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Shear wave splitting and $V_p/V_S$ variations before and after the Efpalio earthquake sequence, western Gulf of Corinth, Greece

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SUMMARY
On 2010 January 18 and 22, two earthquakes of $M_W$ 5.3 and 5.2, respectively, occurred near the town of Efpalio on the western Gulf of Corinth. We performed a shear wave splitting analysis using the cross-correlation method and calculated $V_p/V_S$ ratios for events that occurred in the epicentral area of the Efpalio earthquakes, between 2009 January and 2010 December. The data analysis revealed the presence of shear wave splitting in the study area, as well as variations of the splitting parameters and $V_p/V_S$ ratios. The average values of time-delay, fast polarization direction and $V_p/V_S$ ratio for the time period before the Efpalio earthquakes, were calculated at $2.9 \pm 0.4$ ms km$^{-1}$, $92^\circ \pm 10^\circ$ and $1.76 \pm 0.04$, respectively, while after the occurrence of the earthquakes, including the aftershock sequence, they were calculated at $5.5 \pm 0.5$ ms km$^{-1}$, $82^\circ \pm 9^\circ$ and $1.88 \pm 0.04$. A few months after the occurrence of the Efpalio earthquakes, the mentioned splitting parameters were calculated at $3.6 \pm 0.4$ ms km$^{-1}$ and $83^\circ \pm 9^\circ$. $V_p/V_S$ ratio exhibited a mean value of $1.87 \pm 0.04$. The mean fast polarization directions were in general consistent with the regional stress field, almost perpendicular to the direction of the extension of the Gulf of Corinth. The observed increase in the time-delays and $V_p/V_S$ ratios after the Efpalio earthquakes indicates changes in the crustal properties, which possibly resulted from variations in the pre-existing microcrack system characteristics. We suggest that a migration of fluids in the form of overpressured liquids, which are likely originated from dehydration reactions within the crust, was triggered by the Efpalio earthquakes and caused the observed variations. The findings of this work are consistent with those of previous studies that have indicated the presence of fluids of crustal origin in the study area.

Key words: Seismic anisotropy; Wave propagation; Crustal structure.

1 INTRODUCTION
Shear wave splitting is a phenomenon in which shear waves are separated into two components with different polarization directions and propagation velocities. This can occur during shear wave propagation through an anisotropic medium (Crampin & Chastin 2003; Crampin & Peacock 2005). The two splitting parameters that can be measured through shear wave data processing are the polarization direction $\varphi$ of the fast component of the shear waves, and the time-delay $\delta t$ between the two components. Changes in the splitting parameters have been observed worldwide in relation to earthquakes reflecting changes in the anisotropic characteristics of the medium and/or the stress field (Gao & Crampin 2004; Crampin & Gao 2012). These variations in the shear wave splitting parameters, and specifically variations in shear wave splitting time-delays before and after strong earthquakes, are quite complicated and have often been the subject of debate. Such cases are Peacock et al. (1988), Aster et al. (1990), Crampin et al. (1990, 1991), Seher & Main (2004), Peng & Ben-Zion (2005), Munson et al. (1995), Liu et al. (2004, 2005) and Crampin & Gao (2005). According to Crampin (1999), the principal driving mechanism for these changes is fluid migration along pressure gradients between closely spaced microcracks and pores at different orientations to the stress field. The parameters that control changes to microcrack geometry also control the splitting of shear waves, so that changes in deformation can be directly monitored by analysing the shear wave splitting, making shear wave splitting phenomenon an important tool for determining crustal deformation processes.

The Gulf of Corinth is a continental rift which separates the central Greek mainland from Peloponnese. The rift is approximately 120 km long and 10–20 km wide, with a WNW–ESE orientation, extending from the Gulf of Patras in the west, to the Gulf of Alkionides in the east. The Gulf of Corinth is considered as one of the most active extensional intracontinental rifts in the world (Armijo et al. 1996), with the geodetically measured rates of extension varying from $\sim 5$ mm yr$^{-1}$ at the eastern part, to $\sim 15$ mm yr$^{-1}$ at the
western part (Briole et al. 2000; Avallone et al. 2004). Several studies aimed at interpreting the cause of the high extension rates of the Corinth Gulf. Some have linked the rift formation to the westward motion of the Anatolian microplate and the propagation of the North Anatolian fault (Jackson 1994; Le Pichon et al. 1995). Other studies related the rift formation to the roll-back of the subducting African Plate (Le Pichon & Angelier 1979; Hatzfeld et al. 1997) and others to a combination of both processes (McClusky et al. 2000; Doutsos & Kokkalas 2001). Anisotropy studies of the deep lithosphere, comprising the lower crust and lithospheric mantle have also been performed, improving the knowledge and understanding of the dynamics of extension in parts of the backarc Aegean area, like the Gulf of Corinth (e.g. Hatzfeld et al. 2001; Edrum et al. 2011; Evangelidis et al. 2011 among others). Neotectonic faults (e.g. Jackson et al. 1982; Doutsos & Poulimenos 1992), earthquake focal mechanism solutions (e.g. Rigo et al. 1996; Bernard et al. 1997) and GPS measurements (e.g. Clarke et al. 1998) indicate an approximately N–S direction of extension. The high extension rates in the Gulf of Corinth are accompanied by a high level of microseismic activity, especially at the western part, which is characterized by frequent earthquake swarms and also by the occurrence of large earthquakes across the whole section of the gulf (Bourouis & Cornet 2009). Although the Gulf of Corinth is geographically limited, numerous on- and offshore earthquakes with magnitudes up to 7 were instrumentally recorded or historically reported (Papadopoulos 2000). Some of the large and destructive earthquakes that occurred during the last three decades are the Alkionides seismic sequence in 1981 involving three strong events of Ms 6.7, 6.4 and 6.4 (Jackson et al. 1982), the Ms 5.9 Galaxidi earthquake in 1992 (Hatzfeld et al. 1996), the Ms 5.4 Patras earthquake in 1993 (Karakostas et al. 1994; Tselenitis et al. 1994) and the Ms 6.2 Aigion earthquake in 1995 (Tselenitis et al. 1996; Bernard et al. 1997).

