Dipartimento Difesa del Suolo

Servizio Geologico d'Italia

GEOLOGICAL EFFECTS INDUCED BY THE L'AQUILA EARTHQUAKE (6 APRIL 2009, Ml = 5.8) ON THE NATURAL ENVIRONMENT

PRELIMINARY REPORT

Roma, May 2009

GEOLOGICAL EFFECTS INDUCED BY THE L'AQUILA EARTHQUAKE (6 APRIL 2009, Ml = 5.8) ON THE NATURAL ENVIRONMENT

Authors:

A.M., Blumetti (*), V. Comerci (*), P. Di Manna (*), L. Guerrieri (**) & E. Vittori (*)

(*) Servizio Rischi Naturali
(**) Servizio Istruttorie, raccolta dati, tecnologie del sito

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ANNEXES

Front Cover: ground failures along the shores of the Lake Sinizzo, near San Demetrio ne' Vestini.

1. Introduction

On the 6th of April, 2009, the seismic sequence initiated in December 2008 in the L'Aquila area (Abruzzo region, Central Italy) culminated with a quake of Ml 5.8 at 1:33 GMT. A few hours later, the Geological Survey of Italy – ISPRA started to survey the epicentral area in order to document the geological effects of the earthquake and to identify and assess firsthand the situations of potentially high residual risk due to geological hazards. These activities were conducted under specific request and in strict coordination with the Civil Protection Department of Italy.

This preliminary report is focused on a synthetic description of the geological effects collected in the period 6 April – 7 May. Another important aim was to apply the ESI 2007 scale (Environmental Seismic Intensity scale, Michetti et al., 2007), in order to make an independent assessment of the intensity of the earthquake, only based on its effects on the environment. In this sense, this is a contribute to the INQUA Project #0811 "A global catalogue of earthquake environmental effects", which is specifically focused on the application of the ESI 2007 scale for macroseismic intensity assessment.

Several surveyors of ISPRA[1] have contributed to this data collection. Moreover, these investigations were conducted, and are still ongoing, in strict collaboration with teams from other research and academic institutions and the network of the abovementioned INQUA Project[2], in particular the University of Insubria, the National Research Council (IAMC institute, Naples; IRPI institute, Torino and Perugia; IGG institute, Florence), the Geological Survey of Trento Province, the Birkbeck/UCL – University College of London, the University of Durham and the Geological Survey of Israel.

[1] List of ISPRA surveyors: M. Amanti, A.M. Blumetti, S. Calcaterra, C. Cesi, V. Comerci, G. Conte, M. Di Leginio, A. Di Fabbio, P. Di Manna, D. Fiorenza, F. Fumanti, P. Gambino, E. Guarneri, L. Guerrieri, C. Iadanza, D. Ligato, R. Mazzitelli, G. Monti, G. Motteran, S. Nisio, L. Puzzilli, I. Rischia, L. Serva, D. Spizzichino, E. Vittori

[2] - Amit R., Baer G., Berlusconi A., Campedel P., Cocco S., Cowie P., Esposito E., Guzzetti F., Hamiel Y., La Rocca L., Livio F., Lollino G., Mc Kaffrey K., Michetti A.M., Mushkin A., Philips R., Porfido S., Roberts G., Sacchi M., Salamon A., Sileo G., Violante C., Wilkinson M.

2. The seismic sequence (data from INGV)

Seismological data

On the 6th of April 2009 at 01:33 (GMT) the area of L'Aquila and surroundings was struck by a moderate-size earthquake (Ml 5.8; Mw 6.3; epicentre near Roio, about 5 km southwest of L'Aquila, Fig. 1). Two M > 5 shocks followed on the 7th of April (Ml=5.3; epicentre between Fossa and San Martino d'Ocre and San Felice d'Ocre, about 10 km southeast of L'Aquila) and on the 9th of April (Ml = 5.1; epicentre near Campotosto, about 15 km northwest of L'Aquila).

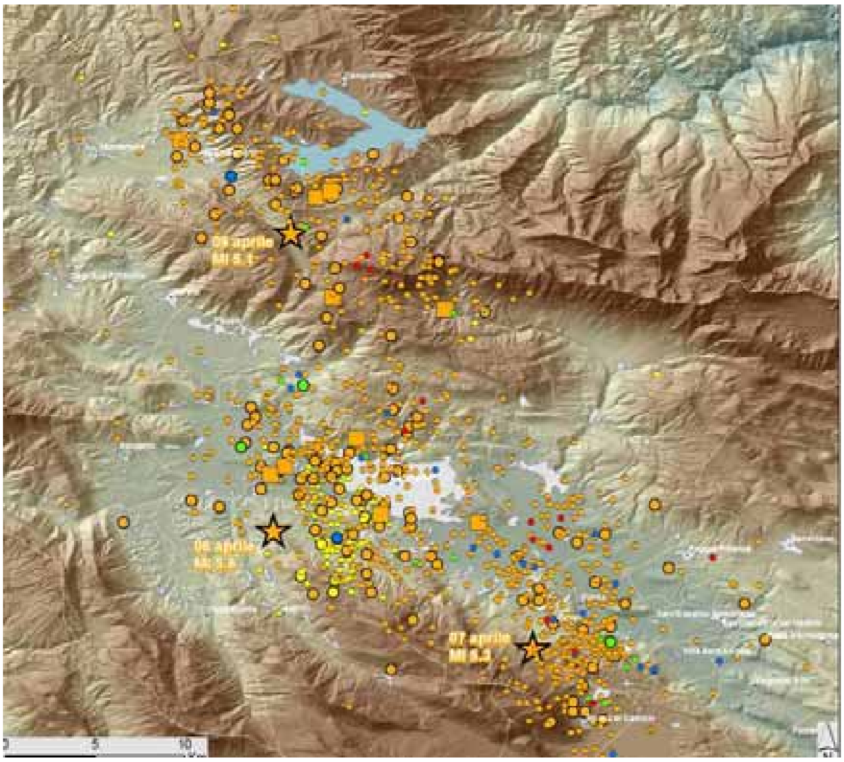


Fig. 1 – Location of the main shocks of the seismic sequence (source: INGV website).

