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AN IMPORTANT NUMBER OF RECENT SIGNIFICANT EARTHQUAKES IN GREECE

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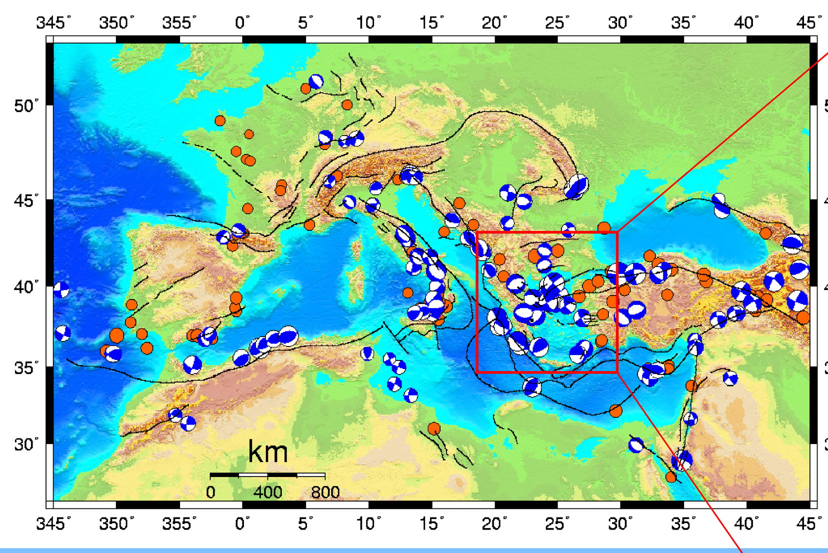
ABSTRACT

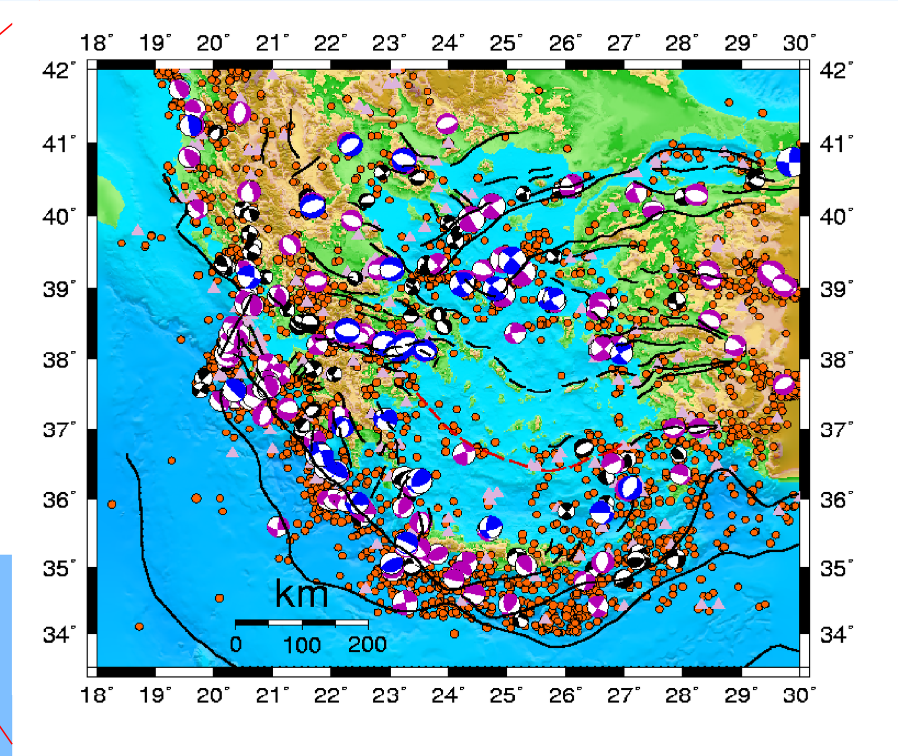
Greece is characterized by high seismicity mainly due to the collision between the European and the African lithospheric plates. During the recent years strong earthquakes occurred in regions with different seismotectonic regimes. Moment tensor inversion was applied to determine the source properties, as well as the dynamic processes of these events. Waveforms recorded in teleseismic distances were used and P , SH and SV synthetic waveforms were calculated for the selected stations. The final solution is obtained by minimizing the difference between the observed and the synthetic waveforms. The obtained source parameters were compared to the seismotectonic characteristics of each seismogenic area. Slip models that were determined for the important events were used to compute the Static Coulomb Stress Changes. This computation was performed in order to examine possible stress transfer to a neighboring area or to explain the spatial distribution of certain aftershock sequences. No static stress transfer was revealed to the epicentral area of the 2008 Leonidion earthquake due to the occurrence of the 2006 Kythira earthquake.

