

A temporary seismic monitoring of the Sulmona area (Abruzzo, Italy) for seismotectonic purposes

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ABSTRACT The seismogenic potential of active faults in the Abruzzo region of central Italy has been tragically brought to the general attention by the April 6, 2009 L'Aquila earthquake. In this region, a system of SW-dipping normal faults has been active both in historical and recent times, with at least three moderate-to-large earthquakes (Avezzano 1915, Barrea 1984, and L'Aquila 2009) and several minor seismic sequences. Some highly populated areas, like the Sulmona basin at the hanging wall of the Mt. Morrone fault (a segment capable of releasing destructive earthquakes, $M_{max} \sim 6.7$), have not experienced significant earthquakes in the last millennium; the time lapse since the last event should therefore be comparable with the recurrence time assigned to this fault, enhancing its contribution to seismic hazard in a time-dependent perspective. With the aim of increasing our knowledge on the active deformation pattern, geometry and seismogenic depth of the potential structures by means of low-magnitude seismicity, a bulk of temporary seismometric stations has been installed in the Sulmona area. The small network is managed by OGS (Istituto Nazionale di Oceanografia e Geofisica Sperimentale) and GeosisLab (Chieti-Pescara University) and it consists of six mobile stations set in continuous recording mode and local data storage. The data processing consists in the recognition on the continuous recordings of local events, undetected by the permanent Italian seismic network managed by INGV (Istituto Nazionale di Geofisica e Vulcanologia), and in the location of these small events. Event identification during an ongoing seismic sequence (in our case the 2009 L'Aquila one) is not easy; when the processing of manual pickings is completed, we expect the temporary seismic network to lower the magnitude of completeness in the Sulmona area by about 1 degree, to $M < 1$ events, with significant advantages for studies with seismotectonic and seismic hazard purposes. Some preliminary results on the quality of the seismic recorded data from May 27 to July 15, 2009 and on their spatial distribution are presented.

Key words: Sulmona, temporary seismometric network, Mt. Morrone fault, extensional tectonics, seismology, seismotectonics.

1. Introduction

The L'Aquila earthquake of April 6, 2009 (M_w 6.3) has dramatically focused attention on the high

seismogenic potential of the central Italy intra-mountain extensional province (Lavecchia *et al.*, 2009a; Boncio *et al.*, 2010 and references therein), characterised by a well-known system of active NNW-SSE striking normal faults, associated with important historical and instrumental events, the largest one being the 1915 Avezzano earthquake (M_w 7.0) (Lavecchia *et al.*, 2002; Boncio *et al.*, 2004; Pace *et al.*, 2002) (Fig. 1a).

In the central Abruzzo region, the easternmost boundary of the extensional seismotectonic province is outlined by the outcrop of active normal faults that follow the Morrone-Porrara fault alignment (MPA), east of the Sulmona basin and west of the Maiella Massif (Fig. 1b). Such an alignment is potentially very dangerous from a seismic hazard point of view, as it consists of fault segments capable of releasing destructive earthquakes ($M_{max} \sim 6.7$), with long mean recurrence times and with a long time interval from the last event (Pace *et al.*, 2006; Ceccaroni *et al.*, 2009; Peruzza *et al.*, 2011). The associated seismic risk is also very high, considering that Sulmona (one of the best preserved Abruzzo historical towns, with an important monumental and artistic heritage, and with a population of about 25,000 inhabitants) is located just at the hanging wall of the Mt. Morrone fault on continental Quaternary deposits (Fig. 2a).

Since early-instrumental times, the MPA has not been associated with any significant earthquake and only minor and sparse instrumental seismicity has been recorded in the last decades by the Italian national seismic network and by local networks with permanent or temporary characteristics (Bagh *et al.*, 2007; Boncio *et al.*, 2009). During the 2009 L'Aquila seismic sequence, an increase in seismic activity was recorded in the area. Four earthquakes with $3.2 \leq M_L \leq 3.8$ that occurred near the Sulmona basin, on the western side of the Maiella anticline (March 17 2009, M 3.6; March 29 2009, M 3.8; April 21 2009, M 3.2; October 11 2009, M 3.3; data taken from ISIDE database managed by INGV and available at: <http://iside.rm.ingv.it>, see Fig. 2a).

Since 2005, the completeness magnitude for the area in between the Maiella Massif, MPA and the Sulmona basin has been about 1.5 for earthquakes shallower than ~ 15 km (Schorlemmer *et al.*, 2010), but the logarithm graph of cumulative events number vs. magnitude (ISIDE database inside a 25 km distance from Sulmona) shows some bumps at M_L 2.7 and 2.1, suggesting completeness problems also at these higher thresholds. We believe that a better knowledge of the space and time distribution of the seismic activity in the Sulmona basin and surrounding areas is feasible with an off-line, continuous seismometric recording that should lower the completeness magnitude by about one unit. With this in mind we installed, six temporary seismic stations (Fig. 2b) in the area at the hanging wall of the Morrone-Porrara faults on May 27, 2009, and we plan to maintain the network for about two years, hopefully after the decay of seismic activity linked to the L'Aquila sequence has gone back to background conditions. This study is not financially supported by any specific project, but based on voluntary efforts and resources of the research teams involved. The data recorded by the temporary OGS-GeosisLab network (hereinafter referred as OGS-GL network) will be further integrated with INGV waveforms available on line and/or upon request. In the case of a significant number of events being located, fault parameters will be constrained and the tomographic inversion of travel times will be performed in order to define a more detailed 3D velocity model. Detected earthquakes will be further reconsidered to improve their location by using a more reliable velocity model. The instrumental seismic information will be integrated with macroseismic and geologic data in order to constrain the active structures and their seismogenic potential for seismic hazard purposes.

The main aim of this paper is to present the OGS-GL network configuration within the Abruzzo

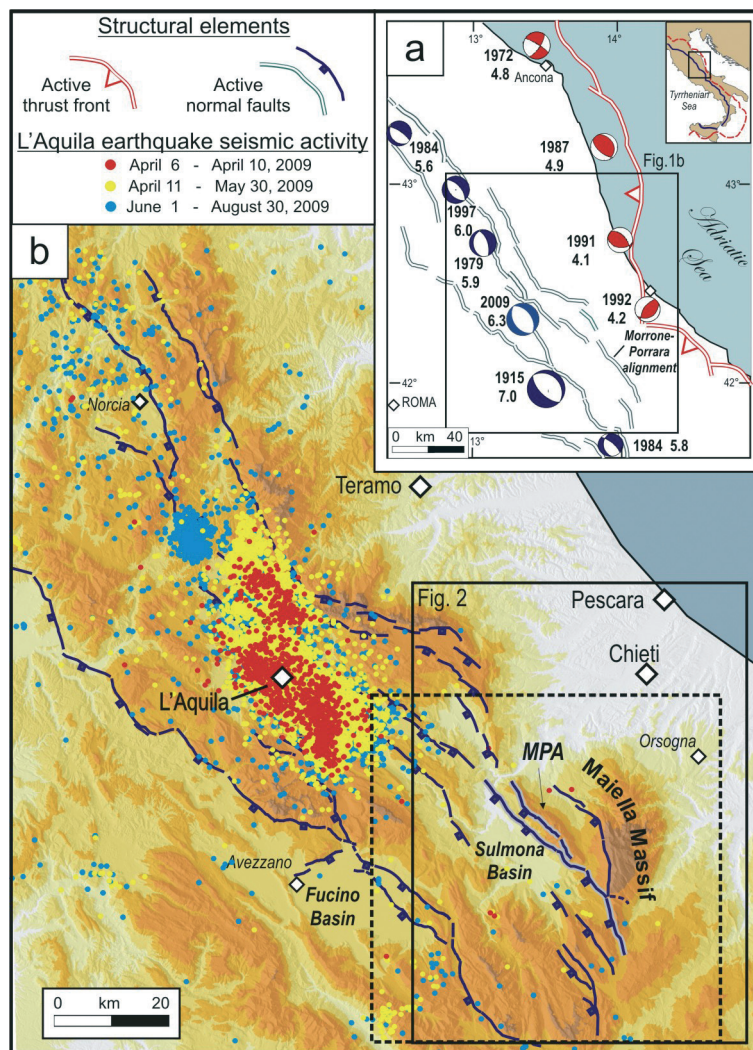


Fig. 1 - Active tectonic setting and instrumental seismicity in the central Appennines: a) active fault alignments and fault mechanisms of major instrumental earthquakes (after Boncio *et al.*, 2004; Lavecchia *et al.*, 2009a); b) location of the investigated area (Sulmona basin and Maiella Massif), with respect to the epicentral area of the L'Aquila 2009 seismic sequence [earthquake data from ISIDE <http://iside.rm.ingv.it>; fault data from Lavecchia *et al.* (2009a) and references therein]; MPA= Morrone - Porrara alignment. The dashed line shows approximately the area investigated by the temporary network.