On 2010 January 18 (GMT 15:56) an earthquake of Ms 5.3 (Efp1) occurred near the town of Efpalio along the northern coast of the western Gulf of Corinth. Four days later, on January 22, about 5 km to the northeast from the first earthquake another Ms 5.2 event occurred (GMT 00:46; Efp2). The two main shocks and the spatiotemporal evolution of the Efpalio sequence were thoroughly studied by Ganas et al. (2013), Sokos et al. (2012) and Karakostas et al. (2012) among others. According to Sokos et al. (2012), the January 18 and 22 earthquakes were located at hypocentral depths of 6.6 and 8.0 km, respectively. Both events exhibit normal faulting along E–W trending planes. More specifically, the first event was related with a south-dipping fault plane (strike 102°, dip 55°), while the second event seemed to be related with a north-dipping plane (strike 282°, dip 52°; Sokos et al. 2012). These structures may coincide with already mapped surface traces of faults. The surface trace for the south-dipping fault of the first event is very well correlated with the Trirkorfo-Filothei south-dipping fault while the extrapolated surface termination of the assumed causative fault for the second event is located offshore, close to the north-dipping fault mapped by Papangikolou et al. (1997).

The purpose of this paper is to study the temporal variability of the shear wave splitting parameters and $V_p/V_S$ ratios during the years 2009–2010 in the epicentral area of the Efpalio earthquakes as well as to investigate the factors that caused these variations. After describing the available data and the methods of the shear wave splitting analysis and the calculation of $V_p/V_S$ ratios which we followed, we will present and discuss the measured parameters. We provide evidence that the observed changes of the aforementioned parameters were possibly caused by temporally evolving conditions in the upper crust. These variations are investigated by comparing measurements from event doublets that have occurred at different time periods (before and after the Efpalio earthquakes) but at the same focal area. Finally, we attempt to interpret the causative factors of the observed temporal variations, associated with the Efpalio earthquakes occurrence, in terms of the regional stress field and the possible involvement of fluids.

## 2 DATA AND METHODOLOGY

For the purpose of this study, we used recordings from six permanent broad-band stations, located on the western part of the Gulf of Corinth, operated under the framework of the Hellenic Unified Seismological Network (HUSN) and the Corinth Rift Laboratory (CRL, http://crlab.eu/). Efpalio (EFP) and Sergoula (SERG) stations were deployed by the University of Patras Seismological Laboratory (UPSL, http://seismo.geology.upatras.gr/) in cooperation with Charles University in Prague (http://geo.mff.cuni.cz/) while the other four seismic stations of Trizonia (TRIZ), Kalithea (KALE), Rodini (ROD) and Lakka (LAKA) were deployed by the CRL in cooperation with the Seismological Laboratory of Athens University (NKUA, http://dgsse.geol.oua.gr/).

The waveform data studied here consists of the background seismicity and aftershocks of the $M_W$ 5.3 and 5.2 Efpalio earthquakes, recorded from 2009 January until 2010 December. The location parameters of the studied events were provided by the Institute of Geodynamics — National Observatory of Athens (IGNOA, http://bbnet.gein.noaa.gr/). The mean location errors in the horizontal and vertical directions did not exceed ±0.6 and ±1.9 km, respectively. In Fig. 1(a) general map of western Gulf of Corinth is presented, showing the seismic stations (triangles) and the events (coloured circles) from which valid splitting results were obtained.

The estimation of the splitting parameters was performed using a cross-correlation method (Ando et al. 1983). Before applying the method, we manually picked $P$- and $S$-wave arrivals. The seismograms were interpolated to 200 samples s$^{-1}$, integrated to displacement and then bandpass filtered between 1 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 each time 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 ($\alpha$) 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 ($\tau$) in a selected time window. When the absolute value of C reaches a maximum, the corresponding values of azimuth ($\alpha$) and time ($\tau$) 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 accept as valid the splitting measurements which conform to the following criteria: (i) the C value is larger than 0.80, (ii) the signal-to-noise ratio is larger than 2.5, (iii) the change of the measured $d\tau$ is less than 0.02 s when the window size is varied by ±0.02 s and (iv) the change of the measured $\phi$ 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. 2. The recordings, from which we calculated the splitting parameters, are derived from seismic events all located within the effective shear wave window (Crampin & Gao 2006) of every station (incidence angle $\leq45°$) at depths ranging from 4 to
An example of a valid splitting measurement of the shear waves.

Figure 1. Map of the study area in western Gulf of Corinth. Seismic stations used for the shear wave splitting analysis are shown as triangles, where green and red colours signify stations operated by the University of Patras Seismological Laboratory (UPSL) and Corinth Rift Laboratory (CRL) in collaboration with the Seismological Laboratory of Athens University (NKUA), respectively. The seismic events (coloured circles) from which the valid splitting results were obtained, the Efpalio earthquakes epicentres (Efp1 and Efp2 as stars), major cities (squares) and major fault traces of the area are also shown. As in Doutsos & Poulimenos (1992), Flotté et al. (2005), Papanikolaou et al. (1997) and Valkaniotis (2009) the major faults shown are: 1 = Psathopyrgos, 2 = Trizonia, 3 = Trikorfo, 4 = Filolthei, 5 = Marathia, 6 = Antirio, 7 = Drosato, 8 = Efpalio, 9 = Selianitika, 10 = Aigion and 11 = offshore fault related to Efpalio sequence and other on- and offshore faults. The orientation of the principal stress axes after Kokkalas et al. (2006) is shown at the top left-hand corner. The depths of the events are colour coded according to the colour scale (bottom-right). The diameters of the circles are proportional to the magnitudes.

