Preliminary report on the Lefkada 17 November 2015 M_w=6.4 earthquake

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Introduction

The island of Lefkada is situated in the Ionian Sea (Fig. 1), on the west coast of Greece, one of the most seismically active regions in the Mediterranean with a surface of 302.5 km^2. It is connected to the mainland by a long causeway and floating bridge. The principal town of the island is Lefkada which is located on its northern part. According to the 2001 national census, there are 22,506 permanent residents on the island.

The study area has experienced frequent intense earthquakes, mostly along the Cephalonia-Lefkada Transform Fault Zone (CLTFZ). The majority of the most destructive events were located close to the northwestern part of the island, while fewer close to the SW edge of Lefkada, where severe damage was observed.

On Tuesday, November 17th, 2015, western Greece was affected by a shallow M_w=6.4 event. The epicentral location of this event is 38.6785°N and 20.5889°E, at the southern part of Lefkada Island. The intensity of the ground shaking generated by the earthquake's occurrence resulted in a series of large landslides that have left very large volumes of debris on the beach of Egremni at the SW edge of the island.

A preliminary study of the earthquake sequence and the source parameters determination of the mainshock and the largest events is presented in this report. The used data, covering the time period of November 17th - December 3rd, 2015, were recorded by stations of the Hellenic Unified Seismological Network (HUSN). The focal mechanisms were determined by moment tensor inversion using recordings in local and regional distances, employing the methodology described by Papadimitriou et al. (2012).

Seismotectonic Setting

The broader area of study is characterized by a series of NW–SE striking geotectonic units, such as the Pre-Apulian (or Paxos) and Ionian (Aubouin, 1957; Mercier et al., 1972; Sorel, 1976), which form the terrain of External Hellenides. These structures, which have been formed under a subduction-related compressional regime, are coaxial with earlier Alpine structures resulting from the collision of the Pre-Apulian plate with Eurasia. The mountain chain of Hellenides, located between southern Albania and the Gulf of Corinth, plays an important role on the seismotectonics of the region.

The tectonic setting of the wider area is dominated by both continental collision between European and Apoulian plates and subduction of the oceanic plate of Tethys beneath the Aegean continental microplate along the active Hellenic Arc in the southwest (Fig. 1). The Ionian Islands mark the transition zone between the northwestern end of this active subduction and the continental collision to the north. This transitional zone is characterized by high rates of crustal deformation, as revealed by intense seismicity, which is the highest in the broader region (Papazachos and Comninakis, 1971; Papadimitriou, 1988; Louvari et al., 1999; Lekkas et al., 2001; Margaris et al., 2003; Karakostas et al., 2004, 2010; Papadimitriou et al., 2006).

The main tectonic structure of this area is the Cephalonia-Lefkada Transform Fault Zone (CLTFZ), which represents the active boundary between the Aegean and the Apulian microplates. It is characterized as an offshore fault system to the west of the island of Cephalonia, an area with a deep bathymetric trough, striking at N20°E, with water depths of more than 3000m (Louvari et al., 1999; Lekkas et al., 2001; Margaris et al., 2003). Analysis of marine geophysical data (Kokkinou et al., 2005; Makris and Yegorova, 2006; Makris, 2010) indicates that this trough represents a transform fault that demarcates the northwestern end of the Hellenic Subduction Zone (Anderson and Jackson, 1987; Jackson and McKenzie, 1988) which is supported by earthquake focal mechanisms (Scordilis et al., 1985; Papadimitriou, 1988; Kiratzi and Langston, 1991; Kassaras et al., 1993; Louvari et al., 1999; Papazachos and Papazachou, 2003; Papadimitriou et al., 2006) that have shown that the CLTFZ is a right-lateral transform fault (Fig. 2). This is in agreement with geodetic data which clearly show that the slip motion has a NNE–SSW direction at a rate of 2–3 $cm \cdot yr^{-1}$ (Kahle et al., 1996; Cocard et al., 1999; Jenny et al., 2004; Lagios et al., 2007; Ganas et al., 2013). The seismic strain rate is well correlated with the principal horizontal axis of the total geodetic strain rate field.