seismotectonic context, to illustrate the first months of experience in the data processing and to give some preliminary results on the activity rate and the seismicity distribution during the first seven weeks of monitoring (May 27 to July 15, 2009).

2. Seismotectonic framework

The area covered by the OGS-GL network (Fig. 2b) is dominated by the presence of SW-WSW-dipping active, normal faults dissecting pre-existing fold-and-thrust structures and associated with intra-mountain extensional basins filled by continental sediments. The extension is considered continuously active at least since the Early Pleistocene, as suggested by the age of the oldest deposits surveyed in the area (Miccadei *et al.*, 1998; Cavinato and Miccadei, 2000; Galadini and Messina, 2004). Clear field evidence of active faulting is exposed along the MPA, which dislocates Late

Pleistocene-Holocene deposits (Galadini and Galli, 2000; Gori *et al.*, 2009).

The Morrone fault system (MF in Fig. 2a) consists of two major sub-parallel WSW-dipping splays, extending for a total of ~25 km along the eastern side of the Sulmona basin and across the Mt. Morrone western slope. Where the fault plane is exposed, an impressive carbonate fault scarp can be observed; it puts Meso-Cenozoic limestones in contact with Early Pleistocene slope deposits. A destructive earthquake (M_w 6.6–6.7) that would have occurred shortly after 147–148 A.D. has been recently attributed to such structure (Ceccaroni *et al.*, 2009). The Porrara fault (PF in Fig. 2a) extends for ~20 km in the WNW-ESE direction along the western side of Mt. Porrara. This fault is commonly associated with the Maiella 1706 (M_w 6.6-6.8) earthquake (Pizzi and Galadini, 2009). Another normal fault of the area is the WSW-dipping Caramanico fault (CF in Fig. 2b), that offsets the western limb of the Maiella anticline for a length of ~25 km (Ghisetti and Vezzani, 2002). The activity status of such a structure is still controversial (Galadini and Messina, 2004).

The seismotectonic setting of the area located east of the Morrone-Porrara fault alignment, that is the Maiella Massif (MM) and the Abruzzo Citeriore foothill and coastal area, is controversial too (Meletti *et al.*, 2008). Active compression has been hypothesised by some authors, based on morphotectonic evidence of active anticline growing in the Orsogna area (Pomposo and Pizzi, 2009), possibly at the hanging wall of an active SW-dipping regional thrust (de Nardis *et al.*, 2008). Such structure (Abruzzo Citeriore Basal Thrust, ACBT, in Fig. 2b) would represent the southern prosecution of the Adriatic Basal Thrust (ABT in Fig. 2b) and might represent an alternative seismogenic source for the 1706 Maiella earthquake (M_w 6.6-6.8), as well as for the 1933 one (M_w 6.0) (Lavecchia *et al.*, 2009b). The macroseismic epicentres (Fig. 2a) and intensity distribution [DBMI08 database, Rovida *et al.* (2008)] of these earthquakes, as well as of the 1881 (M_w 5.6) and 1882 (M_w 5.3) events in the Chieti area, largely occupy areas placed east of the MPA surface trace making an association with such normal faults difficult.

3. The Sulmona OGS-GL temporary seismic network

Mobile networks are often used in tectonically active regions to perform temporary seismic monitoring surveys. Dense continuous seismic recording may help to improve the completeness magnitude of the seismic catalogue, decreasing the earthquake detection threshold. In the time interval 2005-2008, the Italian catalogue was considered complete at M_L 2.9 for the entire Italian peninsula, limited by the geometry of the INGV Centralized National Seismic Network (INGV-RSNC) (Schorlemmer *et al.*, 2010). As previously stated, the completeness magnitude in the study area should decrease to 1.5 for earthquakes at 15 km of depth, but departures from a lin-log trend of a Gutenberg-Richter relationship in the Sulmona area occur at M_L 2.7 and 2.1. In the period 2003-2005, four Italian regions (Alpago-Cansiglio in the Venetian Alps, Città di Castello in the northern Apennines, Marsica in the central Apennines and Val d'Agri in the southern Apennines) were instrumented by INGV temporary arrays (see Chiaraluce *et al.*, 2009 and references herein) to record the minor seismicity, in order to improve the knowledge of the location, geometry and kinematics of faults responsible for moderate-large earthquakes.

The Marsica area, in the central Abruzzo region (~ 5000 km²), was monitored for 18 months from April 2003 (Bagh *et al.*, 2007). The major investigated active structures were the normal fault systems and associated rift basins of the Gran Sasso, Sulmona, L'Aquila, Fucino and Montagna

