The 24 May 2009 Mw5.2 earthquake sequence near Lake Doirani (FYROM - Greek borders): focal mechanisms, slip model, ground motions

Anastasia Kiratzi

Department of Geophysics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
(e-mail: **Kiratzi@geo.auth.gr**)

Abstract

The May 2009 Doirani sequence (Mw5.2) ruptured a ~ 5 km normal fault which strikes N62°E and dips with an angle of ~40° to the south. The focal mechanisms of thirteen of the stronger events clearly show normal faulting sometimes combined with a weak dextral strike slip component. Using broad band waveforms from the Unified Hellenic Seismological Network and neighboring networks I obtained the slip model for the strongest GMT 16:17 event, slip was released in a single slip patch of ~5 km x 5 km, average slip 6.8 cm and I identified the ENE-WSW trending plane that dips to the SE as the fault plane, with its slip vector trending N191°E. The ground motions produced by the strongest Mw5.2 event were very moderate and no damage was expected.

Introduction

This is a preliminary report for the 24 May 2009 moderate magnitude (Mw5.2) sequence at the proximity of the northern bank of Lake Doirani along the borders of Greece with FYROM. The strong events of the sequence were mainly felt at the villages along the borders and also to cities of Valandovo and Thessaloniki, which lie ~20 and ~70 km away from the epicentre, respectively. This report uses the seismological information available so far (June 1, 2009). The sequence occurred 20 km SE of the epicentre of the strong Mw6.7 Valandovo event of 1931, which resulted in 153 casualties and left about 10,000 people homeless (Papazachos and Papazachou, 2003).

Lake Doirani lies between the Vardar - Axios and Struma - Strimon Rivers and has never been the site of a strong event during instrumental times. The available focal mechanisms (Fig. 1) for events of M>=5.0 for the broader region (Kiratzi et al., 2007) clearly show that the recent 2009 sequence occurred in a region characterized by extensional tectonics, with the T-axes having an ~ N-S direction.

Two geologic units dominate in the broader region of the Lakae Doirani seismic activity. The Vardar – Axios zone in the west and the Servomacedonian massif in the east (Mountrakis et al., 1983). The sequence occurred in the Servomacedonian massif, a well-known geologic unit for its intense seismic activity. For example, starting from the north, one can notice a series of strong (Mw≥6) events (Fig. 1): 1931 Valandovo, 1932-1933 Sohos, 1978 Thessaloniki –Mygdonia, 1932 Ierissos, 1995 Arnea. The epicentres of these strong events are aligned along the western border of the Servomacedonian massif, near its contact with the eastern border of the Axios-Vardar zone. A series of grabens with E-W to NW-SE trends were formed by normal faulting in the area of the Servomacedonian massif during the Neogene and Quaternary, one of those is the Mygdonian graben, where the 1978 Mw6.5 Thessaloniki event occurred. The city of Thessaloniki, (population 363,987 in 2001 census) lies in a distance of ~70 km south of the Lake Doirani seismic activity. Taking into consideration that the 1931 Valandovo earthquake produced light damage in the 1931 city of Thessaloniki, and obviously since that time the city has augmented spatially, it is important to examine the so far available seismological data of the present Doirani Lake activity. In this preliminary report, I present a) moment tensor solutions for the stronger events of the sequence, b) the slip model for the so far strongest event and c) I designate the fault that dips south as the fault plane.

Figure 1. Lake Doirani (the site of the Mw5.2 May 24, 2009 sequence, previous focal mechanisms determined by waveform modelling for events with M≥5.0 (beach-balls, green for normal faults; black for strike slip faults) and previous strong Mw>6.0 events (red asterisks). The series of the strong events in the region between the Axios and Strimon Rivers, have their epicenters in the well-known Servomacedonian zone, at the proximity of its contact with the Vardar-Axios zone in the west.

Focal mechanisms of the May 2009 stronger earthquakes

Focal mechanisms for the stronger events of the sequence were computed using the Time-Domain Moment Tensor inversion method (TDMT_INV) developed at the Berkeley Seismological Laboratory (Dreger, 2002, 2003), as it has been further modified for fast applications in Greece (Roumelioti et al., 2008a). Full waveforms of the three recorded components of motion are low-pass filtered and inverted to derive the moment tensor. The tensor is then decomposed into a scalar seismic moment, double couple (*DC*) orientation components and a percentage of compensated linear vector dipole (*CLVD*). Broad band waveforms were retrieved from the Unified Hellenic Seismological Network, the Albanian network and MEDNET. In this sequence, waveforms were band-pass filtered between 0.05– 0.08 Hz for the strongest event (No 4 in Table 1) and between 0.05 and 0.10 Hz for the lower magnitude events. All waveforms were also re-sampled to a frequency of 1 Hz. Synthetic Green's functions were constructed using the FKRPROG code of Saikia (1994) and the velocity model of Novotny et al. (2001).