On the other hand, the aftershock distribution of the 2008 Andravida earthquake extended to an area significantly larger than the one expected according to the magnitude of the main event. On February 2008 an earthquake sequence including three strong events (Mw=6.7, 6.1 and 6.0) occurred South of Methoni, at a segment of the Hellenic arc which was not activated during the instrumental period. This sequence was followed by a large number of aftershocks, the strongest of which were processed to calculate their source parameters. The most recent significant events occurred north of Rhodes on 15 July 2008 (Mw=6.3) and south of Crete on 1 July 2009 (Mw=6.2). The first occurred at a depth of 55 km, was characterized by strike-slip faulting and followed by few aftershocks. On the contrary, the second one was followed by an important aftershock sequence with focal depths in the range of 10-30 km. The Crete earthquake was characterized by reverse faulting. Even though most of the above earthquakes are related to the Hellenic Arc, they are characterized by different seismotectonic features and stress regimes.

Seismotectonic map of the broader Mediterranean region



Seismotectonic map of Greece and adjacent areas

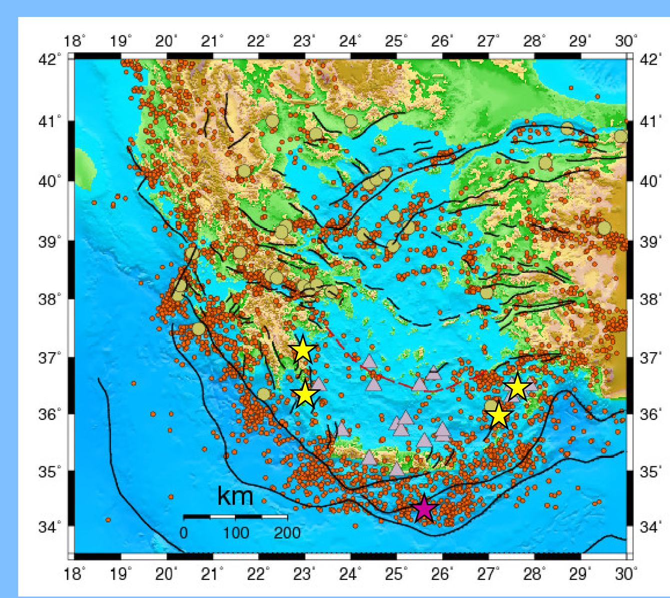


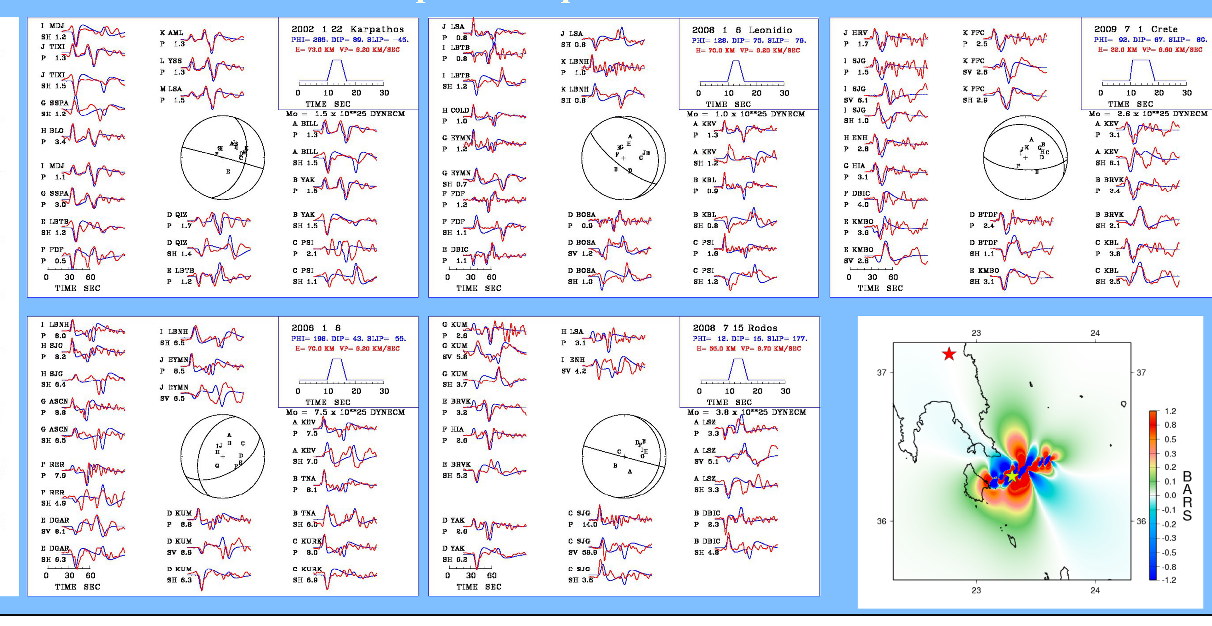
The creation of the Alpine mountain chain which is one of the most important geological features is caused by the collision between Europe and Africa. Furthermore, intense deformation observed in Greece and surrounding areas produces important seismicity concentrated in certain seismic zones (Makropoulos and Burton, 1981), such as the Hellenic Arc, characterized by subduction, the North Aegean, dominated by dextral strike-slip faulting, and the Gulf of Corinth. This process generates high seismicity in the Eastern Mediterranean.

