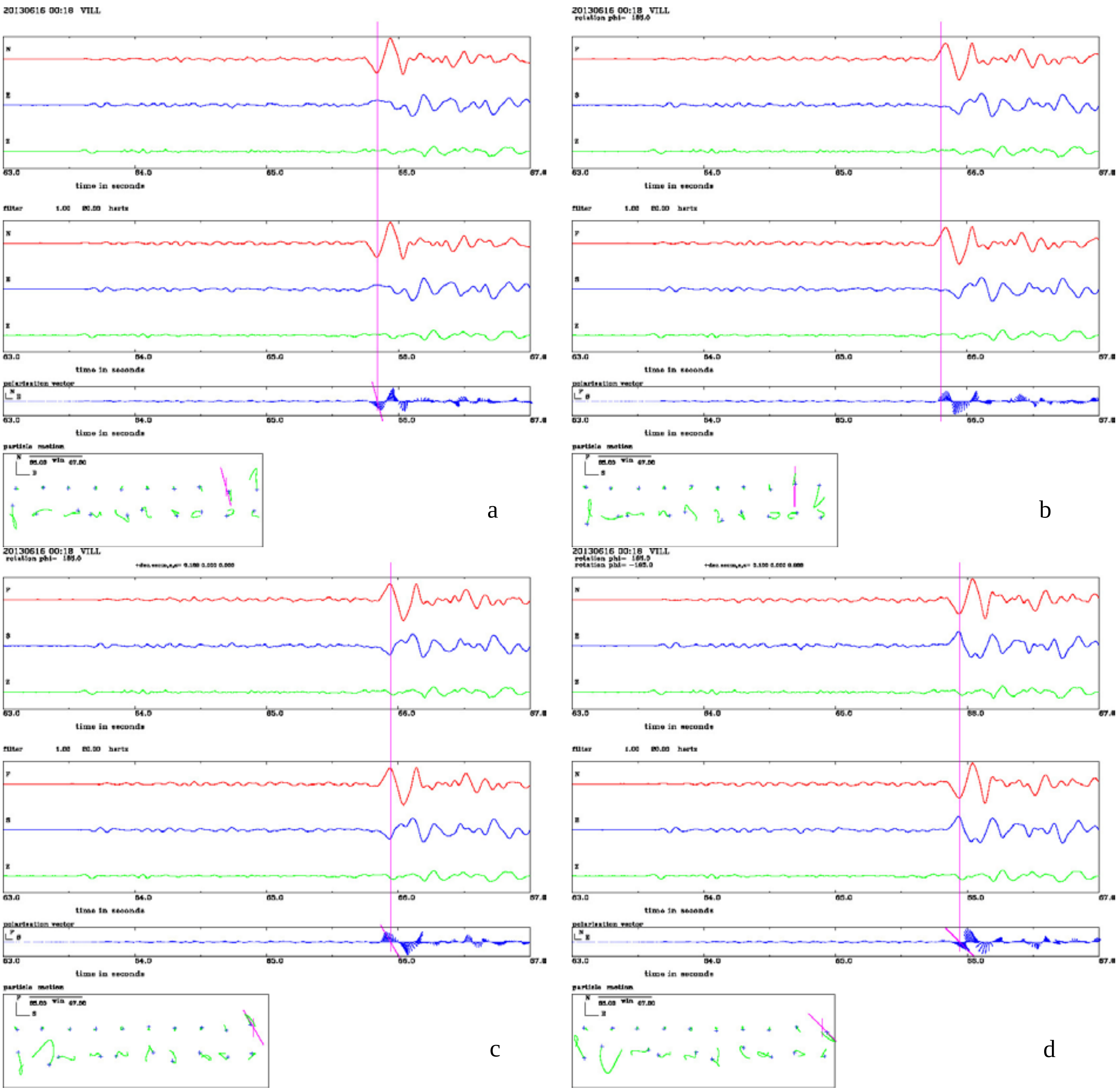

Figure 3. (a) Original traces of an earthquake recorded at VILL station, filtered traces, polarigram and hodogram in the N-E plane where. (b) Horizontal traces rotated to the fast (N165°) and slow (N75°) shear wave directions, filtered waveforms of the rotated traces, polarization vector and hodogram in the fast-slow plane. (c) Measurement of the time delay in the F-S plane. (d) Measurement of the source polarization direction on waveforms re-rotated in the initial direction after time correction.

