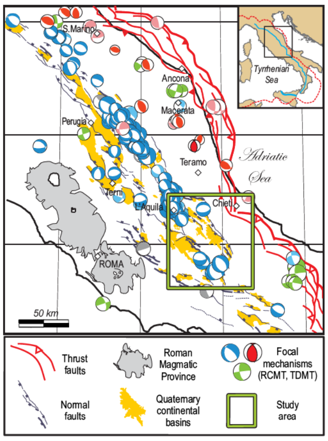
Completeness magnitude and b-value distribution in the Sulmona basin area (Central Apennines): new data from a temporary seismic network

M. A. Romano (a-b), R. de Nardis (a-c), G. Lavecchia (a), M. Garbin (b), L. Peruzza (b), E. Priolo (b), M. Romanelli (b) & F. Ferrarini (a)

(a) *GeosisLab, DiSPUTer, Università G. d'Annunzio, Campus Universitario di Madonna delle Piane, 66013, Chieti Scalo (CH), Italy. E-mail: aromano@inogs.it*
(b) *Centro Ricerche Sismologiche, Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Via Treviso, 55, 33100, Udine, Italy and Borgo Grotta Gigante, 42/C, 34010, Sgonico (TS), Italy*
(c) *Dipartimento della Protezione Civile, Via Vitorchiano, 2, 00189, Roma, Italy*

The Sulmona basin area (Central Apennines)



After the earthquake of 6 April 2009 (M_w 6.3), which struck the town of L'Aquila and surrounding regions, causing hundreds of casualties, the seismogenic potential of the active normal faults in the Abruzzo region (Lavecchia et al., 2009; Boncio et al., 2010) of central Italy are back again at the centre of the scientific debate.

Specifically, the Sulmona basin, bounded to the east by the Morrone-Porrara fault alignment, is considered an high seismic hazard area because the segments of these faults, with along strike lengths up to 20 km, are capable of releasing destructive earthquakes with M > 6 (Boncio et al., 2004; Galadini et al., 2000).

Moreover, the Sulmona town (one of the best preserved Abruzzo historical towns, with an important monumental and artistic heritage, and with a population of about 25000 inhabitants) is located just at the hanging wall of the Mt. Morrone fault, on soft continental Quaternary deposits, and consequently also the seismic risk is very high.

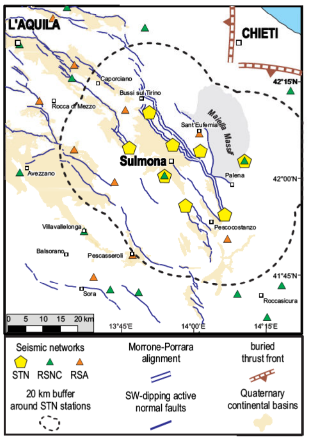
According to Ceccaroni et al. (2009), the last historical event associated to the Morrone segment dates back to the 2nd Century A.D., and the time elapsed since then exceeds the mean recurrence time of maximum magnitude earthquakes estimated for this structure (Peruzza et al., 2011).

In 1706 and 1933 other two strong events, with estimated magnitudes of 6.8 and 6.0 respectively (Rovida et al., 2011), caused severe damages around Sulmona, but their seismogenic sources are still doubtful (Galadini and Galli, 2004; Lavecchia et al., 2010; Gori et al., 2011).

Since early-instrumental times, no significant earthquake occurred in this area, even if during the L'Aquila seismic sequence four earthquakes with $3.2<M_L<3.8$ (ISIDE database) increased the low seismic activity characterizing the basin (de Nardis et al., 2011).

Evidence of stress loading in the studied area, induced not only by the L'Aquila 2009 earthquake at north, but also by the 1984 Val di Sangro earthquake at south, was pointed out by De Natale et al. (2011) based on the results from coseismic Coulomb stress change studies.

The experiment of temporary seismic monitoring



STN, Sulmona Temporary Network; RSNC, Centralized National Seismic Network; RSA, Abruzzo Regional Network

The temporary seismic monitoring survey in the study area was carried out with the aim of increasing the knowledge of its seismic activity, and consequently of the seismogenic potential of existing active faults, not only from a geometrical and kinematic point of view, but also in terms of recurrence times of expected max magnitude earthquakes. By the installation of a local seismometric network, in fact, we intended to lower the completeness magnitude threshold in the Sulmona area, and to estimate reliable parameters of the Gutenberg-Richter model, which are useful for seismic hazard evaluations (e.g. forecasting possible rupture areas along the Morrone-Porrara alignment). Specifically, the b-value is considered a stress-meter and the analysis of its spatial pattern would allow us to distinguish asperities zones (corresponding to low values) from those which act as barrier or are deforming by creep (high values) (Schorlemmer and Wiemer, 2005; Schorlemmer et al. 2005).

