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# Introducing the special issue on the 2009 L'Aquila earthquake

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***ABSTRACT*** The 28th National Congress of the *Gruppo Nazionale di Geofisica della Terra Solida* held in Trieste in November 2009, hosted a special session dedicated to the earthquake that only six months before devastated L'Aquila and many ancient villages spread along the Aterno Valley (Abruzzo, central Italy). We resume here the main geophysical characteristics of that long seismic sequence, before introducing in brief the contents of eight papers that we have solicited amongst the thirty-seven presented in Trieste, plus other three coming from other sessions, all of them dealing with the L'Aquila earthquake.

**Key words:** L'Aquila earthquake, seismology, geophysics, surface faulting, macroseismic survey, site amplification.

## 1. Introducing the 2009 L'Aquila earthquake

This volume collects a selection of papers presented in the special session "*Il terremoto dell'Abruzzo del 6 aprile 2009*" held during the 28th National Congress of the Gruppo Nazionale di Geofisica della Terra Solida (GNGTS; Trieste, November 2009). As convenors of this session, we were asked by Dario Slejko to select a number of works amongst the most interesting and innovative which would have embraced the different scientific issues of this catastrophic earthquake.

The 2009 central Apennine earthquake ($M_w$ 6.3; Fig. 1) devastated the old downtown areas of L'Aquila on the night of April 6, 2009, together with dozens of ancient villages along the Aterno River Valley. The region lies on the well known seismically hazardous area running along the south central Apennines of Italy (http://zonesismiche.mi.ingv.it/ Boschi *et al.,* 2009). Millions of people in central Italy were awakened by the tremors, as were most of the inhabitants of Rome (~100 km from L'Aquila). Its social impact has been very high, both in terms of human loss and from an economical point of view. The death toll reached 308, with 1,568 injured and 67,500 temporary left homeless. Although the magnitude of the mainshock has been conventionally fixed at $M_w$ 6.3 ($M_L$ 5.8), a lower value has been computed according to the time-domain moment-tensor method [$M_w$ 6.1; Scognamiglio *et al.* (2010)]. It has also been reported as $M_w$ 6.3 according to the Quick Regional Centroid Moment Tensor (Pondrelli *et al.,* 2010), and $M_w$ 6.3, $M_s$ 6.3 and $M_b$ 5.9 according to the Harvard Centroid Moment Tensor (CMT, 2009).

The macroseismic survey carried out across more than 300 sites showed that the damage and collapse mainly affected rubble-stone and/or masonry buildings, and especially those overloaded with badly supported reinforced-concrete roofs (Galli *et al.,* 2009; Azzaro *et al.,* 2011). The

