The Efpalio 2010 earthquake sequence interpreted in terms of tectonics of the western Corinth Gulf

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New developements and Results on Seismotectonics

Abstract

This paper investigates the tectonics of the western Corinth Gulf based on the Efpalio 2010 earthquake sequence. The sequence lasted almost six months, and included two magnitude 5 mainshocks of normal mechanism. A unified seismotectonic model of the sequence was constructed, jointly interpreting the earthquake locations, moment-tensors and slip inversions in terms of possible activated fault planes. Previous studies demonstrated the prevailing microseismic activity to be related to a major low-angle, north-dipping structure under the Gulf. The Efpalio sequence basically confirmed such a general trend, but it clearly proved also the so far less recognized shallow activity, possibly connected with the relatively steep faults outcropping on the northern coast. The first mainshock had almost no on-fault aftershocks (i.e. no aftershocks on the ruptured part of the fault). Most likely it occurred on the south-dipping nodal plane. The early off-fault aftershocks formed two separate groups, both probably provoked by the Coulomb stress change due to the first mainshock, and deeper than the mainshock centroid. One of these groups represents a north-dipping structure at which the second mainshock took place, too. Later aftershocks mapped a relatively sharp spatial termination of the sequence towards north-east and south-east. The termination is marked by strike-slip mechanisms, proving a mixture of diverse tectonic elements on this part of the gulf. The SW-NE trending strike slip faults probably acted also as the surfaces along which the two mainshocks (of almost parallel faults), were displaced with each other. The sequence emphasized the role of the transfer faults in western termination of Corinth gulf, linking it with regional structures, such as the Trichonis and Rion-Patras fault system The very shallow parts of the faults (depths 0-4 km) were not activated, or the slip was aseismic there.

Tectonic Setting

Corinth Gulf (CG) is often referred to as a natural laboratory for the study of continental rift tectonics. It is considered as an asymmetric half graben, with high seismicity and rapid extension in N-S direction (Briole et al., 2000, Avallone et al., 2004). Main faults are located at the southern coast, trending WNW-ESE to E-W, and dipping steeply to the north. The extension along the gulf changes from ~5 mm/yr at the eastern part, to ~15 mm/yr at the western part. South dipping faults also exist in the CG, and, towards the west, these are considered to dominate the structural evolution of the Gulf (Bell et al., 2008; Stefatos et al., 2002). Besides the change in rift polarity, the western part of CG is important for its tectonic link with the Rion-Patras fault system (RPFS) to the south (Flotte et al., 2005) and the Trichonis lake fault system (TLFS) to the north, see Fig.1. The most prominent active fault in south cost of western CG, is the Psathopyrgos fault, while on the northern coast, the Marathias fault dips at about 55° to the south with a total length of 12 km (Gallousi and Koukouvelas, 2007, Balkaniotis, 2010). Besides normal faults with a general EW strike there is also a seismological evidence for active transfer faults connecting the major en echelon faults (Pacciani and Lyon-Caen, 2010, Zahradnik et al., 2004).

On January 18, 2010 (GMT 15:56) a moderate size Mw5.3 earthquake occurred near the town of Efpalio on the northern coast of the western Corinth Gulf. Almost immediately the seismic activity expanded ~5 km towards north-east where another event Mw5.2 occurred on January 22 (GMT 00:46). The two mainshocks were followed by an aftershock sequence which lasted for almost six months and spread as much as ~10 km westward and ~20 km south-eastward; Fig.1. To make the Efpalio 2010 earthquake sequence informative in the tectonic context of CG, we construct a unified seismotectonic model, jointly interpreting the mainshock and aftershock locations, moment-tensors calculations and slip inversions.