RESULTS

ANISOTROPY RESULTS IN VILL STATION

During the analysis of the events that were recorded by the VILL station in 2013, the existence of seismic birefringence was observed. An anisotropy study was initiated, considering as candidate the events lying within the shear-wave window. The application of the selection criteria, described in the previous section, yielded a significant number of 201 events that fulfilled the selection criteria (Fig. 2). The angles of incidence of the selected events vary between 14° and 45°, while their back-azimuthal range is quite satisfactory, varying between 4° and 331°. Nevertheless, the majority of the events occurred dring the crisis of June 2013, west of VILL station, having back-azimuths between 75° and 119°.

The anisotropy direction of each event is presented on equal-area projections of the upper hemisphere (Fig. 4a). The length of each bar is proportional to the time delay between the two split shear waves, while the outer circle defines the S-wave window and represents an angle of incidence of 45°. All polarization directions of the fast shear wave are in a NNW-SSE direction, having values between N130° and N190° (N10°), with only one exception (N210° or N30°). The values of the time delays for all analyzed events present a relatively wide range, mainly varying between 0.01 and 0.13 sec, reaching quite high values. Only three exceptions were observed, one presenting no anisotropy and the other two with time delay values of 0.18 sec and 0.19 sec. The temporal variation of the splitting parameters is discussed in detail in the following section.

The S_{fast} polarization directions are presented in Fig. 4b using equal-area rose diagrams. Taking into account all analyzed events, the mean anisotropy direction in VILL station is equal to (N162 ± 12)°, while the mean time delay between the two split shear waves (0.064 ± 0.005) sec. The coherence of the fast shear wave polarizations at VILL station, irrespective of the azimuth of each event, is consistent with shear-wave splitting due to the seismic wave propagation through an anisotropic medium. These observations can be explained by the existence of stress-aligned fluid filled microcracks.

Figure 4. VILL station: (a) Polar equal-area projections on the upper hemisphere of the fast shear wave polarizations. The length of the bars is proportional to the time delay of each event and the circle represents an angle of incidence equal to 45°. (b) Rose diagram of the fast shear wave polarization directions.

PREVIOUS ANISOTROPY RESULTS IN VILLIA AREA

An anisotropy study was carried out in the same area using data of the VIL2 station that was installed in the framework of the Cornet Network, by the Seismological Laboratory of the Geophysics – Geothermics Department of the University of Athens (Papadimitriou et al., 1999; Kaviris, 2003; Kaviris et al., 2008; Papadimitriou et al., 2010). This station was located (Fig. 2) only 6 km NW of the current VILL station. The recordings that were used are microearthquakes that occurred during 1996 and 1997.

After applying all selection criteria, the anisotropy study of the VIL2 station was carried out using 57 microearthquakes (17 were recorded in 1996 and 40 in 1997), 13 of which were located using the HYPO71 program (Lee and Lahr, 1975). The remaining 44 events were recorded only by VIL2 station. The angle of incidence and azimuth for these events were estimated using both the approach proposed by (Kanasewich, 1981) for the first P-wave window and the polarization of the first P-wave motion recorded in the three components. The Kanasewich method is based on the covariance matrix decomposition where the eigenvalues were calculated by diagonalization of the matrix. By the calculation of the eigenvector that corresponds to the maximum eigenvalue, the angle of incidence and the azimuth are estimated. Nevertheless, the results are directly dependent on the selection of the P-wave window and were compared with the ones obtained by the P-wave polarization. Only events with similar results were used.