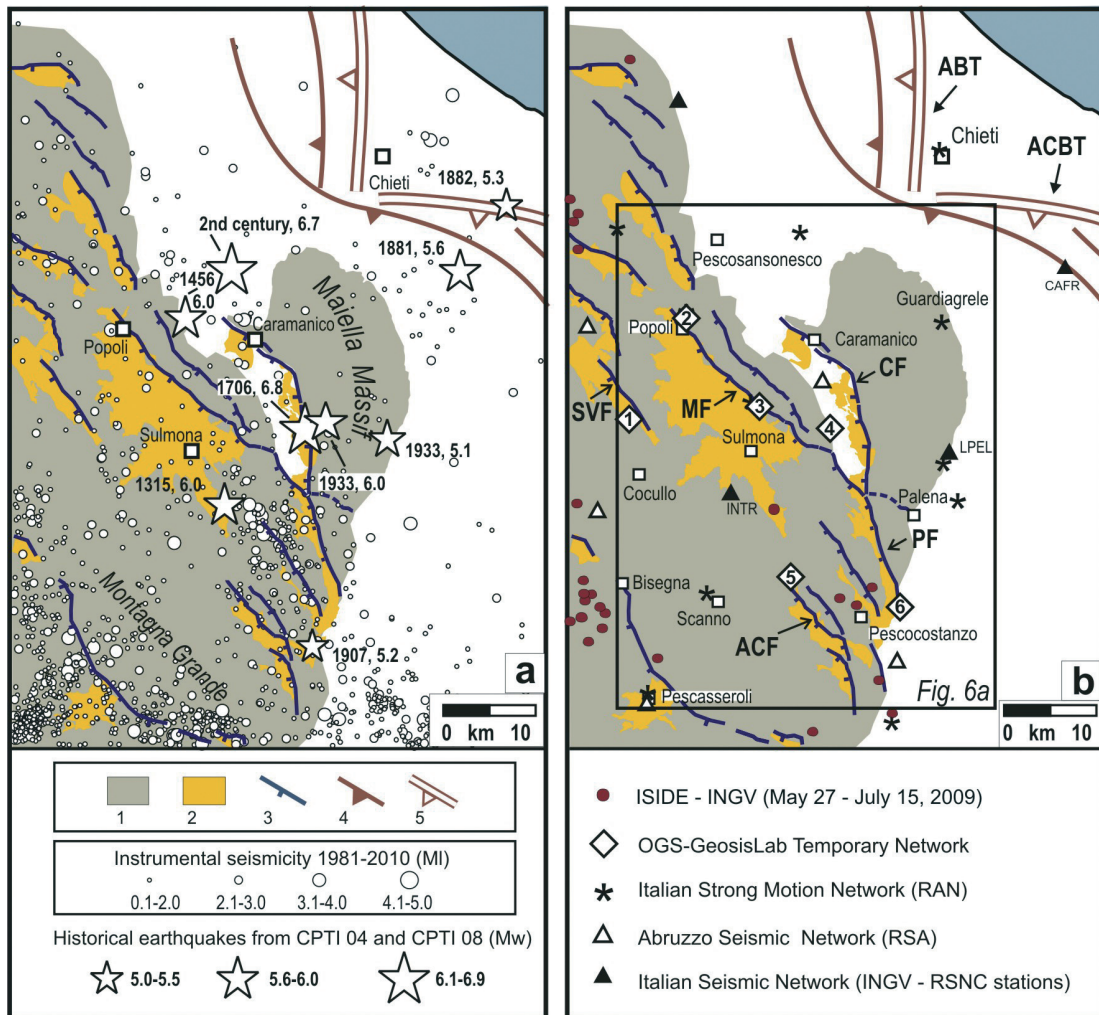


Fig. 2 - Seismicity and seismic station locations in eastern Abruzzo. a) Historical and instrumental seismicity and active fault structures. Key: 1 - Meso-Cenozoic carbonates and overlying flysch deposits; 2 - Quaternary sin-extensional continental deposits; 3 - active normal faults; 4 - Abruzzo Citeriore late Pliocene-Quaternary thrust system; 5 - outer front of the Abruzzo Citeriore thrust system. Instrumental data are represented with circles and taken from CSI (Castello *et al.*, 2006), ISIDE database and Bagh *et al.* (2007); historical data (stars) from Working Group CPTI (2004, 2008). b) Station locations and epicentral distribution of seismic events recorded by INGVR-SNC from May 27 to July 15, 2009 (Italian Seismic Bulletin, contained in ISIDE). The locations of the Italian Strong Motion Network RAN are taken from Gorini *et al.* (2010) and Zambonelli *et al.* (2011); the Abruzzo Seismic Network RSA from Monachesi and De Luca (2007). The OGS-GL stations in May 2010 are referred to with diamonds: 1=SL01; 2=SL02; 3=SLA3; 4=SL04; 5=SL05; 6=SL06 (see Table 1). Key: ACBT = Abruzzo Citeriore Basal Thrust, ABT = Adriatic Basal Thrust, ACF = Aremogna-Cinquemiglia Fault, CF = Caramanico Fault, MF = Morrone Fault, PF = Porrara Fault, SVF = Subaequana Valley fault.

Grande areas. A local mobile network composed of 30 digital stations was deployed by INGV with an average receiver spacing of about 10-15 km. The final data set was integrated with P- and S-wave phases derived from permanent stations of the INGV-RSNC and available regional networks. In order to detect the maximum number of small magnitude earthquakes on the continuous recordings, they applied a STA/LTA trigger algorithm specifically tailored for the detection of very low magnitude

seismic events (Piccinini *et al.*, 2003). During this experiment, the network located 850 events, more than 65% are above the M_L 1.5 threshold; the low seismic rate is interrupted by episodes of clustering both in space and time for the seismic sequences that occurred in the north-westernmost sector of the area (roughly Fucino and L'Aquila basins). The seismicity recorded over a period of 18 months occurred within a depth of 15 km, and did not highlight any clear fault geometry.

After the April 6, 2009 L'Aquila earthquake, several institutions deployed mobile stations to follow the evolution of the seismic sequence (Fig. 1a); most of them were located in the major event epicentral area (L'Aquila basin and Upper Aterno Valley) and in the northernmost Campotosto sector, where earthquakes migrated during the first weeks. Looking for low-magnitude earthquake detection over a small region, on May 27, 2009, we installed a local network of six temporary stations around the Sulmona basin (Fig. 2b) to cover an area not yet monitored by other institutions.

3.1. The OGS-GL Sulmona seismic network

The OGS-GL Sulmona temporary network covers an area of approximately 3500 km² (dashed line in Fig. 1b) and is managed by a research cooperative agreement between OGS and GeosisLab. It consists of six mobile stations (diamonds in Fig. 2b), equipped with Reftek rt130 Digital Acquisition Units, set in continuous recording mode and local data storage, synchronized by GPS receivers; sampling rate is 100 Hz. Four units are equipped with a 1-Hz, three-component seismometer (Lennartz LE-3DLite), two of them with a velocimetric/accelerometric couple (30 s Guralp CMG-40T and Episensor FBA ES-T). Photovoltaic panels, battery and solar charge controller are used, where a main power supply is not available.

The station locations and other characteristics are given in Table 1. Stations acquire off-line and so the data need to be periodically downloaded. Raw data in Reftek format are stored on the electronic archives of OGS (Centro Ricerche Sismologiche Department in Udine) and handled by Antelope software. Since October 2009, thanks to a data exchange agreement, two INGV-RSNC stations (INTR and LPEL, Fig. 2b), located in the same areas, are continuously acquired at the OGS Antelope system and processed, thus integrating the network data set. Two stations (SL03, SL05) have been relocated after a few months of recordings, due to inadequate signal-to-noise characteristics; the new locations are reported in Table 1, but the shift cannot be appreciated on the station map (Fig. 2b). In March 2010, other two stations (SL01, SL06) have been moved, for similar reasons. The average spacing of the final configuration is about 10-13 km.

3.2. Field geology of the OGS-GL stations

The six temporary stations (Fig. 2b, Table 1) are located around the Sulmona basin, mainly at the hanging wall of the MPA and are all close to active structures. With this geometry, the OGS-GL network, integrated with two neighbouring INGV permanent stations, is able to provide reliable locations of micro-earthquakes associated both with the Morrone and Porrara faults.

Station SL01 is located in the Goriano Sicoli village, within the small Subequana Valley basin; the WSW-dipping normal fault bordering east of the basin and dissecting the south-western slopes of the Mt. Urano anticline, is possibly active, representing the southern prosecution of the Middle Aterno valley seismogenic structure (Boncio *et al.*, 2004).

Station SL02 is placed within the Forestry Reserve of Popoli, in between the two parallel SW-dipping segments of the active Morrone fault system; it is located on thin Pleistocene deposits,

Table 1 - Main characteristics of OGS-GL stations: SLA is the identification code of relocated SL0 stations.