15 km. The local magnitudes of the events used in our analysis varied between 2.1 and 3.3.

Following the approach of Nur (1972), under the assumption of linear ray paths, we calculated an average $V_p/V_s$ ratio using the estimated travel times at each station for all the events that satisfied the splitting criteria:

$$\frac{V_p}{V_s} = \frac{t_s}{t_p}$$

with $t_s = T_s - T_o$ and $t_p = T_p - T_o$, where $T_s$ and $T_p$ are the arrival times of the $S$ and $P$ waves, respectively. The calculated $V_p/V_s$ ratios are then compared to the corresponding time-delays, giving additional information about the average properties of the medium along the ray paths.

3 RESULTS

In order to present the findings in a more efficient way, we separated the 2-yr-long data set into three subperiods. The time period before the occurrence of the Efpalio earthquakes, from 2009 January until 2010 January 18 (hereafter called ‘Period I’), the period that began soon after the occurrence of the earthquakes, including the aftershock sequence, from 2010 January 22 until the end of 2010 June (hereafter called ‘Period II’), and the remaining time period until the end of 2010 (hereafter called ‘Period III’). Another important factor for an efficient presentation and interpretation of the measurements, in addition to the previous temporal separation of the data, is the spatial distribution of the studied seismic events. For this reason, we also grouped the data spatially to that located inside and very close to the rupture areas of the Efpalio earthquakes and those located outside. We calculated the approximate dimensions of the rupture areas based on the empirical relationship between the moment magnitude and the rupture area proposed by Wells & Coppersmith (1994). Since the aftershock activity of the Efpalio earthquakes seemed to expand slightly into the surrounding area beyond the calculated boundaries of the rupture areas (see Sokos et al. 2012, Fig. 1b), for selecting the data which were close to the rupture area, we broadened the selection boundaries in accordance with the distribution of the early aftershocks during the first ~30 d after the Efpalio earthquakes as it is shown by Sokos et al. (2012) (see Fig. 3). By separating the studied time period and the data in these ways, considering the occurrence of the Efpalio earthquakes as a significant time point of our study, we are actually focusing on time periods in which the properties of the upper crust possibly exhibit different characteristics.

After the shear wave analysis, using the whole data set, we obtained 439 valid splitting measurements derived from 416 seismic events. Specifically, we obtained 108 valid measurements for the Period I, 257 for the Period II and 74 for the Period III. A first
overview of the results using the complete data set shows that the time-delays estimated for the Period I had a mean value of 2.9 ± 0.4 ms km$^{-1}$ while after the Efpalio earthquakes, in Period II, there was an increase to a mean value of 5.5 ± 0.5 ms km$^{-1}$. In Period III the mean value of $dt$ decreased in 3.6 ± 0.4 ms km$^{-1}$. The mean fast polarization direction varied between 68$^\circ$ at SERG station, and 125$^\circ$ at KALE station, with a mean of 84$^\circ$ ± 9$^\circ$. Fig. 4 shows rose diagrams of the fast shear wave polarization directions as they have been measured during the three subperiods for every single station. The $V_P/V_S$ ratios exhibit an average value of 1.76 ± 0.04 in Period I, while in Periods II and III, the average value significantly increased at 1.88 ± 0.04 and 1.87 ± 0.04, respectively. Table 1 gives a summary showing a list of all the available stations along with the average values of the shear wave splitting parameters. Below, we present in detail the results of this study in accordance with the aforementioned spatio-temporal grouping of the data that we performed.

### 3.1 Within and close to the rupture areas

A number of 261 valid splitting measurements derived from seismic events that occurred within and close to the rupture areas of the Efpalio earthquakes. We obtained 42 valid measurements for the Period I, 167 for the Period II and 52 for the Period III. As shown in Fig. 3, EFP station is the only station which is located just above the rupture areas, making in this way the measurements from this station the most representative of the area very close to the rupture zones. Diagrams showing the variation of (a) the measured shear wave time-delays, (b) fast polarization directions and (c) $V_P/V_S$ ratios from this part of the crust are presented in Fig. 5.
The time-delays estimated for the Period I had a mean value of 2.4 ± 0.5 ms km⁻¹ while after the Efpalio earthquakes, in Period II, there was an increase to a mean value of 5.8 ± 0.5 ms km⁻¹. In Period III the mean value of $\Delta t$ slightly decreased to 5.5 ± 0.4 ms km⁻¹. The increase in time-delays is clearly observed soon after the occurrence of the Efpalio earthquakes, exhibiting a decreasing trend a few months later, after the end of the aftershock sequence (see Fig. 5a). For the Period I, fast polarization directions show a mean value of 59° ± 10°, while in Periods II and III, the mean values were estimated at 82° ± 9° and 69° ± 9°, respectively. The $V_p/V_S$ ratios exhibit an average value of 1.78 ± 0.03 in Period I, while in Periods II and III, the average value significantly increased at 1.85 ± 0.04. Similarly to the previous results from the events inside and close to the rupture areas (Fig. 5a), all seismic stations, except the EFP station, are located outside of the rupture areas (Fig. 3). Diagrams showing the variation of the measured shear wave time-delays (a'), fast polarization directions (b') and $V_p/V_S$ ratios (c') from this area are presented in Fig. 5.

Measurements taken from outside the rupture areas show that the time-delays estimated for the Period I had a mean value of 3.4 ± 0.3 ms km⁻¹ while after the Efpalio earthquakes, in Period II, there was an increase to a mean value of 5.2 ± 0.4 ms km⁻¹. In Period III the mean value of $\Delta t$ slightly decreased in 4.9 ± 0.4 ms km⁻¹. In this case also, an increase in time-delays is clearly observed soon after the occurrence of the Efpalio earthquakes, exhibiting a decreasing trend a few months later, after the end of the aftershock sequence (Fig. 5a''). For the Period I, fast polarization directions show a mean value of 96° ± 9°, while in Periods II and III, the mean values were estimated at 74° ± 9° and 69° ± 9°, respectively. The $V_p/V_S$ ratios exhibit an average value of 1.75 ± 0.03 in Period I, while in both Periods II and III, the average value significantly increased at 1.85 ± 0.04. Similarly to the previous results from the events inside and close to the rupture areas, the average $V_p/V_S$ ratio in Period I is lower than the background values. The calculated $V_p/V_S$ ratio for Period I is lower 1.7 per cent than that estimated from Latorre et al. (2004).

