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Preliminary results from the study of a seismic swarm occurred in February 2008 in NW Peloponnesus, Greece

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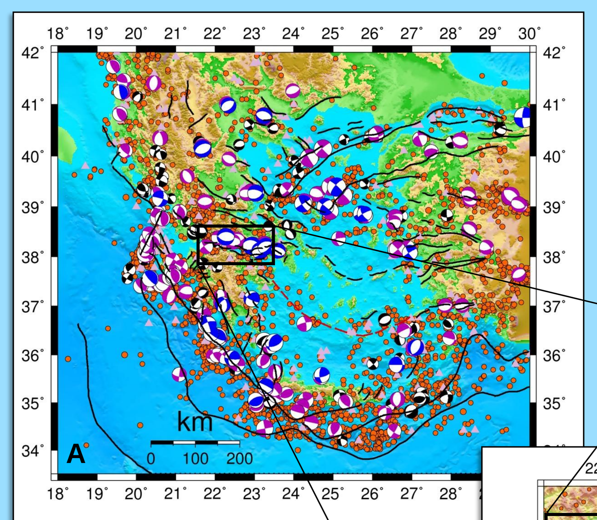
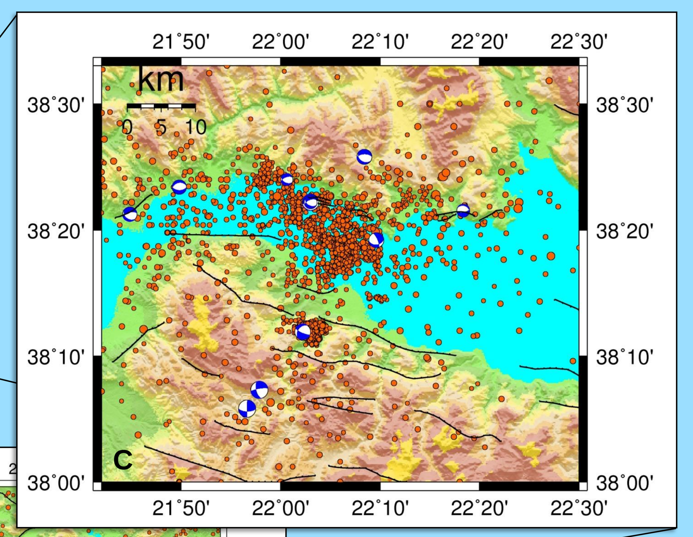
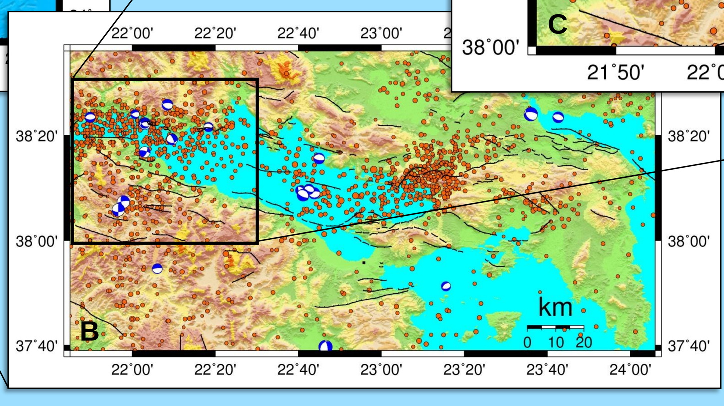
ABSTRACT

On February 4th, 2008, two moderate earthquakes, with moment magnitudes 4.7 and 4.5 respectively, triggered a seismic swarm in NW Peloponnesus, Greece. The epicentral area is close to the Chalandritsa fault which is located in the transition between the normal faulting zone of the southern Corinth rift and a strike-slip faulting zone which characterizes NW Peloponnesus. In this work we present a preliminary relocation of this earthquake sequence using the double-difference method. The focal mechanisms of the two major events were studied with a recently developed methodology based on the generalized inversion, using the singular value decomposition technique. Waveforms from local stations were used and the fit between data and synthetics is well constrained. The relocation reveals two separate main clusters within the swarm, with approximate direction NNW-SSE that is in agreement with the calculated fault plane solutions which indicate a strike-slip type fault. This direction is almost perpendicular to the well-known E-W active normal faults of the area. During the analysis of the data recorded by the LAKA station, the shear wave splitting phenomenon was observed for the events that fulfill the selection criteria. The direction of anisotropy, the time delay between the two split shear waves and the polarization direction of the source were estimated. This swarm was followed by a strong M_w=6.4 earthquake, 4 months later, at about 45km WSW.

INTRODUCTION







Two main fault systems, the Hellenic Trench and the North Aegean Trough, dominate the Eastern Mediterranean, while the majority of the seismicity is located along these tectonic zones. In the above figure focal mechanisms of large (M≥5.8), intermediate (4.5<M<5.8) and small earthquakes (M≤4.5) are presented with blue, purple and black color, respectively. Earthquakes with magnitude greater than 6 for the time period 1900-2008 are shown with purple triangles in Fig. 1_A.

Figure 1: Seismotectonic map of: A) Greece, B) Corinth Gulf broader area, C) western Corinth Gulf.

The Corinth Rift in Central Greece is one of the most seismically active regions in Europe. It is characterized by normal faulting in an approximate E-W direction. The longest active tectonic zone in Greece, known as the Hellenic Arc, is a subduction zone which starts W of Zakynthos island, proceeds SE past Peloponnesus and S of Crete. In NW Peloponnesus, in the area between the Corinth Rift and Zakynthos island, there is a transition zone of dextral strike-slip faulting. A M6.5 earthquake struck this very region on 8th June 2008, close to the city of Andravida. According to the calculated focal mechanisms and in agreement to the field data, that earthquake had a SW-NE direction and was a pure dextral strike-slip.