The Lefkada Island has suffered from numerous strong and destructive earthquakes since the antiquity, as well as during the 20th century (Papazachos and Papazachou, 2003; Makropoulos et al., 2012; Stucchi et al., 2013). Most events were located close to the northwestern part of the island, where severe damage was observed. More specifically, the 22 November 1704 (M=6.3), the 12 October 1769 (M=6.7), the 23 March 1783 (M=6.7), the 28 December 1869 (M=6.4) and the 27 November 1914 (M=6.3) earthquakes were among the most significant, since they caused several deaths, injuries and collapse of buildings. These disasters occurred mainly at the northwestern and central parts of the island, where fissures, liquefactions and landslides were also observed. This is the reason that most epicenters of the historical earthquakes are located close to the northern end of the transform fault, in the Ionian Sea (Kouskouna et al., 1993; Makropoulos and Kouskouna, 1994).

On the contrary, only two large events could be located close to the southwestern edge of the Lefkada Island, before the occurrence of the 17 November 2015 earthquake, an area that belongs to the central part of the CLTFZ, whereas important microseismic activity is observed. The two events that can be related to this area are the 22 February 1723 (M=6.7) and the 22 April 1948 (M=6.5) earthquakes. Concerning the latter event, it caused damage at the SW part of the island, while fissures and tsunami waves were also observed. Two months later, on 30 June 1948, an earthquake of magnitude M=6.4 occurred at the northwestern part of the island (Fig. 2). The two largest events in the area that were studied using body-wave modeling are the ones that occurred in 1983 and in 2003 at the southern and the northern part of the CLTFZ, respectively. On 14 August 2003 (05:14 GMT), a large earthquake (M_W=6.3) occurred close to the NW coast of Lefkada Island, causing some damage, landslides and ground fissures. The epicenter location of this event is 38.86°N and 20.56°E (Papadimitriou et al., 2006).