### 3.2 Outside the rupture areas

Focusing on the area outside of the rupture zones of the Efpalio earthquakes, we obtained a total of 178 valid splitting measurements. Specifically, we obtained 43 valid measurements for the Period I, 72 for the Period II and 63 for the Period III. In this case, all seismic stations, except the EFP station, are located outside of the rupture areas (Fig. 3). Diagrams showing the variation of the measured shear wave time-delays (a'), fast polarization directions (b') and $V_p/V_S$ ratios (c') from this area are presented in Fig. 5.

The time-delays estimated for the Period I had a mean value of 2.4 ± 0.5 ms km⁻¹ while after the Efpalio earthquakes, in Period II, there was an increase to a mean value of 5.8 ± 0.5 ms km⁻¹. In Period III the mean value of $\Delta t$ slightly decreased to 5.5 ± 0.4 ms km⁻¹. The increase in time-delays is clearly observed soon after the occurrence of the Efpalio earthquakes, exhibiting a decreasing trend a few months later, after the end of the aftershock sequence (see Fig. 5a). For the Period I, fast polarization directions show a mean value of 59° ± 10°, while in Periods II and III, the mean values were estimated at 82° ± 9° and 69° ± 9°, respectively. The $V_p/V_S$ ratios exhibit an average value of 1.78 ± 0.03 in Period I, while in Periods II and III, the average value significantly increased at 1.85 ± 0.04. Similarly to the previous results from the events inside and close to the rupture areas, the average $V_p/V_S$ ratio in Period I is lower than the background values. The calculated $V_p/V_S$ ratio for Period I is lower 1.7 per cent than that estimated from Latorre et al. (2004).

### Table 1. Summary of the average values of the shear wave splitting parameters measured per seismic station for the whole data set.

<table>
<thead>
<tr>
<th>Station</th>
<th>Period I</th>
<th>Period II</th>
<th>Period III</th>
<th>Total</th>
<th>$\phi$</th>
<th>$\Delta t$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFP</td>
<td>30</td>
<td>136</td>
<td>39</td>
<td>205</td>
<td>75</td>
<td>3.6</td>
<td>4.9</td>
</tr>
<tr>
<td>SERG</td>
<td>19</td>
<td>64</td>
<td>46</td>
<td>129</td>
<td>68</td>
<td>6.3</td>
<td>4.2</td>
</tr>
<tr>
<td>ROD</td>
<td>16</td>
<td>16</td>
<td>12</td>
<td>44</td>
<td>86</td>
<td>4.2</td>
<td>3.5</td>
</tr>
<tr>
<td>KALE</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>26</td>
<td>125</td>
<td>6.3</td>
<td>4.2</td>
</tr>
<tr>
<td>TRIZ</td>
<td>23</td>
<td>–</td>
<td>–</td>
<td>23</td>
<td>122</td>
<td>3.1</td>
<td>2.7</td>
</tr>
<tr>
<td>LAKA</td>
<td>12</td>
<td>–</td>
<td>–</td>
<td>12</td>
<td>108</td>
<td>1.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Note: Nobs denote the number of observations per station, $\phi$ is the mean of the fast polarization directions based on directional statistics, $\Delta t$ is the average time delays normalized according to the hypocentral distance and $\sigma$ is the standard deviation of these values. Period I: time period before the 1st Efpalio event (January 2009 – Efp1), Period II: time period after the 1st Efpalio event until the end of the aftershock sequence (Efp1 – end of May 2010) and Period III: time period after the end of the aftershock sequence (2010 June–December).
While the average $V_p/V_S$ ratios after the Efpalio earthquakes, for both Periods I and II, are higher 3.9 per cent.

### 3.3 Validation of observations

In order to validate the observed changes of the parameters in time and exclude the possibility that different ray paths bias the measurements values, we followed two procedures. First, we followed a non-parametric hypothesis testing framework. A two-sample Kolmogorov–Smirnov (KS) test was applied to the time-delays and $V_p/V_S$ ratios (Gibbons 1971) and a statistical test appropriate for directional data to the fast polarization directions (Trauth 2010). The statistical tests were applied once between the data sets of Periods I and II and then between the data sets of Periods II and III, with a level of significance of 5 per cent (for details, see the Appendix). The tests revealed (i) that the difference in time-delays values derived from events inside and close to the rupture zones was significant between the periods before and after the Efpalio earthquakes, (ii) the difference in time-delays values derived from events outside the rupture zones was significant but less stronger than the previous one, (iii) the difference in $V_p/V_S$ values was significant between period I and II, and not for the periods II and III and (iv), that the $\psi$ values did not change significantly through the time periods for both the spatial groups of data.

Secondly, we searched our catalogue of the valid measurements for similar earthquakes (hereafter called ‘doublets’). We considered
an earthquake doublet as a pair of earthquakes consisting of an earthquake that occurred before the Efpalio events and an earthquake that occurred after that, with a cross-correlation coefficient greater than 0.7, similar magnitude and spaced in distances less than the mean horizontal and vertical location error. A 0.05–5 Hz bandpass filter was used in pre-processing of the seismic waveforms as the waveforms cross-correlation coefficient is more stable at lower frequencies (e.g. Shearer 1997; Shearer et al. 2005). Waveforms of seventeen such doublets were found recorded by the EFP, SERG and ROD stations (for details, see supporting information). Fig. 6 shows diagrams with the variation of the measured (a) shear wave time-delays $d\tau$, (b) fast polarization directions $\psi$ and (c) $V_p/V_S$ ratios from 2009 January to 2010 December for event doublets. The time-delays were normalized according to the hypocentral distances. Black vertical bars represent measurement errors.