I computed the moment tensor solutions for 13 earthquakes of the sequence, three of which are foreshocks. I indicatively show in Figure 2 the waveform fit for the strongest Mw5.2 event. Table 1 lists the focal parameters and all solutions are shown in Figure 3.

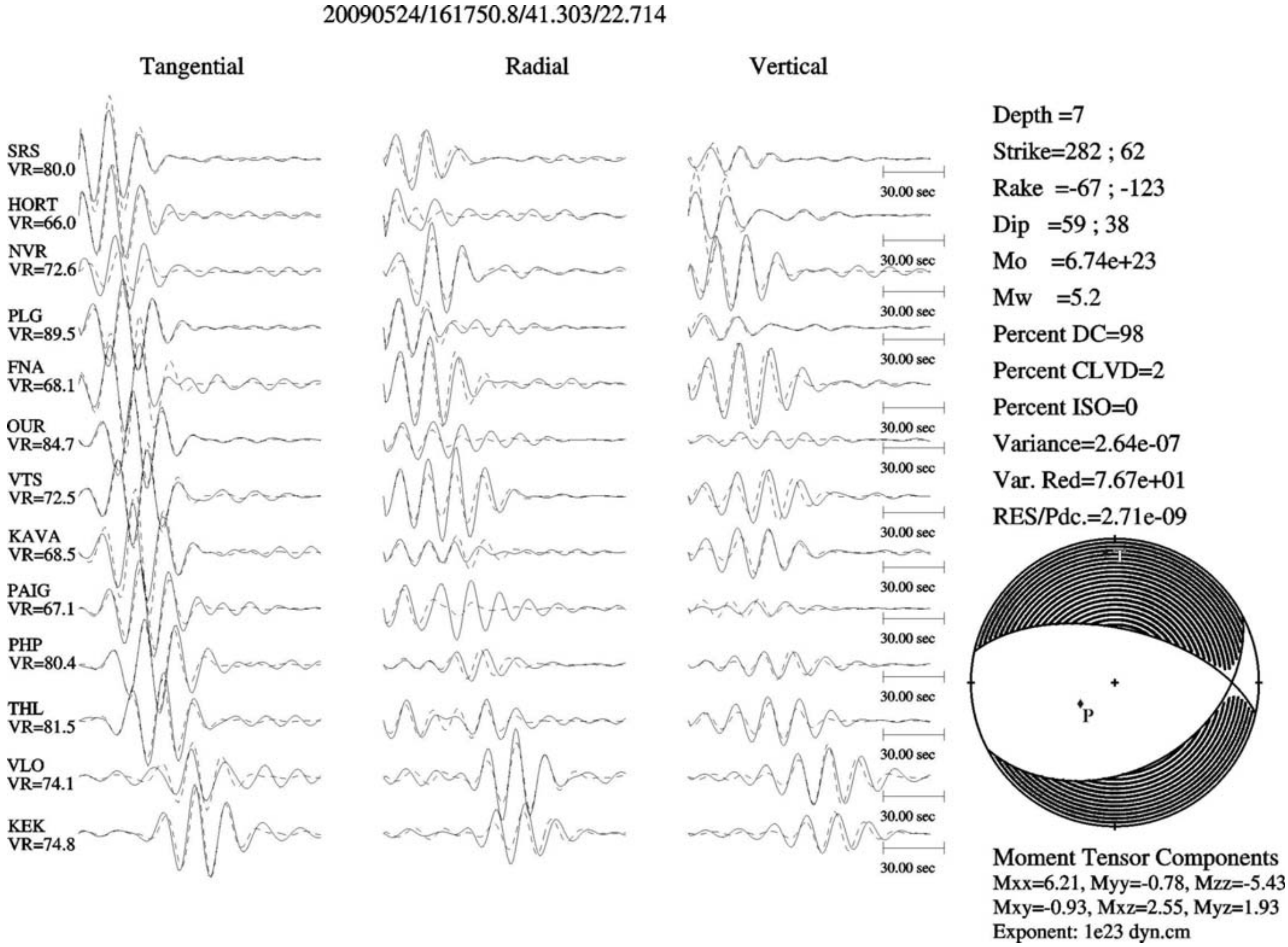

Figure 2. Waveform fit for the 24 May 2009 GMT 16:17 earthquake (No 4 in Table 1). For each station the vertical, tangential and radial components are shown. Observed waveforms are represented with solid lines and synthetics with dashed lines. The stations used in all cases were carefully selected to provide good coverage in azimuth (e.g. stations VTS, PHP, VLO provide coverage from the northern hemispheres). The solution presented here is in very good agreement with all the fast solutions submitted to EMSC after the earthquake.

During the inversions the solutions were stable, and converged to normal faulting focal mechanisms. In this respect, the focal mechanisms of the sequence are clearly connected with activation of a normal fault that strikes NNE-SSW and as shown later, dips south. There are only two pure strike-slip solutions and are both observed at the western border of the Doirani sequence (Fig. 3). In any case a weak right-lateral strike-slip component was evident in most focal mechanisms.

