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Seismic moment tensors of the April 2009, L'Aquila (Central Italy), earthquake sequence

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Summary

On April 6, 2009, the Central Apennines were hit by a Mw=6.3 earthquake. The region had been shaken since October 2008 by seismic activity that culminated in two foreshocks with Mw>4, one week and a few hours before the main shock. We computed seismic moment tensors for 26 events with Mw between 3.9 and 5.5, using the Regional Centroid Moment Tensor (RCMT) scheme. Most of these source parameters have been computed within one hour after the earthquake and rapidly revised successively. The focal mechanisms are all extensional, with a variable and sometimes significant strike-slip component. This geometry agrees with the NE-SW extensional deformation of the Apennines, known from previous seismic and geodetic observations. Events group into three clusters. Those located in the southern area have larger centroid depths and a wider distribution of T-axis directions. These differences suggest that towards south a different fault system was activated with respect to the SW-dipping normal faults beneath L'Aquila and more to the north. These considerations and other analyses have been possible for the rapid availability of these robust moment tensors.

Key-words: seismic moment tensor, seismotectonics, Apennines, Central Italy

Introduction

The Italian Apennines are seat of extensional deformation, concentrated along the inner part of the mountain belt. This phenomenon is a relict of the process, driven by the rolling back subduction of Adriatic plate, that lead to the opening of the Tyrrhenian back-arc basin (Facenna et al., 2004). This NE-SW trending deformation reaches velocities up to 3 mm/yr (D'Agostino et al., 2008). Seismic activity is well known, both historically and instrumentally, and it is spread along the whole length of the mountain chain. Seismic hazard is high all along the Apennines (MPS Working Group, 2004). Typically, earthquakes along Central-Southern Apennines show normal faulting mechanisms and focal depths in the upper 15 km of crust (Vannucci et al., 2004). The most recent examples are the 1915, M=6.9 Avezzano event (Amoruso et al., 1998); 1930, M=6.7 and 1980, M=6.9, Irpinia events (Pino et al., 2008); the 1979, Mw=5.9 Valnerina quake (Boschi et al., 2000); the 1997-1998 Umbria-Marche sequence, that included two events with Mw=5.7 and Mw=6.0 (Ekström et al., 1998). Another recent sequence — 2002, Mw=5.7, S. Giuliano di Puglia twin events — showed instead strike-slip character. It was located off mountain chain, and it has been attributed to deformation within the Adriatic Plate descending beneath the Apennines (Di Luccio et al., 2005)

On April 6, 2009, a Mw=6.3 earthquake occurred in Central Italy, with shallow hypocenter located at the outskirts of the city of L'Aquila, in the Abruzzo region, causing extensive damage and casualties (Figure 1). It followed a seismic activity that initiated in October 2008 and culminated with the Mw=4.4 event of March 30, and the Mw=4.2 earthquake, a few hours before the main shock (Figure 1 and Tables in supplementary material). Thousands of aftershocks have been recorded. Seismic activity in this region had been scarce during past few decades, with only three seismic swarms in 1985 (Ml 4.2), 1994 (Ml 3.9) and 1996 (Ml 4.1) as reported in *Catalogo della Sismicità Italiana* (CSI, Castello et al., 2007). Historical records show instead the occurrence of destructive events, with at least two of them — in 1461 and 1703 — reaching intensities up to X (Gruppo di Lavoro CPTI, 2004). The epicentral area had been identified before the earthquake as a region of higher-than-average earthquake probability, in particular along the Apennines axis (Akinci et al., 2009; Faenza et al., 2003).

Here, we report on source geometries of the L'Aquila seismic sequence. We computed 26 moment-tensor solutions using the same technique we apply to maintain the European-Mediterranean Regional Centroid Moment Tensor (RCMT) Catalog (www.bo.ingv.it/RCMT; Pondrelli et al., 2006 and references therein). They are greatly in agreement with seismotectonics of the region. Comparing definitive to Quick RCMTs computed immediately after the earthquakes, we found really smaller adjustments to quick determinations. This highlights the robustness of RCMT solutions, considering that timely publication of moment tensors for main events of a sequence is a functional tool to support ongoing studies as complex source description and hazard update.