The deformation in the broader area of the southern Ionian islands is characterized by the subduction of a remnant oceanic crust, called Tethys, beneath eastern Europe and the creation of large tectonic features of NW-SE direction in this part of the trench. Large earthquakes in this region revealed reverse faulting with a direction approximately parallel to the Hellenic arc and depths that vary significantly.

Two main systems dominate the East Mediterranean, the North Aegean Trough and the Hellenic trench along which the majority of the seismicity occurs. In the above figure focal mechanisms of large (M≥5.8), intermediate (4.5<M<5.8) and small earthquakes (M≤4.5) are shown in blue, purple and black color, respectively. With purple triangles the earthquakes of magnitude greater than 6.0 are represented for 1900-2010, while red circles represent events with M≥4 for the 1964-2010 time period. Uniformity in focal mechanism solutions is obvious in the Ionian sea, the North Aegean and the gulf of Corinth, whereas to the area located south of Crete different fault plane solutions appear. Focal mechanisms reveal that dextral strike-slip motion is mainly located in Cephallonia-Lefkas and North Aegean areas, reverse faulting is situated to the south of the Ionian islands area and along the Hellenic arc, while normal faulting is mainly situated to the back-arc regions.

Intermediate-depth earthquakes





Since 2002, a series of large earthquakes with intermediate-depth have occurred in the South Aegean area. The source parameters of these events were calculated using body-wave modeling (Agalos et al., 2008; Moshou et al., 2010). The first one occurred on 22 January 2002, 04:53 GMT, close to the Karpathos island (Mw=6.2). The focal depth was 73 km, while the fault plane solution indicated strike slip type faulting with the two planes oriented approximately E-W and N-S.

On Sunday 8th of January 2006, 11:34 GMT, an earthquake of magnitude Mw=6.6 occurred east of Kythira Island. Following the same procedure, the depth of the event was determined at 58 km, while reverse focal mechanism was constrained. The fault planes are oriented in an almost NNE-SSW direction. Two years later, another intermediate-depth event (Mw=6.0) occurred on 6 January 2008, 05:14 GMT. It was located close to the city of Leonidio, 100km north of the Kythira event. The depth of this event was 70 km and was characterized by a reverse focal mechanism, striking NNW-SSE. In order to examine the possibility that the Kythira earthquake accelerated the generation of the Leonidio earthquake, Coulomb Stress Transfer was calculated (Harris and Simpson, 2002) using the obtained slip model. The analysis revealed that the Leonidio event lies within the positive lobe, but the values are too small to support possible stress transfer.