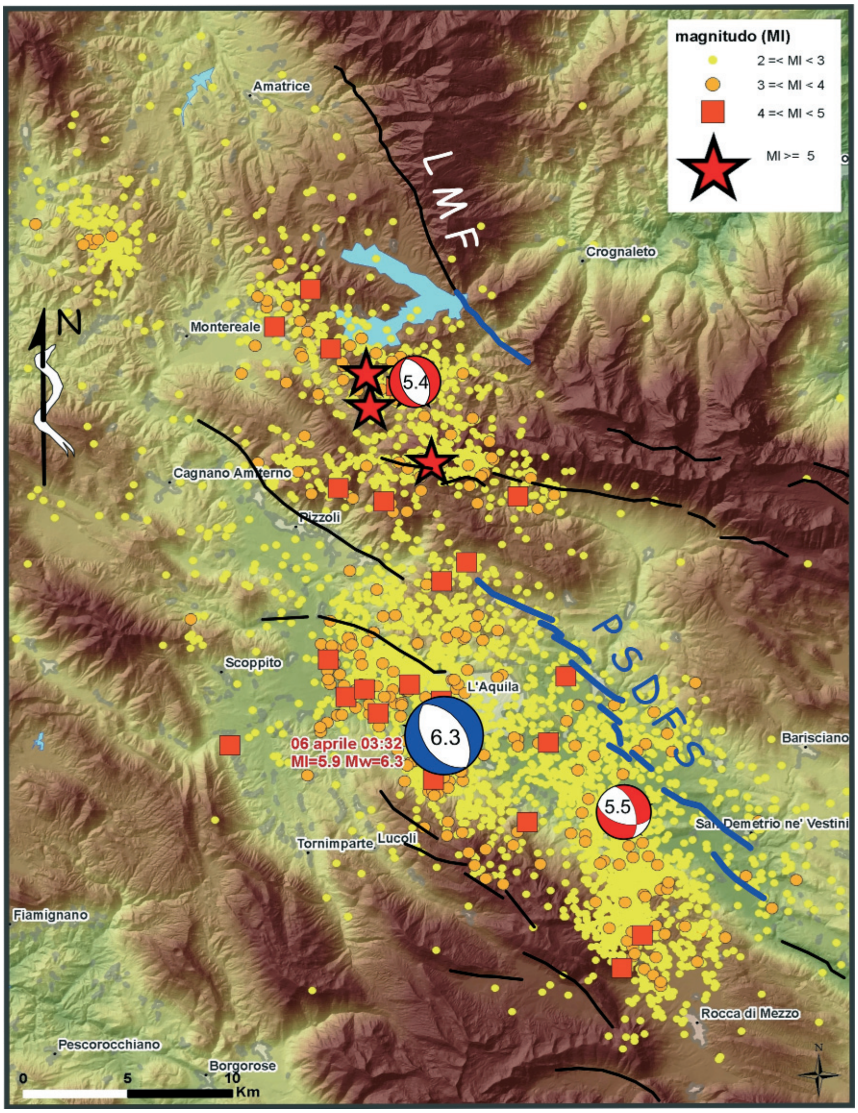

Fig. 1 - Mainshocks and aftershocks distribution of the 2009 L'Aquila event (courtesy of M. Pignone). Bold blue are the surficial expression of the faults responsible for the seismic sequence (PSDFS, Paganica-San Demetrio fault system; LMF, Laga Mts fault). In black the primary active faults of the region (modified from Galli *et al.*, 2010).

reinforced-concrete buildings generally experienced little or moderate structural damage, although ca. 12 showed partial or total collapse (e.g., of the first story). Most of the casualties occurred in downtown L'Aquila (200 people, where there were less than 10,000 residents), and in the village of Onna, which was razed to the ground (41 deaths with 350 residents; $I_s$ IX-X MCS, the maximum intensity). The mesoseismic area (i.e., $I_s$ VII-VIII MCS) was elongated by over 20 km in a NW-SE direction, and it included 16 sites affected by a $I_s$≥VIII, and six affected by $I_s$≥IX (i.e., Castelnuovo and Onna, IX-X MCS). The epicentral intensity was estimated as $I_o$=IX on the MCS scale, whereas the macroseismic equivalent magnitude was $M_w$ 6.1 (Fig. 2).

The mainshock was preceded by a long seismic sequence ($M_L$<4.0) that started in December, just SW of L'Aquila, and culminated on March 30, with a $M_L$ 4.1 event (Chiarabba *et al.,* 2009).

Fig. 2 - View of the ruins of Tempera (IX MCS) at dawn of April 6, 2009. The church clock indicates the time of the earthquake that the night before razed to the ground the entire village (photo P. Galli).

Two strong shocks around midnight of April 5 ($M_L$, 3.9 and 3.5) prompted many people to sleep outside, so that the mainshock at 03:32 resulted in relatively fewer casualties than the seriousness of the damage would have implied. Thousands of events with $M_L$>2.0 were recorded in the following months, with more than 200 with $M_L$>3.0, 20 with $M_L$>4.0, including two strong aftershocks with $M_w$ 5.4 and $M_w$ 5.6.

As far as the seismogenic source is concerned, the mainshock nucleated at ~9 km in depth along a ~N135°-striking normal fault, dipping 50°SW at depth (CMT, 2009; TDMT, 2009; Cirella *et al.,* 2009; Chiaraluce *et al.,* 2011). Seismological data have clearly showed that the fault ruptured from deep to shallow, and then from NW to SE (Di Luccio and Pino, 2011; Di Stefano *et al.,* 2011), in agreement with the macroseismic distribution of effects (Galli *et al.,* 2009). The fault rupture reached the ground surface, causing surficial breaks which have been univocally interpreted as surface faulting (Falcucci *et al.,* 2009; EMERGEO Working Group, 2009; Galli *et al.,* 2010), although the amount of vertical slip measured at the surface was small (<10 cm) if compared to the slip on the fault at depth (Fig. 3). Surficial ruptures were surveyed by earthquake geologists for 19 km along a NW-SE direction between the villages of Collebrincioni (NW) to San Demetrio ne' Vestini (SE); these breaks match with the Paganica-San Demetrio fault system

