SEISMICITY AND SEISMOGENIC STRUCTURES IN CENTRAL ITALY: NEW INSIGTHS FROM THE SLAM PASSIVE EXPERIMENT

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ABSTRACT We investigate the background seismicity of Central Italy in the area including southern Latium, Abruzzi and Molise (SLAM project). This region has been historically affected by many strong earthquakes, some of them very destructive such as the 1349, 1654, and 1805 events. The May 1984 Comino Valley earthquake (Mw 5.9), southeastern Latium, is the largest recent event up to now. The present activity is characterized by diffuse low-magnitude seismicity, marked by some light events ($M_L < 5$) which produced localized sequences during 2009-2013. Our study focuses on the seismicity occurred in such period and, in particular, on the seismic activity currently affecting the Sorano-Marsica area where the last crisis, started with the February 16, 2013 M_L 4.8 mainshock, took place. We present hypocentral locations and focal mechanism solutions obtained by using a refined 1D crustal velocity model. The waveform data set was collected from the digital recordings of the permanent stations of the Italian national seismic network, the Abruzzi and Molise regional seismic networks, and from a dense seismic survey carried out in the region between November 2011 and May 2013. The temporary network consisted of 17 seismic stations typically configured with a Reftek RT130 digitizer and a three-component Lennartz 3D/5s sensor. The deployment of this array improved significantly the detection and location of background seismicity, including the complete observation of the more recent sequence. We relocated more than 4800 events with magnitude M_L ranging from about 0.5 to 4.8. Earthquakes distribution shows hypocentral depths concentrated within the crust, between 5 and 20 km of depth, and is mostly clustered along the Apenninic chain axis. The computed fault-plane solutions generally display normal fault mechanisms, confirming the extensional NE-SW processes active since Pleistocene in the study region.

SEISMOTECTONIC CONTEXT

The **SLAM** (**S**eismicity of **L**atium-**A**bruzzi-**M**olise region) project aims to provide new insights on the seismotectonic and seismogenesis of a wide portion of Central Italy situated between areas affected by recent destructive events such as the 2009, Mw 6.3, L'Aquila earthquake, to the north, and the 2002, Mw 5.8, Molise earthquake, to the east. The planned research activities include precise re-location and magnitude (re-)evaluation of events, fault plane solution and stress field inversion, mapping of *b-value*, and local earthquake tomography. The study region (Figure 1) extends from the Fucino Basin and Maiella Massif, to the north, to the Tyrrhenian coast, to the south, and from the Frentani/Matese Mts., to the east, to the Alban Hills volcano to the west. It includes part of the central Apenninic chain and the peri-Tyrrhenian volcanic complex of Alban Hills and Roccamonfina. These tectonic features and the associated active faults are the result of the Neogene-Quaternary evolution of the Tyrrhenian-Apennine system. In particular, since the early Miocene, after the eastward migration of the Apenninic compressional front, the extension superimposed producing in this portion of the chain a broad and complex system of NW-SE trending normal faults with related large intermountain extensional basins (Galadini and Galli, 2000; Montone *et al.*, 2004). Figure 2 and Table 1 show the main historical events that occurred in the area in the last millennium. Among the strongest earthquakes, the 1456 Molise-Campania event (the largest event ever occurred in peninsular Italy) and the 1915 Marsica event hit very large areas of central-southern Italy, both with effects of the XI degree on the Mercalli-Cancani-Sieberg (MCS) scale. The last raw on Table 1 refers to the May 7, 1984 Comino Valley earthquake, the most important instrumentally recorded event before our observing period. This event was characterized by a Mw 5.9 mainshock followed by intense seismic activity, including the large aftershock on May 11 with Mw 5.5. The focal mechanisms of these events are quite similar, showing solution prevailingly extensional with the extensional axes (T) oriented at about N60ºE (Pace *et al.*, 2002).