4 INTERPRETATION AND DISCUSSION

4.1 Stress field and fast polarization directions

The Gulf of Corinth is considered as one of the most representative and extensively studied areas of active extensional deformation in the world. According to Kokkalas et al. (2006), the extension of the gulf is mainly controlled by WNW and ENE-striking normal faults. Stress tensor analysis in the Gulf of Corinth, presented in the previous study, shows a $\sigma_1$-axis in a nearly N–S direction (Fig. 1, also see fig. 4 of Kokkalas et al. 2006). Small deviation from this general direction is due to the prevalence of one of these two main fault sets. The zones at the junction between the WNW- and ENE-striking faults seem to be notable in terms of the Gulf of Corinth’s seismicity. Areas near the bend of the two fault orientations, acted as initiators of moderate to large earthquakes at the past (e.g. the 1993 $M_L$ 5.6 Patras earthquake and the 1981 Alkionides earthquakes). The computed focal mechanisms of the Epf1 and Epf2 events showed $T$-axis azimuths of 187° and 1° respectively (Sokos et al. 2012), observations that are in agreement in general with the trend of the seismo-tectonic, stress and strain regime of the Gulf of Corinth.

The observed ENE–WSW (84° ± 9°) direction of $\psi$ is in a good agreement with the regional stress and strain field. According to the mean values of $\psi$ in Periods I, II and III derived from events both from inside and outside the rupture areas, and also taking into account their measurement errors, the fast polarization directions did not reveal any significant change. The Efpalio earthquakes seemed to have little or no influence on this parameter. We suggest that the observed ~E–W fast shear wave polarization direction is caused by pre-existing stress-aligned microcracks, oriented parallel or sub-parallel to the horizontal maximum stress axis, which is parallel to the trend of faulting and perpendicular to the N–S extension of the Gulf of Corinth. The orientation of these microcracks most probably did not change after the Efpalio earthquakes. Previous research studies, such as Evangelidis et al. (2011), Edrun et al. (2011) and Hatzfeld et al. (2001), concentrated on deeper parts of the lithosphere investigating the azimuthal anisotropy in the lower crust and mantle across the Hellenic subduction zone and the Aegean region by performing SKS and surface wave anisotropy analyses. It would be interesting to compare our measurements with fast polarization directions deduced for deeper parts of the lithosphere, however, the network coverage that was used from the previous studies was not dense enough in the broader region of our study area. Possible future measurements from a denser network around the study area combined with the measurements of this work could allow us to study, for instance, the degree of the vertical coherence of deformation in the Gulf of Corinth.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Before Efpalio sequence</th>
<th>After Efpalio sequence</th>
<th>Percentage of relative change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi$ (°)</td>
<td>101</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>$d\tau$ (ms km⁻¹)</td>
<td>1.73</td>
<td>2.81</td>
<td>+53 per cent</td>
</tr>
<tr>
<td>$V_p/V_S$</td>
<td>1.80</td>
<td>1.91</td>
<td>+5 per cent</td>
</tr>
<tr>
<td>$V_p$ (km s⁻¹)</td>
<td>6.01</td>
<td>6.11</td>
<td>+0.5 per cent</td>
</tr>
<tr>
<td>$V_S$ (km s⁻¹)</td>
<td>3.34</td>
<td>3.21</td>
<td>−5 per cent</td>
</tr>
</tbody>
</table>

Note: $\psi$ is the mean of the fast polarization directions based on directional statistics, $d\tau$ is the average time delays, $V_p$ and $V_S$ are the P- and S-velocity, respectively.
4.2 Possible causes of $d_t$, $V_p/V_S$ variations

According to Crampin (1999) the principal cause of time-delays variations is fluid migration along pressure gradients between closely spaced microcracks and pores. The CRL’s (http://crlab.eu/) main objective is to investigate the mechanics of active faults in the western Gulf of Corinth, with special emphasis on the role of fluids (e.g. Cornet et al. 2004; Bernard et al. 2006). Within this framework, Bourousi & Cornet (2009) indicated possible overpressure fluid diffusion processes in the western Gulf of Corinth, related to the seismically activated parts of the crust. The previous authors, utilizing also the hydraulic data from a deep well that intersected the Agion Fault (Cornet et al. 2004), suggested that the overpressure conditions within the normal fault system of the area are possibly due to the fact that the faults act as hydraulic barriers in the direction perpendicular to their strike, preventing the fluid flow. In the case of the Agion Fault, it has been shown that the fault core is made of a 0.5-m-thick impermeable clay zone surrounded by permeable cataclastic zones. Existence of fluids in the cataclastic zones of faults in the western Gulf of Corinth has been documented also from geochemical analysis of the faults gouges (Baud et al. 2004; Koukouvelas & Papoulis 2009; Pik & Marty 2009). Other studies that have indicated the presence of fluids in the western Gulf of Corinth and their key role in the development of seismicity are among others Latorre et al. (2004), Gautier et al. (2006) and Pacchiani & Lyon-Caen (2010). Concerning the findings of the previous studies and the observed time-delays variation that we detected, we suggest that the Efpalio earthquakes caused a change in the properties of the crust, as well as in the pre-existing microcrack system geometry. The observed distinctive increase in the time-delays on one hand, and the maintenance of the same mean fast polarization direction before and after the earthquakes on the other hand, suggest that the cause of the observed variations in the splitting parameters was a possible migration of overpressured fluids through the pre-fractured damage zone of the study area. Based on the fact that the increase in the time-delays after the Efpalio earthquakes derived from the data located close to the rupture zones is slightly more intense than the observed increase from the data located outside the rupture areas, we assume that the degree of the changes in the properties of the crust is stronger close to the rupture zones than away from them. A similar example relating to migration of fluids in an overpressured condition within a pre-fracture zone was examined for the case of the 2009 $M_w$ 6.3 L’Aquila earthquake in central Italy by Di Luccio et al. (2010). In summary, the previous study has revealed, among others, diffusion processes of overpressured fluids within the pre-fractured crust following the occurrence of the $M_w$ 6.3 L’Aquila earthquake.