The seismic sequence has affected an about 30 km long, NW-SE trending, zone. The focal mechanisms of the sequence (Fig. 2) clearly define a NW-SE trending normal faulting mechanism. The focal depths are generally within 10-12 km, but the 7 April shock, which is slightly anomalous in terms of focal depth (about 15 km) and focal mechanism (a significant strike-slip component). While most of the main events appear to have occurred on southwest-dipping planes, according to INGV, the few aftershocks associable to the April 7 event do not clearly define a preferred nodal plane for the rupture.

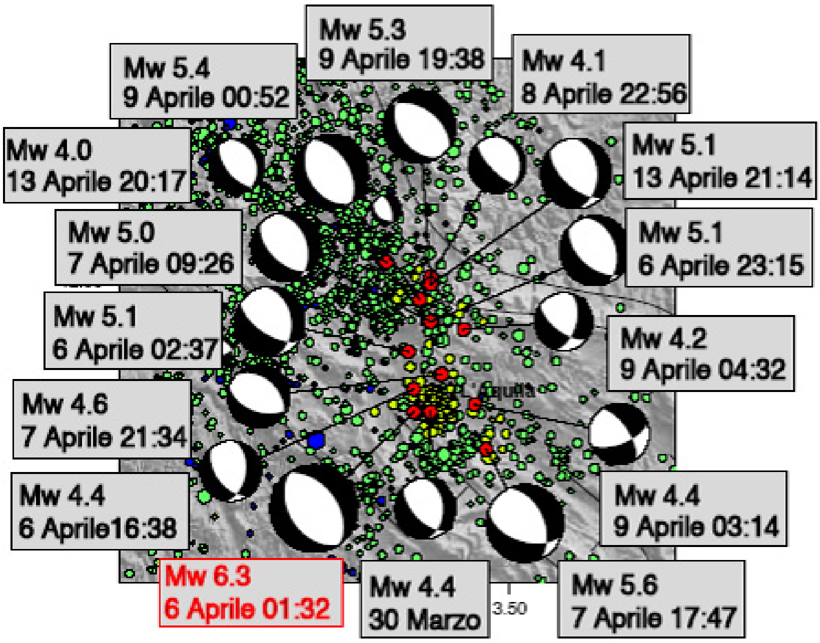


Fig. 2 – Focal mechanisms of the most important events of the seismic sequence (source: INGV).

Macroseismic intensities

The scenario of damages to buildings compiled by the QUick Earthquake Survey Team (QUEST) is very irregular (Fig. 3; source: INGV). The most damaged area stretches northwest-southeast with a remarkable propagation toward southeast. The highest macroseismic intensity values (Is ≥ 9 MCS) have occurred in single localities within areas characterized by a lower level of damages (Is ≤ 8 MCS). These peaks of intensity appear to be caused by a peculiar seismic vulnerability, associated in some cases to evident site effects (e.g., Onna and other villages in the Middle Aterno Valley located on soft alluvial and lake sediments).

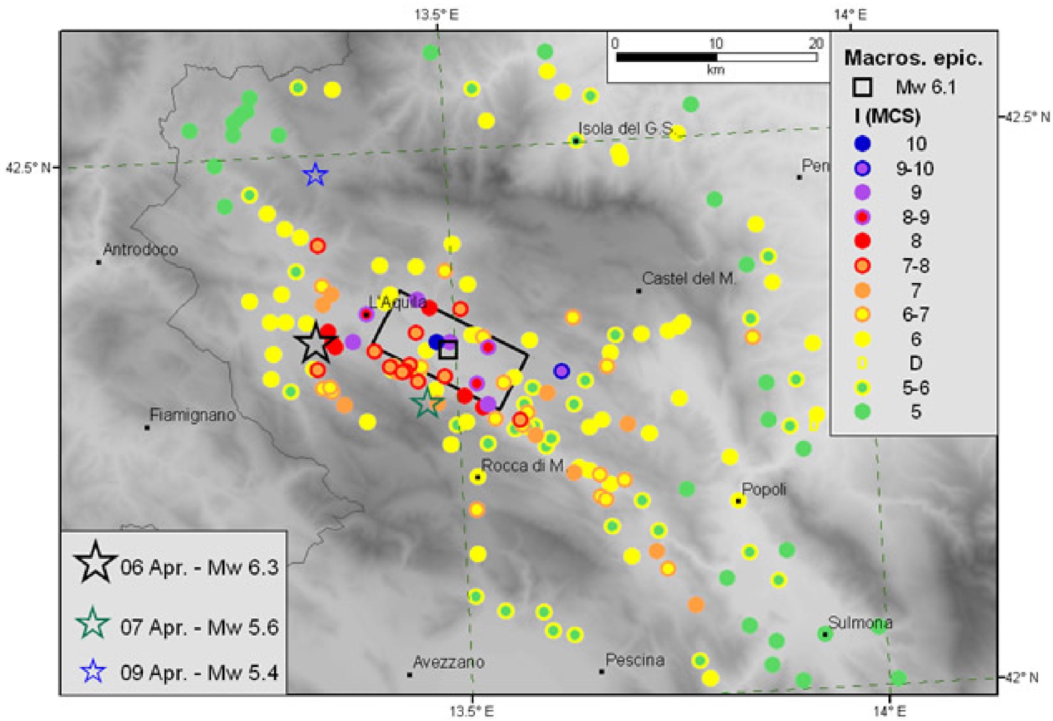


Fig 3 - MCS local intensity distribution (source: INGV).