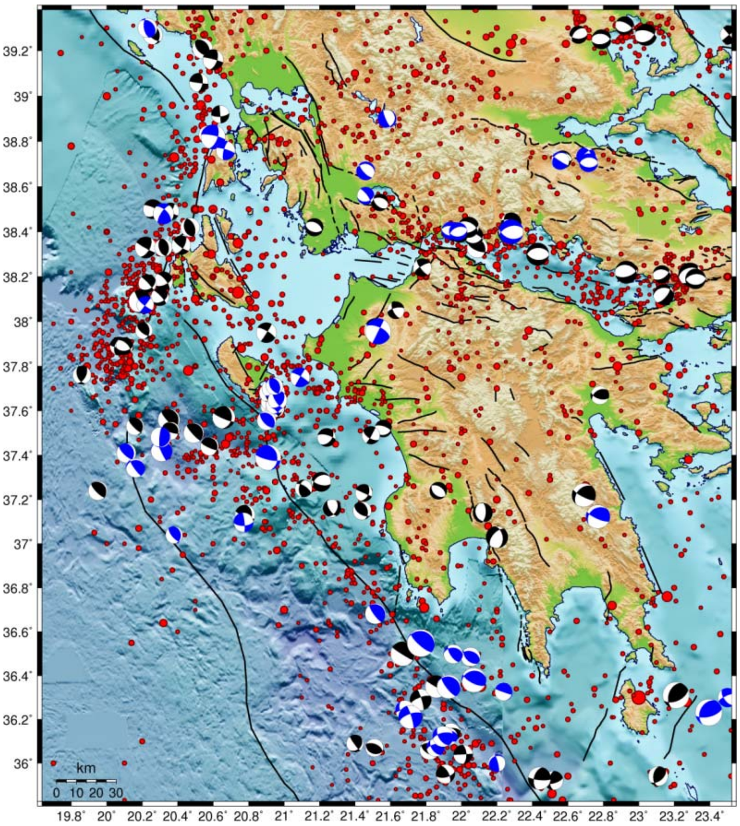

Figure 1. Seismotectonic map of Western Greece

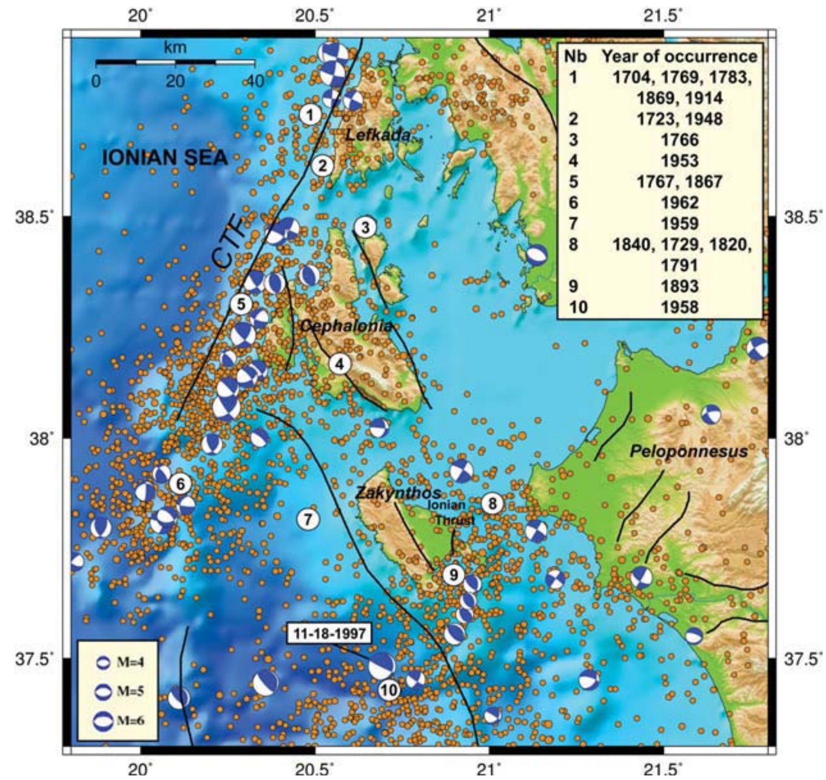

Figure 2. Tectonic setting of the Ionian Sea. Main earthquakes since 1700. Circles close to Lefkada Island labeled 1–8 represent earthquakes that occurred on 1704, 1722, 1723, 1769, 1783, 1869, 1914 and 1948, respectively. Similarly, for Cephalonia, the event dates are 1766, 1767, 1867, 1953, 1972 and 1983 and for Ithaki 1915 (Papadimitriou et al., 2012).

Aftershock sequence and Coulomb stress changes of the 14 August 2003 Lefkada earthquake

On 14 August 2003 a strong (M_W=6.3) event occurred NW of the Lefkada Island (Benetatos et al., 2005; Zahradnik et al., 2005). The source parameters of this event were determined by Papadimitriou et al. (2006) using body-wave modeling. The focal depth was found equal to 9 km and the constrained focal mechanism revealed dextral strike–slip motion. The aftershock epicentral distribution was composed of two clusters. The first was located close to the epicentral area of the mainshock, in agreement with the source dimensions. The second occurred to the south, close to the NW coast of the Cephalonia Island and could not be related to the activated part of the fault zone.

In order to interpret the existence of this important activity, Coulomb Failure Stress, ΔCFS (Harris, 1998; Harris and Simpson, 2002), was used. This technique, which has been applied in various regions worldwide, can reasonably explain the spatial distribution of the aftershocks, as well as the existence of distant events triggered by stress changes of less than 1 bar, even of the order of 0.1 bar, that can cause microseismicity rate changes (Reasenberg and Simpson, 1992). The locations with positive values of ΔCFS are considered as advancing towards failure, while the locations with negative values are delayed from failure and are commonly called stress shadows.

Coulomb stress changes were calculated by Papadimitriou et al. (2006) for the case of the Lefkada 2003 earthquake (Fig. 3), using the source parameters determined in the study. The calculation was performed considering that the length of the main rupture fault is 24 km and its width extends from 2 to 12 km. In the same figure, the aftershock locations are also plotted. The first cluster that is located close to the main rupture fault was anticipated on the basis of the Coulomb failure criterion. More specifically, the events occur where Coulomb stresses have risen. The activity along the rupture fault is successfully predicted, as well as the off-fault activity by the northern and southern lobes. Furthermore, the spatial distribution is not only restricted along the western coast of the Lefkada Island, but it is also expanded in the northeastern part of the island. This observation is coherent with the existence of the northwestern lobe.