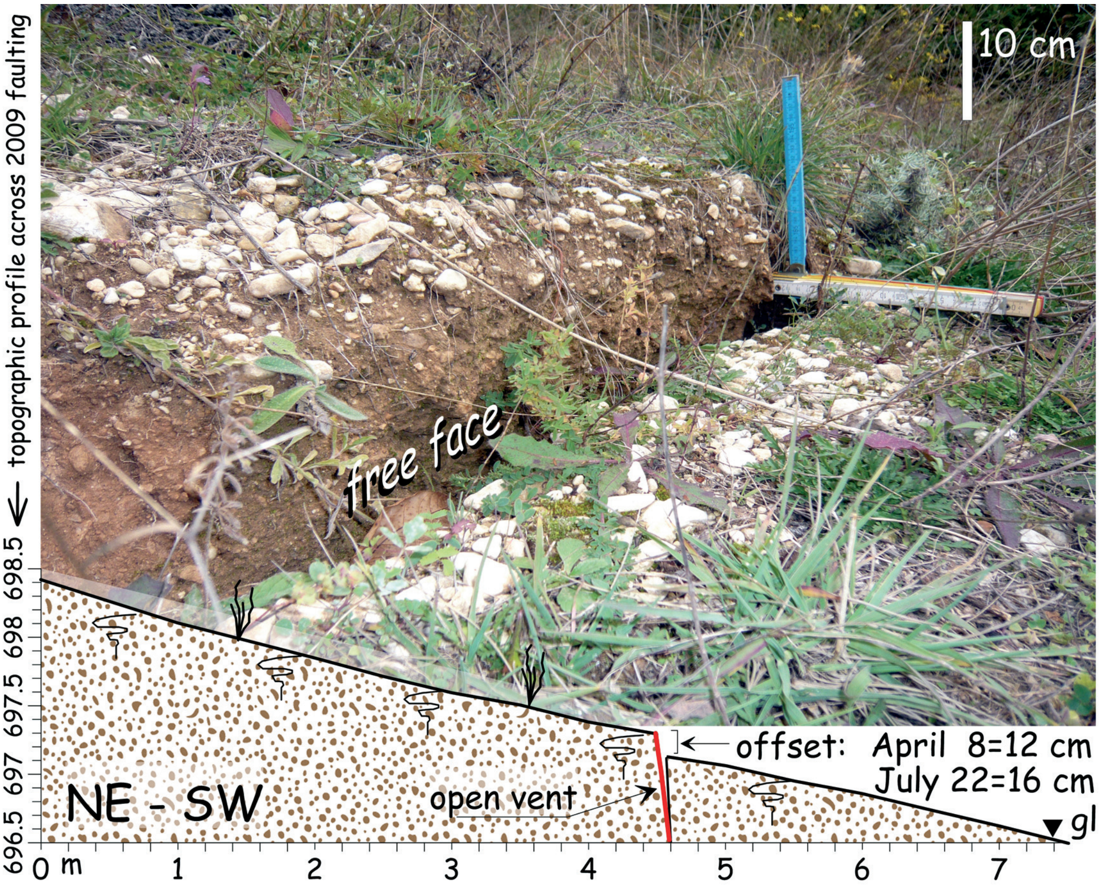

Fig. 3 - View of the coseismic surficial breaks affecting Late Pleistocene deposits between Tempera and Paganica (photo P. Galli).

which has been likely responsible in the past also for the 1461 event ($M_w$ 6.4) and for the February 2, 1703 earthquake ($M_w$ 6.7). As shown by paleoseismological studies (Galli *et al.,* 2010, 2011), in 1703 the Paganica faults ruptured together with the Mt. Marine-Mt. Pettino fault system, along more than 30 km of length.