The S_{fast} polarization directions for VIL2 station are presented using equal-area projections of the upper hemisphere and rose diagrams in Fig. 5a and Fig. 5b, respectively. The coherence of the fast shear wave polarizations at VIL2 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 values of the time delays at VIL2 station vary between 0.040sec and 0.184sec, while the polarization directions of the fast shear wave between N125° and N163°. The mean anisotropy direction is equal to N142°, while the mean time delay 0.090 sec. It is worth noting that no temporal variations of the anisotropy direction and of the time delay between the two split shear waves were identified (Kaviris, 2003). These observations were interpreted with the extensive dilatancy anisotropy (EDA) model.

Figure 5. VIL2 station: (a) Polar equal-area projections on the upper hemisphere of the fast shear wave polarizations. The length of the bars is proportional to the time delay of each event and the circle represents an angle of incidence equal to 45°. (b) Rose diagram of the fast shear wave polarization directions.

TEMPORAL VARIATIONS OF SPLITTING PARAMETERS

The temporal evolution of shear-wave splitting parameters can be related to variations in the stress-field (Miller and Savage, 2001; Hiramatsu et al., 2010) which may exhibit anomalies prior to the occurrence of major earthquakes (i.e. Gao and Crampin, 2004; Crampin et al., 2008; Hiramatsu et al., 2010). In order to investigate for possible anomalies, we have considered the temporal evolution of the anisotropy direction, ϕ, and of the time-delay between fast and slow shear-waves, δt, during the study period. The direction of anisotropy at station VILL is quite temporally stable at $\phi = (162 \pm 12)°$ without any sudden or otherwise significant changes.

The time-delay, δt, has been proven in the literature (Gao and Crampin, 2006; Crampin et al., 2013) to be sensitive to changes in the aspect ratio of micro-cracks (due to stress field variations) when the seismic ray-path angle with the crack plane lies within “Band-1”, a double-leafed solid angle between 15° and 45° on both sides of the average crack plane (as defined by the mean anisotropy direction) and within the shear-wave window. The time-delay, Δt, is normalized by the hypocentral distance to account for the length that the seismic-rays have propagated. However, the mean azimuth of station VILL relative to the epicenters is such that the majority of the analyzed events lie outside “Band-1”, implying that the sensitivity of the calculated splitting parameters to stress-field variations which cause changes in the aspect ratio of micro-cracks may be low.

Nevertheless, the temporal evolution of the normalized time-delay (Fig 6b) exhibits several different characteristics. It begins with a long period of relative stability of its average value with a slow gradual decrease (January-May), which is however characterized by large standard deviation due to a few events with normalized time-delays $\Delta t > 11$ ms/km. This period is followed by a month of complex changes during the seismic crisis in Porto Germeno (June-July, Figs 6a and 6c) which is displayed in detail in Fig 6d. The activity included an M_L=3.5 event on 11 June which temporarily increased the Δt by about 3-4 ms/km before it dropped to 2 ms/km by 13 June. A short period of gradual increase followed, which culminated with the highest value in the measurements of Δt for June (12 ms/km), and a sudden decrease to ~2 ms/km by the end of 15 June, as indicated by two measurements. An M_L=3.0 event occurred the next day, increasing the Δt to a stable value of ~6 ms/km until 21 June. On 22 June there was an increase in seismic activity without any major events, which lowered the Δt abruptly to 2 ms/km. Then the average values show a gradual increase up to 24 June when another increase in seismic activity was detected, including two M_L=2.9 events. The normalized Δt values then drop to below 2 ms/km, and they are slightly raised to ~4 ms/km before a pair of M_L=3.1 and M_L=3.2 events that occurred on 25 June, which were followed by yet another decrease reaching down to a measurement of $\Delta t = 0$ by the end of the same day. The last burst of seismicity occurred on 26 June, including an M_L=3.3 event. From that point on, the measurements become sparse and the normalized Δt values exhibit a slow gradual increase between September-November. The M_L=4.4 event of 20 September and its few aftershocks are too far from station VILL to be of any use for the present study.