A second cluster is located about 20 km south of the main rupture, while a “gap” of seismic activity is observed between the two clusters. This cluster consists of events that are characterized by low magnitudes, while their number during the first hours after the occurrence of the mainshock is significantly smaller, compared to the northern cluster. Furthermore, all large aftershocks for the same time period were located at the area covered by the northern cluster.

All events of the southern cluster occurred within the southern lobe that was calculated by the Coulomb stress changes. This area is loaded with additional stress, larger than 0.15 bar. Thus, it is reasonable to propose that the small perturbation of the stress field caused by the 2003 Lefkada earthquake played a major role in triggering the activation of this cluster by producing microseismicity rate changes. In addition, a seismic “gap” was observed in the area between the two clusters. Papadimitriou et al. (2006) suggested that this area of enhanced Coulomb stress, where lack of seismicity was also observed, should be regarded as candidate for a future main event. Indeed, the 17 November 2015 earthquake occurred within the area indicated by the above-mentioned study.

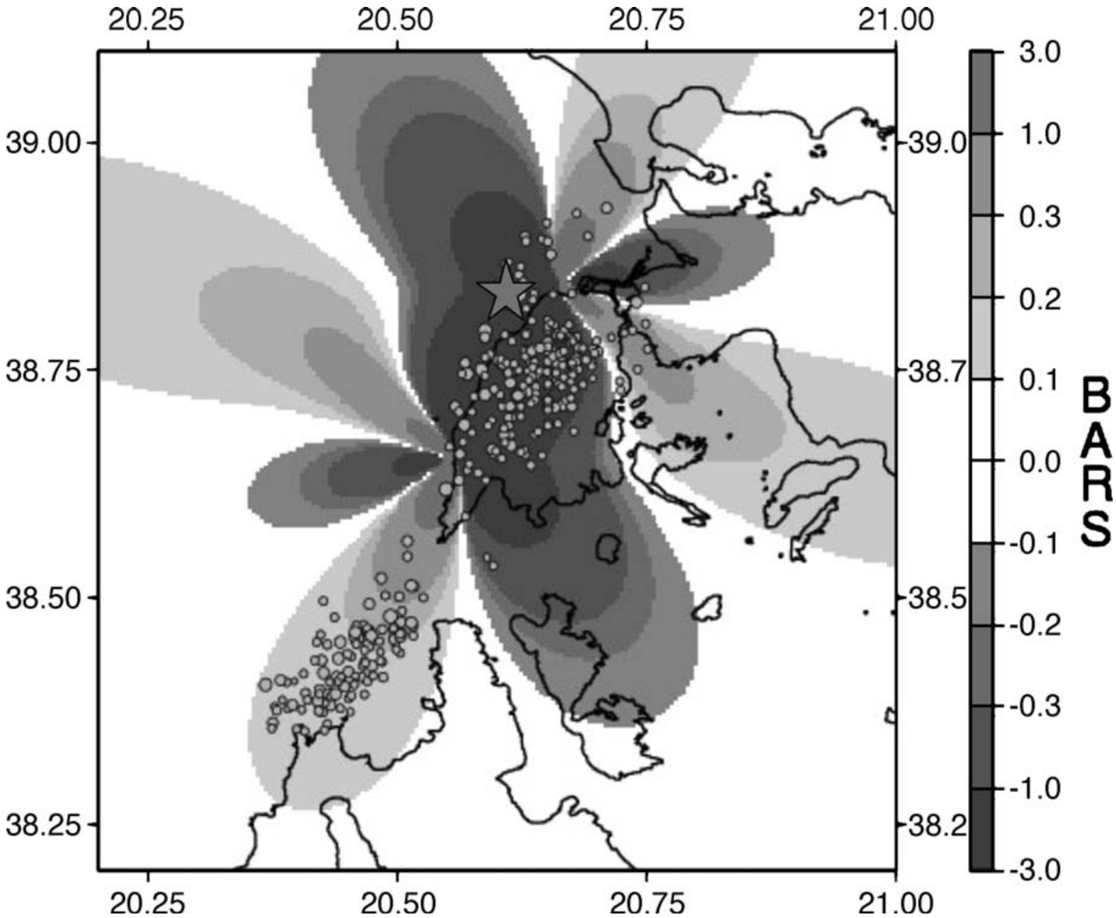

Figure 3. Static Coulomb stress changes caused by the 2003 Lefkada earthquake. The star represents the epicenter of this mainshock. Aftershocks are also presented (Papadimitriou et al., 2006).