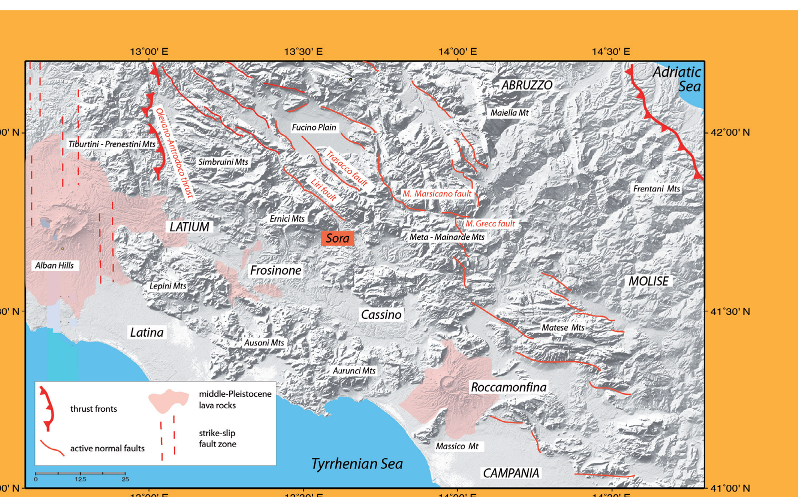

Figure 1. Map of the SLAM study area with the main tectonic-structural elements

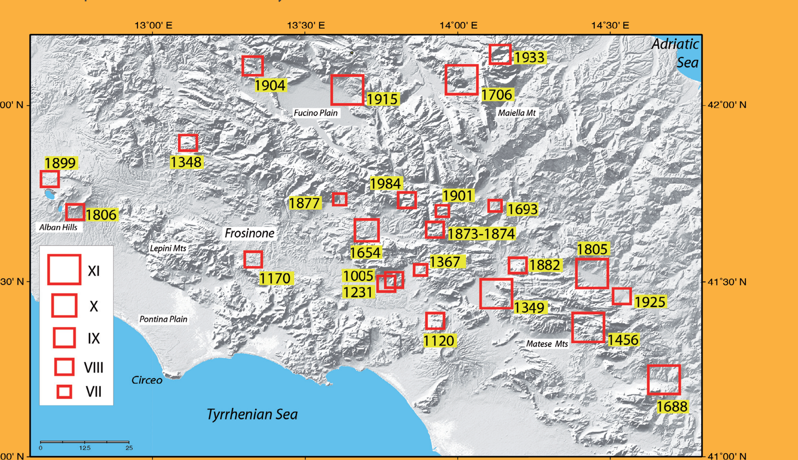

Figure 2. Historical seismicity from the **CPTI**11 (**C**atalogo **P**arametrico dei **T**erremoti **I**taliani, version 2011) database (Rovida *et al.*, 2011)

Year-Month-Day	Imax(MCS)	Mw	Epicentral Area
1005	VII	5.1	Cassino
1231-06-01	VIII	5.1	Cassino
1120-03-25	VIII-IX	5.8	Rocca d'Evandro
1170-05-09	VIII	5.6	Ceccano
1348-09-13	VIII	5.6	Subiaco
1349-09-09	X	6.6	Southern Latium-Molise
1367	VII	5.1	Sant'Elia Fiumerapido
1456-12-05	XI	7.2	Molise-Campania
1654-07-24	X	6.3	Sorano-Marsica
1688-06-05	XI	7.0	Campania
1693-03-24	VII	5.3	Molise
1706-11-03	X-XI	6.8	Maiella
1805-07-26	X	6.6	Matese
1806-08-26	VIII	5.5	Alban Hills
1873-07-12	VII-VIII	5.4	Meta Mt.
1874-12-06	VIII	5.5	Meta Mt.
1877-08-24	VII	5.2	Sorano
1882-06-06	VIII	5.3	Matese
1899-07-19	VII	5.1	Alban Hills
1901-07-31	VII	5.2	Meta Mt.
1904-02-24	IX	5.6	Marsica
1915-01-13	XI	7.0	Marsica
1925-09-24	VII-VIII	5.2	Molise
1933-09-26	IX	6.0	Maiella
1969-04-17	VII-VIII	4.6	Cassino
1984-05-07	VIII	5.9	Sorano-Marsica

Table 1. Parameters of historical seismicity displayed in Figure 2.

THE SLAM PASSIVE EXPERIMENT

As an important task of the SLAM project, we carried out a dense seismic survey of the area under study using high-dynamic portable stations in continuous mode recording at a sampling rate of 125 sps. The field experiment started at the beginning of November 2011 and lasted up to the end of May 2013. Figure 3 displays the station distribution of the temporary array (red squares) along with the existing permanent networks. Site locations and operating period of the SLAM stations are listed in Table 2. The mobile stations were equipped with a high-dynamic (24 bit) Reftek RT130 digitizer, a three-component sensor, mostly extended-band Lennartz 3D/5s sensor (sensitivity of 400 V/m/s and velocity response flat in the range 0.2 - 40 Hz), a 12 V battery linked to a 70 W solar panel as power supply, and a 2Gb flash memory card as storage system. Data temporization was obtained by GPS signal. Almost all the stations were installed on bedrock formations or concrete floor on rock formation (Figure 4). Site selection was performed by analyzing also the Power Spectral Density (PSD) of ground acceleration samples (Cimini *et al.*, 2006; Trnkoczy, *et al.*, 2012).