The Sulmona Temporary Network (STN) was installed on 27 May 2009, about 50 days after L'Aquila earthquakes, and worked till 22 November 2011. It consisted of 6 mobile stations and 2 permanent stations belonging to the RSNC (Centralized National Seismic Network), deployed all around the Sulmona plain (yellow symbols in the figure). Placed mainly at the hangingwall of the Morrone-Porrara alignment, at an inter-station distance of about 10 km, STN stations covered an area of 400 km². All mobile stations were equipped with high sensitivity instrumentations in order to record earthquakes as small as possible. Four units are equipped with a 1 Hz three-component seismometer and two of them with a velocimetric/accelerometric couple, while the data-logger was the same for all stations. Their signals (sampled at 100 Hz) were continuous, and the great amount of acquired data (about 170 Gb) was managed off-line.

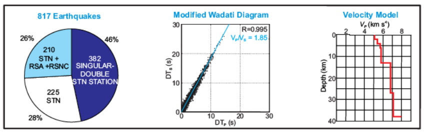
A semi-automatic procedure was adopted for processing and analysing the first seven months of seismic recordings, similar to that used by Garbin and Priolo (2013) for detecting small magnitude events in the Trento province. It uses (1) Antelope (BRTT, 2004) for acquiring/storing data, recognizing earthquakes automatically, and extracting earthquake waveforms; and (2) a "pick server" for phase picking and location, performed by Seisgram2K (Lomax, 2008) and Hypo71 (Lee and Lahr, 1975), respectively. The automatic procedure, applied to the data set from 27 May to 31 December 2009, extracted about 16000 windows of signal, including teleseismic events, regional events (e.g. L'Aquila aftershocks), local earthquakes (our target) and false events. All the windows were visually inspected, but only those containing local events (with time difference between P and S arrivals of less than about 3 s) were analysed.

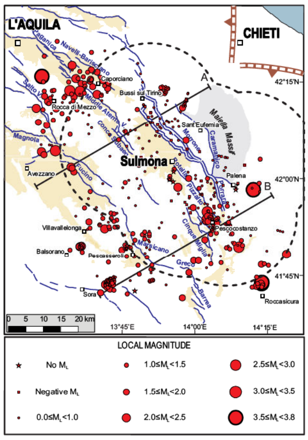
Location of recorded microearthquakes

With the aim of strengthening our earthquake catalogue, we enriched the dataset of STN arrival times with data from the Abruzzo Seismic Network (RSA) and from the Centralized National Seismic Network (RSNC). We evaluated their general quality and consistency by using the modified Wadati method (Chatelain, 1978), which compares the time difference of P and S phases recorded by pairs of corresponding stations.

From 27 May 2009 to 31 December 2009, totally 817 small earthquakes have been detected, and 535 of them were located by using Hypoellipse (Lahr, 1999). The velocity model was estimated ad hoc for this area, and a V_P/V_S of 1.85 was derived by orthogonal regression of Wadati diagram samples (Romano et al., 2013). In detail, 382 events were identified by 1 or 2 STN stations, and located only if having at least 4 phase readings; 225 were located exclusively by STN stations; and 210 were located through observations of STN, RSA and RSNC stations.

The local magnitude (M_L) was estimated for all the events, with the exception of eight (little stars) characterized by a low signal-to-noise ratio. M_L values range from 1.5 to 3.7. Note that negative magnitudes (little squares) are associated only to events located close to the temporary stations, where the STN detection capabilities are the highest. The largest magnitude values are associated to four events, from north to south: M_L 3.5 on 21 June 2009 (near L'Aquila), M_L 3.7 on 15 September 2009 (near Palena municipality), M_L 3.5 and 3.6 on 4 August 2009 (near Roccasicura locality).