Regional CMT solutions: data analysis

We compute seismic moment tensors using an extension of the global CMT scheme, based on fitting fundamental-mode Rayleigh and Love waves recorded at regional distance (Arvidsson and Ekström, 1998). This process is particularly appropriate to study intermediate-magnitude events, and produces robust seismic moment tensors and Mw, fully compatible with other source parameters (e.g., Global CMTs, Ekström et al., 2005).

We use three-component seismograms, low-pass filtered with cut-off frequencies ranging from 1/30 to 1/50 Hz, depending on magnitude, to select the broadest spectrum with good signal-to-noise ratio. When signal-to-noise ratio allows it, long-period body waves are added in the inversion, as for 9 of the 26 RCMTs computed for this sequence (Figure and Table 2 in Supplementary Material). Data retrieval and pre-processing are done automatically, but each inversion is always controlled and reviewed by an operator. We commonly use 5 to 15 stations with a distance range between 3 to 15 degrees, belonging to MedNet and GEOFON networks. Located closer to the source region, these stations are the most useful to study European-Mediterranean smaller magnitude events, and provide good azimuthal coverage. When new seismograms from other networks become available through ORFEUS (www.orfeus.org), we revise and update the solutions. Here we present the definitive RCMTs for 26 events with a Mw between 3.9 and 6.3, including the two greater foreshocks of March, 30 and April, 5 (Tables in supplementary material). NW-SE striking extensional moment tensors dominate, with tensional axes oriented between 40° and 60° (Figure 2). Only in a few cases, a pronounced strike-slip component characterizes the source geometry as for the April 7, 17:47 aftershock. Most of these solutions have “A“ quality flag, that means greatest stability (see Pondrelli et al., 2006 for quality evaluation); only four smaller magnitude events have a “C” flag because their inversion required to fix the location (Table 2 in Supplementary Material). Centroid depth of all solutions is in general agreement with preliminary locations; only two cases have a final location 5 km deeper with respect to initial one. Most events have the typical depth, within the top 15 km, of seismic sequences occurred previously in the Apennines. Only a few of them are deeper, down to 26 km, mainly those located southward and with a more prominent strike-slip component (Tables in Supplementary Material). A comparison with solutions produced by other groups with other techniques (www.csem-eu.org; http; TDMT on earthquakes.rm.ingv.it) shows an unquestionable similarity of focal geometries. Our Mw values are in good agreement with those from other agencies, mainly for greater events and have a regular behaviour respect to ML (Figure 2). Comparing definitive RCMTs to Quick RCMTs computed (when M>4.0) within one hour after the earthquake occurred, we found really small changes to quick determinations. This promotes the robust reliability of QRCMTs, at least for the Central Mediterranean, where on-line seismograms ensure a fast and good azimuthal coverage.

RCMT solutions in a seismotectonic framework

The extensional geometry of mechanisms of L'Aquila earthquakes is the same of other important seismic sequences along the Apennines, such as the 1980, M=6.9, Irpinia earthquake and the Umbria-Marche seismic sequence in 1997-1998. The seismic sequence started beneath the city of L'Aquila and spread along a 40 km area into three main clusters (Figures 1 and 2). This migration of hypocenters was also seen in the 1997-1998 Umbria-Marche sequence. The foreshocks, the main shock and most of the activity of the first three days are part of the central cloud of seismicity, located beneath the town. The seismic activity that preceeded the sequence and the two main foreshocks also occurred in this area (Figures 1 and 2). All RCMTs of this central cluster have a shallow centroid depth (within 14 km). The northern seismicity cluster activated just after the main shock (Mw=5.1 on April 6, at 23:15, Table 1 in supplementary material) and continued with its northernmost expression with the two Mw 4.0 and 4.1 events on April

14 and 15. Depths for two of these events exceed 15 km. The southern seismicity cluster started later, with the Mw 5.6 aftershock, on April 7. Here are located the deepest events of the sequence, with hypocentral centroid locations deeper than 20 km and characterized also by a consistent strike-slip component. The T axes distribution is NE-SW, roughly perpendicular to the Apennines, in the central and northern seismicity clusters, whereas the southern one is more heterogeneous (Figure 2).