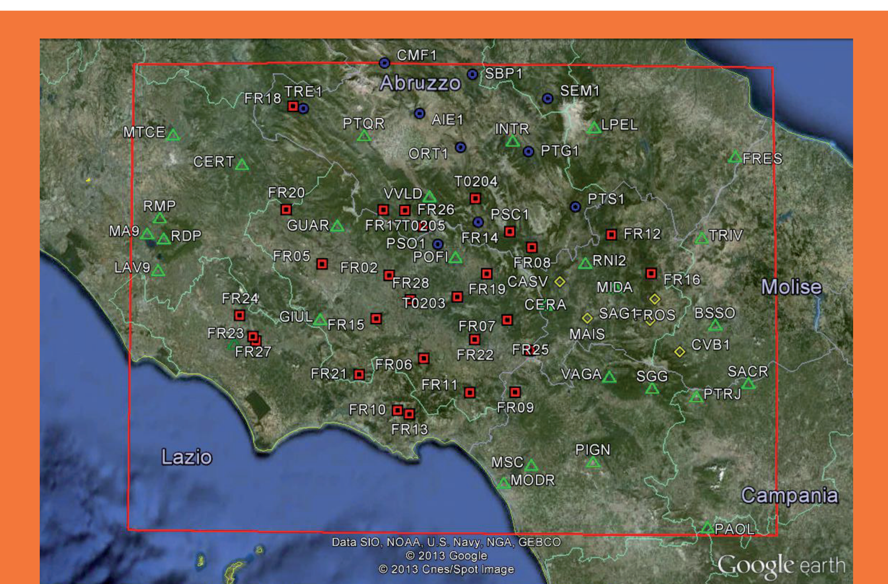

Figure 3. Seismic stations used in this study. Red squares are the temporary stations deployed for the passive experiment between November 2011 and May 2013. Green triangles indicate the permanent stations of the Italian national network. Blue circles and yellow diamonds indicate respectively the Abruzzi and Molise regional networks

Code	Location	Lat. (N)	Lon. (E)	Elev. (m)	Operating Period
T0203	Casalattico (FR)	41.61870	13.72131	562	04/11/2011 – 20/05/2013
T0204	Pescasseroli (AQ)	41.86654	13.72131	1376	02/11/2011 – 12/04/2012
T0205	Ridotti (AQ)	41.79539	13.60451	686	04/11/2011 – 30/11/2011
FR02	Casamari (FR)	41.67198	13.49025	266	04/11/2011 – 23/05/2013
FR05	Ferentino (FR)	41.69937	13.26305	387	12/11/2011 – 23/05/2013
FR06	Monte Leuci (FR)	41.46246	13.60844	478	18/11/2011 – 22/05/2013
FR07	Valvori (FR)	41.56089	13.89065	417	11/11/2011 – 21/05/2013
FR08	Barrea (AQ)	41.74404	13.97256	1182	14/11/2011 – 27/01/2012
FR09	Rocca d'Evandro (CE)	41.37758	13.91817	468	11/11/2011 – 17/08/2012
FR10	Itri (Sant. Civita) (LT)	41.33012	13.52067	642	03/11/2011 – 10/12/2011
FR11	Castenuovo Parano (FR)	41.37620	13.76489	465	01/12/2011 – 22/05/2012
FR12	Vastogirardi (IS)	41.77654	14.24302	1170	13/01/2012 – 20/05/2013
FR13	Itri (Rif. Tozze) (LT)	41.32087	13.56061	795	17/12/2011 – 22/04/2012
FR14	Civitella Alfedena (AQ)	41.78347	13.89761	1054	30/01/2012 – 21/05/2013
FR15	Pofi (FR)	41.56271	13.44679	141	23/02/2012 – 08/03/2013
FR16	Chiauci (IS)	41.67845	14.37870	940	02/03/2012 – 20/05/2013
FR17	Rendinara (AQ)	41.83607	13.46975	817	21/03/2012 – 30/10/2012
FR18	Carsoli (AQ)	42.09734	13.15863	485	16/11/2011 – 07/06/2012
FR19	Gallinaro (FR)	41.67727	13.82039	484	12/04/2012 – 21/05/2013
FR20	Piglio (FR)	41.83632	13.13841	856	24/04/2012 – 06/05/2013
FR21	Vallecorsa (FR)	41.42057	13.38977	326	22/05/2012 – 22/05/2013
FR22	Villa S. Lucia (FR)	41.51108	13.78065	346	09/06/2012 – 20/05/2013
FR23	Sezze Scalo(LT)	41.50267	13.03823	113	29/06/2012 – 16/08/2012
FR24	Valvisciolo (LT)	41.56753	12.98173	154	16/08/2012 – 08/11/2012
FR25	Radicosa (FR)	41.48366	13.96897	671	17/08/2012 – 21/05/2013
FR26	S. Giovanni V. R. (AQ)	41.83552	13.54277	304	30/10/2012 – 23/05/2013
FR27	Sezze - Casali (LT)	41.51420	13.02805	417	09/11/2012 – 29/04/2013
FR28	Fontana Liri (FR)	41.61039	13.56237	379	08/03/2013 – 23/05/2013