An additional interpretation concerning the possible involvement of overpressure fluids in the study area is the $V_p/V_S$ ratios measurements. Due to the sensitivity of $V_p/V_S$ ratios in pore fluids, this parameter is an appropriate tool not only for detecting fluid activities, but also for determining the possible fluid phase (gas or liquid phase). $V_p/V_S$ ratios reflect also the properties of the upper crust, varying with mineral, rock compositions and generally with lithology (Fernandez-Viejo et al. 2005). These kinds of changes in lithology occur during much larger timescales than the 2-yr of our data set. For this reason, variation in lithology does not seem to be a decisive factor that can influence the observed variations. Seismic tomography studies in different geological systems, like volcanic and geothermal, were successful to delineate zones of high or low $V_p/V_S$ ratios (e.g. Gunasekara et al. 2003; Chiarabba & Moretti 2006 and others). These studies have highlighted the dominant role of fluids in influencing the values of $V_p/V_S$ where liquids result in high $V_p/V_S$ ratios, by lowering the $V_S$, while gases shift the ratio to lower values as they affect more the $V_p$ in the rock. In order to investigate in more detail the causes of the increase of $V_p/V_S$ after the Efpalio earthquakes, under the assumption of linear ray paths, we calculated apparent $V_P$ and $V_S$ velocities for the same set of events that had an estimated $V_P/V_S$ ratio. We averaged these values for each of the three subperiods and we also compared them with the background values for the top 15 km of the crust derived from the seismic velocity model of Latorre et al. (2004). The averaged values of the measured $V_P/V_S$, $V_P$ and $V_S$ for each period along with the percentage of their relative change from the background values are shown in Fig. 7. The measurements of the apparent $V_P$ and $V_S$ shows that the observed changes in $V_P/V_S$ ratios after the Efpalio earthquakes were due to an increase in $V_P$ and a decrease in $V_S$. This observation is reflected from data recorded both from inside and outside of the rupture areas. It is important to mention that despite the aforementioned variations in the $V_P$ and $V_S$, their values were still higher than the background ones proposed by Latorre et al. (2004) (see Fig. 7). The previous observed influence of the fluids in the $V_P/V_S$ ratios was also validated by the averaged apparent $V_P$ and $V_S$ values derived from the doublets. In that case, the values of the calculated apparent velocities (see Table 2) show that the occurrence of the Efpalio earthquakes affected more the $V_S$ values than the corresponding $V_P$ since $V_S$ exhibited a 5.5% per cent decrease after the Efpalio earthquakes, while $V_P$ increased by 0.5 per cent. Based on the observed high $V_P/V_S$ ratios after the Efpalio earthquakes and the fact that $V_S$ is decreasing while $V_P$ is increasing, we infer that pore and cracks space in the overpressured cracked rock is most probably filled with liquid.

Latorre et al. (2004) performed a three-dimensional delay travel-time tomography by re-analysing a large updated data set, collected in 1991 during a 2-month passive tomographic experiment. The result of this work was the construction of detailed $V_P$ and $V_S$ images of the upper 11 km of the crust in western Gulf of Corinth. The authors pointed out a quite complex structure, identifying two distinct zones exhibiting different characteristics. A shallow structure between 0 and 5 km and a deeper one between 7 and 11 km. The limit between the two zones (5–7 km) was suggested by the recovery of a large-scale vertical velocity anomaly and an increase in the seismicity rate (see figs 13–16 of Latorre et al. 2004). At depths larger than 5–7 km, a significant increase in $V_P/V_S$ ratios was found. Vertical $V_P/V_S$ profiles indicated a possible correlation between the observed $V_P/V_S$ anomalies and earthquake clusters located in the study area. According to Latorre et al. (2004), fluid saturation in fractured rocks could explain the high $V_P/V_S$ ratio caused by the increase of $V_P$ and decrease of $V_S$. More specifically, metamorphic processes involving phyllosilicate rocks may be responsible for the release of structural water by dehydration reactions. Because the previous authors and other studies (e.g. Dornsiepen et al. 2001; Xypolias & Koukoulwas 2001, among others) have suggested the presence of phyllosilicate-rich rocks within the studied part of the crust, the high $V_P/V_S$ might be caused by the aforementioned metamorphic processes. One could argue that the fluids might have an alternative origin, suggesting for instance that fluids are possibly upper mantle sourced. A database of helium isotope measurements around Greece and surrounding areas compiled by Pik & Marty (2009) does not seem to support such an explanation for our study area. The results of the previous work show a remarkable absence of mantle-He signal in the Corinth rift fluids. Pik & Marty (2009) interpreted the high proportion of crustal helium in the Gulf of Corinth suggesting that the fault system is rooted in the upper crust and is
Figure 7. Validation of the variation of the average values of the splitting parameters and \( V_p/V_s \) ratios that was observed through the studied time period, after the application of non-parametric hypothesis testing. A two-sample Kolmogorov–Smirnov (KS) test (Gibbons 1971) was applied for the time-delays and \( V_p/V_s \) ratios, while a statistical test relative to directional data (Trauth 2010) was applied for the polarization directions (for details about the statistical testing, see the Appendix). The percentage of the relative change between the observed average \( V_p/V_s \) ratios, \( V_p \) and \( V_s \) velocities and the background values derived from the velocity model proposed by Latorre et al. (2004) is also shown.

not connected at depth with zones where mantle-He has possibly been trapped.