3. Geological framework and historical seismicity

Geological framework

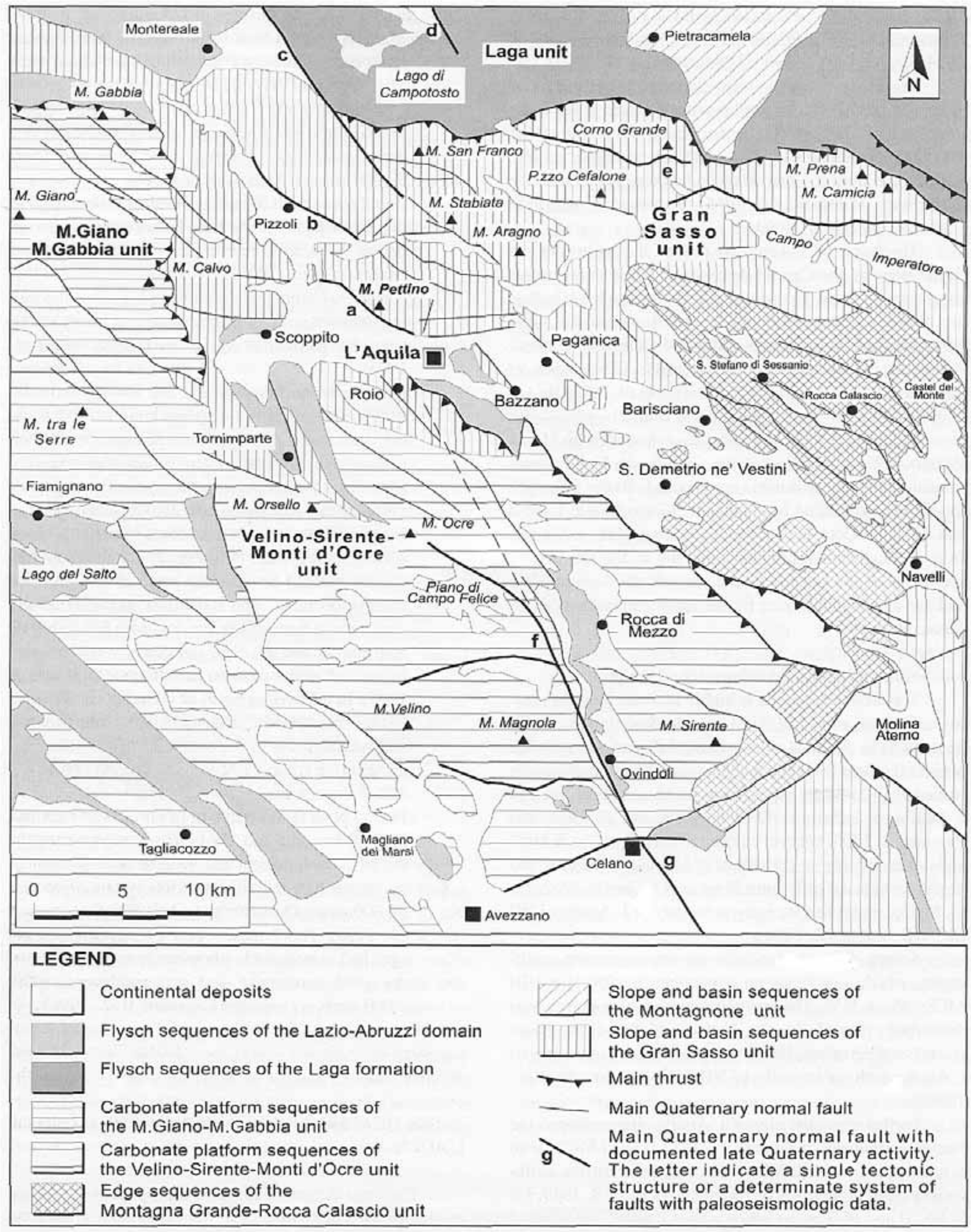


Fig. 4 –*Schematic geologic map of the area (source Blumetti et al., 2002)*

The epicentral area of the L'Aquila seismic sequence is characterised by a system of NW-SE trending tectonic depressions, located between the Gran Sasso and the Monti d'Ocre morphotectonic units (Fig. 4).
The outcropping geological formations and the geophysical data reveal a complex structural setting given by several overthrusted tectonic units belonging to the transitional domain between the Lazio-Abruzzi carbonate shelf platform and the

Umbria-Marche pelagic basin (Vezzani & Ghisetti, 1998; Servizio Geologico d'Italia, 2006).

Basically, the present tectonic structure of the region is the result of compressive orogenic tectonics (Messinian - Middle Pleistocene in age, Patacca et., al 1992) followed by extension.

Crustal extension is still ongoing in this area, as demonstrated by geodetic data (D'Agostino ed al., 2001; D'Agostino ed al., 2008), as well as active tectonics and paleoseismological data (Fig. 4; Bagnaia, 1992; Blumetti, 1995; Moro et al., 2002). The typical block-faulted morfostructural setting characterised by tectonically controlled basins and ranges (Serva et al., 2002; Blumetti et al., 2004; Blumetti and Guerrieri, 2007) is the cumulative effect of this extensional activity over a time interval of at least several hundreds of thousands of years.

In Annex 1, an extract of the official Italian Geological Map at scale 1:50,000 is given (359 Sheet "L'Aquila" CARG project, Servizio Geologico d'Italia, 2006, http://www.apat.gov.it/Media/carg/index.html).