Table 2. Location parameters and operating period of the SLAM temporary stations

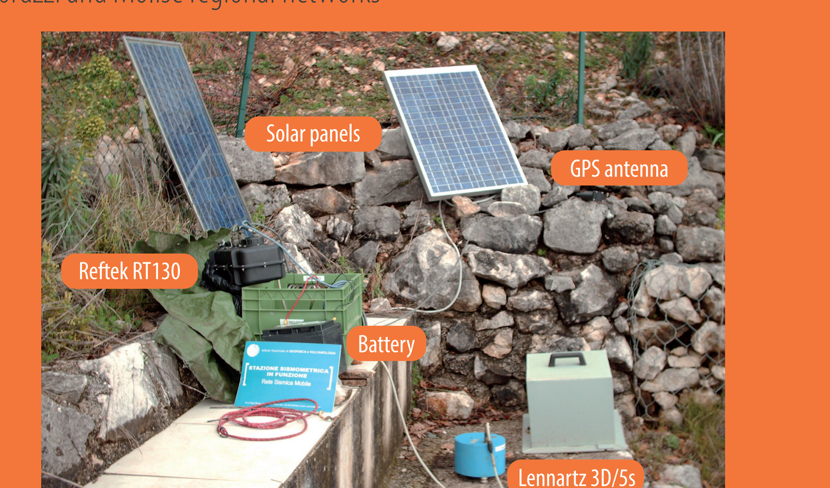

Figure 4. Seismic instrumentation installed at station site FR22

SEISMIC RECORDINGS AND ANALYSIS

During the time interval January 2009 - May 2013, we collected seismic recordings for more than 5000 local earthquakes, 4849 of which were relocated using the Hypoellipse location program (Lahr, 1999) and a regional 1D velocity model with an average V_p/V_s ratio of 1.80. The value of V_p/V_s ratio, determined with the Wadati method, is in line with the V_p/V_s ratios retrieved for other seismogenic zones of the Apenninic chain (Abruzzo region, V_p/V_s = 1.83, Bagh *et al.*, 2007; Lucanian Apennines, V_p/V_s = 1.83, Frepoli *et al.*, 2011). Our arrival times dataset consists of 39322 *P*-wave picks and 32600 *S*-wave picks. Figures 5 and 6 display the relocated hypocenters respectively within the SLAM study area and in the Sorano-Marsica zone where about 51% of the examined seismicity occurred. Figure 6 also shows a number of well-constrained focal mechanisms computed by using the P-wave first motion polarity method and the FPFIT code (Reasenberg and Oppenheimer, 1985). This fault plane solutions were obtained with a maximum of 2 discrepant polarities and a minimum number of 10 observations homogeneously distributed on the focal sphere (Table 3).

Figures 7 to 10 give a close look on the February 16, 2013 earthquake and related aftershocks activity. The mainshock (Figure 7) was preceded by some foreshocks occurred the day before at approximately the same depth (≅ 20 km).