The 17 November 2015 (M_w=6.4) Lefkada earthquake sequence

On 17 November 2015 (07:10 GMT) a destructive earthquake occurred along the SE coast of Lefkada Island, in the vicinity of Athani village. There were two fatalities, one due to rockfall and one caused by a paddock collapse. Eight people were injured, two of which children. Certain collapses, rockfalls and landslides have been reported.
The epicenter of the mainshock was automatically determined within 1-2 minutes after its occurrence by the Seismological Laboratory of the National and Kapodistrian University of Athens (NKUA-SL) and the automatic solution was promptly available online for the public (www.geophysics.geol.uoa.gr/stations/maps/recent.html). Manual analysis was later conducted for the mainshock and for more than 1100 aftershocks. In addition, an automatic event-detection and picking procedure, based on waveform similarity (Kapetanidis and Papadimitriou, 2011), was also applied to enrich the catalogue with a large number of highly correlated, smaller events.
The mainshock of 17 November 2015 resulted in a rich aftershock sequence of over 2600 events up to 3 December 2015. Hypocenters were determined using a local velocity model that was calculated for that purpose. The daily number of aftershocks is presented in the histogram of Fig. 4.

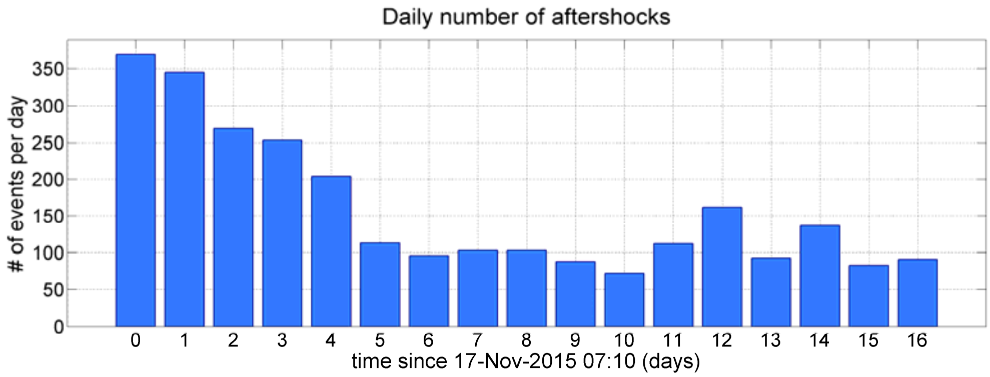

Figure 4. Histogram of earthquakes per 24 hr since the mainshock of 17 November 2015, 07:10 (GMT), up to 3 December, 2015.

Double-difference relocation was applied, using both catalogue and waveform cross-correlation data, to reduce errors caused by unmodeled velocity structure as well as arrival-time reading errors and to improve the relative location of spatially clustered events. The aftershock distribution (Fig. 5) spans ~65 km in length in a SSW-NNE direction, parallel to the western coast of Lefkada island with most of the epicenters located ~2-3 km onshore Lefkada while a second, spatially separated group of activity is spreading to the south, towards the N tip of Cephalonia island. The focal depths mainly range 5-10 km under Lefkada and 5-15 km for the southern spatial group. The activity of the southern group appears to be divided in smaller sub-clusters.

The strongest aftershock of the Lefkada 2015 sequence occurred on 17 November, 08:33 (GMT) with M_w=5.0, about 4 km SSW of the mainshock. On the following days, a few events with $M \geq 4.5$ occurred at various places along the aftershock region, including another M_w=5.0 event on 18 November offshore the northern coast of Lefkada island and an M_w=4.7 event on 20 November at the southernmost part (northern tip of Cephalonia island). The activity is mostly concentrated at the dense cluster in the middle of Lefkada and at the southern group, N of Cephalonia. The temporal distribution (Fig. 4) presents a relatively smooth exponential decay, with the exception of a small secondary outburst of activity on 29 November (day #12) at the dense cluster, including two events with $M\approx4$. The largest event that has occurred since 4 December is an M_w=4.2 event on 14 December near Preveza, slightly beyond the northernmost edge of the aftershock zone.