The location and focal mechanism for the main shock suggest that this event occurred on the Paganica fault, a 10-15 km length, NW-SE striking, SW-dipping structure previously identified in the field (Vezzani e Ghisetti, 1998). The geometry of this fault is in agreement with our source parameters. This hypothesis was supported also by aftershock distribution (Chiarabba et al., 2009), DinSAR analysis (Atzori et al., 2009), geodetic and geological surveys (Anzidei et al., 2009; Emergeo Working Group, 2009). The northern cluster of the sequence shows a distribution that may be in agreement with an activation of the Campotosto fault, another normal fault, NNW-SSE striking and SW dipping (Galli et al., 2008; Boncio et al., 2004). Also our focal mechanisms are in agreement with the geometry of this fault. The southernmost cluster, where events with deeper location and with a greater strike-slip component are located, has a less-clear geometry and appears to be connected to a different system of faults. In this area previous studies identified the NNW-SSE Mt. Ocre fault system (Salvi et al., 2003). Because of its strike direction, it could be related to the present-day seismicity that at south privileges a NNW-SSE trend, rotated with respect to the NW-SE distribution of the two other clusters. However, at south the poor definition of any structure from hypocentral location makes any relation more doubtful.

Deeper events also showed relevant strike-slip components in previous Apenninic seismic sequences, such as in the 1997-1998 Umbria-Marche sequence (Ekström et al., 1998) or in the 2002 S. Giuliano di Puglia sequence (Di Luccio et al., 2005). This vertical distribution of deformation styles is interpreted as an extension working on the thrust and fold belt while deeper deformation occurs within the Adria plate located beneath the belt.

Conclusions

We computed seismic moment tensors for 26 events with Mw between 3.9 and 6.3 belonging to the 2009 L'Aquila (Central Italy) seismic sequence. RCMTs gave immediately the indication that this seismicity, from the seismotectonic point of view, is similar to previous extensional activity occurred along this mountain belt, also in the vertical distribution of hypocenters and deformation styles. NW-SE striking focal planes agree with mapped faults of the region, allowing to infer which tectonic structures have been activated. For some events a relevant strike-slip component is observed, mainly when the hypocenters are deeper. This occurs mainly at south with respect to the entire activated region.

Seismotectonic analysis of the ongoing seismic sequence has been supported by the prompt availability of RCMTs, quick solutions first and definitive solutions successively. Our results provide crucial information for a number of ongoing studies about different aspects of the seismic sources. We conclude on the feasibility and importance of application of our inversion scheme for the early and reliable analysis of seismic sequences.

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Figure captions

Figure 1 - Map of seismicity. Blue stars – events of the sequence with Ml >5.0; red square – historical seismicity with Imax > 7.5 (Gruppo di Lavoro CPTI, 2004); white circles – previous seismicity (Castello et al., 2007); grey circles –events from January to April 2009; red circles– seismicity from April 6 to 9; orange – from 9 to 11; yellow – from 11 to 30; light yellow – from May 1 to July 27 (iside.rm.ingv.it). Upper right: Italy map with L’Aquila as a red square. Below: cumulative seismic energy release (joule) from January to July 2009.

Figure 2 - RCMTs with their epicenters (in red) and the smaller magnitude seismicity of the sequence (in yellow). In the background (white dots) previous seismicity (CSI, Castello et al., 2007) and previous available RCMTs (small focal mechanisms, Pondrelli et al., 2006; http://www.bo.ingv.it/RCMT/Italydataset.html). Upper left: Ml vs Mw in comparison to the regression line for these kind of magnitudes (Gruppo di Lavoro CPTI, 2004). Upper right, lower left and right: rose diagrams representing respectively the different T axes distribution in the three areas where seismicity occurred.