Four months before the occurrence of the Andravida earthquake, on February 4th 2008, two moderate earthquakes ~M4.6 triggered a seismic swarm about 40km NE of the epicenter of this event. A known normal fault in the vicinity of the epicentral area is the Chalandritsa fault. It is interesting that the calculated focal mechanisms of the 2 main events of this swarm show dominant strike-slip. The fault plane possibly has a N-S strike. Under this consideration the rupture was a sinistral strike-slip. This is not in agreement with the well-known normal faults of the area which have a dominant E-W strike, thus it is an interesting case of transition between normal and strike-slip faults.

WAVEFORM CROSS-CORRELATION / COHERENCE

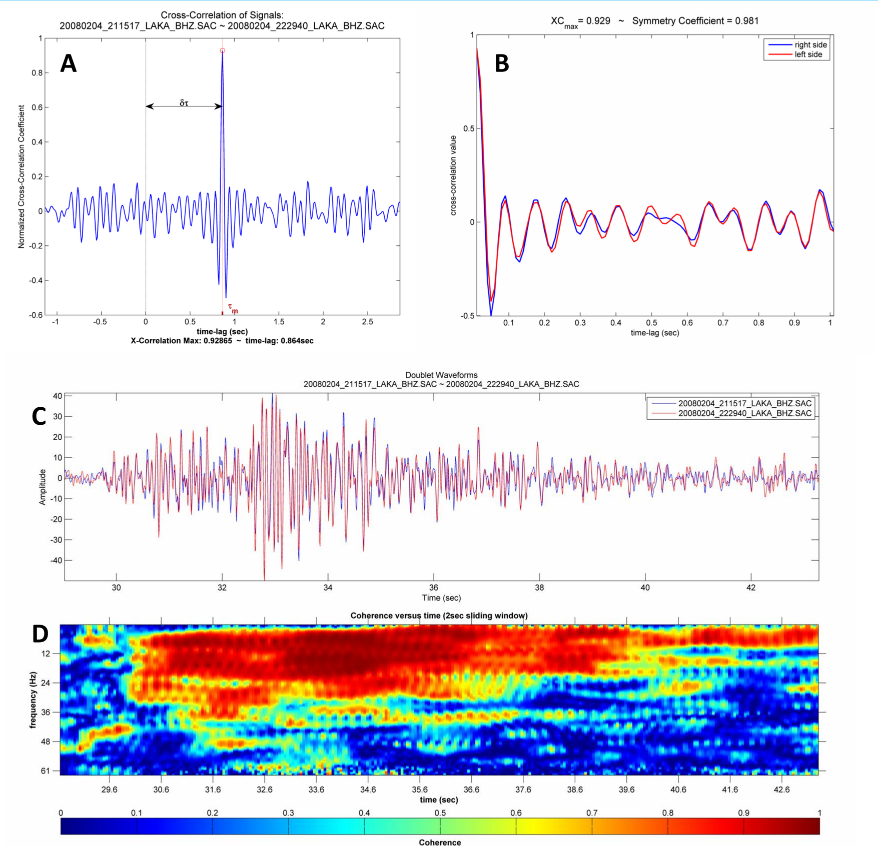


Figure 2: A) Cross-Correlation function, B) Symmetry of Cross-Correlation, C) Doublet waveforms, D) Spectral Coherence versus time.

The LAKA station, installed by the University of Athens, is located about 15km N of this earthquake swarm. The relatively small distance of this station permits the detection of many microearthquakes within the swarm, most of which occur in small volumes and consist multiplet clusters. Such microearthquakes have similar seismic parameters and thus produce similar waveforms when recorded at a station on the surface.

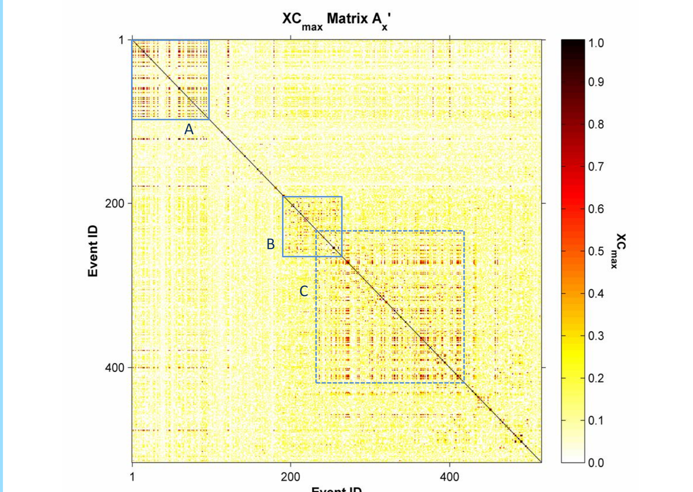


Figure 3: The Cross-Correlation Matrix.

The maximum value of the cross-correlation function of waveform pairs (Fig. 2_A) provides good means to estimate the similarity between waveforms that have been recorded by the same station and component. The mean spectral coherence between pairs of waveforms is another way to measure similarity. In Fig. 2_D it is shown that strong coherence between earthquake doublets appears in a limited band of frequencies. This means that the waveforms must be properly filtered, in order to permit the cross-correlation to provide valid results in the time domain. In this case band-pass filtering between 2-20Hz seems appropriate.

Fig. 3 presents the Cross-Correlation matrix. Each pixel represents an event pair, the color shows the value of the waveform Cross-Correlation maximum, $\mathbf{XC_{max}}$, of the corresponding pair of events. Each row or column represents the Event-ID which increases downwards and rightwards, from the oldest to the latest event. Event pairs with high $\mathbf{XC_{max}}$ are mainly concentrated inside the boxes A, B and C. This result shows a clear existence of at least 3 separate earthquake groups, each of which consists of smaller multiplet clusters. Earthquakes in each square are generally similar to each other but earthquake pairs outside these squares are not. These groups also appear to be temporally separated from each other.