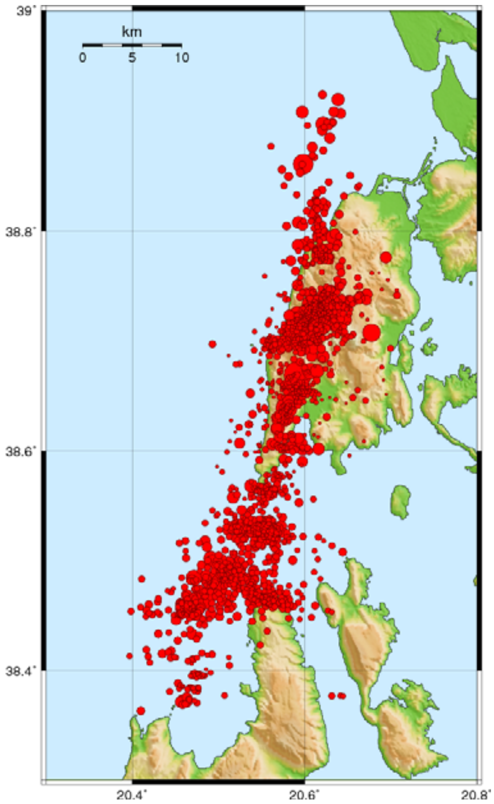

Figure 5. Relocated epicenters of the aftershock sequence in Lefkada island between 17 November and 3 December, 2015.

Regional moment tensor inversion was employed for the focal mechanism determination of the major events of the sequence. The frequency-wavenumber integration method (Bouchon, 1979, 2003) was used to calculate Green functions. Afterwards, synthetic waveforms are generated and compared with the observed ones for a given velocity structure, as described by Papadimitriou et al. (2012). The developed methodology was successfully applied (Papadimitriou et al., 2015) in the recently activated Santorini region, during the 2011-2012 seismic crisis (Kaviris et al., 2015).

The seismic moment of the mainshock was calculated $M_0=4.3\cdot10^{25}$ dyn·cm and the determined focal mechanism indicates dextral strike-slip type faulting with the fault plane oriented in a NNE-SSW direction ($\varphi=22^o$, $\delta=72^o$ and $\lambda=161^o$), (Fig. 6). Fault plane solutions of the 18 largest aftershocks have also been determined, indicating a similar type of faulting, and are published in the website of the Seismological Laboratory of the University of Athens (www.geophysics.geol.uoa.gr). The focal mechanism of an aftershock that occurred eight days after the mainshock is presented in Fig. 7.

The determined focal mechanisms, based on moment tensor inversion, revealed the activation of an almost vertical right-lateral strike-slip fault, in agreement with the SSW-NNE oriented CLTFZ. Preliminary results indicate that the dimensions of the activated fault, located between the main aftershock cluster in the central part of the island and the one that occurred SSW of Lefkada, are 25 km length and 10 km width.