In the same Annex, the distribution of capable faults in the region is also reported, as shown by the ITHACA (ITalian Hazard from Capable faults) catalog (see: http://www.apat.gov.it/site/it-IT/Progetti/ITHACA_-_catalogo_delle_faglie_capaci

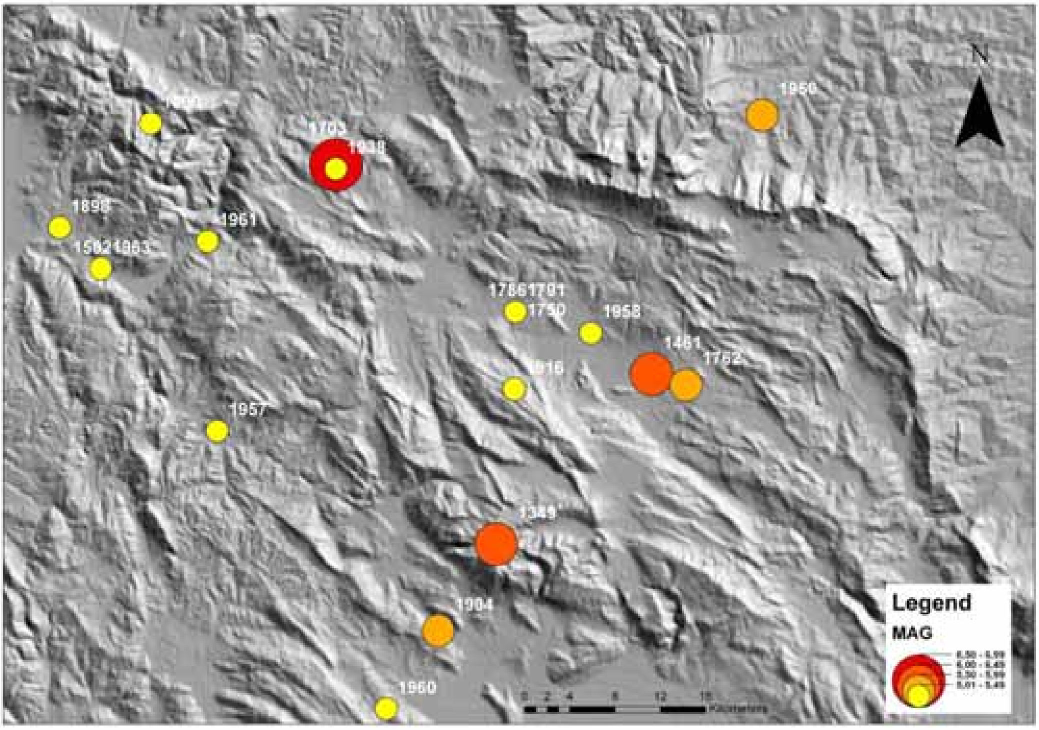
Historical seismicity

The epicentral area was affected in the past by several moderate to strong earthquakes (see Fig. 5).

Two events with Intensity X MCS occurred in 1461 and in 1703, located near the epicentre of the 2009 events. Moreover, two other destructive earthquakes (in 1349, IX-X MCS, and in 1762, IX MCS) hit the same area in historical times.

Concerning the 1703 seismic sequence, it was characterised by three main shocks, that shifted in a few days along a NNW-SSE alignment:

- the first shock, Norcia event, took place on January 14 (intensity XI MCS), caused by the faults bordering the Norcia basin and at the foot of the Mt. Alvagnano ridge, where surface faulting occurred (Baratta, 1901; Blumetti, 1995). This earthquake completely destroyed many localities in Southern Umbria;
- the second event, on January 16 (Intensity VIII MCS), hit a small area among the towns of Montereale, Cittareale, Accumuli and Amatrice;
- the third event, on February 2 (Intensity X MCS), produced surface faulting along the Pizzoli fault for a length of about 20 km (Blumetti, 1995; Moro et al., 2002). Impressive secondary effects were induced by this event (see Fig. 6). Among them, a huge deep-seated gravitational slide on the Mt. Marine ridge, a large slope movement at Villa Camponeschi, near Posta, several rockfalls and liquefaction phenomena along the Aterno River (Parozzani, 1887; Uria de Llanos, 1703). The earthquake destroyed the city of L'Aquila, causing 2500 casualties (Baratta, 1901; CPTI, 2008).



Year	Month	Day	Latitude of epicentre	Longitude of epicentre	Magnitude	MCS Intensity
1349	9	9	42..170	13.380	6.5	IX-X
1461	11	26	42.308	13.543	6.5	X
1502	0	0	42.383	12.950	5.2	VII
1703	2	2	42.470	13.200	6.7	X
1750	2	1	42.356	13.396	5.0	VI-VII
1760	1	0	42.500	13.000	5.2	VII
1762	10	6	42.300	13.580	5.9	IX
1786	7	31	42.356	13.396	5.2	VII
1791	1	0	42.356	13.396	5.4	VII-VIII
1898	6	27	42.415	12.905	5.5	VII-VIII
1904	2	24	42.100	13.320	5.7	VIII-IX
1916	4	22	42.294	13.396	5.2	VI-VII
1938	8	12	42.467	13.200	5.0	VI
1950	9	5	42.516	13.657	5.7	VIII
1957	4	11	42.256	13.079	5.2	VI
1958	6	24	42.340	13.477	5.2	VII
1960	3	14	42.037	13.266	5.2	VII
1961	10	31	42.407	13.064	5.1	VII-VIII
1963	2	2	42.383	12.950	5.2	VII

Fig. 5 – Historical seismicity of the L'Aquila basin and surroundings (source: CPTI08)