Fig.1

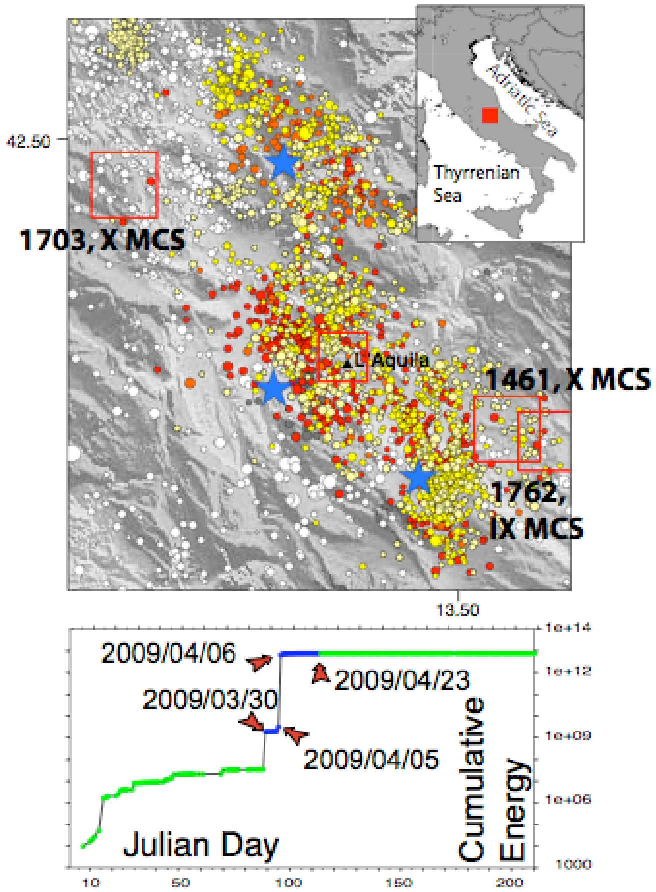
Adriatic Sea
Thyrrenian Sea
42.50
1703, X MCS
L'Aquila
1461, X MCS
1762, IX MCS
13.50
2009/04/06
2009/04/23
2009/03/30
2009/04/05
Julian Day
Cumulative Energy
1e+14
1e+12
1e+09
1e+06
1000
10
50
100
150
200

Fig.2

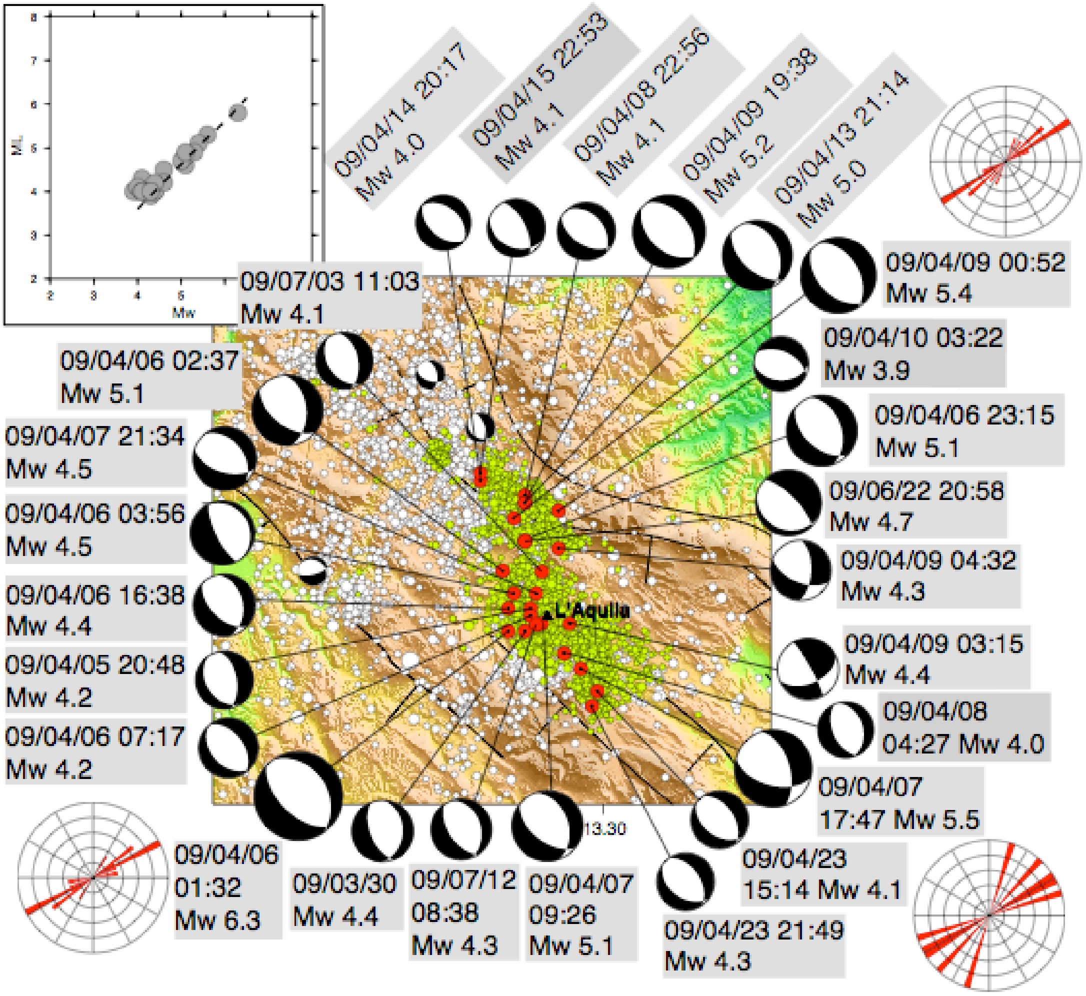
ML
Mw
2
3
4
5
6
7
8
09/04/14 20:17 Mw 4.0
09/04/15 22:53 Mw 4.1
09/04/08 22:56 Mw 4.1
09/04/09 19:38 Mw 5.2
09/04/13 21:14 Mw 5.0
09/04/09 00:52 Mw 5.4
09/07/03 11:03 Mw 4.1
09/04/10 03:22 Mw 3.9
09/04/06 02:37 Mw 5.1
09/04/06 23:15 Mw 5.1
09/04/07 21:34 Mw 4.5
09/06/22 20:58 Mw 4.7
09/04/06 03:56 Mw 4.5
09/04/09 04:32 Mw 4.3
09/04/06 16:38 Mw 4.4
L'Aquila
09/04/09 03:15 Mw 4.4
09/04/05 20:48 Mw 4.2
09/04/08 04:27 Mw 4.0
09/04/06 07:17 Mw 4.2
09/04/07 17:47 Mw 5.5
13.30
09/04/06 01:32 Mw 6.3
09/03/30 Mw 4.4
09/07/12 08:38 Mw 4.3
09/04/07 09:26 Mw 5.1
09/04/23 15:14 Mw 4.1
09/04/23 21:49 Mw 4.3