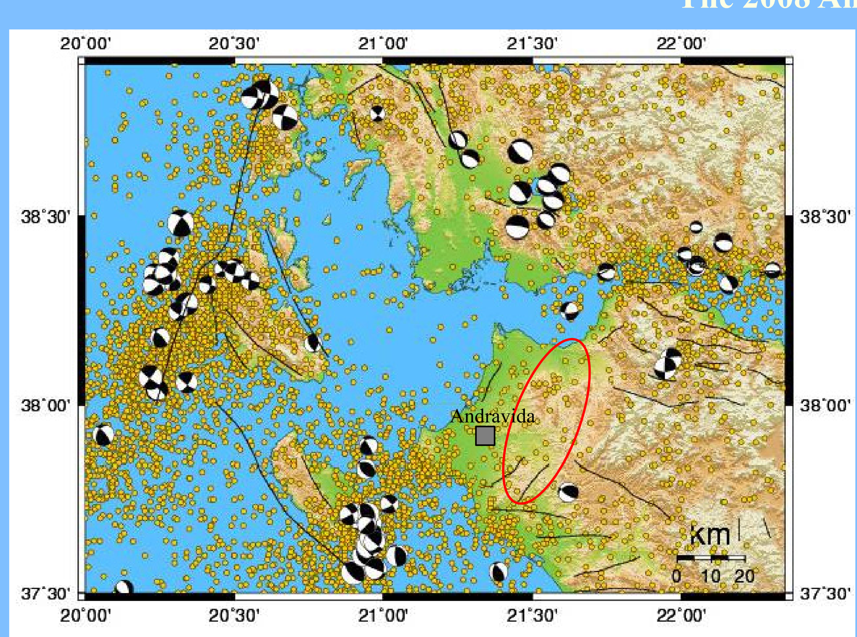
Six months later, on 15 July 2008, 03:26 GMT, a Mw=6.3 event occurred close to Rhodes island, 120 km north-east of the Karpathos 2002 event. The calculated source parameters resulted focal depth of 55 km and strike-slip focal mechanism similar to the one of the Karpathos event.

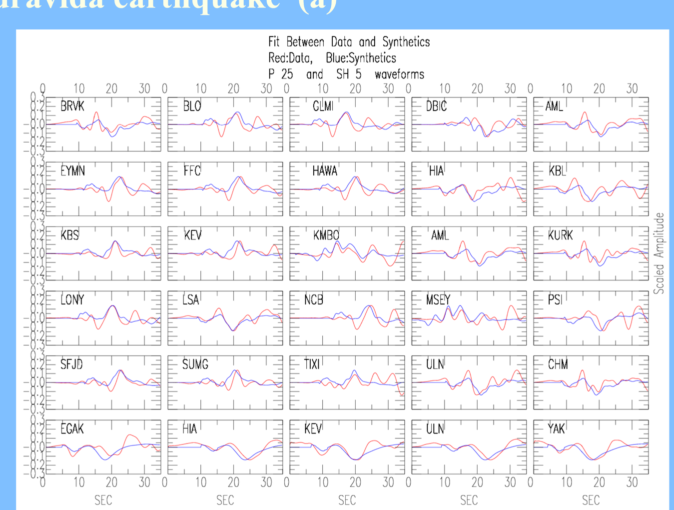
The most recent large event in the South Aegean occurred on 1st July 2009, 09:30 GMT (Mw=6.2), south of Crete island. The depth of the event was determined at 22km, which can be attributed to the fact that it was located close to the Hellenic arc.

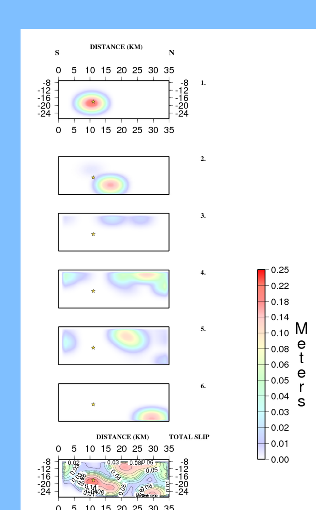
It is worth noticing that the above mentioned intermediate-depth events were not followed by important aftershock activity and their slip distribution was almost similar, indicating a simple source. On the other hand the Crete event was followed by a noticeable aftershock sequence with depths ranging between 10 and 30km.

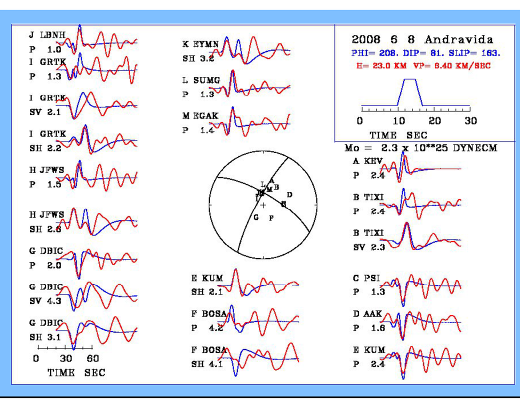
Concluding, focal mechanisms of intermediate-depth earthquakes located east of Crete differ from the ones west of the island. East of Crete strike-slip faulting is indicated and P-axes are almost parallel to the Hellenic Arc, whereas to the west fault plane solutions mainly indicate reverse faulting and P-axes are oriented almost perpendicular to the Hellenic Arc.