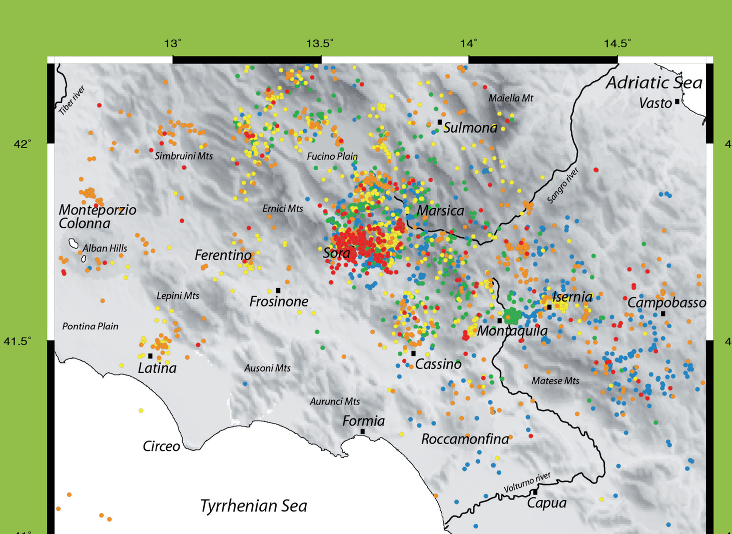

Figure 5. Map view of the relocated seismicity (4849 events; average *rms* 0.124s) occurred within the SLAM area from 2009 to half 2013. Earthquake were relocated using P and S-wave arrival times handpicked on the recordings of the integrated network shown in Figure 3. Coloured dots differentiate the seismic activity through years (**2009**, blue dots, 1821 events; **2010**, green dots, 602 events; **2011**, yellow dots, 1345 events; **2012**, orange dots, 561 events; **2013**, red dots, 520 events). Most of the seismicity is concentrated along the main axis of the Apenninic chain. In the Sorano-Marsica area, to the south of the Fucino Plain, are located the three main sequences recorded during our observing period. The first two sequences occurred nearby the town of Campoli Appennino, in September-October 2009 and May 2011. The third sequence is associated to the recent M_L 4.8 Sora earthquake (February-May 2013). The green cluster in the upper Volturno Valley shows the May 2010 Montaquila seismic sequence, while the orange one, to the north of the Alban Hills, shows the Monteporzio-Colonna sequence of June-July 2012. Finally, the yellow-orange clusters in the Pontina Plain are the two small sequences of July 2011 and February 2012, respectively.