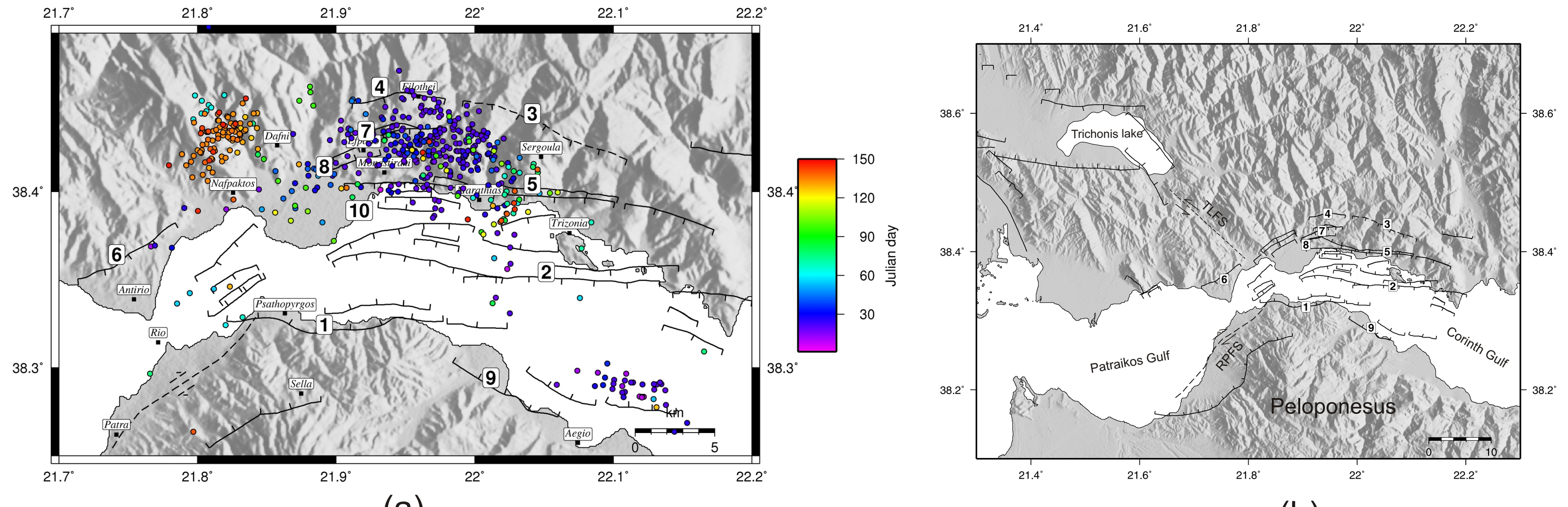

Figure 1. a)Western part of the Corinth Gulf and the Efpalio earthquake sequence (circles), from January to May 2010 (color scale refers to the Julian day). Major faults are shown: 1= Psathopyrgos, 2=Trizonia, 3=Trikorfo, 4=Filothei, 5=Marathia, 6=Antirio, 7=Drosato, 8=Efpalio, 9=Selianitika, 10=off shore fault related to Efpalio sequence and other on- and off-shore faults. Fault traces were taken from Valkaniotis 2009 and Papanikolaou et al.1997 b) the broader tectonic framework

Mainshocks

Using data from local and regional seismic stations, e.g. Hellenic Unified Seismic Network (HUSN), Corinth Rift Laboratory network (CRLNET), combined with data from a temporal installation of six seismic stations the seismicity was accurately located. Moreover data were used for slip inversion of the mainshocks and moment tensor inversion of major aftershocks.

A two-step relocation of the two mainshocks (M1, M2) was selected. During the first step regional stations (up to ~70 km distance) were used to locate the epicenter, while, in the second step, the epicenter was held fixed, and the depth was grid searched to minimize the residuals at near stations only. The mainshock hypocenters determined in this way are listed in Table 1 and plotted in Fig. 2 and Fig. 3 (epicenters A and A', for M1 and M2, respectively). Alternative solutions with omission of a few stations and azimuthal weights are denoted B and B'. Furthermore, for the M1 event, relocation was done also using a foreshock, which occurred 25 seconds before the main event. Thanks to its small magnitude (2.5ML), unclipped P- and S-waves were available at near stations, whose readings strongly constrained the foreshock depth at 6km. Using the foreshock residuals at near-stations as station corrections for the M1 mainshock, we located M1 at the depth of 5.9 km, close to the above two-step result (Fig.2, epicenter D). The two-step approach was selected because the use of regional stations (which are useful for correct epicenter position thanks to their good azimuthal coverage) shifted hypocenter towards larger depths (8-11km). The depth bias was confirmed by comparing with depths derived from the moment tensor inversion of strongest aftershocks. Comparing solutions A to D for M1 and A' to C' for M2 (Fig. 2), we obtain a rough estimate of the possible location bounds.