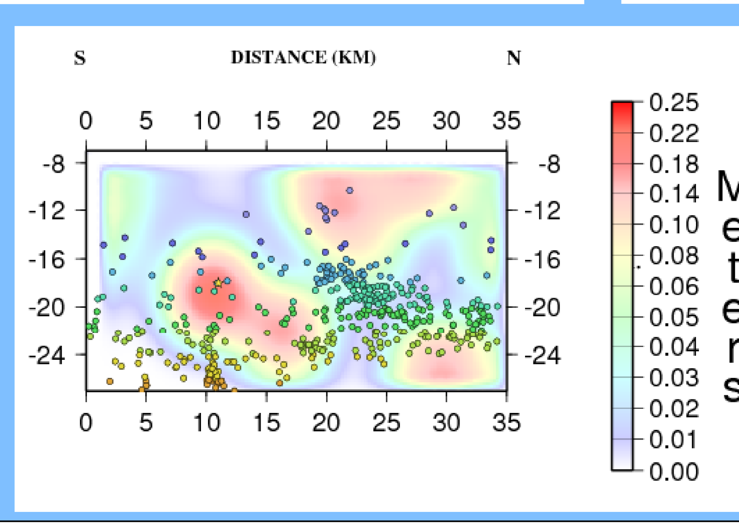
The 2008 Andravida earthquake (a)