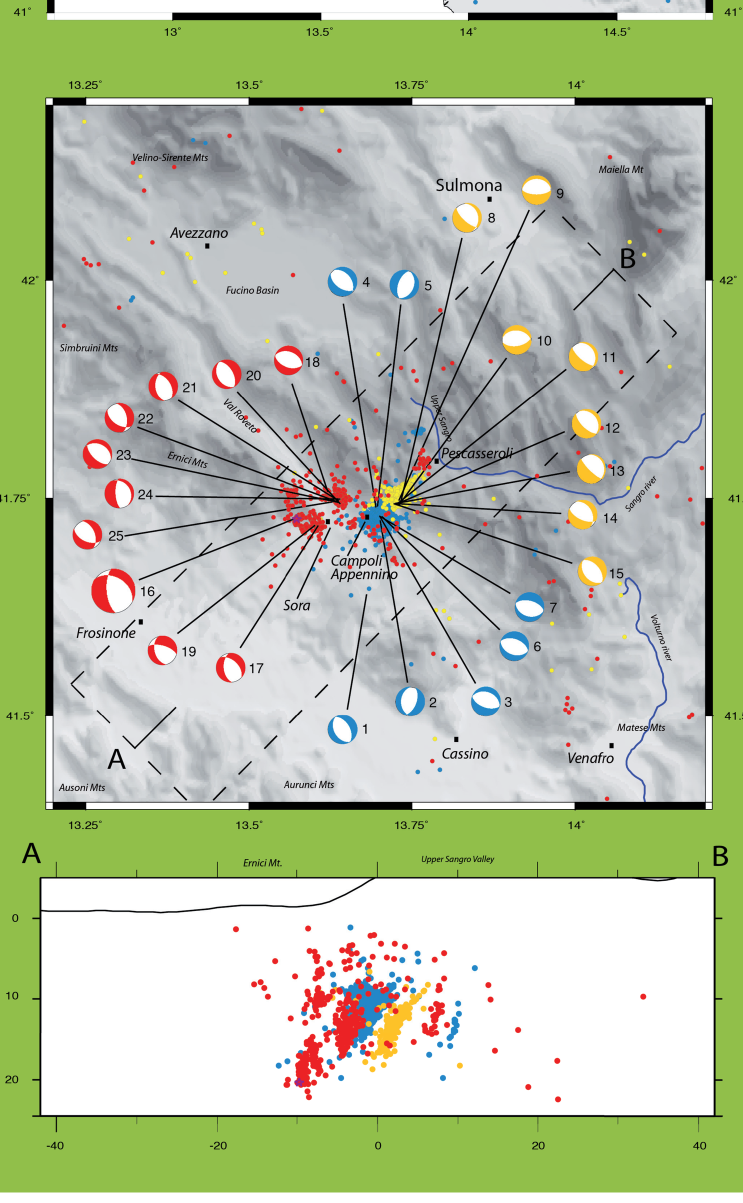

Figure 6. Map view and SW-NE cross-section of the seismicity relocated in the Sorano-Marsica area (2486 events; average *rms* 0.116s). Blue dots indicate the first Campoli Appennino sequence (September-October 2009; 1204 events), yellow dots the second Campoli Appennino sequence (May 2011; 781 events), and red dots the Sora sequence (February-May 2013; 501 events). Focal mechanisms for a set of 25 events are also displayed. The largest red beach-ball (number 16) is the focal mechanism of the February 16, 2013 Sora earthquake (purple star). Most of the fault plane solutions have pure dip-slip kinematics with nodal planes oriented NW-SE in agreement with the anti-Apenninic extensional regime. Some solutions show nodal planes with a N-S orientation (number 2, 5, 16, 21, and 24). The N-S nodal plane of the M_L 4.8 event has a large dip angle (65°) coherent with the near-vertical cluster of events relocated at 13-21 km of depth. In the map view, the two Campoli Appennino sequences (blue and yellow dots) partially overlaps, nevertheless the SW-NE cross section clearly shows two planes dipping to the SW with an angle of about 50°. On this plane, only hypocenters with horizontal distance ≤7 km from the vertical profile were projected. Two small clusters with an almost subvertical dip angle (~70°) are located close to the upper Sangro Valley (nearby the town of Pescasseroli) and are expression of the 2009 (blue dots) and 2013 (red dots) sequences, respectively.

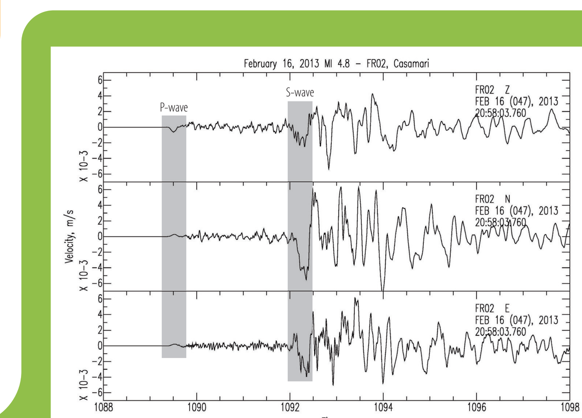

Figure 7. Seismograms of the February 16, 2013 earthquake recorded at the closest station of the SLAM array. Station FR02 (Casamari) was located SW the epicenter at about 10 km.