Frequency-Magnitude Distribution

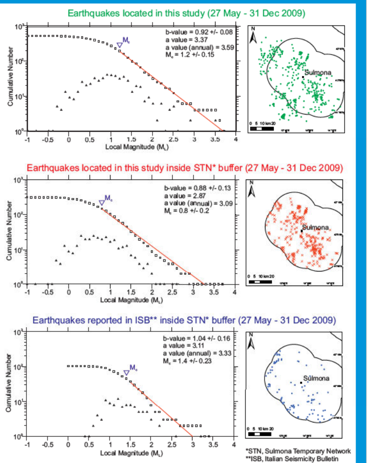
The high detection capabilities of STN have let us to compile a very detailed catalogue of instrumental seismicity for the study area. We were able to locate accurately hundreds of microearthquakes, also with negative magnitudes, not identified by the national seismic network.

In order to perform the statistical analysis of the magnitude vs event frequency relationship, we used ZMAP software (Wiemer, 2001), which allows an estimation of both the completeness magnitude (M_c) and the parameters of the Gutenberg-Richter model.

The M_c has been evaluated with the maximum curvature method (Wiemer and Wyss, 2000); it is equal to 1.2, with an uncertainty of 0.15, estimated by bootstrapping 100 samples with an M_c correction of 0.2. The parameters of the Gutenberg-Richter relationship have been obtained by the maximum likelihood method (Utsu, 1965; Aki, 1965). The a-value, which indicates the seismic activity level, is equal to 3.37 and the b-value, which describes the relative number of small and large events in the time interval, is equal to 0.92 ± 0.08.

These values are not only representative of the Sulmona basin, because part of the L'Aquila seismic sequence (NW sector of the study area) and many events in the Sora region (SW sector of the study area) fall inside the relocated events. If we spatially select the events within a buffer zone of 20 km around the STN stations, the M_c reduces to 0.8 ± 0.2, a-value to 2.87 and b-value to 0.88 ± 0.13. Nevertheless, the shortness of the time interval investigated and the limitations in the data sample do not allow for interpreting these low b values as a stress indicator (see, for example, Gulia and Wiemer, 2010). In the Sulmona area, stationary background conditions might have been influenced by static/dynamic stress changes induced by the main earthquakes of the L'Aquila seismic sequence.

For comparison, we performed the same analysis on earthquakes reported by the Italian Seismic Bulletin for the same period and within the same buffer zones. It can be observed that the fewer number of events (i.e. the stronger ones) located by RSNC, implies an higher value of M_c (1.4) and a less constrained Gutenberg-Richter relation.



*STN, Sulmona Temporary Network
**ISB, Italian Seismicity Bulletin

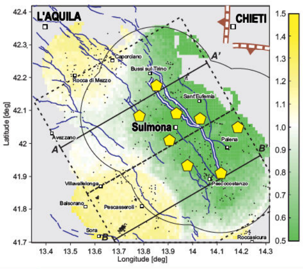
M_c and δM_c maps

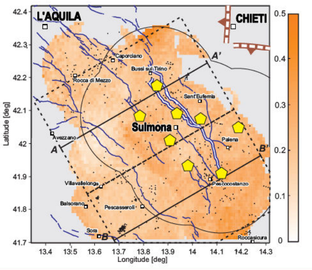
After computing the overall M_c, assuming that the located earthquake population exhibits a Gutenberg-Richter power law (Wiemer and Wyss, 2000), we also investigated the M_c spatial variability in the study area, by using ZMAP and the maximum curvature method.

We chose to subdivide the area in a 0.01° x 0.01° grid of points, compatible with the horizontal error (~ 1 km) of earthquakes locations. At each grid node, M_c was determined only if minimum 20 events with $M > M_c$ (N_{min}) were available between all the sampled earthquakes within a constant radius of 20 km. This setting was the best compromise among the number of recorded earthquakes within the M_c threshold, a reliable trend of M_c and an adequate emphasis on the expected M_c differences. An higher N_{min} would have produced gaps in the M_c map, while a greater search radius would have hidden the variations existing in the area.

The left map shows that the completeness magnitude increases from 0.5 to 1.5 moving from the STN centre towards outside. This very clear variability is consistent with the detection capabilities of the local network, which are maximum close to its stations (inside the buffer zone) and diminish with the distance. Consequently, the catalogue we compiled in the first seven months of monitoring results of high quality in correspondence of the Morrone-Porrara alignment.

The right map represents the pattern of the M_c standard deviation, evaluated by a bootstrap approach. It is substantially homogeneous, indicating a similar uncertainty level in the M_c estimations.