MULTIPLET CLUSTERS

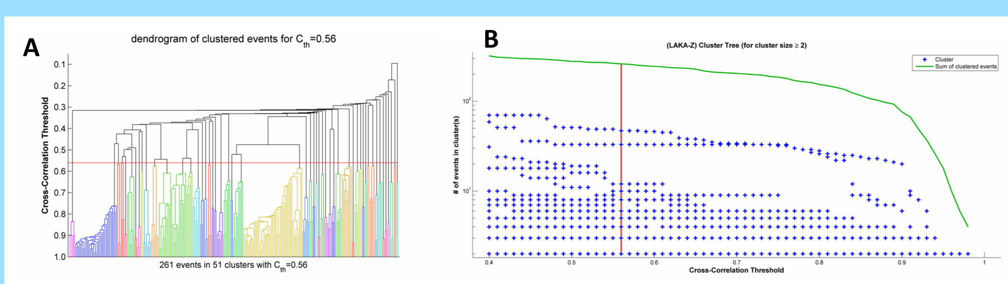


Figure 4: A) Dendrogram of clustered events with the 'nearest neighbor' linkage. B) Clusters size (blue crosses) and sum of clustered events per threshold (green line). Red line depicts the optimum threshold.

After the construction of the cross-correlation matrix, events are grouped in multiplet clusters. A dendrogram is constructed (Fig. 4_A) by using the 'nearest neighbor' clustering algorithm. Depending on the threshold value, $\mathbf{C_{th}}$, different groupings of events can be created. For a certain cross-correlation threshold value, the difference between the sum of clustered events and the size of the largest cluster is maximized. This is considered as the optimum threshold for the available data and in this case is $\mathbf{C_{th}=0.56}$ (red line in Fig. 4_B)

A total of 261 events out of 515 are found inside clusters of two or more events for this threshold. The largest cluster has a size of 47 events, with cluster-ID (CLID) 27, and is the cyan colored one in Fig. 5. Waveforms of 3 events from this cluster are shown there, while in Fig. 6_A more waveforms from the same cluster can be seen and compared to each other.

CLID 17 is a cluster formed during the time period between the two major shocks. Waveforms can be seen in Fig. 5 on the left and in Fig. 6_B. Although the horizontal distance from CLID 27 is only 5km, there is a significant difference between their waveforms, as well as in the P/S amplitude ratio. CLID 31 (Fig. 5, at the right) is closer to CLID 17 than CLID 27, however their waveforms are dissimilar enough to be grouped in different clusters.

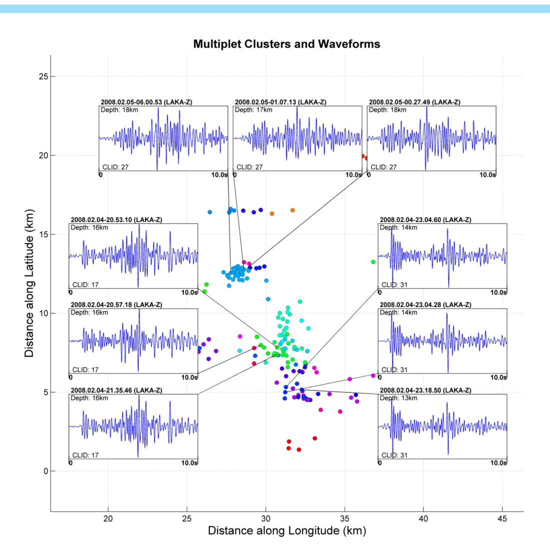


Figure 5: Epicenters of clustered events from the swarm of February 4th in NW Peloponnesus, after relocation. Different colors represent different clusters. Each cluster is characterized by an ID. Three waveforms from each of the three largest clusters of this swarm are displayed, CLID 27 being the largest and most spatially dense. P-waves are weak in CLID 27, getting stronger for earthquakes belonging to more southern clusters. Clusters in the middle such as CLID 17 are mainly formed in the time period between the two major shocks which corresponds to the box B shown on the cross-correlation matrix (Fig. 3).

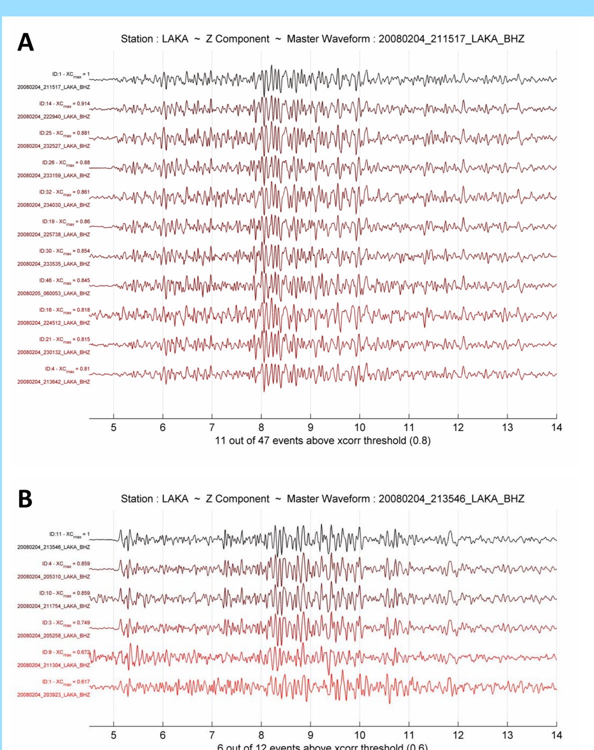


Figure 6: Comparison of multiplet waveforms: A) from Cluster ID 27 (largest cluster), B) from Cluster ID 17. Waveforms in each subfigure are cross-correlated to the top one. The cross-correlation maximum, $\mathbf{XC_{max}}$, is shown on the left of each trace. All waveforms are band-pass filtered between 3-15Hz.

The clustering procedure is a part of qualitative analysis. It helps on the mapping of event groups with different characteristics, such as horizontal location, depth and focal mechanism, no matter how close they appear to be. By using a threshold we can also minimize the process time needed for the calculation of cross-correlation data for the relocation procedure, as only known pairs of similar events have to be correlated.