N	Date	UTC time	Lat. (N)	Lon. (E)	Depth (km)	Strike	dip	Rake	N. of Polarities	Q_f	Q_p	M_L
1	06-08-2009	15:36	41 38.78	13 41.03	16.94	150	40	-90	25	A	A	4.2
2	30-09-2009	19:52	41 43.48	13 42.27	15.01	20	55	-80	38	A	A	3.5
3	06-10-2009	19:38	41 44.20	13 42.51	12.91	110	55	-90	23	A	A	3.1
4	07-10-2009	04:44	41 44.05	13 42.24	13.14	125	50	-100	20	A	A	3.2
5	08-10-2009	00:51	41 44.48	13 42.75	12.29	20	35	-90	31	A	A	3.6
6	08-10-2009	19:14	41 43.95	13 42.24	11.73	110	40	-90	10	A	A	1.4
7	09-10-2009	19:27	41 43.83	13 42.22	11.74	105	35	-90	11	A	A	1.2
8	05-05-2011	02:19	41 45.09	13 43.44	14.85	345	25	-60	17	A	A	2.1
9	05-05-2011	03:34	41 45.00	13 43.76	15.09	90	65	-90	18	A	A	2.1
10	06-05-2011	02:06	41 45.06	13 43.42	14.72	80	55	-100	19	A	A	1.9
11	06-05-2011	16:14	41 44.92	13 43.87	14.89	130	70	-100	17	A	B	2.0
12	08-05-2011	22:39	41 44.92	13 43.89	14.87	325	25	-80	21	A	A	2.2
13	08-05-2011	22:58	41 44.93	13 43.83	14.03	345	15	-60	16	A	A	1.7
14	09-05-2011	03:48	41 45.35	13 43.77	13.80	115	60	-110	17	A	A	1.9
15	18-05-2011	17:58	41 44.97	13 43.76	14.59	140	40	-90	13	A	B	2.4
16	16-02-2013	21:16	41 43.47	13 34.35	20.77	175	65	-60	92	A	A	4.8
17	16-02-2013	22:24	41 43.19	13 36.15	17.90	175	50	-60	33	A	A	2.3
18	17-02-2013	17:27	41 45.10	13 37.07	15.58	110	50	-90	26	A	A	2.2
19	20-02-2013	19:16	41 42.99	13 35.27	19.23	165	45	-40	20	A	B	1.6
20	23-02-2013	05:02	41 44.48	13 38.13	13.52	150	35	-90	25	A	A	2.0
21	23-02-2013	10:27	41 44.62	13 38.16	13.31	175	45	-70	36	A	A	2.8
22	23-02-2013	16:30	41 44.52	13 38.29	14.33	125	50	-120	23	A	A	2.0
23	23-02-2013	16:36	41 44.59	13 38.04	13.45	135	60	-80	23	A	A	2.1
24	23-02-2013	17:17	41 44.52	13 38.18	13.28	325	25	-120	42	B	A	3.1
25	23-02-2013	18:02	41 44.70	13 37.78	12.78	115	50	-120	19	A	B	1.8

Table 3. Fault plane solutions, Sorano-Marsica area, 2009-2013.

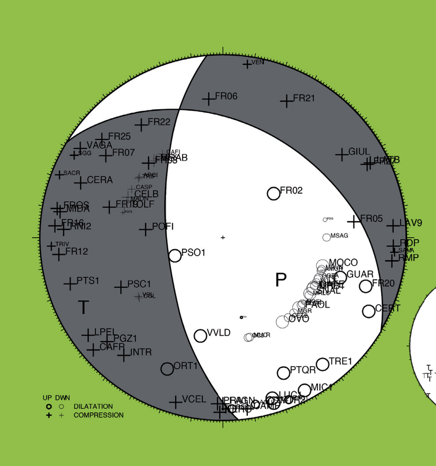

Figure 8. Focal mechanism and distribution of P/T axes for the February 16, 2013 event. Sectors in gray are the compressional quadrants. The solution shows a normal fault mechanism with a small strike component. Solution parameters are highlighted in Table 3.