Table 1. Hypocenters and centroids of the two mainshocks.

	(H) hypocenter	H-depth (km)	(C) Centroid	C-depth (km)	Mo (Nm)	Mw	NP1 strike°	NP1 dip°	NP1 rake°	NP2 strike°	NP2 dip°	NP2 rake°
Jan 18 2010 15:56	38.4198 21.9153	6.6	38.42201°N 21.94160°E	4.5	0.97e17	5.3	102	55	-83	270	36	-100
Jan 22 2010 00:46	38.4295 21.9622	8.0	38.43099°N 21.96444°E	6	0.70e17	5.2	78	40	-108	282	52	-75

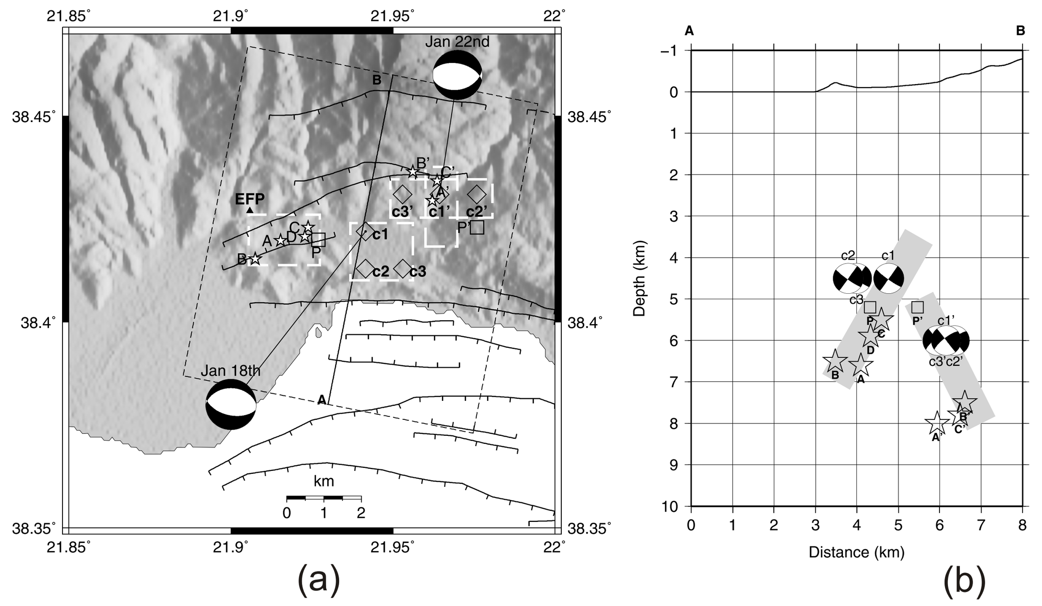

Figure 2. Hypocenters and centroids of the two mainshocks. The solutions listed on Table 1 (hypocenters A, A' and centroids C1, C1' for M1 and M2, respectively) are shown, also a few alternative positions inside the solution bounds (dashed white rectangles). Open squares P and P' mark the patches from the slip inversion. a) map view, b) vertical cross-section N10°E. The gray strips in cross section schematically demonstrate the likely fault planes.