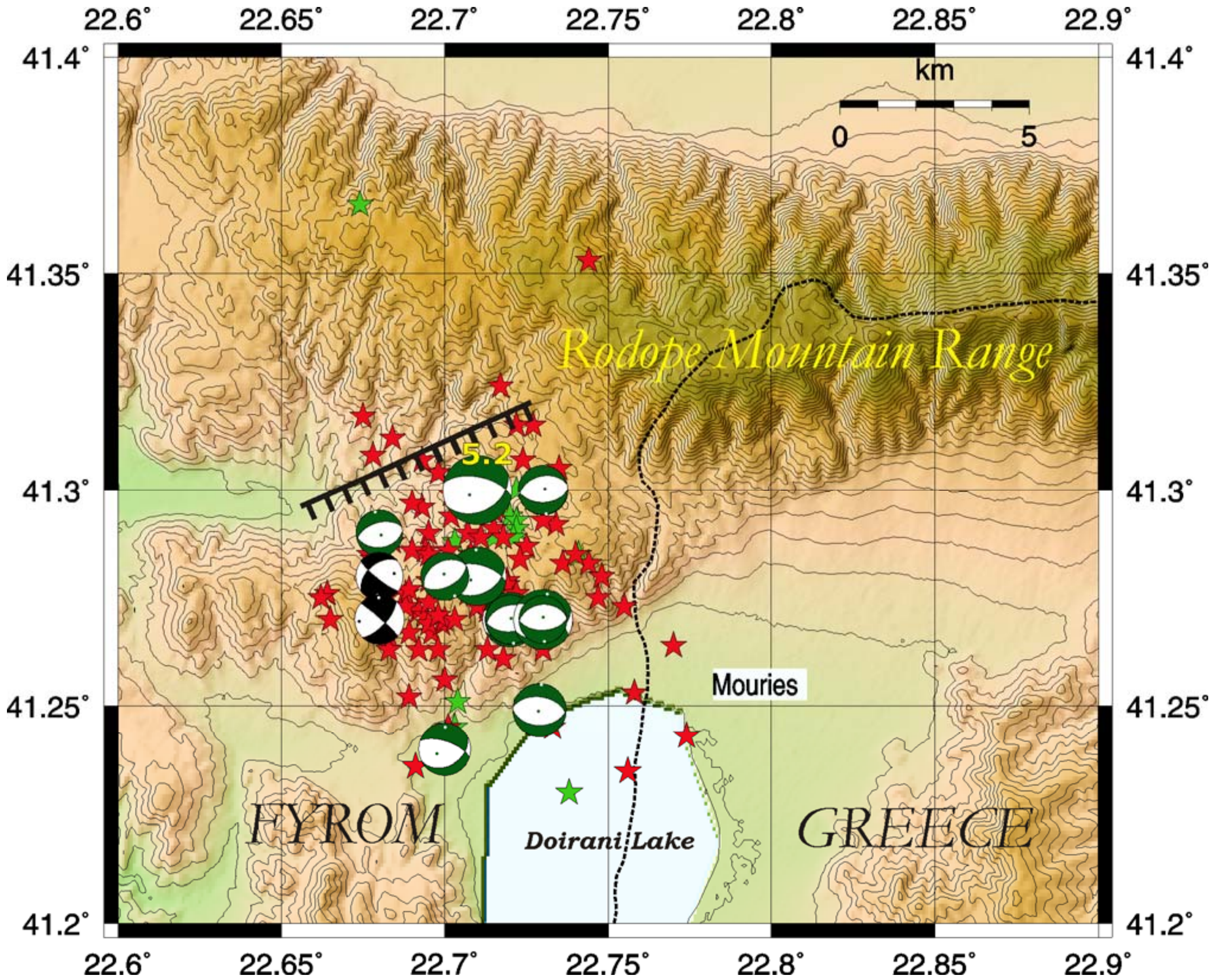

Figure 3. Focal mechanisms (beach ball size scaled with magnitude) for the May 2009 seismic sequence at the proximity of Lake Doirani, determined using moment tensor inversion (Table 1 for parameters). Green beach balls denote normal faulting whereas black beach balls denote pure strike-slip faulting. Clearly normal faulting is prevailing combined with strike-slip motions. Asterisks denote the seismicity of the period 18 April – 31 May, 2009. Green asterisks for seismicity prior to 24 May 2009 GMT 16:17, red asterisks for the seismicity following the occurrence of the so far strong Mw5.2 event. The hatched normal fault is a sketch simply showing the orientation and sense of dip of the activated structure.