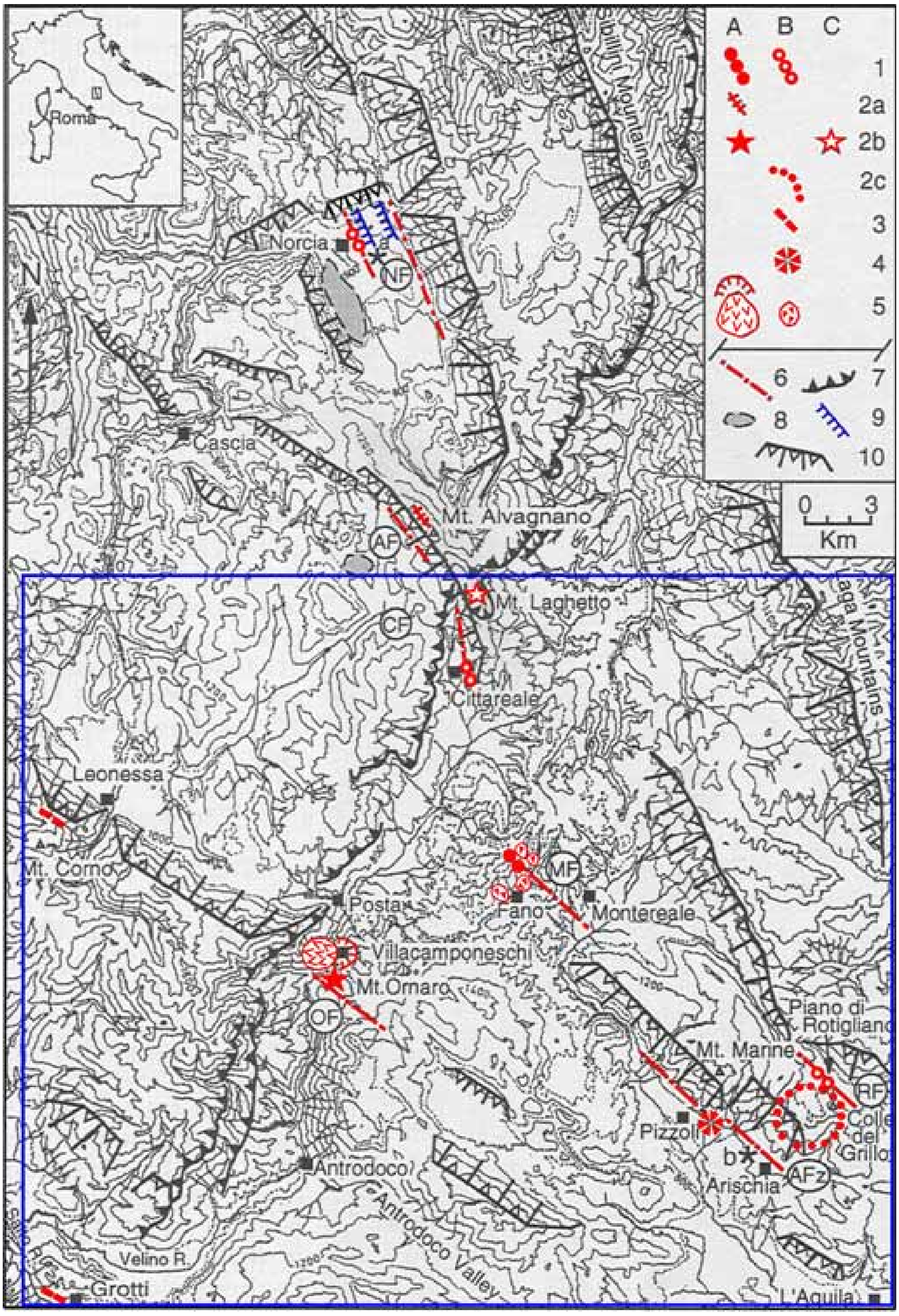


*Fig. 6 – Map of surface effects produced by the 1703 Norcia and L'Aquila earthquakes. The blue inset box includes the effects due to the 2nd of February, Intensity X MCS, L'Aquila shock. Legend: A) certain location (trace identified on the ground); B) approximate location (uncertinaties lower than 2 km),); C) possible location: 1) Primary ground rupture; 2) subordinate ground rupture, 2a) tectonic-gravitational phenomena, 2b) tectonic-karstic phenomena, 2c) boundary of Colle del Grillo zone where huge and complex tectonic-gravitational phenomena occurred; 3) ground failure; 4) liquefaction; 5) landslide; 6) fault reactivated during the 1703 seismic sequence, NF) Norcia fault, AF) Alvagnano fault, CF) Cittareale fault, OF) Ornaro fault, MF) Montereale fault, RF) Rotigliano fault, ARF) Arischia fault zone; 7) main over-thrust; 8) after-shock cluster of the 1979 Norcia earthquake, 9) main fault scarp; 10) main active fault escarpment, *a) and *b) paleoseismological sites.*

4. Geological effects induced by the earthquake on the natural environment

In the period 6 April – 7 May 2009, a total amount of 184 effects have been collected by the ISPRA Italian Geological Survey team and mapped over an area of at least 1000 km^2. Their location is reported in Annex 2.