Pore pressure diffusion in media with hydraulic diffusivity is the main mechanism which controls the triggering and the spatio-temporal evolution of an aftershock seismicity (Shapiro et al. 2003). When pore pressure diffusion processes operate, an envelope of cloud of events can be recognized in a plot of the distance of the pressure front from the fluid source versus time. Assuming a homogeneous isotropic medium, the distance of the pressure front from the triggering front (fluid source) can be approximated by the theoretical curve \( r = (4 \pi D t)^{1/2} \) where the distance \( r \) is a function of the diffusivity \( D \) and time \( t \) (Shapiro et al. 1997; Di Luccio et al. 2010). In the case of the Efpalio earthquake sequence, we analysed the aftershocks distribution from the Efp1 up to February 25th. The data used for this analysis consisted of 288 seismic events. The source parameters of the data were provided by Sokos et al. (2012).

In a distance versus time diagram (\( r-t \)) we identify a triggering front with a diffusivity of 4.5 m\(^2\) s\(^{-1}\) (see Fig. 8). The procedure for fitting the theoretical curve \( r = (4 \pi D t)^{1/2} \) to the data was to select the farthest earthquakes that occurred in consecutive, non-overlapping time windows of 5 d, and search using a least squares search the diffusivity \( D \) value that provided the best fit. The estimated model of the spatio-temporal evolution of the aftershock seismicity (Fig. 8) indicates that the diffusion process started soon after the Efp1 event since it was not observed any time lag between the Efp1 and the triggered earthquakes. The estimated diffusivity value of about 4.5 m\(^2\) s\(^{-1}\) is within those reported in the literature (e.g. Talwani et al. 2007) and, in addition with the observed variation of the \( V_p/V_s \) ratios, it strongly supports the involvement of liquid fluids within the fractured medium. For the case of the study of the spatio-temporal evolution of an earthquake swarm occurred in the southern coast of the western Gulf of Corinth (2001 Agios Ioannis earthquake swarm), Pacchiani & Lyon-Caen (2010) estimated a hydraulic diffusivity equal to 0.1 m\(^2\) s\(^{-1}\). It appears that the fluids in the epicentral area of the Efpalio earthquakes were more diffusible within a possibly more fractured crust. Another comparison can be made with the case of the L’Aquila earthquake, in which Di Luccio et al. (2010) estimated a \( D \) value of about 4.5 m\(^2\) s\(^{-1}\) for the foreshocks and a value of 80 m\(^2\) s\(^{-1}\) for the aftershocks. According to the authors, the value of 80 m\(^2\) s\(^{-1}\), a threshold value for the
diffusivity of crustal rocks, reflected the involvement of mantle sourced CO2-rich fluids. The difference between the $D$ values derived from the previous studies and from this work, reflecting different degrees of diffusion processes, is possibly due to the different properties of the fractured crust at the time periods when the studies were conducted and also due to the different magnitudes of the earthquakes of each case. The largest event of the Agios Ioannis earthquake swarm (Pacchiani & Lyon-Caen 2010) had a moment magnitude of 4.3, while the L’Aquila earthquake, as previously mentioned, it was an $M_w$ 6.3 event.

Finally, it is noteworthy to mention the variation of the time-delays in Period III and how it reflects the properties of the crust. After the significant increase that was observed in time-delays after the Efpalio earthquakes, this parameter appears to have a decreasing trend, moving to background values. According to Crampin & Gao (2006), changes of stress affect the geometry of the microcrack system by changing the crack density and aspect-ratios, a process which is directly monitored by variations in average time-delays. It seems possible that the cracks, started to close after the earthquakes due to stress relaxation and the crack density became smaller resulting in smaller values of time-delays.

5 CONCLUSIONS

The results presented in this study can be summarized as follows: (i) shear wave splitting processes were observed in the western end of the Gulf of Corinth during the years of 2009–2010, (ii) fast polarization directions presented a general E–W orientation, which is in agreement with the regional stress and strain field, (iii) fast polarization directions did not change after the Efpalio earthquakes, (iv) a distinct increase in time-delays and $V_p/V_S$ ratios was observed soon after the Efpalio earthquakes, followed by a decrease after the end of the aftershock sequence and (v) after the Efpalio earthquakes, a migration of overpressured liquid fluids through the fractured damage zone is possibly the main cause of the observed increase in time-delays and $V_p/V_S$ ratios. The previous observed variations in the $d_r$ and $V_p/V_S$ ratio after the Efpalio earthquakes seemed to be slightly stronger close to the rupture areas than outside of them, which are possibly reflecting different degree of changes in the properties of the crust.

These results provoke the need for further investigations, to study for example in more detail the conditions needed for the presence of overpressured fluids in an area which is characterized by extension and how important could be the role of these fluids in the possibility of generation of slip along low dipping faults. Toward this direction, a time-lapse (4-D) tomography is recommended to be performed as a future work in order to delineate the areas of fluid saturation and their changes over time, since a considerable amount of seismic data recorded during the last ~20 yr in the Corinth Gulf region is available and appropriate for such a study.

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**APPENDIX: STATISTICAL TESTING**

**A1 Two-sample Kolmogorov–Smirnov test**

In the geosciences, there are a lot of occasions where we want to test the hypothesis that two data sets derive from the same statistical distribution. However, the kind and sizes of the samples do not allow any assumption about their distribution (e.g. Gaussian distributed).