Figure 4 presents a cross section along a line nearly perpendicular to the strike of the activated fault, projecting the seismicity of April – May 2009, and the focal mechanisms here determined. The sequence extends in depth up to ~10 km, and most of the strong events have depths in the range of 5 to 7 km. It is evident from this cross-section that the plane that dips ~40^o south is the fault plane.

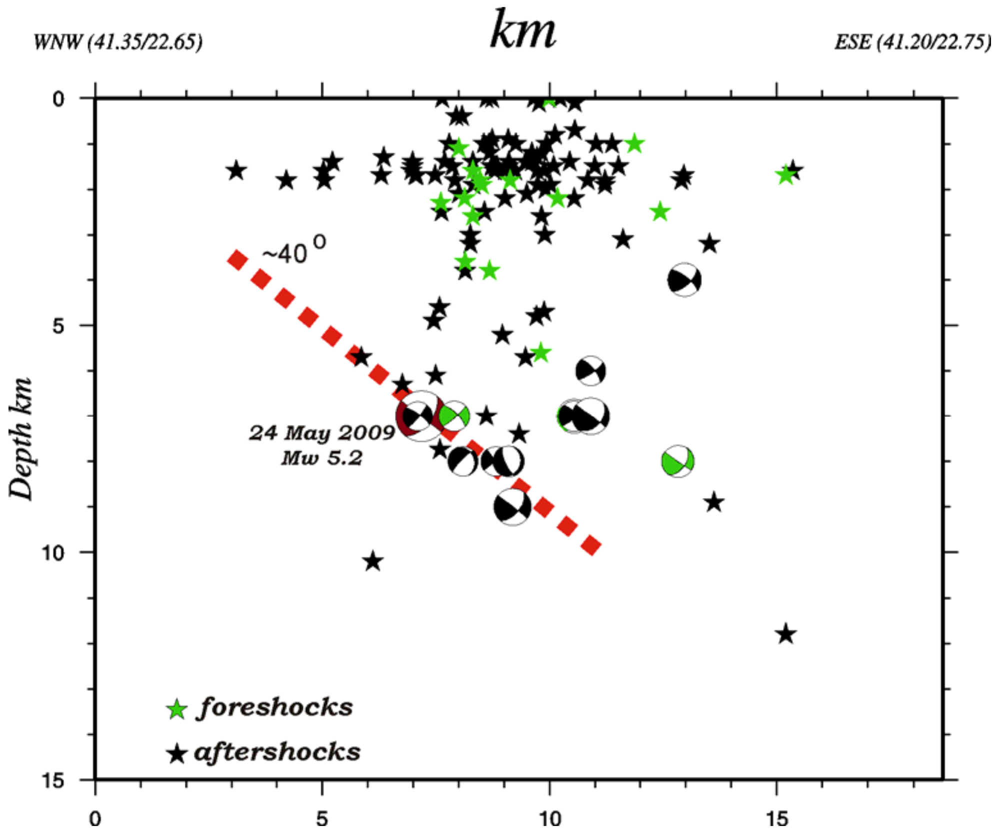

Figure 4. Cross section along a line nearly perpendicular to the strike of the activated fault (coordinates are given in the fig.), and projection onto the section of the seismicity (asterisks) and of the focal mechanisms of the 2009 Doirani sequence. Green beach-balls and asterisks denote seismicity prior to 24 May 2009 GMT 16:17 and black beach balls and asterisks denote seismicity following the occurrence of the so far strongest event. The fault clearly dips S-SE at an angle of ~ 40^{o}.