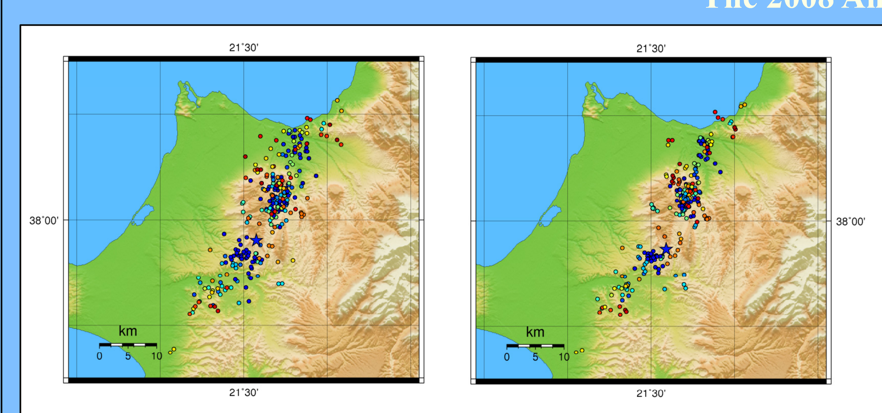


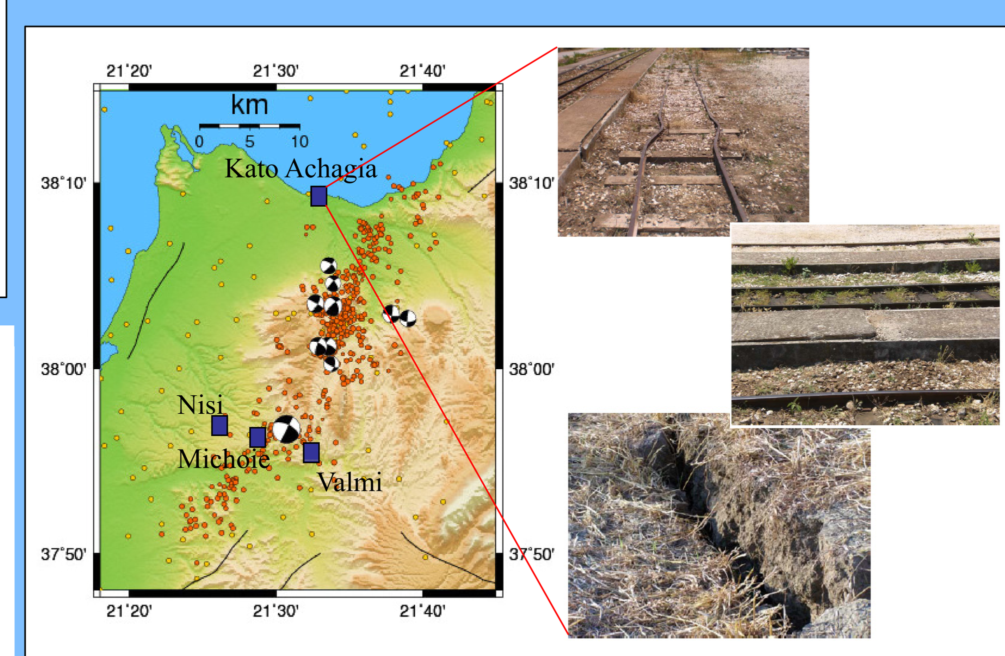


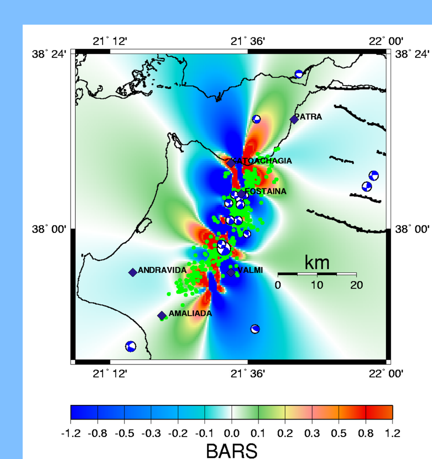


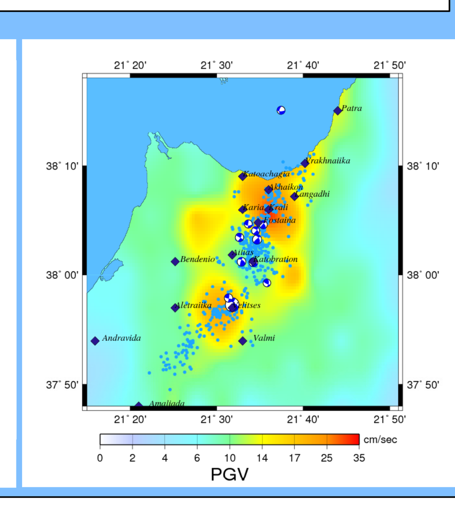
On 8 June 2008 the Andravida earthquake, with Mw=6.4, occurred on NW Peloponnesus. Low seismicity was observed in the epicentral area for the years 1964-2007, as indicated by the red ellipse, setting it as candidate for a forthcoming event (Papadimitriou, 2008). No historical large events have been reported in this area, where furthermore no evidence of surface faults existed. Strike-slip faulting has been observed in the surrounding region, while the type of motion in the study area remained under discussion. More specifically, the two moderate Chalandritsa events (Mw=4.5) occurred NE of the focal area four months before the Andravida earthquake (Kapetanidis et al., 2008). In addition, reverse faulting dominates along the Hellenic Arc to the west (Papadimitriou et al., 2006), while to the NE in the Gulf of Corinth the main active faults are normal with an approximately E-W direction. The source parameters of the Andravida earthquake were calculated using body-wave modeling for a simple trapezoid source time function. The depth is equal to 23 km, while the fault plane solution indicates dextral strike-slip faulting, oriented in a NNE-SSW direction. The slip distribution (Hartzell and Heaton, 1983) indicates a complex rupture propagation towards the north. The majority of aftershocks were located in areas with low slip values, as shown in the cross-section.

The 2008 Andravida earthquake (b)









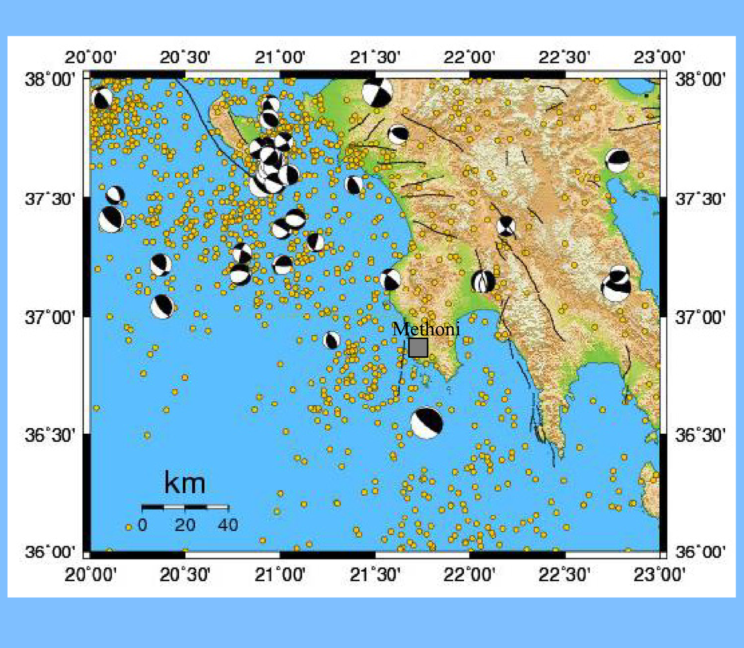
After the occurrence of the Andravida earthquake an important number of aftershocks were located using data from the Hellenic Unified Seismological Network (HUSN). The best-located events for the period 8-26 June 2008 were 490. Following, cross-correlation and nearest-neighbor linkage (Kapetanidis et al., 2010) were applied, resulting in several multiplet clusters. Finally, relocation was performed (Karakonstantis and Papadimitriou, 2010) using the double-difference algorithm HypoDD (Waldhauser and Ellsworth, 2000) with both catalogue and cross-correlation differential travel-time data.