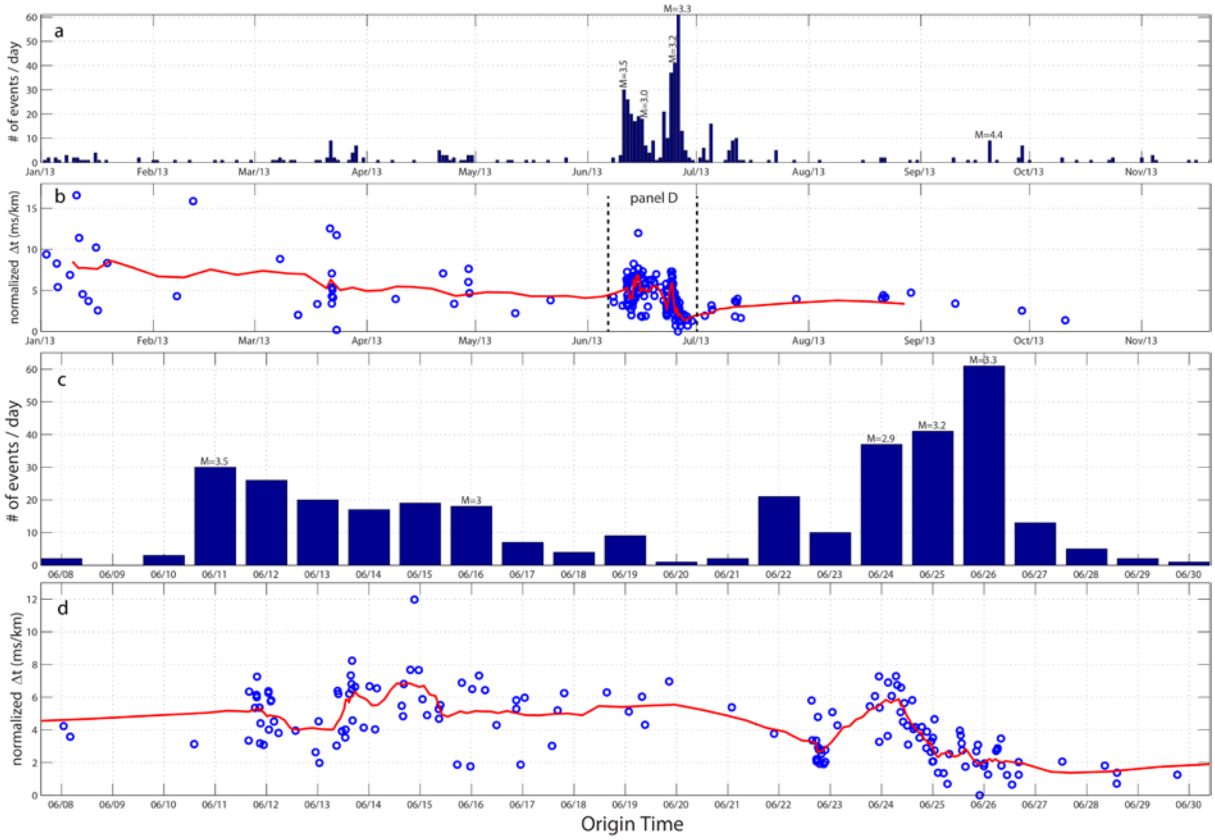

Figure 6. (a) daily earthquake occurrence for a 20 km radius around station VILL during 2013, (b) normalized time-delays (Dt) for the period of study, displayed as open circles. The red line is the 9-point average, (c) same as A but for the period between 8 and 30 June 2013, (d) same as B but for the period between 8 and 30 June 2013. The narrow time-window of panel D is also indicated in panel B.

CONCLUSIONS

Data recorded by the VILL station, installed at the eastern Corinth Gulf (Greece) during 2013 were analyzed, including a seismic swarm that occurred in June less than 10 km west of the station. The existence of seismic birefringence for the vast majority of the recorded events was evident. Strict criteria were applied for the selection of the events that were used for the anisotropy study. Visual inspection, polarigrams and hodograms were used to determine the splitting parameters. The coherent anisotropy directions that were obtained, irrespectively of the hypocentral location of each event, can be explained by the existence of fluid-filled microcracks, preferentially aligned with the current stress field.