Table 1 - Centroid locations and difference from preliminary information (dlat, dlon, ddep), preliminary Ml (INGV), Mw computed for events reported here (R=RCMT) and those computed by other agencies (G=: Global CMT Catalog, E=ETHZ, U=USGS from www.emsc-csem.org, T=TDMT from earthquake.rm.ingv.it).

Date	Time	CMT Lat.	dlat	CMT Lon.	dlon	CMT depth	ddep	Ml	Mw R	Mw G	Mw E	Mw U	Mw T
03/30	13:38	42.33	0.00	13.26	0.10	14.0	-3.0	4.0	4.4	---	---	---	4.0
04/05	20:48	42.45	-0.09	13.36	0.01	10.0	0.0	4.0	4.2	---	---	---	3.9
04/06	01:32	42.30	0.03	13.31	0.02	11.6	-1.6	5.8	6.3	6.3	---	6.3	6.1
04/06	02:37	42.29	0.12	13.39	-0.07	12.9	-2.9	4.6	5.1	---	---	4.9	4.8
04/06	03:56	42.38	0.00	13.34	0.00	10.0	0.0	4.5	4.5	---	---	---	4.3
04/06	07:17	42.39	-0.04	13.30	0.07	10.0	0.0	3.9	4.2	---	---	---	---
04/06	16:38	42.29	0.07	13.29	0.04	10.8	-0.8	4.0	4.4	---	---	4.7	4.2
04/06	23:15	42.37	0.08	13.36	0.00	11.8	-1.8	4.8	5.1	---	5.2	4.9	5.0
04/07	09:26	42.26	0.08	13.41	-0.02	13.6	-3.6	4.7	5.1	---	5.2	4.8	4.9
04/07	17:47	42.31	-0.03	13.48	-0.02	20.5	-5.5	5.3	5.5	5.5	5.6	5.5	5.4
04/07	21:34	42.33	0.05	13.29	0.09	11.7	-1.7	4.2	4.5	---	4.7	---	4.3
04/08	04:27	42.23	0.07	13.41	0.02	12.2	-2.2	4.0	4.0	---	---	---	---
04/08	22:56	42.42	0.09	13.33	0.03	14.1	-4.1	4.3	4.1	---	---	---	4.0
04/09	00:52	42.48	0.00	13.34	0.00	15.4	-0.4	5.1	5.4	5.4	5.5	5.3	5.2
04/09	03:14	42.26	0.08	13.43	0.01	26.0	-8.0	4.2	4.4	---	---	---	4.3
04/09	04:32	42.41	0.03	13.35	0.07	12.8	-2.8	4.0	4.3	---	---	---	4.2
04/09	19:38	42.51	-0.01	13.26	0.10	15.6	1.4	4.9	5.2	5.2	5.2	5.0	5.0