RELOCATION & SPATIO-TEMPORAL DISTRIBUTION

The double-difference method, implemented in the HYPODD algorithm, was adopted in order to relocate hypocenters. Catalog as well as Cross-Correlation differential time data were used in order to achieve the best possible results. Earthquakes with similar waveforms are bound together in small multiplet clusters.

The preliminary results of the relocation process reveal two spatially separated groups of events within the swarm and another cluster to the NNE of the swarm, west of AIO station (depicted with red color in Fig. 7). The temporal sequence shown in Fig. 8 reveals the existence of foreshocks of the second major event ($\mathbf{EQ_2}$) during the time-period **B**, right after the occurrence of the first major event ($\mathbf{EQ_1}$). Activity around $\mathbf{EQ_1}$ appears to be triggered by $\mathbf{EQ_2}$. Hypocentral depths vary between 15-19km.

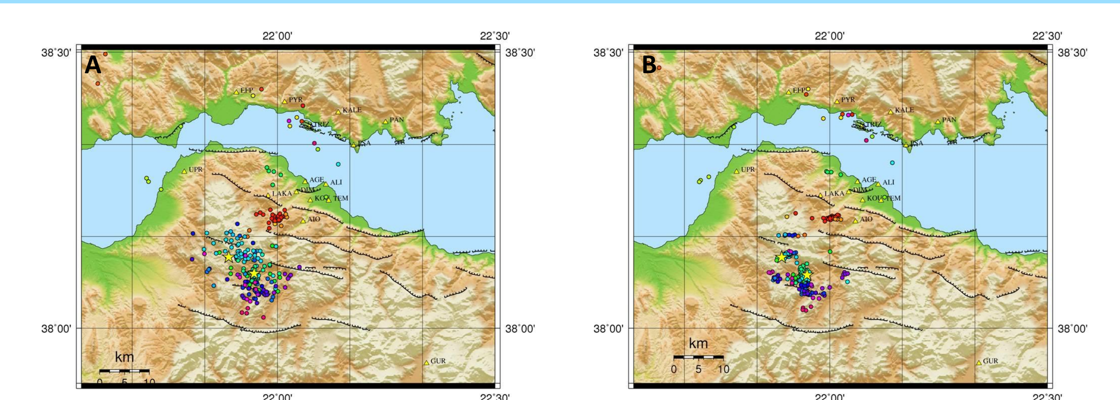


Figure 7: Multiplet Clusters: A) before relocation, B) after relocation. Colors represent different clusters. The major events are depicted as yellow stars

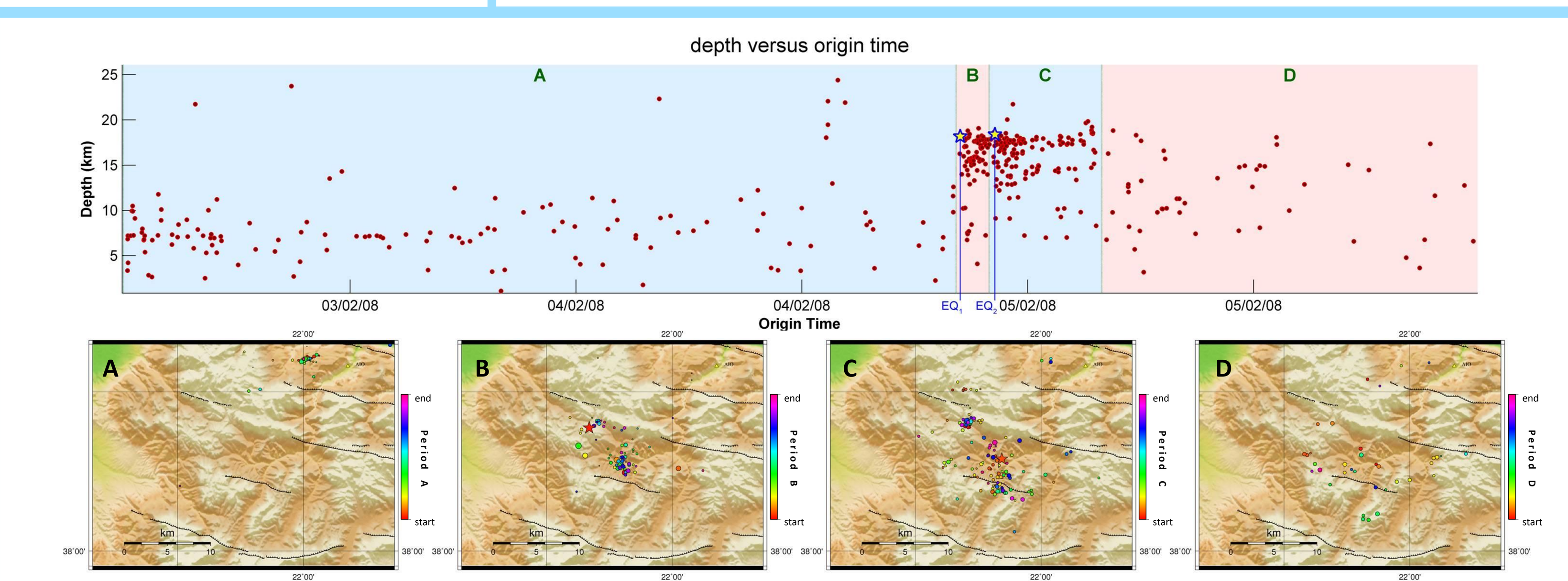


Figure 8: Temporal sequence of events: A) before $\mathbf{EQ_1}$, B) between $\mathbf{EQ_1}$ and $\mathbf{EQ_2}$, C) sequence after $\mathbf{EQ_2}$, D) dispersed background seismicity afterwards. Color of epicenters represents origin time.