Table 1 Focal mechanism parameters for the strongest events of the May 2009 sequence at the proximity of Lake Doirani, which I determined using broadband records and moment tensor inversion. The so far mainshock is listed in bold, note that for three foreshocks mechanisms are also available. (CLVD % and Variance reduction %, VR as well as the number of stations, NR used in the inversion, are also listed).

No	Date	hh:mm:ss	Lat N	Lon E	h (km)	Mw	strike 1	dip 1	rake 1	strike 2	dip 2	rake 2	P *az*	P *pl*	T *az*	T *pl*	CLVD %	VR %	NR
1	20090523	23:22:35.2	41.30	22.73	7.00	3.7	89	48	-81	256	43	-100	62	83	173	3	13	83	5
2	20090524	14:29:16.2	41.27	22.72	7.00	4.1	64	31	-130	288	67	-69	231	62	3	19	4	71	9
3	20090524	14:34:04.3	41.24	22.70	8.00	3.9	61	35	-132	289	65	-65	238	61	1	16	19	60	9
4	20090524	16:17:50.8	41.30	22.71	7.00	5.2	62	38	-123	281	59	-67	237	67	355	11	2	77	13
5	20090524	16:23:09.8	41.28	22.71	9.00	4.4	66	39	-120	283	57	-68	241	69	357	9	0	66	4
6	20090524	18:12:54.1	41.29	22.68	7.00	3.5	84	38	-82	254	52	-96	134	81	348	7	9	66	7
7	20090524	18:50:18.0	41.27	22.72	7.00	3.7	85	49	-85	257	41	-96	36	84	171	4	5	60	9
8	20090524	19:37:05.5	41.27	22.73	7.00	4.5	68	38	-137	302	65	-60	254	59	11	15	3	74	9
9	20090524	22:20:09.9	41.27	22.73	6.00	3.6	88	53	-88	265	37	-92	7	82	177	8	0	74	10
10	20090524	22:46:53.9	41.28	22.68	8.00	3.6	129	81	-44	228	47	-167	79	36	186	22	8	71	9
11	20090525	04:50:03.6	41.28	22.70	8.00	3.6	64	53	-88	241	37	-92	343	82	153	8	2	78	8
12	20090525	07:59:41.3	41.27	22.68	8.00	3.7	43	68	-175	311	85	-22	265	19	359	12	6	61	8
13	20090601	08:03:40.0	41.25	22.73	4.0	4.0	90	42	-96	278	48	-85	237	85	4	3	13	82	6

Slip model for the 24 May 2009, GMT 16:17 Mw 5.2 event

To obtain the slip distribution model for the GMT 16:17 Mw 5.2 event (Figure 5) the methodology of Dreger and Kaverina (2000) and Kaverina et al. (2002) was used, in which regional distance ground motions recorded on broadband instruments are inverted for slip following the representation theorem for an elastic dislocation. We use a variety of simplifying assumptions including constant rupture velocity and dislocation rise time. We further apply slip positivity, seismic moment minimization and smoothing constraints to provide stability to the inversion. The description of the application of the method in Greece is described in Roumelioti et al. (2008b) and Kiratzi et al. (2008).

Both nodal planes are tested and the methodology applied is capable of uniquely determining the causative fault plane of the earthquake, the dimensions of the slip patches (both along strike and down dip), the earthquake rupture velocity, and a reasonable characterization of the gross slip distribution, suggesting that the derived source parameters may be used to simulate near-source strong ground motions. For the earthquake studied here, the nodal plane that dips to the SSE (that is the one with strike 62^o) was statistically detected (VR 65%) as the fault plane, compared to the other nodal plane (VR 61%). This implies that the azimuth of the slip vector is N191^{o}E and its plunge 31^o.