The results of the present study were compared with those obtained for the old VIL2 station, located 6 km NW of the VILL station, using data recorded during the period 1996-1997. A difference of about 20° has been identified in the mean anisotropy direction of the two stations (Fig. 7) that can be attributed to the APE model which is related to the stress-sensitive behaviour of fluid-saturated microcracked rocks. The APE model is based on the changes occurring in the saturated cracks due to the general stress field, being able to interpret anisotropy directions that are not in agreement with the dominant stress field, as well as changes due to the local stress field.

The mean time delay value of VILL station is smaller than the one determined for VIL2. This can be attributed to the largest ray path for VIL2 of the vast majority of analyzed events which is probably due to the different elevation of the two stations. More specifically the elevation of the VILL station is 650 m, whereas of VIL2 1384 m. The temporal variation of the normalized time-delay, Δt, for station VILL during 2013 shows a gradual decrease in large-scale, interrupted by anomalies during the seismic crisis of Porto Germeno in June-July. A pattern of increasing Δt followed by an abrupt decrease has been detected prior to an M_L=3.0 event on 16 June, as well as another period of gradual increase between 22-23 June followed by a significant gradual decrease supported by a series of measurements during a second outbreak of activity at Porto Germeno between 24-25 June, reaching down to zero time-delay before 26 June, which was the most seismically active day of 2013 for the region around station VILL. It is noteworthy that such anomalies have been detected even though very few events of those used in the present study belong to "Band-1". The detected levels of Δt by the end of 2013 have been low. Further research must be carried out to investigate for future gradual increases of Δt in the area which may be followed by precursory abrupt decreases.

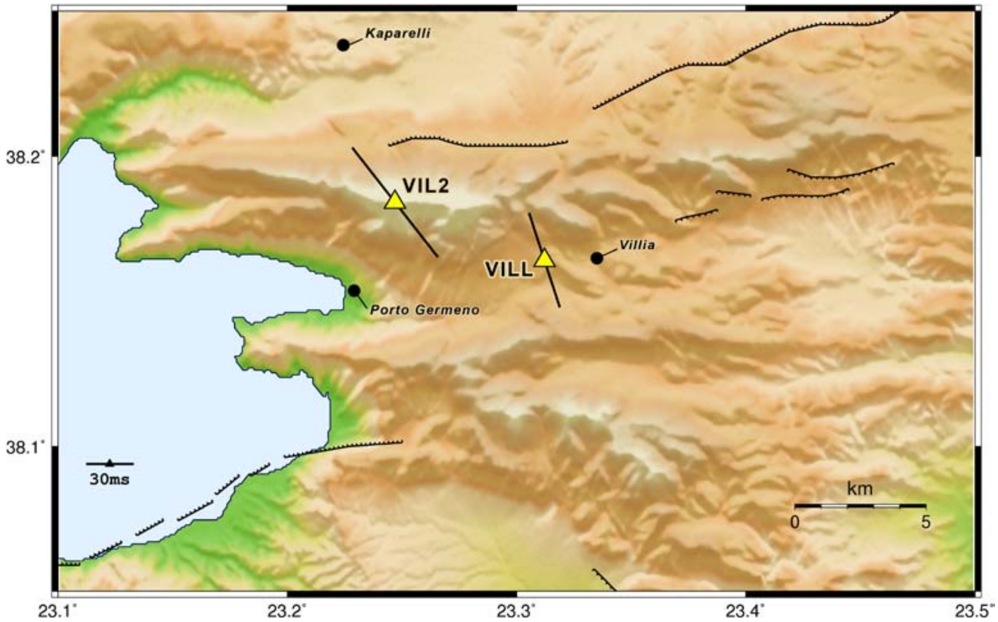

Figure 7. Mean anisotropy directions determined at the VILL and VIL2 stations. The length of the bar is proportional to the mean time delay.

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