Aftershocks

Two datasets of aftershock locations are presented i) the strongest aftershocks of the sequence (M>~3.5) for the period 18th of January to 17th of February 2010 (125 events), and ii) smaller events (M~2.5), using stations at epicentral distance up to 20km, for the 19th and 20th of January only (96 events). The first dataset was used in order to capture the overall sequence evolution, while the second one was used for enhanced location accuracy and for checking the aftershock distribution related to M1 event. Initial location was performed using Hypoinverse code using the gradient crustal model of Latorre et al., 2004. Furthermore, the HypoDD method (Waldhauser, 2001) was applied. The HypoDD processing included also the two mainshocks, M1 and M2. Their epicenters were found within 1 km relative to those of Table 1, but the hypocenter depth of M1 was ~3 km deeper. The reason is the inadequacy of the crustal model leading to biased depths when location has to rely on near and distant stations simultaneously. Therefore, the HypoDD depths for events with small number of near-source picks were shifted by ~3-km upwards.

To further justify the 3-km common upward shift of the aftershocks, we analyzed centroidal depths from 30 aftershocks (M>3.1). For small events the centroid and hypocenter are close to each other, but the MT depth may often be more reliable than the location depth. It is because the relatively low-frequency MT inversion is less sensitive to the adopted crustal model and enough sensitive to depth (Zahradnik et al., 2008). The comparison showed that, indeed, the MT depths were systematically shallower than the HypoDD depths, on average by 3.4km. Furthermore, event location depths obtained using local stations only and depths from MT inversion agree very well (~1km difference) providing a further argument for upward shift of events not having enough picks for local stations (e.g. events that occurred during 18th and 19th of January).