4.1. Primary effects

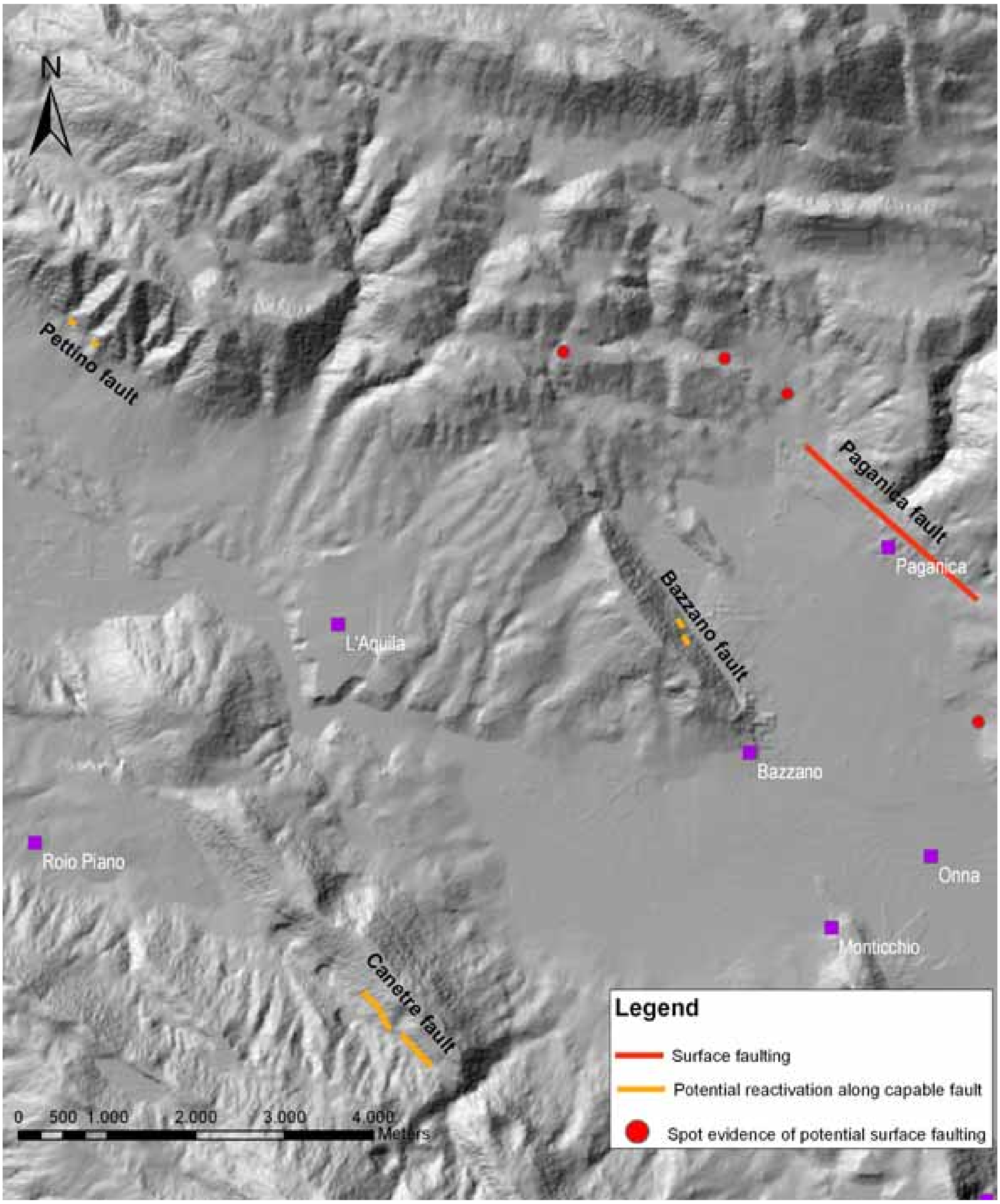


Fig. 7– Primary effects along the Paganica fault, and along other active faults showing evidence of potential reactivation

Ground ruptures along the Paganica fault

A set of discontinuous but well aligned ground ruptures was found in correspondence of the Paganica fault. These ruptures, trending between N120 and N140, could be traced for a length of about 2.6 km, reaching in some sites vertical offsets of 7-8 cm (see Figs. 8 – 18, from NW to SE). They could be easily observed on paved/concrete and often dirt roads and on other artificial surfaces, as well as on buildings and hard fences. Particularly evident was the pipeline rupture of the Gran Sasso aqueduct (see ahead). The same set of fractures was locally well evident also on natural/farmed soil.
A detailed map of the ground ruptures along the Paganica fault is in Annex 3.

Fig. 8 - Ground ruptures near Tempera, NW of Paganica

Fig. 9 - Ground ruptures between Tempera and Paganica

Fig. 10 - Ground ruptures in Paganica some tens of meters west of the broken aqueduct

Fig. 11 - The site where the aqueduct was broken. The location of ground ruptures (before being covered) is pointed out by red arrows

Fig. 12 - Ground ruptures in Paganica about 20 meters east of the broken aqueduct

Fig. 13. Fractures in paved roads in Paganica some tens of meters east of the broken aqueduct

Fig. 14. Two ruptures affecting a modern building and a house-yard in Paganica

Fig. 15. The ruptures affected the ground, some buildings and concrete roads continuously for several hundreds of meters with offsets up to 7-8 cm.

Fig. 15. The ruptures were clearly visible also on the road from Paganica to Camarda.

Fig. 16. Fractures in paved roads at Paganica, Via del Caldarello

Fig. 17. Ground ruptures with centimetric offset at Paganica, Via Rodrigo De Paulis.

Fig. 18. Fractures in buildings and paved road at Paganica, Via delle Volpi.

These ruptures are a clear evidence of coseismic surface faulting. This interpretation is in good agreement with the seismological data (distribution of the aftershocks, focal mechanisms, etc.) and with the coseismic field of deformations resulting by the comparison of pre- and post- event SAR images (Fig. 19 source INGV website).

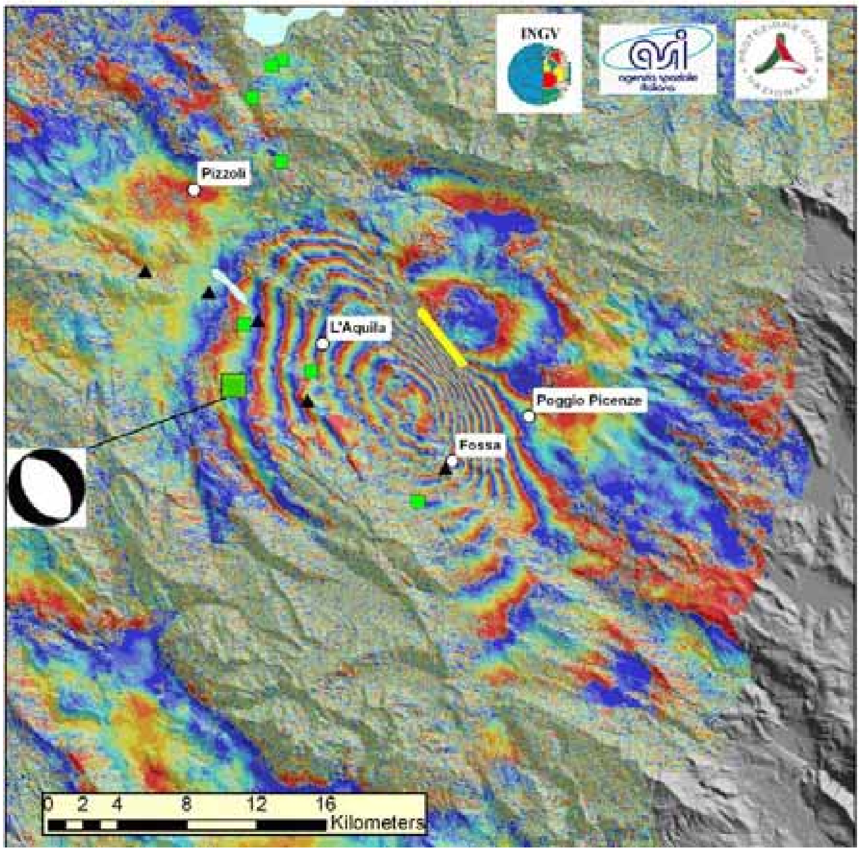


Fig. 19 – ENVISAT interferogram from two images (1 February – 12 April 2009). The maximum lowering, in the order of 25 cm, is located between L'Aquila and Fossa.