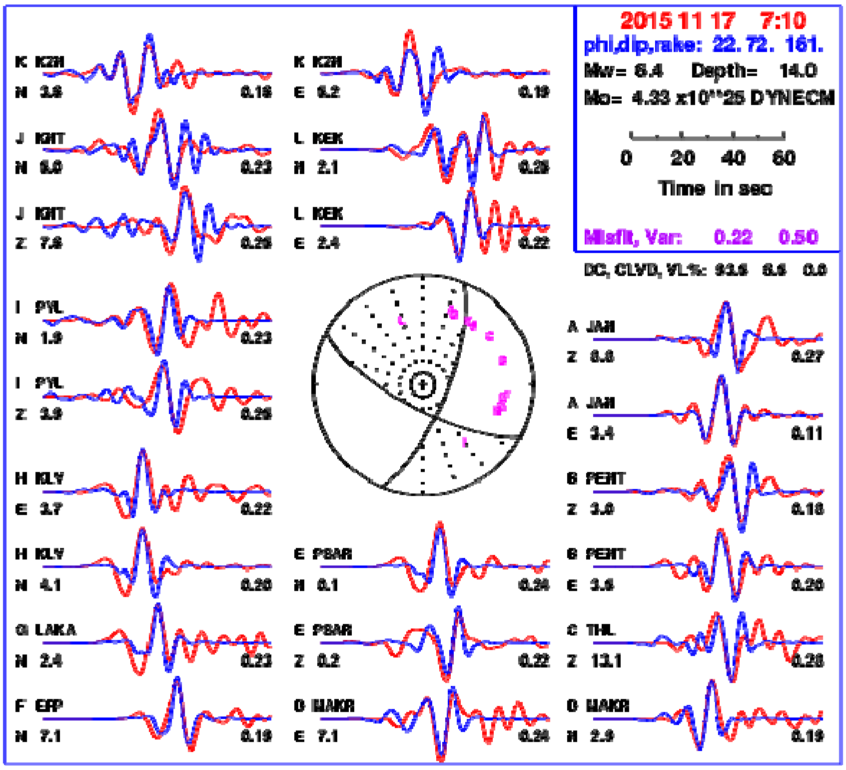

Figure 6. Source parameter determination for the 17 November 2015 Lefkada mainshock, using moment tensor inversion and recordings in local and regional distances. Red and blue colour lines represent the observed and synthetic waveforms, respectively.

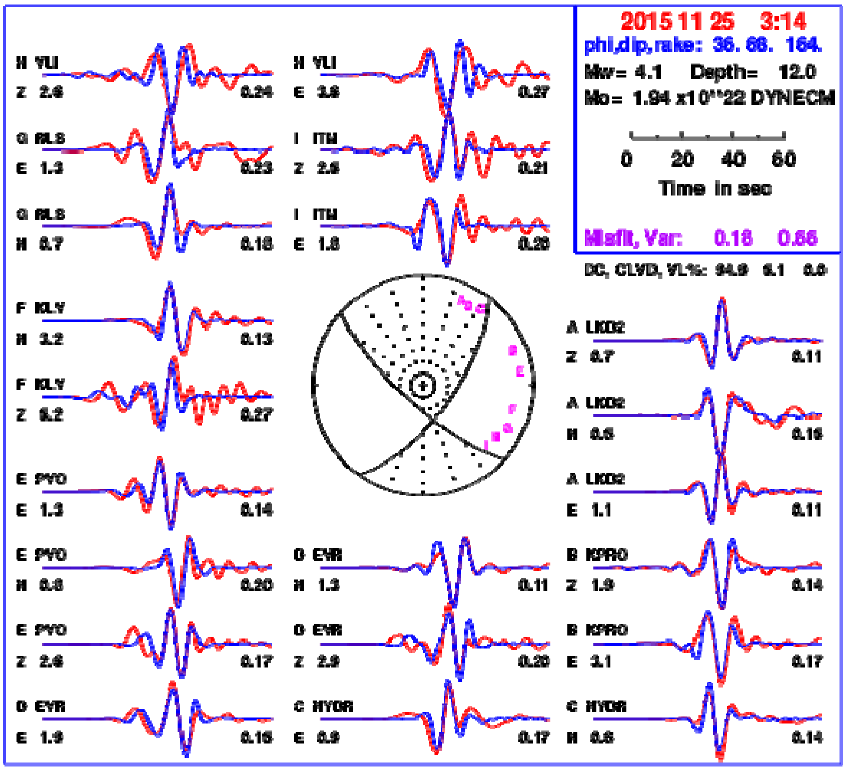

Figure 7. Source parameter determination for the a major aftershock that occured on 25 November 2015 in Lefkada, using moment tensor inversion and recordings in local and regional distances. Red and blue colour lines represent the observed and synthetic waveforms, respectively.

The 17 November M_w=6.4 Lefkada earthquake is located at the southwestern part of the island, in a region where a deficit of resolved aftershocks is observed. The aftershock sequence is characterised by the existence of several clusters. The most important one is located at the central part of the island. In addition, intense seismic activity occurred to the south, close to the NNW part of Cephalonia island. The majority of the determined focal mechanisms is related to a type of faulting which is similar to the one of the 2003 Lefkada earthquake. In addition, dextral strike-slip faulting was also revealed for the two earthquakes that occurred in Cephalonia during January – February 2014. The events located close to Lefkada island are related to the main tectonic feature of the area, the Cephalonia-Lefkada Transform Fault Zone, along which other significant earthquakes have occurred in the past, such as the 1983 Cephalonia earthquake.

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