Station Code	Locality	LON (°)	LAT (°)	Elevation (m asl)	Date ON	Date OFF	Soil Type	Sensor	Acquisition System
SL01	<i>Goriano Sicoli (AQ)</i> Private house	13.7827	42.0835	769	27-05-2009	24-03-2010	Floor	Lennartz 3DLite	A928
SLA1	<i>Goriano Sicoli (AQ)</i> Fenced private property	13.7729	42.0789	718	24-03-2010		Soft land fill	Lennartz 3DLite	A928
SL02	<i>Popoli (PE)</i> Nature reserve	13.8539	42.1745	684	27-05-2009		Concrete base	1)CMG40 2)FBA ES-T	921D
SL03	<i>Sulmona (AQ)</i> Sanctuary of Ercole Curino	13.9336	42.0890	484	27-05-2009	01-10-2010	Concrete base	Lennartz 3DLite	A894
SLA3	<i>Sulmona (AQ)</i> Sanctuary of Ercole Curino (box RAN)	13.9342	42.0895	523	01-10-2010		Concrete base	Lennartz 3DLite	A894
SL04	<i>Passo S. Leonardo</i> Garage of a hotel	14.0296	42.0730	1281	26-05-2009		Concrete base	Lennartz 3DLite	A909
SL05	<i>Rocca Pia (AQ)</i> Site under viaduct (near new buildings)	13.9787	41.9371	1067	26-05-2009	01-10-2010	Soft land fill	Lennartz 3DLite	A916
SLA5	<i>Rocca Pia (AQ)</i> Municipally owned building	13.9773	41.9325	1108	01-10-2010		Floor	Lennartz 3DLite	A916
SL06	<i>Palena (CH)</i> Valico della Forchetta	14.1127	41.9083	1279	26-05-2009	24-03-2010	Soft land fill	1)CMG40 2)FBA ES-T	912A
SLA6	<i>Palena (CH)</i> Sanctuary of Madonna dell'Altare	14.1198	41.9454	1313	24-03-2010		Concrete base	1)CMG40 2)FBA ES-T	985A

belonging to the Sulmona basin infilling sediments, covering the Meso-Cenozoic carbonate bedrock (APAT, 2005).

Station SLA3 is placed at the Ercole Curino site on the surface fault plane of the innermost Morrone fault (e.g., the Sulmona basin bordering fault). The exposed fault plane has an average dipping direction of 225° and a dip angle of ~ 60°. The station is located on Upper Pleistocene slope debris deposits (APAT, 2005).

Station SL04 is placed on the eastern flank of the Morrone ridge, at the hanging wall of the WSW-dipping Caramanico Fault; it is located on late Messinian turbidites (“Porrara flysch”), characterised by pelites and marls overlapped on the early Pliocene-Messinian deposits of the “Maiella flysch” (Vezzani and Ghisetti, 1998).

Station SL05 is located in the centre of the Rocca Pia village, at the northern end of the western segment of the Mt. Aremogna-Cinquemiglia active normal fault. The segment shows a general NW-SE direction, with a high angle of dip (nearly 80°) towards SW, for a length of about 18 km (D’Addezio *et al.*, 2001; Boncio *et al.*, 2004). The station is located on polygenic conglomerates (APAT, 2011).

Station SL06 is placed at the southern end of the WSW-dipping Mt. Porrara fault, on Miocene alternating clays and sandstones (Vezzani and Ghisetti, 1998).

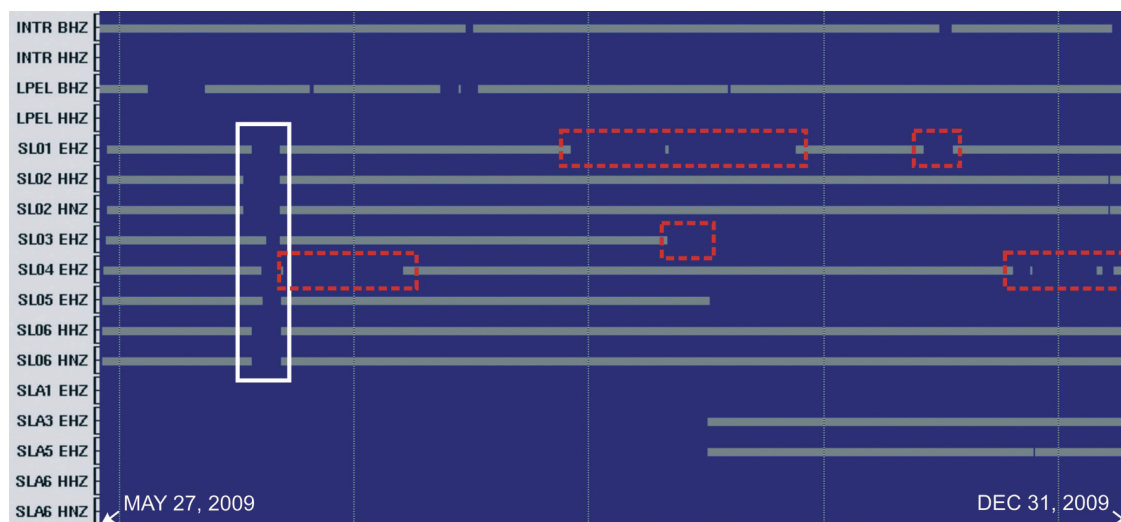


Fig. 3 - Functioning of the OGS-GL network during the first months of the experiment (May 27 to December 31, 2009). INTR and LPEL are permanent stations of the INGV-RSNC, acquired off-line as data exchange. Note the lack of data inside the white rectangle due to memory fullness and within the red dashed rectangles due to instrumental problems at station SL01 and SL04; two stations (SL03 and SL05) were relocated in autumn 2009. Stations with multiple sensors have double track.

3.3. First months of experience

The first months of monitoring (June-August 2009) were quite problematic, for the ongoing intense activity of the seismic sequence in the L'Aquila area. Fig. 3 shows the fully operative status of temporary stations and two permanent INGV-RSNC stations, from the installation of the seismic network till the end of December 2009; note that some acquisition problems occurred. The data processing consisted in the extraction from the continuous recordings of data signals of interest, i.e., local earthquakes, undetected or poorly located by the permanent INGV-RSNC network.

At first, on data acquired from May 27 till August 26, 2009, the Antelope STA/LTA trigger algorithm [*dbdetect*, BRTT, (2004)] was used to recognize candidate earthquakes, jointly with an original association routine (Garbin, 2009). The automatic earthquake recognition passes through the tuning of several parameters involved both in the STA/LTA trigger algorithm, acting on a single station, and on the array of stations. The main parameters were qualitatively tuned according to the low magnitude threshold we expected ($M_L=1.0$), and are very similar to the one adopted by other temporary monitorings (e.g., Bagh *et al.*, 2007). The trigger algorithm is applied to all three channels (ZNE); the data are filtered through a 5-30 Hz pass-band filter; the length of the short time and long time windows are set at 2 s and 20 s respectively, while the threshold values of the trigger and de-trigger are set at 3 and 1.5, respectively. In Fig. 4, we show the distribution in time of “trigger-on” conditions, at the different stations; note the peculiar characteristics in terms of signal/noise ratio at the various stations, and the problems of memory saturation, due to the high number of events linked to the seismic sequence in the L'Aquila area.

The association routine identifies the detections consistent among the stations within a common time window. Given the maximum inter-distance between the seismometric stations (50 km), this time interval has been safely set at 9 s to approximately accommodate the maximum delay between