The coseismic reactivation of the Paganica fault caused the rupture of the Gran Sasso aqueduct. The rupture of the aqueduct provided an extraordinary exposure of faulted sediments, clearly showing the occurrence of previous coseismic surface faulting events (Fig. 20).

Fig. 20 – Paleoseismic evidences near the broken aqueduct

It is important to underline a remarkable post-seismic evolution of these ruptures, in terms of progressive increasing of offsets, lengths and widths. Eye-witnesses have reported the occurrence of new fractures also some days after the main shock. Several research teams have started to monitor these fractures, documenting post-seismic creep of at least several millimetres.
Some other evidence (discontinuous but aligned ground cracks) which could be interpreted as the northwest prosecution of the Paganica ground ruptures have been found in the area of Tempera and in two quarries (see location in Fig. 7)
Moreover, near Collebrincioni the University of Camerino found a centimetric offset in a debris along a minor fault trending again about N130.
Furthermore, we have to take into account the presence of a coseismic fracture opened in cultivated fields N of Onna and W of San Gregorio hill, with a length of some hundred metres and direction N140-N160. According to the farmer, the day after the main quake, it was possible to observe a longer extension of the fissure in the ground, up to the San Gregorio hill.
If we include these evidence in the rupture zone of the seismogenic fault, the length of the surface rupture may reach about 6 km.

Surface effects along other active faults

Specific surveys were conducted along the mapped active faults in the area.
Along the Pettino fault only local ground ruptures, some tens of meters in length with offsets up to 10 cm were found (Figs. 21-22). This evidence is very discontinuous and cannot be interpreted as proof of actual surface faulting.
Along the Bazzano fault, which is a N310 trending normal fault antithetic to the Paganica fault, we observed a discontinuous free face with offsets locally up to 5-6 cm, marked also by the distribution of moss (Fig. 23). This evidence might be interpreted as a centimetric coseismic surface reactivation of the Bazzano fault together with a significant debris compaction, as shown by the irregular distribution of offsets.
Another free face was found along the N125 trending Canetre fault not far from Roio (Fig. 24). A constant offset of about 1 cm was seen for at least 1 km. This effect was evident not only along debris-rock contacts but also along rock to rock contacts.
Another NW-SE trending ground rupture at least some hundreds of meters long and offsets up to 30 cm, was found by the Birbeck / University College of London along the Campo Imperatore active faults system (Fig. 25). A correct interpretation of this feature is not possible yet, since the area is partially covered by snow.

Fig. 21 - Pettino fault. Ground crack with about 10 cm offset pointed out by the uplifted leaf blanket

Fig. 22. - Pettino fault. Free face about 10 cm high and a few meters long shown by displaced pine needles.

Fig. 23 - Bazzano fault. Discontinuous free face, tens of meters to hundreds of meters long. Its thickness ranges from 2 to 8 cm

Fig. 24 - Canetre fault (Roio). Its potential reactivation is suggested by a continuous free face with constant offset of about 1 cm (shown by the red arrows) and length of at least 1 km. The free face was evident not only along debris-rock contacts but also along rock to rock contacts.

Fig. 25– Campo Imperatore fault. A 20-30 cm rupture exhuming the roots of juniper bushes was evident for at least 300 m (courtesy of G. Roberts)

4.2. Secondary effects

Secondary effects (basically gravitational movements and fractures) induced by the ground shaking have had a widespread distribution. Their percentage distribution by type is shown in Fig. 26.