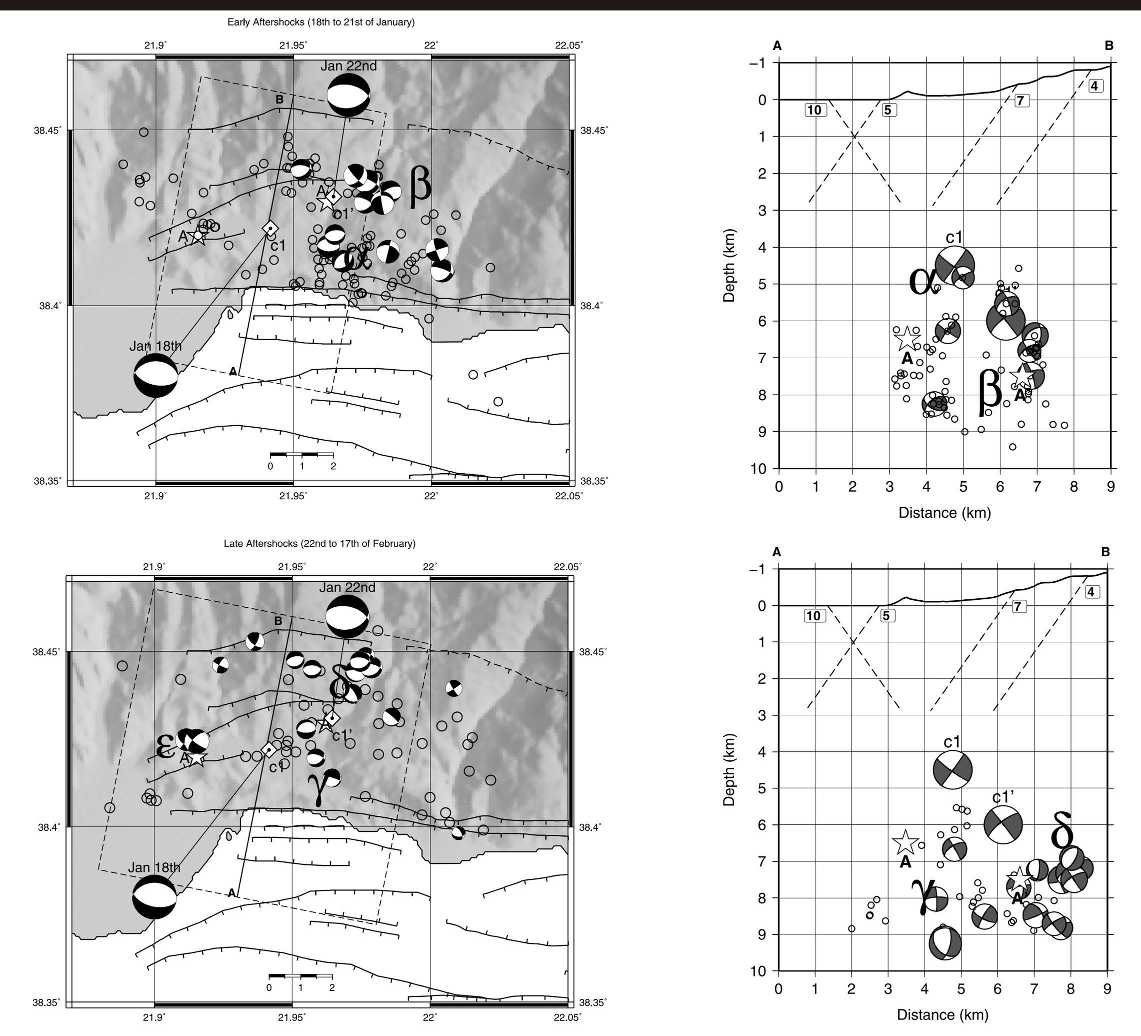

Figure 3. Aftershocks and (selected) focal mechanisms: a) map view, b) cross section N10°E. Both the map view and the cross section are presented separately in two panels, one for early aftershocks, denoted α and β (between the occurrence of M1 and M2), and the other for later aftershocks, denoted γ, δ and ε (after M2, up to February 17th).

Synthesizing seismological data

Here we combine diverse parameters of the Efpalio 2010 sequence, namely hypocenters, centroids, and focal mechanisms, including the two mainshocks and their aftershocks. The intention is to build-up a possible unified seismotectonic model of the sequence in terms of the likely fault planes.

The M1 and M2 fault planes. The H and C positions are discussed from the purely geometrical viewpoint of the H-C method (Zahradnik et al., 2008). The comparison of the alternative hypocenter and centroid positions of the M1 event favor the south-dipping fault plane (strike 102°, dip 55°), while M2 seems to be related rather with the north-dipping plane (strike 282°, dip 52°).

Early aftershocks of M1 (up to occurrence of M2). As seen from Fig.3a close to M1 centroid there are just few events. Size of such a 'gap' is in rough agreement with the assumed fault size ~4x4 km (Somerville et al., 1999). Thus M1 can be interpreted as a relatively simple rupture, generating almost no on-fault aftershocks. The early aftershocks occurred preferentially in two groups, south-east (α) and north-east (β) of M1.The south-east group fits with the M1 interpretation in terms of the south-dipping plane (Fig.3b). These aftershocks are probably situated off the mainshock rupture, although geometrically lying on the same plane; otherwise the mainshock rupture plane length would be too large ~ 6km. This cluster, as well as a smaller group of events to the west, close to M1 epicenter, could mark the east and west ends of the ruptured fault plane and might have been triggered by the stress change at the mainshock fault edge. The north-east group (β) clearly clustered close to place where (later) the second mainshock M2 occurred.

Later aftershocks (up to February 17th). Interpretation of aftershocks occurring after M2 is difficult. It can hardly be made in terms of the individual mainshocks, since both M1 and M2 might have contributed. But what is well seen from the map view (Fig.3b) is the sharp termination of seismicity to the west (close to cluster (ε)), which is also marked by a series of the strike-slip mechanisms. These strike-slip mechanisms seem to mark a boundary at the west of the sequence with a NNE strike. Finally, during this later phase of the sequence the existence of a sub parallel surface at the depth of 8-9km is marked by seismicity and focal mechanisms. This is most probably connected with the detachment zone proposed by Rigo et al. (1996), or with the brittle-ductile transition zone according to Hatzfeld et al. (2000).