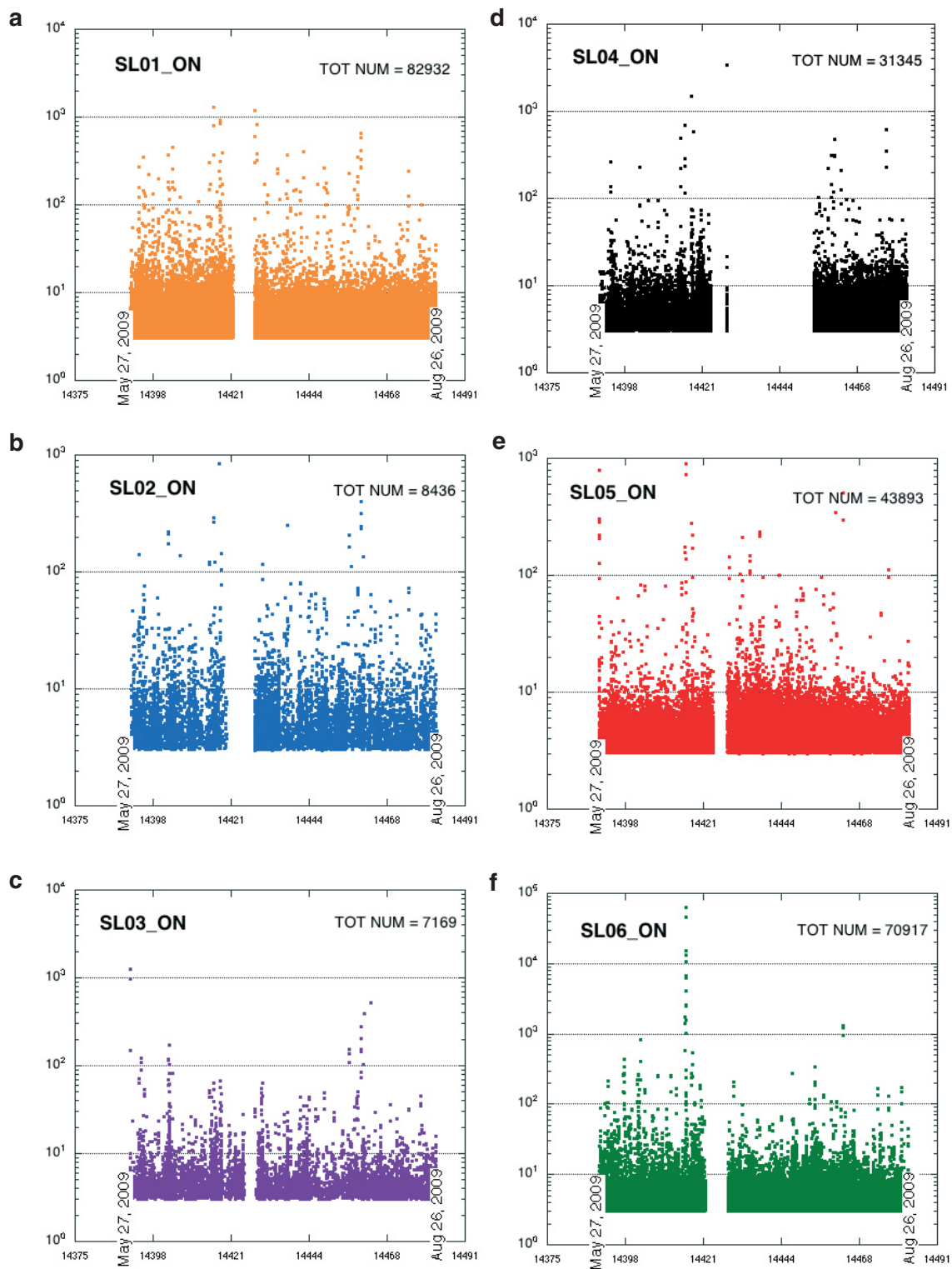


Fig. 4 – Daily number of trigger ON condition at the different stations, with standard STA/LTA Antelope algorithm during the first three months of acquisition; time in Unix epoch (days since January 1, 1970).

a P phase and an S phase, since the detections are not always set at the P-wave arrival time. The minimum number of stations needed to automatically recognize an event has been set at 3. Once an event was identified, the first trigger time was anticipated by a fixed pre-event time (15 s) and a post-event time (30 s) was added to the last de-trigger. The total number of candidate earthquakes recorded in about three months was 1964. Frequent episodes of high noise levels at some stations were recognized by visual inspection of the drum plots.

The manual picking of the seismograms revealed some new local events (here an event is defined a local one if the S-P delay at the nearest station is less than 3 s), a great amount of noisy windows, but also some pitfalls in the trigger/association algorithms, as some of the ISIDE events¹ have not been identified and extracted from continuous recordings. Therefore, we started a sensitivity analysis to obtain an automatic procedure for event-identification with better performances. At first, we defined the target of our analysis that consists in a list of manually identified events on a test time window of 10 days (15-24 June 2009). From this visual inspection 475 events were identified from a continuous recording (“Target” in Fig. 5); only 19 are reported on the ISIDE database, within the area represented as a dashed line in Fig. 1b, during the same period (blue crosses in Fig. 5). Three of these 19 ISIDE events were fakes because, the visual inspection did not allow us to identify any phases in our continuous recordings and four others are still dubious (both represented by b/w squares in Fig. 5). Note that the previously described extraction (1st method in the figure legend) lost seven events (red bars) with respect to the ISIDE subset, but only five (numbered in black) if the fake ISIDE locations are excluded.

During the test period, 20 additional events, selected by the 1st method, were recently identified as local earthquakes (black crosses indicated as 1st Local in Fig. 5); not all of them have a reliable location, due to the few or badly defined phases. New trigger algorithms based on a Matlab[®] routine were then tested, varying some parameters (e.g., BandPass Filter, STA, LTA, Average Time Length, Trigger threshold). Matlab[®] codes handle association too, with a minimum number of stations set at 3. The best parameter calibration (in Fig. 5 represented by the 2nd method) shows promising results as the mismatch between manual and automatic selection is very good, and the number of noisy windows sharply decreases with respect to the 1st method. Only 3 dubious ISIDE earthquakes are again lost (violet bars, numbered in green, Fig. 5), and 28 local events are identified by S-P delay time (mostly, but not all coincident with the 1st method ones). This test briefly shows the capabilities and the problems of temporary monitoring. The number of extracted windows increases exponentially as long as the signal-to-noise threshold decreases, and this fact implies huge, manual window selection for pickings. On the other hand, automatic procedures for event identification and pickings turned out to be unsatisfactory for our purposes, as local events were missed, and fake ones were generated. Even if we are still working on event identification problems, the waveforms extracted during the first months with the second triggering algorithm (2nd method) have been processed and preliminary results are shown in the next section.

3.4. Preliminary data analysis

The seismic signals recorded by the six temporary stations and by the two national permanent ones, LPEL and INTR, were integrated and visually inspected. P- and S-wave arrival times were hand

¹ This analysis was done in February 2010, using the events reported in the ISIDE database at that time. Some events may be different from the ones now reported in the final revised INGV bulletin of June 2009.

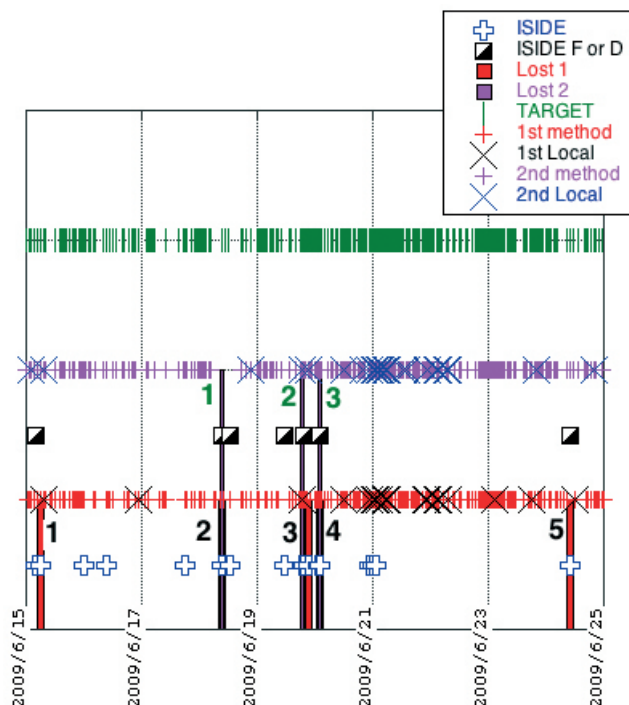


Fig. 5 - Comparison of different methodologies in event detection, during a selected subset of the data stream (June 15-24, 2009). Target indicates events manually identified by *dbpick* (BRTT, 2004) on vertical component of the six stations, ISIDE indicates earthquakes located in the study area by the INGV-RSNC (release available on February 2010). More details in the text.

picked on digital waveforms only for events with S-P distance less than ~ 3 s from the closest station. A preliminary location was performed using a standard procedure that uses the Hypo71 code (Lee and Lahr, 1975) after selecting a general velocity model (Italian Seismic Bulletin, 2003-2010). The earthquake magnitude was estimated by the duration of the signal (M_d) using the formula by Rebez and Renner (1991). During the first 50 days of seismic monitoring, from May 27 to July 15, 2009, the temporary OGS-GL network recorded a total of 622 P- and 618 S-arrival times associated to 157 earthquakes located within the dashed-line boundaries in Fig. 1b. Magnitudes were assigned on duration readings ($M_d \geq 0.4$), and for only 35 of these earthquakes it was not possible to evaluate the length of the coda because of the level of uncertainty due to seismic noise. In particular, 98 of the 157 earthquakes occurred within the area of the detailed map of Fig. 6a. More than 150 events, not located in this study, were also recorded at a single station.