FOCAL MECHANISMS - MODELING

The first major event of February 4th 2008 occurred at 20:25GMT, located at 38.13°N, 21.89°E. The second one occurred at 22:14GMT and was located at 38.09°N, 21.95°E. In order to calculate the source parameters of the two events, synthetic seismograms were generated using a discrete wavenumber method in regional – local distances. This methodology is based on the generalized inversion using the singular value decomposition technique.

The used waveforms were recorded by local stations of the University of Athens, as well as by stations of the CRL, NOA, UPSL and AUTH networks. The selected records were instrumentally corrected and, following, integrated to produce displacement waveforms. The data were band–pass filtered between 0.02 – 0.1 Hz. Finally, the horizontal N-S and E-W components were rotated to produce SV and SH components.

The source parameters of the first event were calculated using KALE, LAKA, TRIZ, KEK, ITM, LTK and APE stations. The best fit was found for a hypocenter at the depth of 15km and the calculated seismic moment is 1.2 • 10^{23} dynes • cm. The inversion indicates a strike-slip type faulting with the focal planes oriented in roughly N-S (φ=351°, δ=78°, λ=-36°) and E-W (φ=90°, δ=55°, λ=-165°) directions, respectively (Fig. 9).

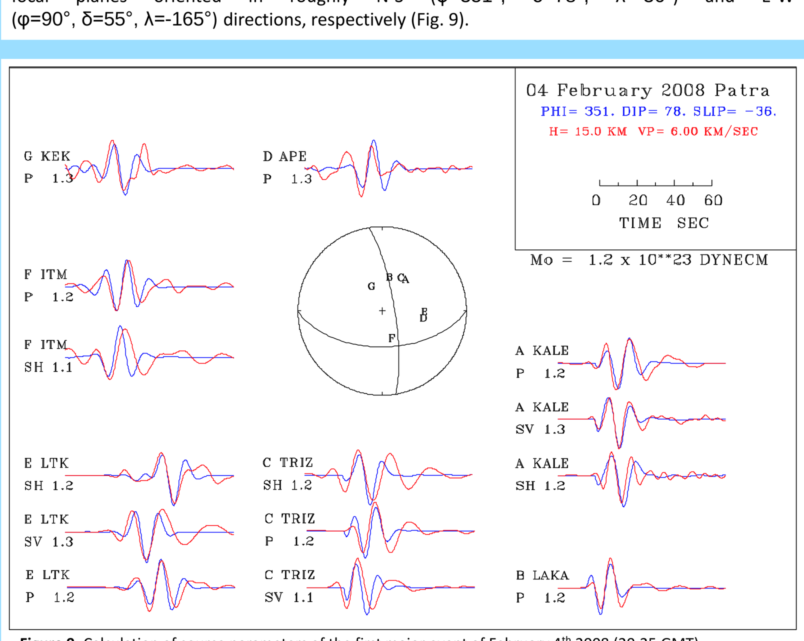


Figure 9: Calculation of source parameters of the first major event of February 4th 2008 (20:25 GMT)

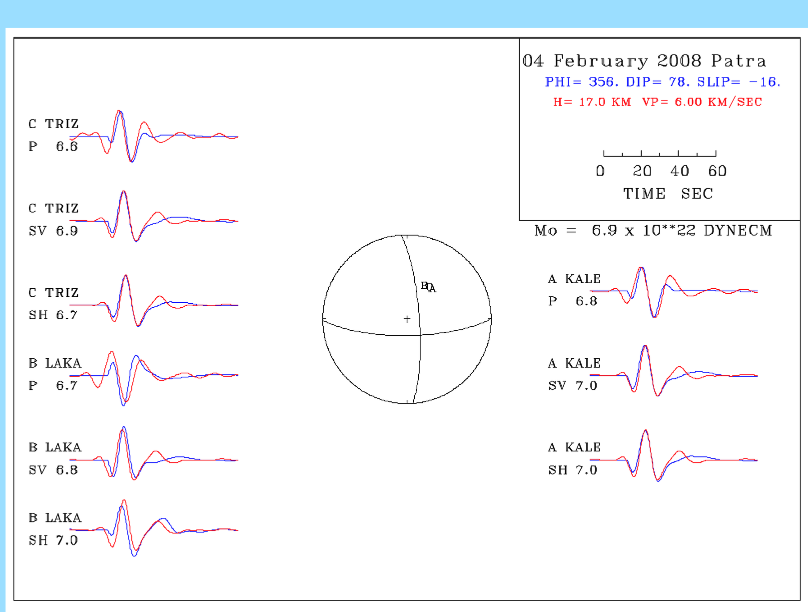


Figure 10: Calculation of source parameters of the second major event of February 4th 2008 (22:15 GMT)

The source parameters of the second event were calculated using only the stations KALE, LAKA, TRIZ. The best fit was found for a hypocenter at the depth of 17km and the calculated seismic moment is 6.9 • 10^{22} dynes • cm. The inversion indicates a type of faulting similar to the first major event, with the focal planes oriented in approximately N-S (φ=356°, δ=78°, λ=-16°) and E-W (φ=90°, δ=74°, λ=-167°) directions, respectively (Fig. 10).

These focal mechanisms are different from the one calculated for the main shock of the April 2001 swarm that occurred close to the AIO station, about 12km NE of the swarm of the present study, and indicated a normal fault in a NE-SW direction with a small strike-slip component.

The region is characterized by normal faults, striking in an almost E-W direction and dipping North, while some south-dipping antithetic normal faults are also present. However, the two recent earthquakes indicate a different type of faulting (strike-slip) which is observed for the first time in this area. On the contrary, the NW part of Peloponnesus is characterized by similar type of faulting, as in the case of the Andravida 2008 large earthquake.