Conclusions

We arrived at the following scenario of the studied part of the sequence (January 18th to February 17th). The first mainshock (M1) had almost no aftershocks close to the main ruptured region. The relative position of the hypocenter and centroid, as well as the spatial distribution of the early aftershocks indicate that M1 ruptured a south-dipping plane. The early aftershocks formed two separate groups, both likely provoked by the Coulomb stress. Group (β) Fig. 3b, represents a north-dipping structure at which, later, the second mainshock (M2) occurred. After the occurrence of M2, seismicity started to spread out of the M1-M2 focal area. The sequence termination towards north-east and south-east is marked by strike-slip mechanisms, illustrating effect of the faults striking in the SW–NE direction.

These deep structures, based solely on seismological data, may be related to mapped surface traces of faults. For example, if we upward extrapolate the constant fault dip to the surface, the surface trace for the south dipping fault of M1 is very well correlated with the Trikorfo-Filothei south dipping fault (no.4 in Fig.1). Similarly the causative fault for M2 is located offshore (no.10 in Fig.1).

This interpretation can be compared with other models for Western Corinth gulf, e.g. Rigo et al, 1996. The comparison is included in Fig.4 and it shows that the 2010 Efpalio sequence did not significantly deviate from the general trend, except one important aspect: this sequence clearly proved also a shallower activity, possibly related with the relatively steeply dipping surface faults. The deeper part of the Efpalio sequence correlates nicely with a almost flat structure at the depth of ~8 km. In the regional scale (Fig.1b) the most important is the displacement of parallel normal faults, by strike-slip faults (while the latter also affected the sharp spatial termination of the activity). All this pattern seems to fit well in a regional tectonic system, demonstrated in Fig.1b.

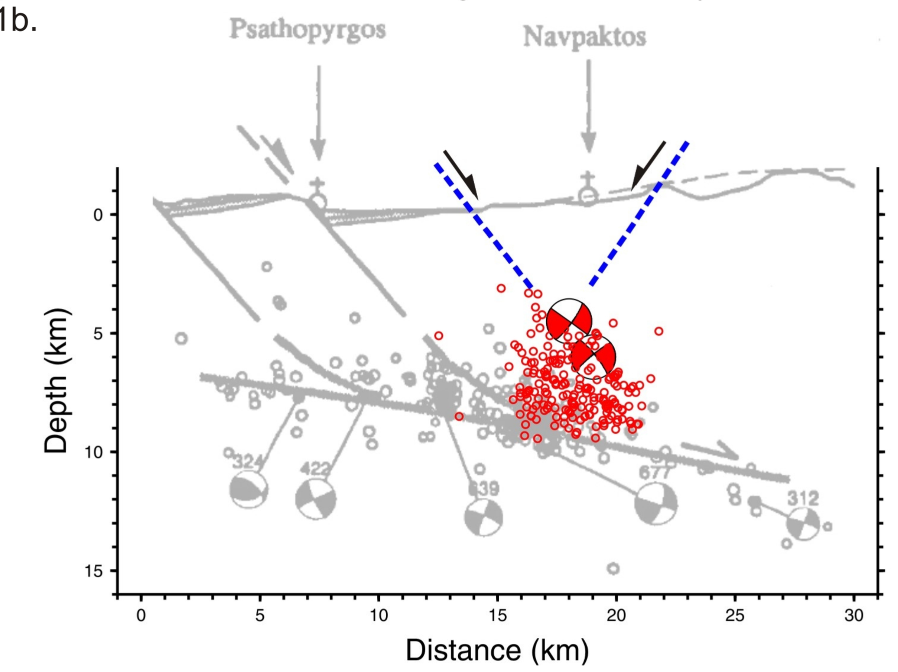

Figure 4. Comparison of the Efpalio sequence with the previously reported seismic activity and the major north-dipping structure under the Corinth Gulf. The plot superimposes our data with Fig.12 of Rigo et al., 1996. It shows that the Efpalio sequence did not deviate from a general trend of seismic activity below the Gulf, but it emphasized a link with shallower, more steeply dipping fault structures of the northern coast.

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