The distribution of the P and S residuals, of the root mean square (rms) of the solution travel-time and of the magnitudes of the recorded events are shown in the histograms in Fig. 7. These diagrams point out that the majority of P and S residuals are smaller than 1.0 s (Fig. 7a and 7b) and most of the located earthquakes have rms in the 0.5-1.0 s range (Fig. 7c). The magnitude ranges between 0.4 and 3.2 and duration magnitude seems to be complete at least down to M_d 0.8-0.9 (Fig. 7d).

A preliminary analysis of the seismicity rate (events/day) and of the cumulative number of events indicates that the occurrence of the earthquakes in the study area was almost constant during the first 30 days with a mean rate of ~ 2.2 events/day (Fig. 6b). The cumulative number shows an abrupt increment in the period June 21-23, 2009 with about 10 events/days and a decreasing trend with a mean rate of ~ 1.3 events/day in the following 10 days. In Fig. 6b, this distribution was depicted and

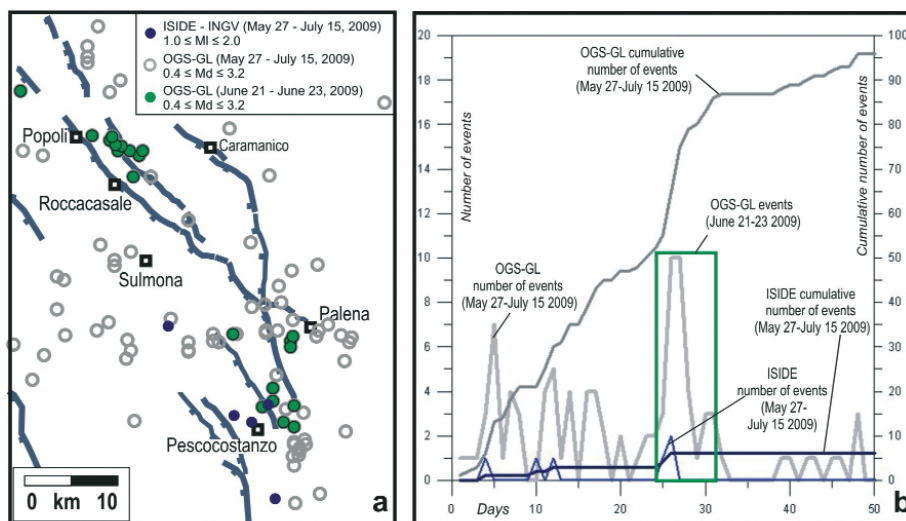


Fig. 6 – Epicentral distribution of seismicity recorded from May 27 to July 15, 2009, within the study area represented in Fig. 2b. a) Earthquake locations given by the OGS-GL temporary network (98 events) and by the INGV-RNSC (6 events). The full green dots are the events that occurred on June 21-23, 2009. They correspond to the maximum activity rate in Fig. 6b. b) Daily event distribution and the cumulative number of events recorded by OGS-GL network (light grey and dark grey lines) and by INGV-RNSC as reported on the ISIDE database (blue and black lines).

compared with the seismicity rate as listed in the ISIDE database. The earthquakes detected by the OGS-GL network were by far more than the ones detected by the permanent national network that recorded only 6 events, with local magnitude $1.0 \leq M_L \leq 2.0$, in the same period within the same study area (blue dots, in Fig. 6a).

The observed seismicity is sparsely distributed in space with the exception of two minor clusters of events located at the northern end of the Morrone fault and at the southern end of the Porrara fault (Fig. 6). Although the hypocentral parameters are obtained with standard absolute location algorithms in this preliminary analysis, some information about the depth distribution can be inferred. As shown in Fig. 8, the events located at the hanging wall of the Porrara fault and in the Palena area occur at upper crustal depths (<15 km), whereas those located close to the Morrone fault and westwards of the Sulmona basin mainly occur in the 15-30 km depth range. It is interesting to note the contemporaneous activation of both the clusters in the June 21-23 period, that is the time-period with a relative remarkable increase of seismic activity.

4. Final remarks

The seismotectonic framework of the Abruzzo region (central Italy) is quite complex (Fig. 1). The active extensional province of the intra-mountain sector is juxtaposed to the east by the Maiella Massif and by the Abruzzo Citeriore foothills and the coastal area is characterized by an undefined active deformation field. Unlike the internal western sector, struck by both historical and instrumental destructive earthquakes (the last one on April 6, 2009), only historical events (such as the 1706 event, M_w 6.6-6.8) affected the external eastern sector. Recent papers (e.g., Pace *et al.*, 2006)

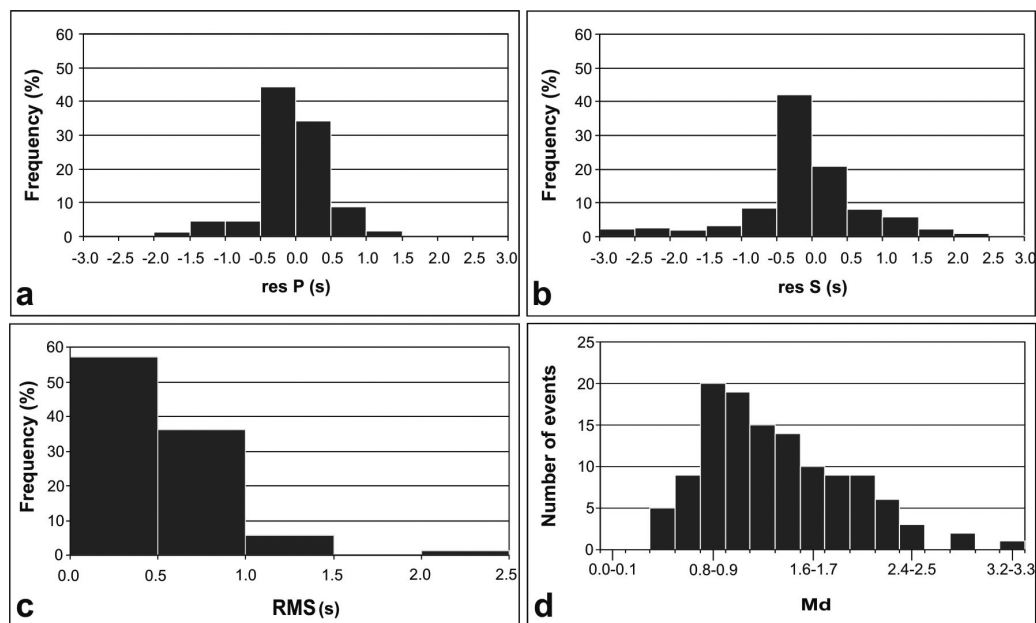


Fig. 7 – Data quality of the earthquake locations from May 27 to July 15, 2009: a) and b) distribution of residuals of P and S-phases, respectively; c) distribution of error in location given in terms of rms; d) number of events for different classes of duration magnitude M_d .

assign a high seismogenic potential to the Mt. Morrone normal fault, due to the long time lapse since the last destructive event (Ceccaroni *et al.*, 2009), and the debate on the last activation of the southern segment of the alignment (Mt. Porrara fault) is still open. In order to improve our knowledge about the seismotectonic framework of the Morrone-Porrara fault alignment and of the surrounding areas, we decided to monitor the seismic activity through the installation of a temporary seismic network around the Sulmona basin and the Maiella Massif. In this way, we expect to lower the local completeness magnitude with respect to the one given by the permanent INGV-RSNC network. Our final aim is to estimate the active deformation pattern, define the geometry and kinematics of local faults and constrain the seismogenic layer thickness and depths, also verifying the hypothesis of a possible co-existence of two distinct seismogenic layers, a shallower extensional one (0-15 km depth range) and a deeper underlying compressional one (15-30 km depth range), as in the coastal areas of the Marche region (Lavecchia *et al.*, 2007).