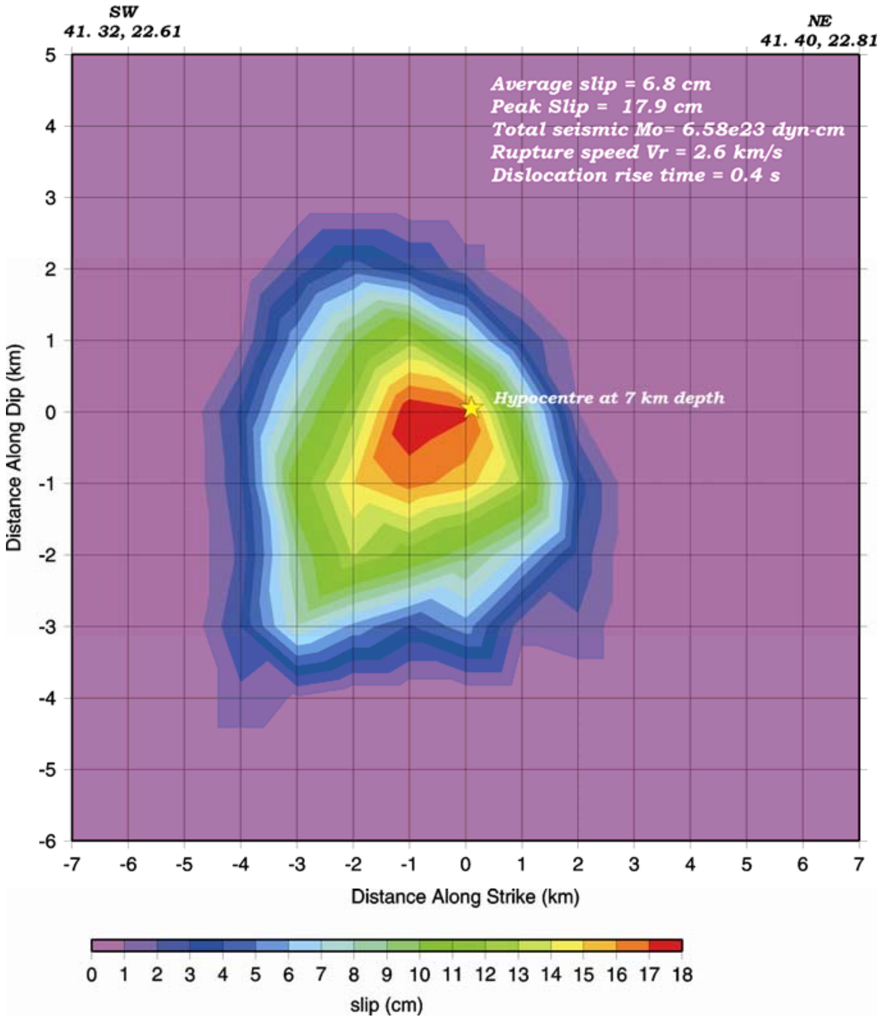

Figure 5. Slip distribution (slip in cm) for the 24 May 2009; GMT 16:17:51 Mw5.2 event, onto the fault plane (e.g. the nodal plane that dips S-SE). The area of strongest slip is ~ 5 km x 5 km, the asterisk denotes the initiation of the rupture. Note that the 0 in this figure corresponds to the depth of 7 km obtained from the MT solution.

Deterministic Computation of PGV maps (Shake Map) for the strongest Mw 5.2 event

I used the regionally derived slip model (Fig. 5) to simulate the distribution of near-source strong ground motion and obtain PGV and intensity maps, using the procedures developed at Berkeley University as applied in Greece (for details see Roumelioti et al., 2008b; Kiratzi et al., 2008). The predicted strong motion parameters are improved by applying site corrections to the synthetic ground motions, based on the procedure implemented by Wald and Allen (2007) who classified the site geology based on the topography gradient as a proxy.

The predicted ground motions were very weak and are not shown here. For reasons of comparison I also computed PGA and PGV maps (Fig. 6a and 6b, respectively) using empirical relations applicable to Greece, as proposed by Skarlatoudis et al. (2003, 2007). The empirically expected ground motions are also very moderate. In fact the strong Mw 5.2 event triggered a number of close accelerograph stations operated by the Institute of Earthquake Engineering and Engineering seismology, and at the closest station (station KNT at a distance of ~20 km south of the epicenter) the accelerations were of the order of 40mg (Nikos Theodulidis, personal communication).