ANISOTROPY STUDY – LAKA STATION

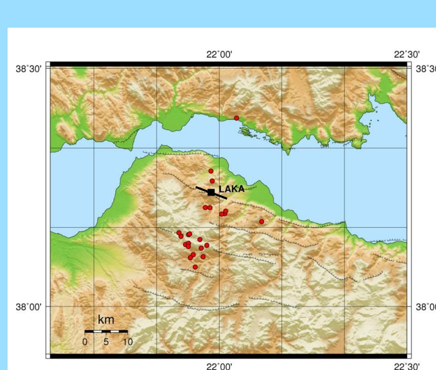


Figure 11: Selected events for the anisotropy study at LAKA station and mean polarization direction (N110°)

The analysis of earthquakes of the 3-5 February 2008 sequence in NW Peloponnesus that were recorded by the LAKA station revealed the existence of shear-wave splitting. For this station, 23 events were used for the anisotropy study (Fig. 11). The angles of incidence of these events vary between 13° ≤ i_h ≤ 43° while their azimuthal range is 118° -351°, with the 87% of the events having azimuths between 142° and 225°.

Fig. 12 presents an earthquake recorded by the LAKA station where a band-pass filter in the frequency range 0.1-25 Hz was used. The event occurred on 3/2/2008 01:02 GMT, with an azimuth equal to 206° and an angle of incidence equal to 38°, within the shear-wave window. The angle between the north and the fast axis direction is the polarization direction, which is equal to N103°, as shown in Fig. 12_A. Then the seismograms are rotated in the fast and slow direction and the obtained polarigram and hodogram are presented in Fig. 12_B. In this Figure the obtained polarization vector is oriented almost parallel to the fast component. The measured time delay is equal to 0.070 sec and is removed (Fig. 12_C) in order to obtain the polarization direction of the source, which is equal to N160° (Fig. 12_D).

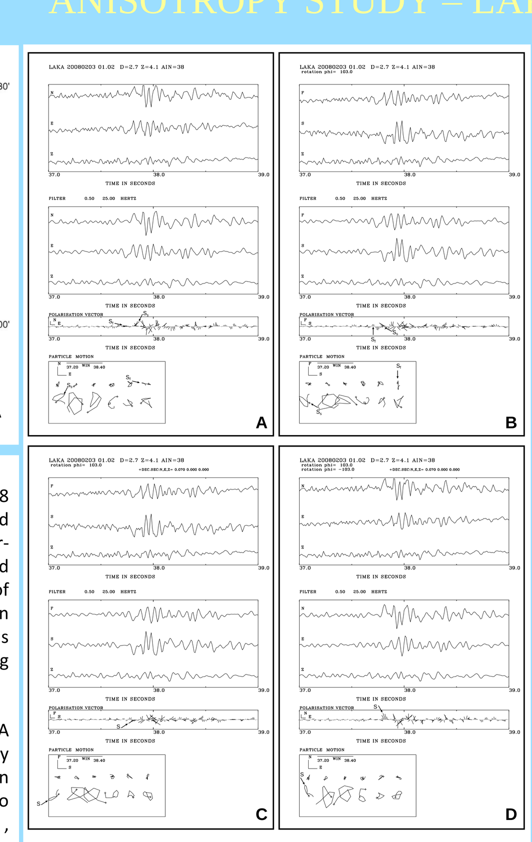


Figure 12: (A) Original traces of three component seismograms of an earthquake recorded at LAKA station, filtered traces, polarigram and hodogram in the north-east plane. (B) Traces rotated parallel and orthogonal to the polarization direction of the fast shear waves, filtered waveforms of the rotated traces, polarization vector and hodogram in the fast-slow plane where the time delay is measured. (C) Traces rotated parallel and orthogonal to the polarization direction of the fast shear waves after the correction of the time delay, filtered waveforms, polarigram and hodogram. (D) Traces rerotated to the North and East directions, filtered waveforms of the rerotated traces, polarization vector and hodogram from which the polarization of the source is estimated.

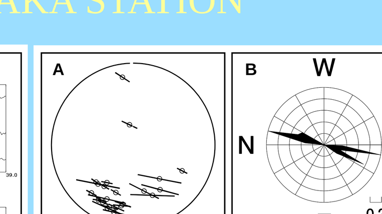


Figure 13: (A) Polar equal-area projections on the upper hemisphere of the fast shear wave polarizations at LAKA station. The length of the bars is proportional to the time delay of each event and the circle represents an angle of incidence equal to 45°. (B) Rose diagram of the fast shear wave polarization directions at LAKA station.

Figure 14: Polar equal-area projections on the upper hemisphere of the source polarization directions for events recorded by the LAKA station

The S_{fast} polarization directions for the selected events regarding LAKA station are presented in Fig. 13_A, using equal-area projections of the upper hemisphere. The outer circle defines the S-wave window and represents an angle of incidence of 45°. The length of the bars is proportional to the time delay between the fast and slow shear waves. The values of the time delays at LAKA station vary between 0.020sec and 0.080sec. It is important to notice that the time delays before the occurrence of the first major shock vary between 0.060 and 0.080 sec, while afterwards between 0.020 and 0.030 sec (with one exception of 0.040 sec). This decrease clearly indicates a change of the medium's properties after the occurrence of the first major event. The polarization directions of the fast shear wave for all the analyzed events vary between N92° and N125°.

The rose diagram for all the selected events at the LAKA station is presented in Fig. 13_B. Two main S_{fast} polarization directions of N100° and N120° are observed, with a mean value equal to N110°±2°, as presented in Fig. 11. It is worth noticing that in a previous anisotropy study performed for the LAKA station using events recorded during the year 2000, similar directions (main N123°, secondary N100°) were measured.

From both equal-area projections and rose diagrams, the coherence of the fast shear wave polarizations at LAKA station, irrespective of the azimuth of each event, is consistent with the general NNE-SSW direction of extension of the Gulf of Corinth and, therefore, in agreement with the Extensive Dilatancy Anisotropy (EDA) model.

The source polarization directions are presented in Figure 14. Concerning the events located S of the station, different orientations are obtained for each of the observed clusters. This fact implies that the rupture process of each cluster is different.