So far, we have processed only the first seven weeks of the data acquired starting from the end of May 2009, although we have already collected more than a year of continuous recording. At first, we used a standard automatic procedure to identify seismic events on a continuous signal, based on an Antelope STA/LTA trigger algorithm and original association routine. The high level of signals (partially due not to the station characteristics, but also linked to the seismic sequence that followed the L'Aquila April 6, 2009 earthquake) makes event detection quite problematic. The comparison of preliminary results with manual inspection of seismograms pointed out some weaknesses, such as many false triggers and mismatches with the ISIDE local events. In order to obtain a more efficient procedure, we processed a subset of ten days, calibrating the sensitivity of detection with respect to

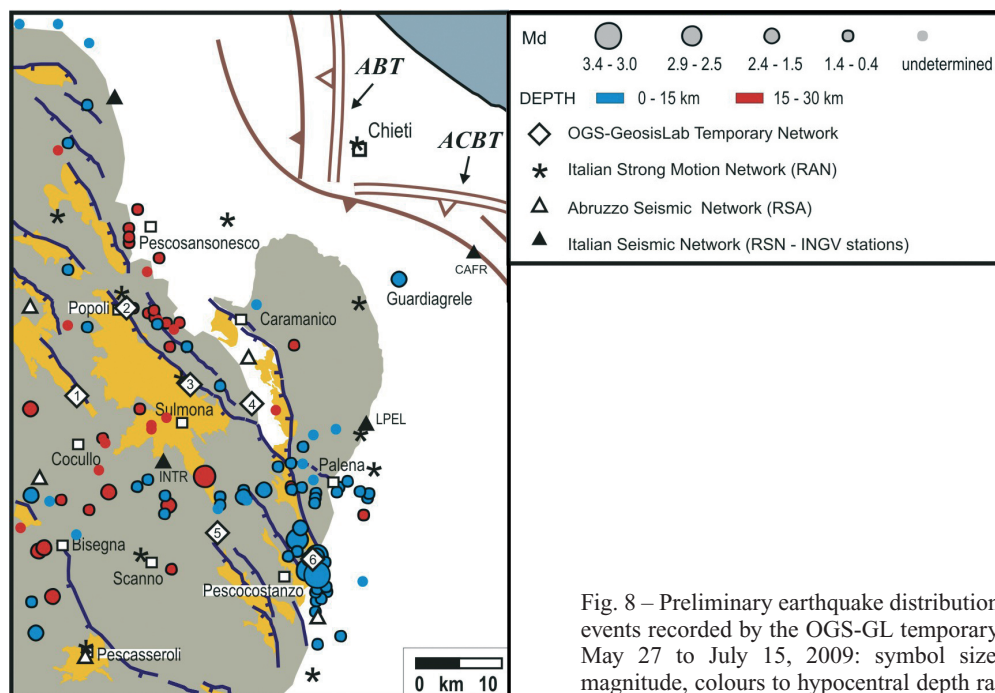


Fig. 8 – Preliminary earthquake distribution of the seismic events recorded by the OGS-GL temporary network from May 27 to July 15, 2009: symbol size according to magnitude, colours to hypocentral depth ranges.

our target, that is local earthquakes (S-P delay less than 3 s) previously undetected. The results obtained from the first data analysed (from May 27 to July 15, 2009) are promising. In this period, we identified 98 new local events (Fig. 6), vs. only 6 events reported by the ISIDE database for the same area and period. In general, the data set recorded by the OGS-GL network seems to be complete at least down to M_d 0.8. When the full processing of new phases is performed, we do expect to significantly increase the data set of local earthquakes.

The space and time distribution of the new local events deserves special interest; the depth distribution of the recorded seismicity highlights two spatially distinct seismogenic layers (0-15 and 15-30 km). This result, if confirmed, might have important seismotectonic implications and might support the hypothesis advanced by Lavecchia and de Nardis (2009) about the co-existence of an upper crust layer corresponding to the Morrone-Porrara seismogenic sources and an underlying deep crust layer corresponding to the activity of the Abruzzo Citeriore basal thrust. In conclusion, we are hopeful that the new instrumental data set will help to enhance the seismotectonic interpretation of the eastern Abruzzo region, with crucial implications in terms of seismic hazard assessment.

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REFERENCES

- APAT; 2005: *Foglio 369 Sulmona, Carta Geologica D'Italia. Scala 1:50.000*. http://www.isprambiente.gov.it/MEDIA/carg/369_SULMONA/Foglio.html, last accessed on July 2011.
- APAT; 2011: *Foglio 378 Scanno, Carta Geologica D'Italia. Scala 1:50.000*. http://www.isprambiente.gov.it/MEDIA/carg/378_SCANNO/Foglio.html, last accessed July 2011.
- Bagh S., Chiaraluce L., De Gori P., Moretti M., Govoni A., Chiarabba C., Di Bartolomeo P. and Romanelli M.; 2007: *Background seismicity in the Central Apennines of Italy: the Abruzzo region case study*. *Tectonophysics*, **444**, 80-92.
- Boncio P., Lavecchia G. and Pace B.; 2004: *Defining a model of 3D seismogenic sources for seismic hazard assessment applications: the case of Central Apennines (Italy)*. *Journal of Seismology*, **8**, 407-425.
- Boncio P., Pizzi A., Brozzetti F., Pomposo G., Lavecchia G., Di Naccio D. and Ferrarini F.; 2010: *Coseismic ground deformation of the 6 April 2009 L'Aquila earthquake (Central Italy, Mw 6.3)*. *Geophys. Res. Lett.*, **37**, L06308.
- Boncio P., Tinari D. P., Lavecchia G., Visini F. and Milana G.; 2009: *The instrumental seismicity of the Abruzzo Region in Central Italy (1981-2003): seismotectonic implications*. *Italian Journal of Geosciences (Bollettino della Società Geologica Italiana)*, **128**, 367-380.
- BRTT; 2004: *Evolution of the Commercial ANTELOPE Software*. Open file Report at <http://www.brtt.com/docs/evolution.pdf>.
- Castello B., Selvaggi G., Chiarabba C. and Amato A.; 2006: *CSI Catalogo della sismicità italiana 1981-2002, versione 1.1*. INGV-CNT, Roma, <http://csi.rm.ingv.it/>
- Cavinato G. P. and Miccadei E.; 2000: *Pleistocene carbonate lacustrine deposits: Sulmona basin (central Apennines, Italy)*. In: Gierlowsky-Kordesch E.H. and Kelts K.R. (eds), *Lake Basins Through Space and Time*. *Studies in Geology*, vol. **46**, American Association of Petroleum Geologists, pp. 517-526.
- Ceccaroni E., Ameri G., Gómez Capera A. A. and Galadini F.; 2009: *The 2nd century AD earthquake in Central Italy: archaeo-seismological data and seismotectonic implications*. *Natural Hazards*, **50**, 335-359, doi: 10.1007/s11069-009-9343.
- Chiaraluce L., Valoroso L., Anselmi M., Bagh S. and Chiarabba C.; 2009: *A decade of passive seismic monitoring experiments with local networks in four Italian regions*. *Tectonophysics*, **476**, 85-98.
- D'Addezio G., Masana E. and Pantosti D.; 2001: *The Holocene paleoseismicity of the Aremogna-Cinque Miglia fault (Central Italy)*. *Journal of Seismology*, **5**, 181-205.
- de Nardis R., Pace B., Lavecchia G., Visini F. and Boncio P.; 2008: *Geological and macroseismic data for seismotectonic purpose: the 1706 Maiella (Abruzzo, Italy) earthquake case study*. In: AGU, Fall Meeting 2008, abstract #T21B-1946.
- Galadini F. and Galli P.; 2000: *Active tectonics in the Central Apennines (Italy) - Input data for seismic hazard assessment*. *Natural Hazard*, **22**, 225-270.
- Galadini F. and Messina P.; 2004: *Early-Middle Pleistocene eastward migration of the Abruzzi Apennine (central Italy) extensional domain*. *Journal of Geodynamics*, **37**, 57-81.
- Garbin M.; 2009: *Reti sismometriche in modalità di acquisizione continua: procedure di identificazione e selezione automatica di eventi sismici e di strutturazione dei dati estratti per elaborazioni con Pickserver*. Rel. OGS 2009/135 – CRS 15 APSES.
- Ghisetti F. and Vezzani L.; 2002: *Normal faulting, trans-crustal permeability and seismogenesis in the Apennines*. *Tectonophysics*, **348**, 155-168.
- Gori S., Ciaccio B., Galadini F., Falcucci E., Messina P., Sposato A. and Dramis F.; 2009: *Active normal faulting along the Mt. Morrone south-western slopes (Central Apennines, Italy)*. *International Journal of Earth Sciences*, doi: 10.1007/s00531-009-0505-6.
- Gorini A., Nicoletti M., Marsan P., Bianconi R., de Nardis R., Filippi L., Marcucci S., Palma F. and Zambonelli E.; 2010: *The Italian strong motion network*. *Bulletin of Earthquake Engineering*, **8** (5), 1075-1090.
- Lavecchia G. and de Nardis R.; 2009: *Seismogenic sources of major earthquakes of the Maiella area (Central Italy): constraints from macroseismic field simulations and regional seismotectonics*. UR 4.01- S1-29. Poster at the ING-DPC meeting, Rome, November 2009.
- Lavecchia G., Boncio P., Brozzetti F., de Nardis R., Di Naccio D., Ferrarini F., Pizzi A. and Pomposo G.; 2009a: *The April 2009 L'Aquila (Central Italy) seismic ssequence (Mw 6.3): a preliminary seismotectonic picture*. In: Guarnieri P. (ed), *Recent Progress on Earthquake Geology*, Nova Science Publishers, Inc., pp. 1-18.