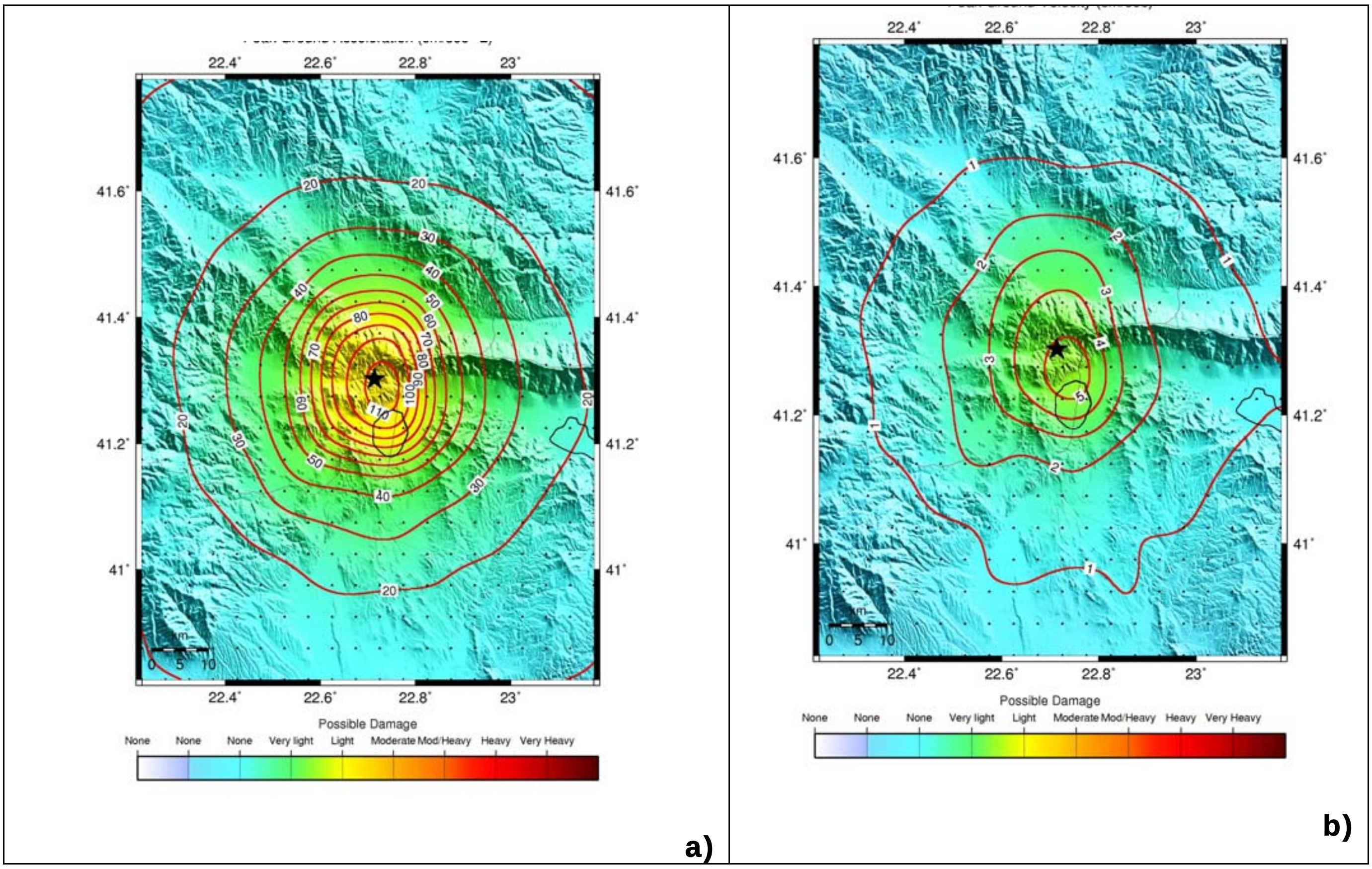

Figure 6. a) Distribution of PGA and b) PGV's obtained using the empirical relations of Skarlatoudis et al. (2003, 2007) for the strongest 24 May 2009 GMT 16:17 Mw5.2 event of the Doirani sequence. Moderate ground motions are predicted, in accordance with the low PGA's (~40 mg) observed in the closest (~20 km) stations (Theodulidis, N. pers. communication).

Acknowledgements

The broad band waveforms used for the inversions have been provided by the Unified Hellenic Seismological Network of Greece. Broad band stations of MEDNET and of the Albanian Network are also acknowledged. The parameters of the earthquakes have been retrieved from the on-line catalogues of the Department of Geophysics of the Aristotle University of Thessaloniki (http://geophysics.geo.auth.gr/ss/REAL_TIME_MAPS/index.htm), and thanks are due to the daily observers for their careful analysis. Thanks are also due to Roula Roumelioti and Christoforos Benetatos, my former students, for extensive script writing to facilitate the inversions, and to D. Dreger from the Seismological Laboratory, University of Berkeley, California for providing the inversion codes.