DISCUSSION

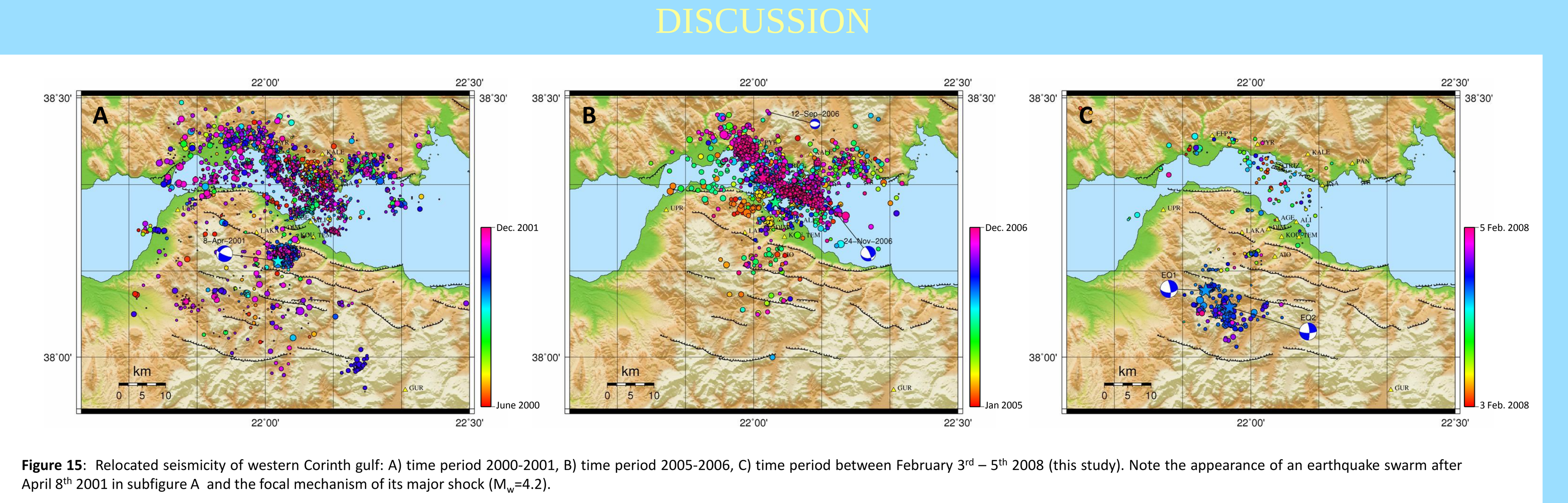


Figure 15: Relocated seismicity of western Corinth gulf: A) time period 2000-2001, B) time period 2005-2006, C) time period between February 3rd – 5th 2008 (this study). Note the appearance of an earthquake swarm after April 8th 2001 in subfigure A and the focal mechanism of its major shock (M_w=4.2).

Comparison with the seismicity of the previous years in the same region of western Corinth gulf (Fig. $15_{A,B,C}$) shows little or no activity around the epicentral area of the February 4th 2008 sequence. A swarm that occurred between April and July 2001, with a major event of M_w=4.2 on April 8th 2001, indicated the re-activation of a paleostructure in a direction almost perpendicular to the dominant active normal faults of the area, dipping 40° NW. This claim is also supported by the spatial distribution of the relocated hypocenters of this swarm. The best fit plane of the spatial distribution has indeed a roughly SW-NE direction, dipping NW.

The available local network data from the February 4th 2008 sequence are, however, not enough for an accurate depth estimation and, consequently, for the estimation of a fault plane based on the spatial distribution. Epicenters lie outside of the local network and the azimuthal coverage is poor. The relocation procedure helps to minimize some location uncertainties but still needs good quality primary location data to produce the best results. Since the magnitudes of the two major shocks are almost identical and the length of the horizontal distribution of the whole sequence is quite large (almost 10km), this is not a case of a clear mainshock-aftershock or foreshock-mainshock but most likely a case of two swarms on separate faults, with lengths less than 4km.

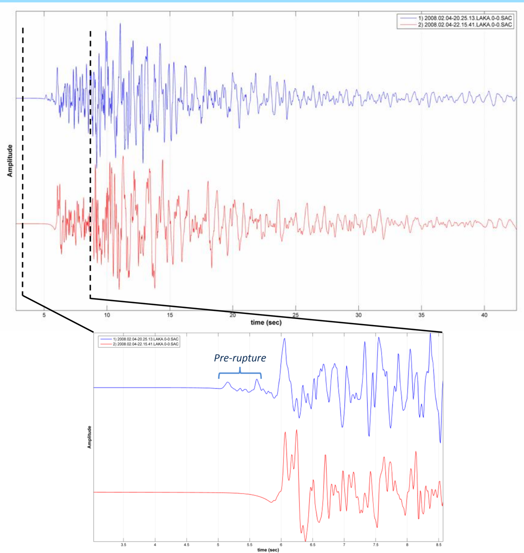


Figure 16: Waveforms of the two major events of February 4th 2008

Fig. 16 shows the waveforms of the two major earthquakes of the February 4th 2008 sequence, recorded on the vertical component of the LAKA station. The full-waveform cross-correlation maximum of the unfiltered traces is only 0.47. The waveforms have been band-pass filtered between 1-20Hz, however this results to a lower $\mathbf{XC_{max}}$ value of 0.35. By correlating only the P-waves, $\mathbf{XC_{max}}$ rises only up to 0.38, while the waveforms are aligned as shown in the close-up.

The lower panel of Fig. 16 reveals a pre-rupture stage on the blue waveform that belongs to the first major shock, lasting about 1sec. This may explain some uncertainties of the manual locations of this event by several institutes, as the pre-rupture stage is usually unclear on the S-waves. On the contrary, it can be seen more easily on the P-waves and taken as the first arrival. Both major shocks locations lie in the vicinity of some clusters. However, in terms of waveform similarity they do not belong to any of them. This is mainly due to the larger source duration that they have in comparison to the rest of the microearthquakes. Removal of the source effects is necessary in order to observe any similarity.