Fault kinematics and in-depth geometry were also calculated from the inversion of satellite geodetic data [both synthetic aperture radar (SAR) and global positioning system (GPS) data]. The differential SAR interferograms showed a deformation pattern generated by the fault slip, along with a large amount of sinking of the down-thrown block [~ -25 cm, vs. ~ +5 cm observed in the footwall; Atzori *et al.,* 2009). Similar values of the co-seismic deformation were calculated from GPS inversion (Cheloni *et al.* (2010)], and from the re-levelling of two geodetic lines (more than -27 cm in the hanging wall, and ~ +4 cm in the foot wall; R. Giuliani, personal communication).

Both SAR and GPS datasets allowed the modelling of the source parameters, which are quite consistent with a NW-SE normal fault, dipping ~ 55°SW, emerging at the surface in the narrow band affected by the surface faulting. All models reveal a strongly heterogeneous slip distribution on the fault, ranging from a few centimetres to more than 1 meter. The maximum slip (~ 0.9-1.1 m) was focused below the Aterno Valley, at ~ 7-8 km depth (see also Cirella *et al.,* 2009). Geodetic data also showed the occurrence of post-seismic slip on the fault in the weeks following the main rupture (Amoruso and Crescentini, 2009; Cheloni *et al.,* 2010; Lanari *et al.,* 2010). These two evidence (heterogeneous coseismic slip and post-seismic deformation) are important for the understanding of how the Apenninic normal faults work, and should be considered in seismic hazard scenarios.

## 2. The selected papers from the Trieste 28th GNGTS congress

The L’Aquila earthquake is certainly the best recorded event in the seismological history of Italy, thanks to both the improvement of permanent seismic networks (Amato and Mele, 2008; De Luca *et al.,* 2009) and the deployment of a very dense temporary network. These data allowed to constrain the first details of the fault geometry at depth (Chiarabba *et al.,* 2009), that are better constrained here in Chiaraluce *et al.,* 2011, and of the crustal structure (Di Stefano *et al.,* 2011). Also, data from permanent networks were used to retrieve variations of the crustal properties in the preparatory phase of the main shock, emphasizing the involvement of fluids in the source region (Di Luccio *et al.,* 2010; Lucente *et al.,* 2011; Terakawa *et al.,* 2011).

In particular, in this volume Chiaraluce *et al.* (2011) present a detailed analysis of the aftershock distribution at depth, pointing out the presence of a complex system of SW-dipping faults with variable dip (from 50° for the main Paganica fault to 35° for the Campotosto-Monti della Laga fault) and *en-échelon* geometry. Minor faults are also recognized by aftershock locations, most of which are shallow ($h<10$ km) with one exception in the southern area where a deeper (13-15 km), antithetic fault is evident.

Di Luccio and Pino (2011) use data from permanent seismic networks to show how they can be used to retrieve basic information on the characteristics of the fault, quickly and with simple procedures. The authors describe how to infer rupture directivity from the simple observation of $M_L$ values azimuthal distribution. Other information on the slip distribution, static surface deformation, and the discrimination of the fault plane can also be retrieved efficiently. For the April 6 main shock, the authors show that the faulting occurred in two stages, with initial updip propagation, and then toward SE, possibly on a different plane.

Faenza *et al.* (2011) present the procedure running at INGV since 2006 for generating Shakemaps, focusing on the performance of it during the L’Aquila earthquake. The first map was published 30 minutes after the earthquake, even if it underestimated the ground shaking. The authors emphasize the importance of using finite fault models to make realistic predictions of the expected ground motion. They also stress the importance of strong motion data in the near source, and encourage data providers (particularly the RAN data by DPC) to strengthen real time data distribution.

Sabetta (2011) describes the characteristics of the strong ground motions recorded during the Abruzzo seismic sequence and of their attenuation with distance, together with a comparison of the loss simulation scenario with the damage building surveys performed after the earthquake. Besides the already mentioned SE directivity effect, well evident in the data set, Sabetta (2011) shows how the predictive equations available in literature, underestimate the PGA values closest to the epicenter and overestimate those in the backward directivity direction. The author also describes the response spectra of the recordings closest to L'Aquila town, that show very high values of acceleration in the interval 2-10 Hz, corresponding to the fundamental frequencies of most of the buildings in the area.