- Lavecchia G., Boncio P., Brozzetti F., de Nardis R. and Visini F.; 2009b: *The contribution of structural geology and regional tectonics to the definition of large-scale seismotectonic provinces and individual seismogenic sources: application to the extensional belt of central Italy*. In: Guarneri P. (ed), Recent Progress on Earthquake Geology, Nova Science Publishers, pp. 165-188.
- Lavecchia G., Boncio P., Brozzetti F., Stucchi M. and Leschiutta I.; 2002: *New criteria for a 3D seismotectonic zoning of Central Italy*. Bollettino della Società Geologica Italiana, volume speciale **1**, 881-890.
- Lavecchia G., de Nardis R., Visini F., Ferrarini F. and Barbano S.; 2007: *Seismogenic evidence of ongoing compression in eastern-central Italy and mainland Sicily: a comparison*. Bollettino della Società Geologica Italiana (Italian Journal of Geosciences), **126**, 209-222.
- Lee W. H. K. and Lahr J. C.; 1975: *HYP071 (Revised): A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes*. Open File Report 75-311, U. S. Geological Survey.
- Meletti C., Galadini F., Valensise G., Stucchi M., Basili R., Barba S., Vannucci G. and Boschi E.; 2008: *A seismic source model for the seismic hazard assessment of the Italian territory*. Tectonophysics, **450**, 85-108.
- Miccadei E., Parotto M. and Piacentini T.; 1998: *Assetto geologico-strutturale dei Monti della Conca Subequana (Appennino abruzzese, Italia centrale)*. Geologica Romana, **34**, 31-50.
- Monachesi G. and De Luca G.; 2007: *Database on line della Rete Sismometrica Abruzzese*. Istituto Nazionale di Geofisica e Vulcanologia, Dipartimento della Protezione Civile, Laboratori Nazionali del Gran Sasso dell'Istituto Nazionale di Fisica Nucleare, L'Aquila, http://protezionecivile.regione.marche.it/dbrsm/D_disclaimer.html.
- Pace B., Boncio P. and Lavecchia G.; 2002: *The 1984 Abruzzo earthquake: an example of seismogenic process controlled by interaction between differently oriented syn-kinematic faults*. Tectonophysics, **350**, 237-254.
- Pace B., Peruzza L., Lavecchia G. and Boncio P.; 2006: *Layered seismogenic source model and probabilistic seismic-hazard analyses in Central Italy*. Bull. Seism. Soc. Am., **96**, 107-132.
- Peruzza L., Pace B., Visini F. and Boncio P.; 2011: *Fault-based earthquake rupture forecast in Central Italy: remarks after the L'Aquila Mw 6.3 event*. Bull. Seism. Soc. Am., **101**, 404-412, doi: 10.1785/0120090276.
- Piccinini D., Cattaneo M., Chiarabba C., Chiaraluce L., De Martin M., Di Bona M., Moretti M., Selvaggi G., Augliera P., Spallarossa D., Ferretti G., Michelini A., Govoni A., Di Bartolomeo P., Romanelli M. and Fabbri J.; 2003: *A microseismic study in a low seismicity area of Italy: the Città di Castello 2000-2001 experiment*. Annals of Geophysics, **46**, 1315-1324.
- Pizzi A. and Galadini F.; 2009: *Pre-existing cross-structures and active fault segmentation in the northern-central Apennines (Italy)*. Tectonophysics, **476**, 304-319.
- Pomposo G. and Pizzi A.; 2009: *Evidenze di tettonica recente ed attiva nel settore esterno sepolto dell'Appennino centrale abruzzese*. Rendiconti on line della Società Geologica Italiana, **5**, 176-178.
- Rebez A. and Renner G.; 1991: *Duration magnitude for the northeastern Italy seismometric network*. Boll. Geof. Teor. Appl., **33**, 186-177.
- Rovida A., Locati M., Camassi R., Azzaro R. and CPTI08 Working Team; 2008: *The new release of the Italian macroseismic intensity database (DBMI08)*. In: European Seismological Commission 31st General Assembly, Hersonissos, Greece, 7-12 September 2008.
- Schorlemmer D., Mele F. and Marzocchi W.; 2010: *A completeness analysis of the National Seismic Network of Italy*. Journal of Geophysical Research, **115**, B04308, doi:10.1029/2008JB006097.
- Vezzani L. and Ghisetti F.; 1998: *Carta geologica dell'Abruzzo*. Scala 1:100.000. S.EL.CA., Firenze.
- Working Group CPTI; 2004: *Catalogo Parametrico dei Terremoti Italiani (CPTI04)*. INGV, Bologna. <http://emidius.mi.ingv.it/CPTI/>.
- Working Group CPTI; 2008: *Catalogo Parametrico dei Terremoti Italiani (CPTI08)*. INGV, Bologna. <http://emidius.mi.ingv.it/CPTI/>.
- Zambonelli E., de Nardis R., Filippi L., Nicoletti M. and Dolce M.; 2011: *Performance of the Italian strong motion network during the 2009, L'Aquila seismic sequence (central Italy)*. Bull. Earthq. Engin., **9**(1), 39-65.

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