CONCLUSIONS

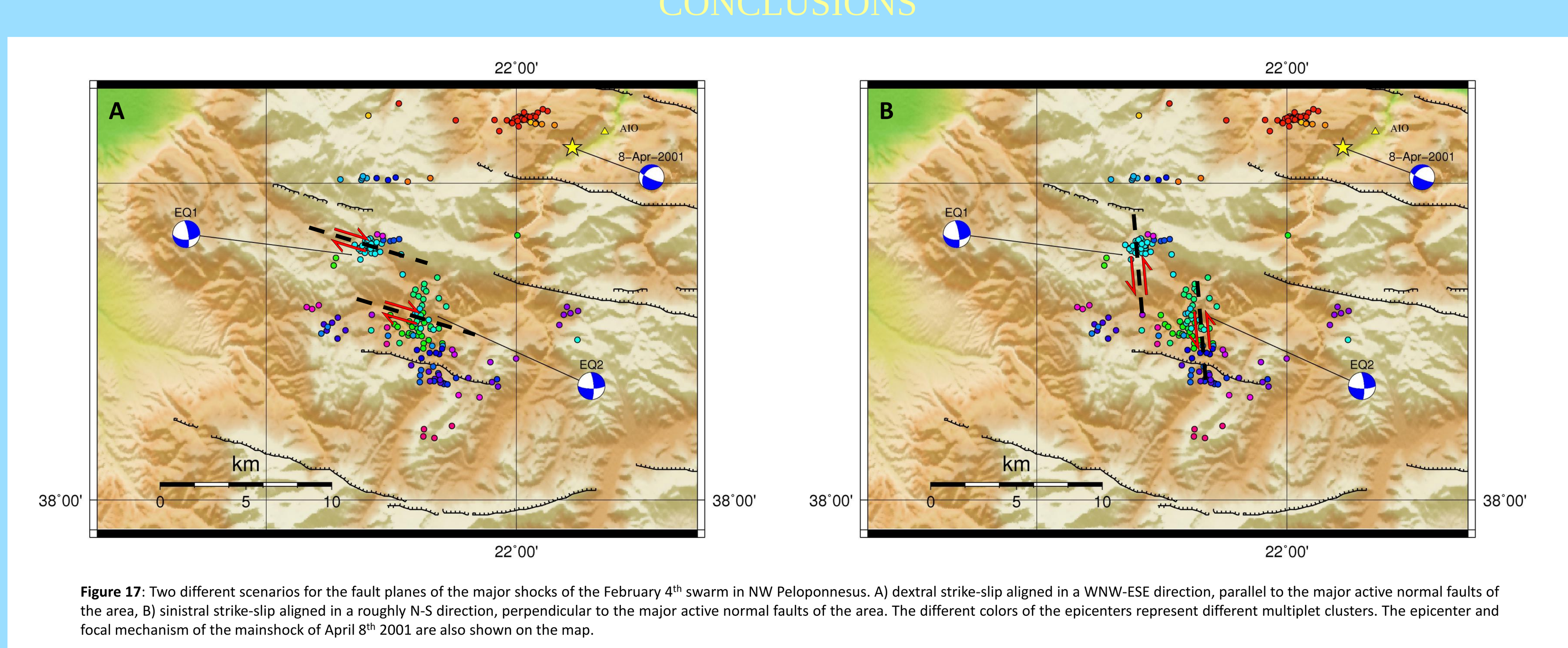


Figure 17: Two different scenarios for the fault planes of the major shocks of the February 4th swarm in NW Peloponnesus. A) dextral strike-slip aligned in a WNW-ESE direction, parallel to the major active normal faults of the area, B) sinistral strike-slip aligned in a roughly N-S direction, perpendicular to the major active normal faults of the area. The different colors of the epicenters represent different multiplet clusters. The epicenter and focal mechanism of the mainshock of April 8th 2001 are also shown on the map.

The results of this preliminary study reveal that the swarm of February 4th 2008 in NW Peloponnesus consists of two separate groups. The first earthquake occurred on the northern group while the second earthquake occurred, about two hours later, on the southern group in a similar depth of about 17km. Taking into account all the events in the NNW-SSE direction, the length of the swarm is close to 10km, which is considered to be too long for a couple of moderate earthquakes, if their fault planes are indeed almost perpendicular to the dominant active WNW-ESE normal faults. Since this is not the case of mainshock/largest aftershock, two different scenarios are considered to be probable. As depicted in Fig. 17, the first scenario (A) is that the strike of the rupture planes is parallel to the known normal faults of the area. The second case (B) is that the fault planes are aligned in a roughly N-S direction.

The anisotropy study performed in LAKA station reveals that the mean polarization direction (N110°) is in agreement with the NNE – SSW direction of extension of the Gulf of Corinth and in agreement with the Extensive Dilatancy Anisotropy (EDA) model. Finally, it is worth mentioning that an important reduction of time delay values was observed immediately after the occurrence of the first major event.

In addition to the swarm of February 4th 2008, microseismic activity was observed one day before on another region, about 12km NE of the mainshock epicenter, near the station AIO of the Corinth Rift Laboratory (CRL). The same area was activated after an M4.2 earthquake that occurred on April 8th, 2001. The calculated focal mechanism of that mainshock, as well as the hypocentral distribution of the relocated aftershock sequence is also in contradiction with the known tectonic regime, as the fault plane has N240°E strike and 40°NW dip. The waveforms of the events that belong to the cluster that was formed on February 3rd 2008 present strong spectral coherence. Similar observations had been made for the 2001 swarm.

Addition of data from more stations and process of a temporally wider sample covering the rest of the sequence may produce a better image of this seismic swarm. However, it is clear that the microearthquakes of the northern part of the February 4th 2008 swarm share similar source parameters, while the similarity of waveforms from microearthquakes in the southern part is less obvious. Consequently, the relocation process resulted to a tighter northern cluster and a more widely spread southern cluster.