04/10	03:22	42.49	0.00	13.42	0.00	10.0	0.0	4.0	3.9	---	---	---	---
04/13	21:14	42.47	0.03	13.29	0.07	11.8	-1.8	4.9	5.0	---	5.1	---	4.8
04/14	20:17	42.61	-0.08	13.14	0.14	10.0	0.0	4.1	4.0	---	---	---	3.7
04/15	22:53	42.54	0.00	13.28	0.00	10.0	0.0	4.0	4.1	---	---	---	---
04/23	15:14	42.22	0.03	13.54	-0.05	11.0	-1.0	4.0	4.1	---	---	---	3.9
04/23	21:49	42.24	-0.01	13.35	0.13	10.0	0.0	4.0	4.3	---	---	---	4.2
06/22	20:58	42.45	0.00	13.36	0.00	12.0	-2.0	4.5	4.7	---	---	---	4.5
07/03	11:03	42.41	0.00	13.39	0.00	10.0	0.0	4.1	4.1	---	---	---	3.6
07/12	08:38	42.34	0.09	13.38	0.12	10.0	0.0	4.0	4.3	---	---	---	4.2

Table 2 - Qf is the Quality flag (Pondrelli et al., 2006), data used (S: only surface waves, C: body and surface waves; * for RCMT recovered later), focal plane parameters and T and P axes directions.

Date	Time	Qf	Data	str1	dip1	sl1.	str2	dip2	sl2	T az	T dip	P az	P dip
03/30	13:38	A	S	2	35	-70	158	57	-104	258	11	31	74
04/05	20:49	A	S*	147	37	-108	349	55	-77	70	9	300	76
04/06	01:32	A	C	326	35	-80	134	56	-97	229	10	20	78
04/06	02:37	A	S	355	46	-53	128	55	-122	240	5	341	64
04/06	03:56	C	S*	340	25	-103	175	66	-84	260	21	96	68
04/06	07:17	A	S*	138	41	-93	323	49	-87	51	4	261	86
04/06	16:38	A	C	348	40	-64	135	55	-111	239	8	353	72
04/06	23:15	A	C	341	44	-68	132	50	-109	236	3	339	75
04/07	09:26	A	S	341	41	-64	128	54	-111	233	7	344	72
04/07	17:47	A	C	105	53	-134	342	55	-48	44	1	312	57
04/07	21:34	A	C	321	41	-64	108	54	-110	213	7	325	72
04/08	04:27	A	S*	344	38	-84	156	52	-95	250	7	39	82
04/08	22:56	A	S	319	40	-76	121	51	-101	219	5	340	80
04/09	00:52	C	C	329	45	-81	136	46	-99	233	0	326	84
04/09	03:14	A	S	67	50	-170	331	83	-40	25	21	281	33
04/09	04:32	A	C	113	57	-144	2	61	-39	58	2	326	47
04/09	19:38	A	C	321	44	-83	132	46	-97	227	1	331	85
04/10	03:22	C	S*	91	41	-108	294	51	-75	14	5	260	77
04/13	21:14	A	C	337	38	-71	133	54	-104	233	8	359	76

04/14	20:17	A	S	309	42	-92	132	48	-88	221	3	65	87
04/15	22:53	C	S*	113	33	-126	333	64	-69	48	17	279	65
04/23	15:14	A	S	126	43	-105	326	49	-76	46	3	301	79
04/23	21:49	A	S	323	27	-95	149	63	-87	237	18	65	72
06/22	20:58	C	S	113	19	-112	315	72	-83	29	27	236	62
07/03	11:03	C	S	144	42	-108	348	50	-74	67	4	318	77
07/12	08:38	A	S	342	35	-76	146	56	-99	243	11	26	77

Data (blue) and syntethics (red) for some of seismograms used for the inversion of April 6, 2009 Mw 6.3 event. In the upper group of stations body and surface waves are used, in the lower only surface waves.