References

Dreger D. S. (2002). Time-Domain Moment Tensor INVerse Code (TDMT_INVC) *Version 1.1, Berkeley Seismological Laboratory, pp. 18.*

Dreger D. S. (2003). TDMT_INV: Time Domain Seismic Moment Tensor INVersion, International Handbook of Earthquake and Engineering Seismology, *W. H. K. Lee, H. Kanamori, P. C. Jennings and C. Kisslinger (eds.), Vol. B, pp. 1627.*

Dreger, D. S., & Kaverina A., (2000), Seismic remote sensing for the earthquake source process and near-source strong shaking: a case study of the October 16, 1999 Hector Mine earthquake, *Geophys. Res. Lett. 27, pp. 1941–1944.*

Kaverina A., Dreger D., & Price E., (2002). The Combined Inversion of Seismic and Geodetic Data for the Source Process of the 16 October 1999 Mw 7.1 Hector Mine, California, Earthquake, *Bull. Seism. Soc. Am. 92, pp. 1266-1280.*

Kiratzi, A., Benetatos, C. and Z. Roumelioti (2007). Distributed earthquake focal mechanisms in the Aegean Sea, *Bulletin of the Geological Society of Greece,* Vol. XXXX, 1125-1137.

Kiratzi, A., Roumelioti, Z. and C. Benetatos (2008). Real-time Seismology and Shake Maps in Greece. Proc. of the 31st General Assembly of the European Seismological Commission, ESC 2008, Hersonissos, Crete, Greece, 7-12 September 2008, pp. 228- 236.

Mountrakis, D., Psilovikos, A. and B. Papazachos (1983). The seismotectonic regime of the 1978 Thessaloniki earthquakes. In the special volume "The Thessaloniki northern Greece, earthquake of June 20 1978, and its seismic sequence", Papazachos, B. and P. Carydis editors, Publ. of the Technical Chamber of Greece, pp. 11-27.

Novotný O., Zahradník J., & Tselentis G.-A. (2001). North-Western Turkey earthquakes and the crustal structure inferred from surface waves observed in Western Greece, *Bull. Seismol. Soc. Am., 91, pp. 875-879.*

Papazachos B. C., and C. Papazachou (2003). The earthquakes of Greece. Ziti Publ. Co., Thessaloniki, Greece, 286 pp (in Greek).

Roumelioti, Z., Benetatos, C., Kiratzi, A. & D. Dreger (2008a). Near-real time moment tensors for earthquakes in Greece based on seismological data of the Hellenic Unified Seismological Network, *3rd National Conference of Earthquake Engineering and Engineering Seismology, Athens, 5-7 November, 2008, paper ID:1789.*

Roumelioti, Z., Kiratzi, A. & D. Dreger (2008b). Near-Real Time Shake Maps for Earthquakes in Greece: pilot application, *3rd National Conference of Earthquake Engineering and Engineering Seismology, Athens, 5-7 November, 2008, paper ID: 2105.*

Saikia C. K. (1994). Modified frequency-wavenumber algorithm for regional seismograms using Filon's quadrature; modeling of Lg waves in eastern North America, *Geophys. Journ. Int., 118, pp. 142-158.*

Skarlatoudis, A. A., Papazachos C. B., Margaris B. N., Theodulidis N., Papaioannou Ch., Kalogeras I., Scordilis E. M., & Karakostas V., (2003). Empirical peak ground-motion predictive relations for shallow earthquakes in Greece, *Bull. Seism. Soc. Am. 93, pp. 2591-2603.*

Skarlatoudis, A. A., Papazachos C. B., Margaris B. N., Theodulidis N., Papaioannou Ch., Kalogeras I., Scordilis E. M., & Karakostas V., (2007). Erratum to "Empirical peak ground-motion predictive relations for shallow earthquakes in Greece, *Bull. Seism. Soc. Am. 97(6), pp. 2219-2221, doi: 10.1785/0120070176.*

Wald, D. J., & Allen T. I., (2007). Topographic slope as a proxy for seismic site conditions and amplification, *Bull. Seism. Soc. Am. 97(5), pp. 1379-1395, doi: 10.1785/ 0120060267.*

Wessel, P., & Smith, W.H.F., (1998). New improved version of the Generic Mapping Tools released", *EOS Trans. AGU 79, 579.*