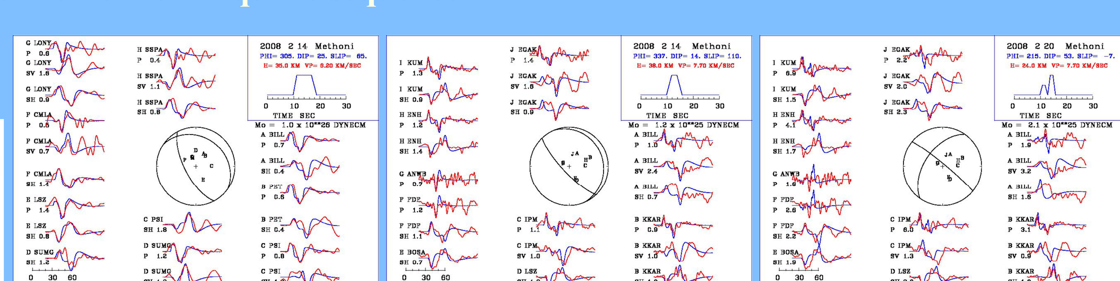
The spatial distribution of the relocated aftershocks covers an area of about 40km length in a NNE-SSW direction, in agreement with the constrained focal mechanism of the mainshock. Fault plane solutions of the largest aftershocks indicate type of faulting similar to the one of the major event.

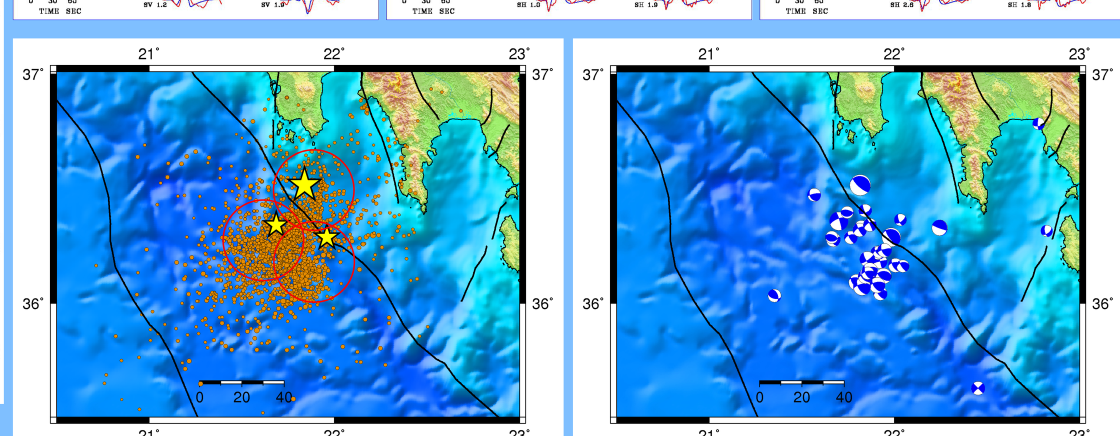
The length of the main rupture is approximately 25km, while, as it was previously mentioned, the aftershock area extends to more than 40km. The seismicity at the two edges of the activated fault can be attributed to stress transfer caused by the mainshock, as revealed by Coulomb Stress Analysis.

PGV distribution (Bouchon, 1981) was obtained using the determined slip model. High PGV values between 17 and 20cm/sec were observed at the northern edge, where many structural damages were reported, in an area that was not ruptured. The observed damage can be attributed to stress transfer.