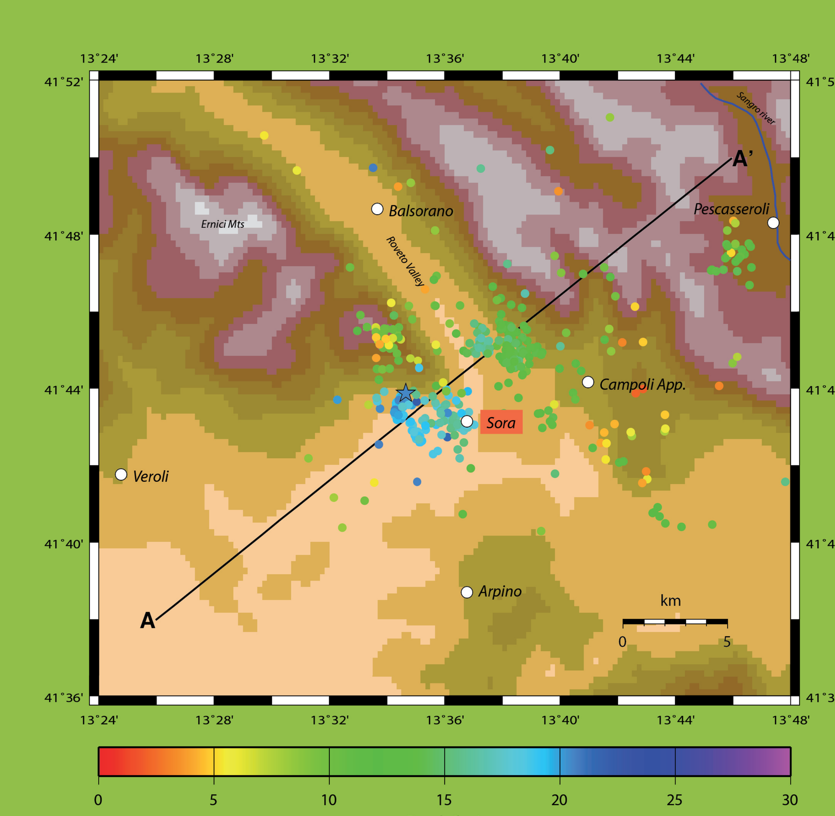

Figure 9. Seismic activity recorded in the area surrounding the city of Sora between February and May 2013. Blue star indicates the M_L 4.8 epicentral location. The black line AA' identify the cross-section profile represented in Figure 10.

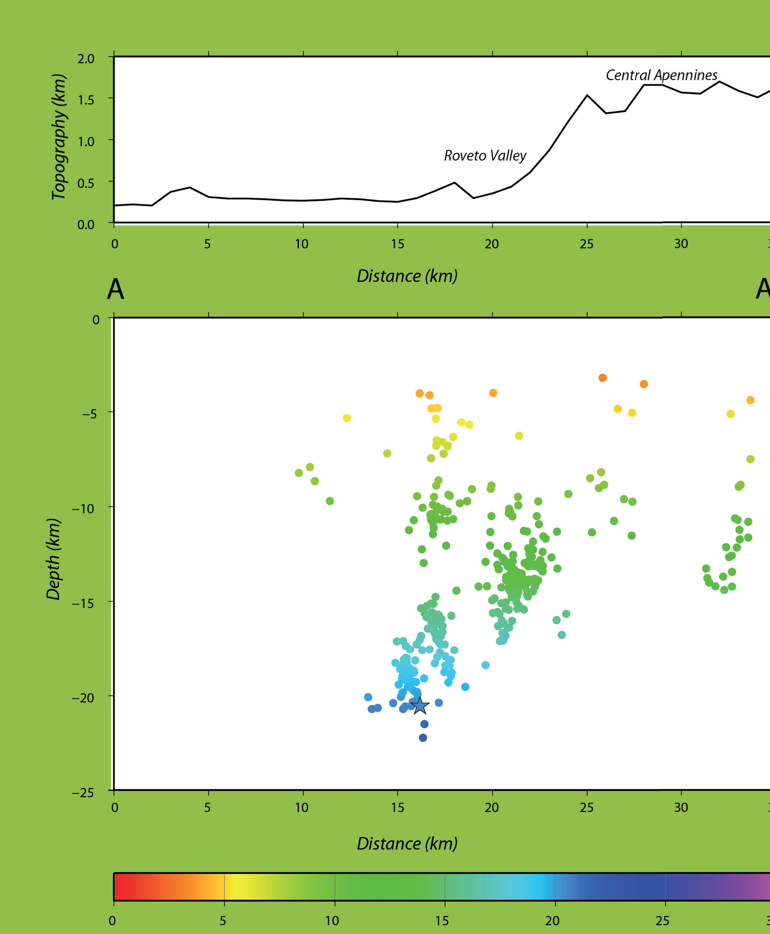

Figure 10. SW-NE cross-section showing the depth distribution of events. The location displayed on the plot are those with an horizontal distance ≤5 km from the vertical profile. The mainshock (blue star) is located at about 21 km depth, in the deeper part of a recognizable SW-dipping seismogenic structure.

CONCLUSIVE REMARKS

The data integration we have performed by merging seismic recordings from permanent and temporary networks provided more constrained earthquake locations and focal mechanism solutions in a large area of Central Italy, characterized by a very high seismic hazard.

The deployment of the SLAM temporary array has proved very effective in the acquisition of the widespread background seismicity and of four distinct sequences occurred during the seismic survey.

Fault plane solutions evaluated using P-wave polarity data show the predominance of normal faulting mechanisms with NE-trending direction of extension coherent with the regional stress field active in this sector of the Apennines.

In the Central Apennines of the Sorano-Marsica area, a persistent, light to moderate, seismic activity is occurring since 2009. Three main sequences, marked by maximum magnitude of 3.6, 3.0, and 4.8, have been recorded so far at time intervals among the episodes of approximately 1.5 years. The seismological analysis presented in this study delineates an articulate fault system constituted by major sub-parallel, SW-dipping fault planes extending from 5 km down to at least 20 km depth in the lower crust. Sub-vertical, N-S oriented, fault segments are also recognizable as secondary or even independent structures.

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