In these cases, we need a non-parametric two-sample statistical test for checking this hypothesis. Such a test is the two-sample Kolmogorov–Smirnov (KS) test (Gibbons 1971). The two-sample KS test is one of the most used and general non-parametric method for comparing two populations, as it is sensitive to differences in both the location and shape of the empirical cumulative distribution functions of the two samples. Specifically, let us assume $X_1$, $X_2$, two data sets, of length $n$ and $m$, respectively, and let $F_{1,n}(x)$, $F_{2,m}(x)$ be their empirical distributions. We need to test under what circumstances the hypothesis $F_{1,n}(x) = F_{2,m}(x)$ (the null hypothesis) is valid. In this case, the KS statistic is:

$$D_{n,m} = \sup_x |F_{1,n}(x) - F_{2,m}(x)| \quad \text{(A1)}$$

and the null hypothesis is rejected, with a level of significance $\alpha$ if:

$$q = \sqrt{\frac{nm}{n+m}} > K_\alpha,$$  \quad \text{(A2)}

where $K_\alpha$ is a constant threshold value that is derived from the Kolmogorov distribution. We applied this hypothesis-testing procedure in $V_p/V_S$ ratios and time delays data, with a significance level $\alpha = 5$ per cent.

**A2 F statistic test for directional data**

Let us consider: $\theta_1$, $\theta_2$, ..., $\theta_n$, $\varphi_1$, $\varphi_2$, ..., $\varphi_m$ as the two sets of azimuth measurements. We wish to statistically test the hypothesis that they belong to the same distribution. Before using the appropriate statistic, a specific analysis relative to the directional data has to be followed (Trauth 2010). The characteristics of the directional data are described by measures of central tendency and dispersion, which are similar to the statistical characterization of univariate data sets. Initially, we need to calculate the resultant or mean direction for the sets of angular data according to the relationships:

$$x_{1r} = \sum \sin \theta_i$$  \quad \text{(A3)}

$$y_{1r} = \sum \cos \theta_i$$  \quad \text{(A4)}

and

$$x_{2r} = \sum \sin \varphi_i$$  \quad \text{(A5)}

$$y_{2r} = \sum \cos \varphi_i.$$  \quad \text{(A6)}

The resultant directions of the data are given by:

$$\bar{\theta} = \tan^{-1} \left( \frac{x_{1r}}{y_{1r}} \right)$$  \quad \text{(A7)}

and

$$\bar{\varphi} = \tan^{-1} \left( \frac{x_{2r}}{y_{2r}} \right),$$  \quad \text{(A8)}

and the mean resultant lengths are:

$$R_1 = \frac{1}{n} \sqrt{x_{1r}^2 + y_{1r}^2},$$  \quad \text{(A9)}

and

$$R_2 = \frac{1}{m} \sqrt{x_{2r}^2 + y_{2r}^2},$$  \quad \text{(A10)}

respectively.

The test statistic that we used for testing the similarity between the two mean directions is the $F$-statistic, and it is given by the relationship:

$$F = \left(1 + \frac{3}{8k}\right) \frac{(N - 2)(R_1 + R_2 - R_{all})}{N - R_1 - R_2},$$  \quad \text{(A11)}

where $k$ is the concentration parameter, which can be obtained from tables using $R_{all}$, $R_1$ and $R_2$ are the mean directions (resultants) of the two data sets, respectively, and $R_{all}$ is the resultant of the combined data sets. The calculated $F$-statistic is compared with the critical values from the standard $F$ tables, and the two mean directions are not significantly different if the measured $F$
is lower than the critical $F_{cr}$. As previously, we applied the aforementioned statistical test to our data with a level of significance 5 per cent.

**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Diagrams showing the variation of the measured shear-wave time-delays $d_t$ (a), fast polarization directions $\phi$ (b) and $V_P/V_S$ ratios (c) from all the available data recorded between January 2009 and December 2010 per station. The time-delays were normalized according to the hypocentral distances. Black vertical bars represent measurement errors. The names of the stations are shown at the top left corner of each panel.

**Figure S2.** Diagrams showing the variation of the measured shear-wave non-normalized time-delays $d_t$ per station. Black vertical bars represent measurement errors. The names of the stations are shown at the top left corner of each panel.

**Figure S3.** Application of non-parametric hypothesis testing on the average values of the splitting parameters and $V_P/V_S$ ratios. A two-sample Kolmogorov–Smirnov (KS) test (Gibbons 1971) was applied for the time-delays and $V_P/V_S$ ratios, while a statistical test relative to directional data (Trauth 2010) was applied for the polarization directions. The percentage of the relative change between the observed average $V_P/V_S$ ratios, $V_P$ and $V_S$ velocities and the background values derived from the velocity model Latorre et al. (2004) is shown also.

**Figure S4.** Diagrams showing the variation of the measured shear-wave non-normalized time delays $d_t$ with time. Black vertical bars represent measurement errors.

**Figure S5.** Equal area projections of the fast polarization directions. (a) whole time period (January 2009–December 2010), (a1) time period before the 1st Efpalio event (January 2009 – Efp1 (January 18, 2010)), (a2) time period after the 1st Efpalio event until the end of the aftershock sequence (Efp1 – end of May 2010) and (a3) time period after the end of the aftershock sequence (June 2010–December 2010). The radius of the plots is scaled to an incidence angle of 45° (effective shear-wave window (Booth & Crampin 1987)).

**Figure S6.** (a) & (b) Waveforms of ‘earthquake doublets’ or ‘similar earthquakes’ recorded by the EFP, SERG and ROD stations. We considered the similar earthquakes/earthquake doublets as a pair of earthquakes consisting of an earthquake that occurred before the Efpalio events and an earthquake that occurred after that, with a cross-correlation coefficient greater than 0.7, similar magnitude and spaced in distances less than the mean horizontal and vertical location error. A 0.05–5 Hz band-pass filter was used in pre-processing of the seismic waveforms as the waveforms cross-correlation coefficient is more stable at lower frequencies (e.g. Shearer 1997; Shearer et al. 2005).

**Table S1.** Data availability for the studied time period. Months with at least some data are plotted in grey.

**Table S2.** Pairs of earthquake doublets with the corresponding splitting parameters ($\phi$ and $d_t$) as well as the corresponding values of $V_P/V_S$ ratio, $V_P$ and $V_S$. (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggu467/-/DC1).

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