The 2008 Methoni earthquake sequence







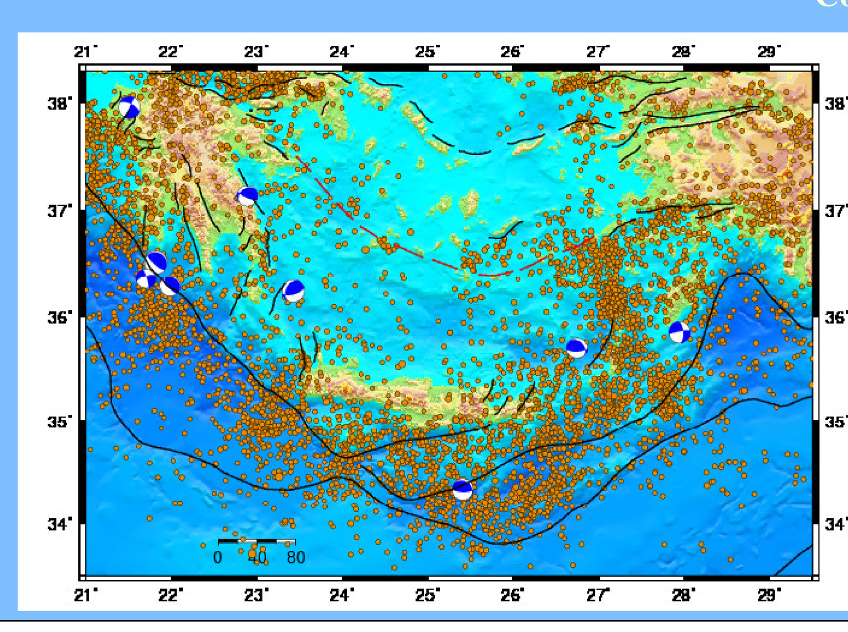
On 14 February 2008, 10:09 GMT, a Mw=6.7 event initiated an important seismic sequence in an area of low background seismicity, close to the SW part of the Hellenic Arc, near the city of Methoni. The most recent significant event in the area occurred in 1997 with Mw=6.0.

The focal depth of the main event was 35km, while a reverse focal mechanism was determined. It was followed, two hours later, by an earthquake of magnitude Mw=6.1, with similar focal depth and fault plane solution. A third large event (Mw=6.0) occurred on 20 February 2008, 18:27 GMT, at 24km depth, characterized by strike-slip faulting.

The intense aftershock sequence is characterized by the existence of an important number of moderate events that have been analyzed to calculate their source parameters. Three clusters can be distinguished within the aftershock spatial distribution. The northern cluster includes the main event, while the two other large events lie within the southern and the western cluster, respectively.

A moment tensor inversion technique was applied using regional data for the determination of 19 focal mechanisms. Two different types of fault plane solutions can mainly be distinguished: a) reverse type faulting, in a general NW-SE direction, as the first two large events and b) strike-slip type of faulting, as the third large one. The focal depths of the events vary between 10 and 40km.

Conclusions



An important number of large earthquakes have occurred recently in Greece, especially during 2008. Furthermore, during the last decade several significant intermediate-depth earthquakes have occurred in the South Aegean area. This activity, which was absent during the instrumental period until 2002, can be related to the subducting lithosphere.

Furthermore, the rupture process is differentiated in the western and eastern parts of the Hellenic Arc. Large deep events in the western part are related to reverse faulting, while those in the eastern to strike-slip faulting.

During the same time period a shallow part of the SW Hellenic Arc (Methoni area) was activated producing a very important earthquake sequence. The focal depths vary between 20 and 40km, while both reverse and strike-slip type of faulting were determined.

The 2008 Andravida earthquake is of great interest, since it is located in an area where no historical or instrumental large events have been reported. Furthermore, there was no evidence of surface ruptures that could justify the occurrence of such a large event. Additionally, it lies in a transition zone between the Hellenic Arc, dominated by reverse faulting, at the west and the Corinth rift, characterized by normal faults, to the NE.

The Andravida earthquake occurred along a right lateral strike-slip fault with NE-SW direction. Regional waveforms were used to calculate the source parameters of the largest aftershocks. The depth distribution of the relocated aftershocks ranges between 10 and 30km along an area of approximately 40km length. The source parameters of the mainshock, as well as the rupture process were also calculated. The determined slip model was used to obtain a synthetic shakemap (PGV) and detailed static stress changes. The slip model revealed the rupture of a fault whose length is close to 20-25km. The slip distribution is related with at least two main sources and with significant source directivity towards the NE. The shakemap describes well the regions with damages. The length of the aftershocks spatial distribution is more than 40 km, significantly larger than the calculated ruptured length which is about 25km. In order to examine this discrepancy, Coulomb stress analysis was performed, indicating increased stress values (>0.5 bars) at the two edges of the activated fault in a NNE-SSW direction, as indicated by the red lobes. These values are high enough to justify the seismicity, as well as the observed damages.

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Acknowledgements

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