As far as the geophysical analyses aimed at investigating the subsoil image of the fault, in this volume Balasco *et al.* (2011) show the deep trace of the Paganica fault by means of Deep Electrical Resistivity Tomography carried out by using a dipole-dipole array configuration composed by 21 measurement stations located along a 8000 m long profile, for an investigation depth of about 1,000. These data were integrated through a Magnetotelluric profiling, a passive geophysical technique which, studying the propagation of the natural geomagnetic field in the Earth, allows to obtain the subsurface electrical properties of the investigated site. The abrupt resistivity changes at depth evidenced the possible trend of the Paganica fault, together with its antithetic Bazanno fault and other secondary structures.

In turn, the shallow image of the Paganica fault has been revealed by several Electrical Resistivity Tomography (ERT) carried out by Giocoli *et al.* (2011) at three different sites. ERT were performed by using both Wenner-Schlumberger and Dipole-Dipole configurations, and electrode spacing spanning from 1 to 10 m. This allowed to reach in the same site different length (47-470 m) and depth (10-100 m) of investigation. The analyses evidenced the internal architecture of the fault zone, allowing robust cross-correlations with the local stratigraphy, and showed that the Paganica fault segment consists of at least three sub-parallel main splays which have a staircase normal fault geometry in the investigated area.

On the other hand, four papers deal with strong motions and the modification of ground motion due to site effects.

Pacor *et al.* (2011) present an overview of the main features of seismic ground shaking during the L'Aquila sequence, referring to records of the mainshock and of the two strongest aftershocks. They discuss the dependence of the strong-motion parameters on distance, azimuth and site conditions as well as the characteristics of near-fault strong-motion records, concluding that because of the near-fault conditions, the complex geological setting and the availability of several good-quality near-fault records, the 2009 L'Aquila sequence provided an impressive and instructive picture of strong ground motion in the epicentral region of a normal fault earthquake.

In the immediate aftermath of the mainshock, several groups of researchers and professional geologists and engineers started investigation on small scale effects leading on differential damages in neighbouring areas. After few days, the Dipartimento della Protezione Civile (National Department of Civil Protection – DPC) decided to build on this effort a coordinated microzonation study whose aim was twofold: assistance in the emergency phase for the location of sheltering structures and help to urban planners for the reconstruction phase. This activity also aimed at the field validation of the recently published guidelines for seismic microzoning. The study area was subdivided into 12 "macro-areas", each including several municipalities and settlements with severe earthquake damage. For each macro-area, several geological, geophysical and geotechnical surveys were planned, carried out by about 150 researchers and technicians from 8 universities, 7 research institutions, 4 regional and provincial authorities, and the Association of Professional Geologists from the Abruzzo region.

The paper of Boncio *et al.* (2011) describes the studies carried out for the macro-areas 3 and 5 (comprising the villages of Paganica, Tempera, Bazzano, Onna and San Gregorio). In particular, they deal with the geological aspects of the seismic microzonation, discussing its implications in terms of site response measured with noise and earthquake recordings.

Albarello *et al.* (2011) focus on the techniques based on ambient vibration measurements, both on the single-station HVSR approach (widely applied by several research group in the first exploratory phase) and to seismic array configurations (later applied to constrain geological reference models and local $V_s$ profiles). The parallel application of other prospecting techniques (geological surveys, resistivity prospecting, drilling, etc.) allowed the authors to validate the experimental procedures adopted and to define protocols useful for future applications.

Gallipoli *et al.* (2011) compare the available geological data and HVSR measurements with the amplification measured by recordings of the temporary accelerometric array deployed in most affected area. Their main conclusions are that 1) the HVSR curves obtained by ambient noise are representative of the actual presence of resonant layers; 2) the standard geological maps do not have the appropriate scale for a right attribution of lithology; 3) the outcropping soil is not a sufficient criterion to explain the presence/absence of seismic amplification, but a more comprehensive geological model is needed.

Finally, Azzaro *et al.* (2011) present an application of the European Macroseismic Scale (EMS) applied to 70 villages within the epicentral area, comparing the results with those gathered from the quick MCS macroseismic survey. According to the authors, the use of the EMS scale, taking into account the vulnerability of buildings and their grade of damage, provided a more coherent evaluation of the intensity also in the case of settlements made up of very different building typologies.

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