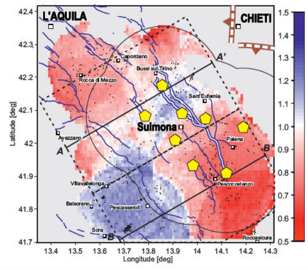


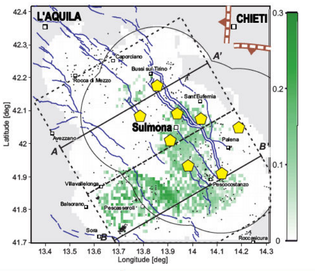


b-value and δb-value maps

The figure on the right represents the b-value spatial variability in the Sulmona basin area, computed by using the same input parameters (search radius of 20 km, N_{min} equal to 20 and grid spacing 0.01° x 0.01°) of the M_c map. The estimates of the Gutenberg-Richter slope were made systematically for each grid point by applying the maximum likelihood technique (Utsu, 1965; Aki, 1965). The punctual b-values derive from small samples of earthquakes and suffer of not negligible uncertainties (Wiemer and Wyss, 2002); consequently, we did not consider such estimates in an absolute sense, but only for highlighting their spatial trend. We intended to distinguish areas characterized by b-values greater or lesser than 1 (its typical reference value), as they would indicate low or high stress conditions, respectively.

As the variations of the G-R slope may be compared only for the same Mc, we separately analysed the b-value pattern inside and outside the STN buffer. Inside the buffer, a quite uniform distribution of low b-values, probably indicating a stress build-up, is interrupted by a spot of higher values at north-east of the Sulmona town. This could indicate the existence of a creeping zone, or even a seismogenic barrier, close to the city. Outside the buffer, the difference of b-values between NW and SW can be explained taking into account the maximum magnitude of located events; indeed the earthquakes belonging to the Sora sequence have ML lower than those near L'Aquila. These changes recognized in the study area, can be considered enough significant, as they exceed the standard deviations (obtained by bootstrapping) of the b-values (Schorlemmer et al., 2004).

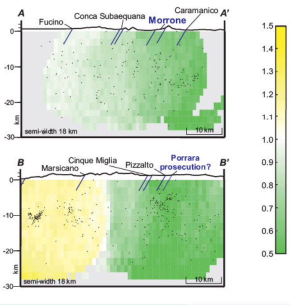


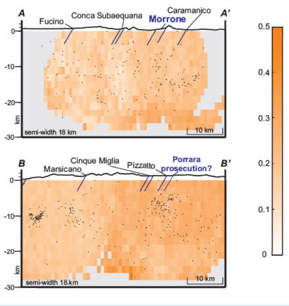


M_c and δM_c cross-sections

All the located events, with exception of those near Roccasicura and some of L'Aquila aftershocks, were projected on two vertical cross-section planes, trending perpendicular to the Morrone-Porrara alignment trace and with a semi-width of 18 km.

The input parameter scheme for obtaining M_c depth distribution is the same used for the M_c maps (see above). The grid spacing now is of 1 km in the horizontal direction and of 2 km in the vertical one, compatibly with the error location distribution. No variation of the M_c with depth can be appreciated, as the search radius and the maximum depth of events are similar. As a consequence, the cross-section patterns correspond to the map view, showing the lowest values of M_c through the volumes sampled by STN stations, and the highest ones at the study area edges. Also the distribution of M_c standard deviation does not change with depth, remaining quite homogeneous and guaranteeing the similar level of uncertainty in the M_c estimations.





b-value and δb-value cross-sections

By projecting the located events along two cross-sections as previously described, and by applying the same input parameters used for obtaining M_c and δM_c depth distributions, we estimated the b-value and δb-value cross-sections.

The lateral heterogeneities of b-values observable in such sections substantially retrace those already evidenced on the map. Specifically, on the northern section, the high b-value spot, which in map is located close to Sulmona, corresponds to the crustal volume under the depth prosecution of the Morrone fault segment; all around, b-value tends to diminish. According to this pattern, it can be hypothesized that the northern part of the Morrone-Porrara alignment deforms by creep or even acts as a tectonic barrier, unlike the surroundings. On the other hand, the clear decreasing of b-values from SW, where the Sora seismic sequence occurred, towards NE, near the southern end of the Porrara active fault, suggests a build-up of stress just in correspondence of this seismogenic structure. Also in this case, the standard deviation distribution confirms the spatial variability of b-value.