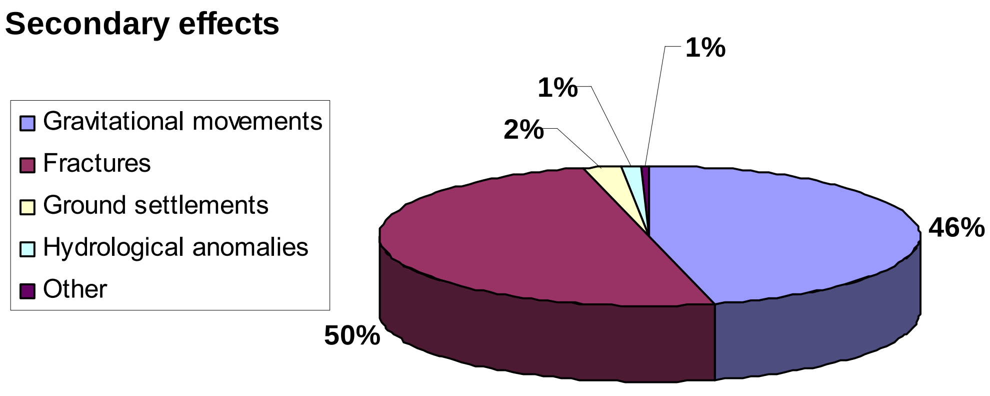
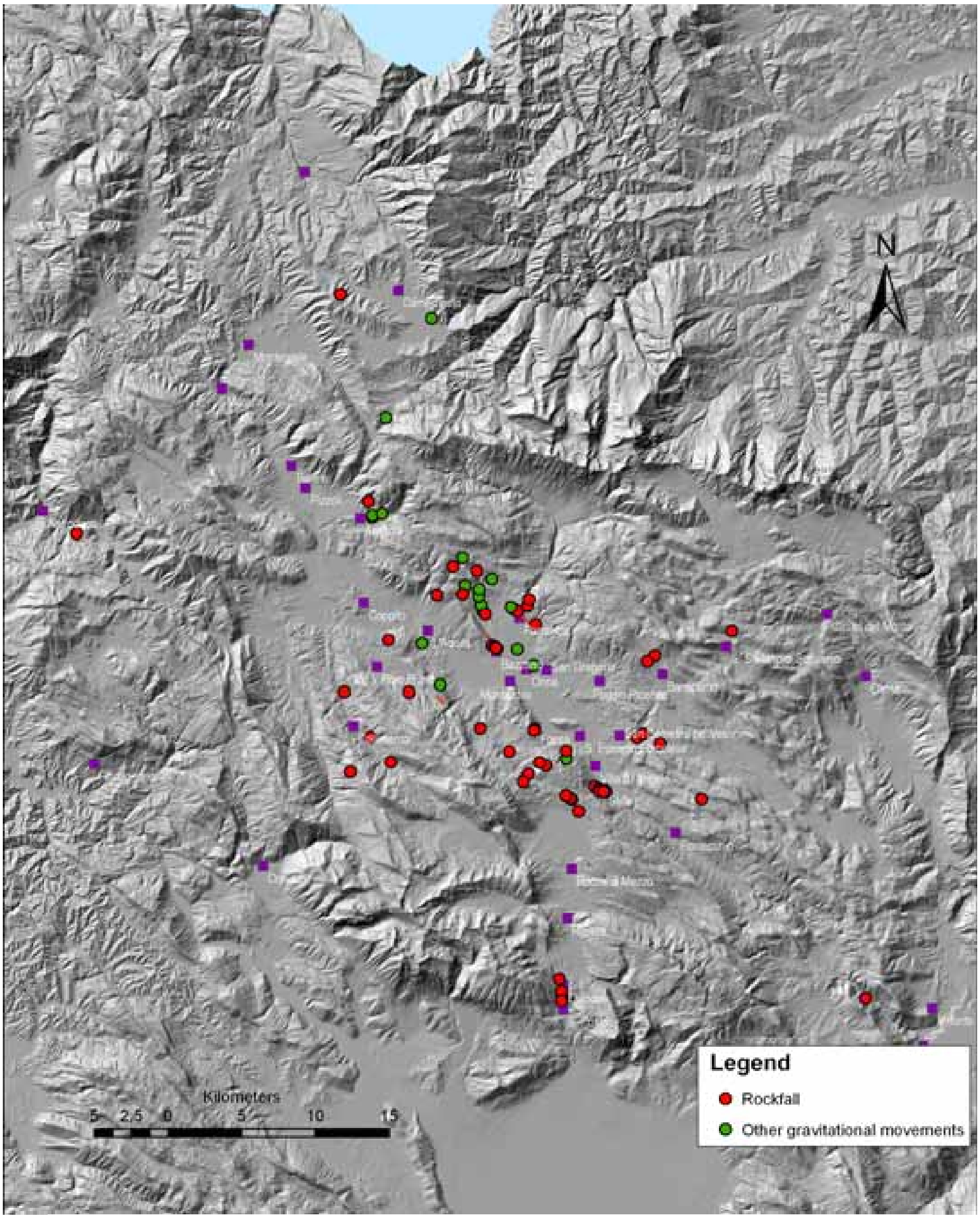


Fig. 26 Percentage distribution of secondary effects by type

Gravitational movements

Numerous rock falls (78% of gravitational movements, Fig. 27) occurred especially from calcareous slopes. Among them, one of the most impressive took place above the village of Fossa, which was directly damaged by huge boulders (Fig. 28-29). The falling of blocks from the slope has continued for a long period also independently from the aftershocks, posing a significant residual risk for the area.
Residual risk of rock falls has caused the temporary closure of some important roads like the SS17 (at San Venanzio Gorges, Fig. 30), the SS 696 (at San Potito, Fig. 31), the Paganica – Camarda road (at S. Maria d'Apparì). and the access road to the Stiffe cave (Fig. 32).

Other important rock falls have been surveyed within the Gran Sasso mountain range (rock avalanches), along the NE slope of Mt. Bazzano (several cubic meters in size, Fig. 33)
Other types of slope movements, generally affecting artificial material and anthropic deposits, occurred along the SS80 (Fig. 34), at San Giacomo, near Collebrincioni (Fig. 35) and along the access road to the Bazzano village.
Around the Lake Sinizzo, near San Demetrio ne' Vestini, very impressive ground failures along the whole shoreline were observed (see front cover and Fig. 36). Their post-seismic evolution was very high. In the other sinkholes of the area (generally empty of water) no remarkable effects were found.



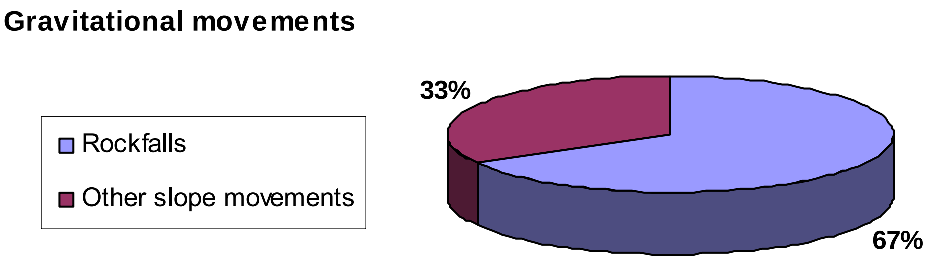


Fig. 27 Distribution of gravitational movements by type

Fig. 28 – Panoramic view of the rockfall above Fossa

Fig. 29 – Fossa rockfall: huge boulders on a paved road.

Fig. 30 – Rockfalls in the San Venanzo Gorges caused the interruption of the viability on the SS 17 Road.

Fig. 31 – Boulders along the SS696 near San Potito. The presence of instable blocks on the steep slope caused the interruption of the viability for several days.

Fig. 32 – A huge block damaged the cafe near the entrance of the Stiffe Cave

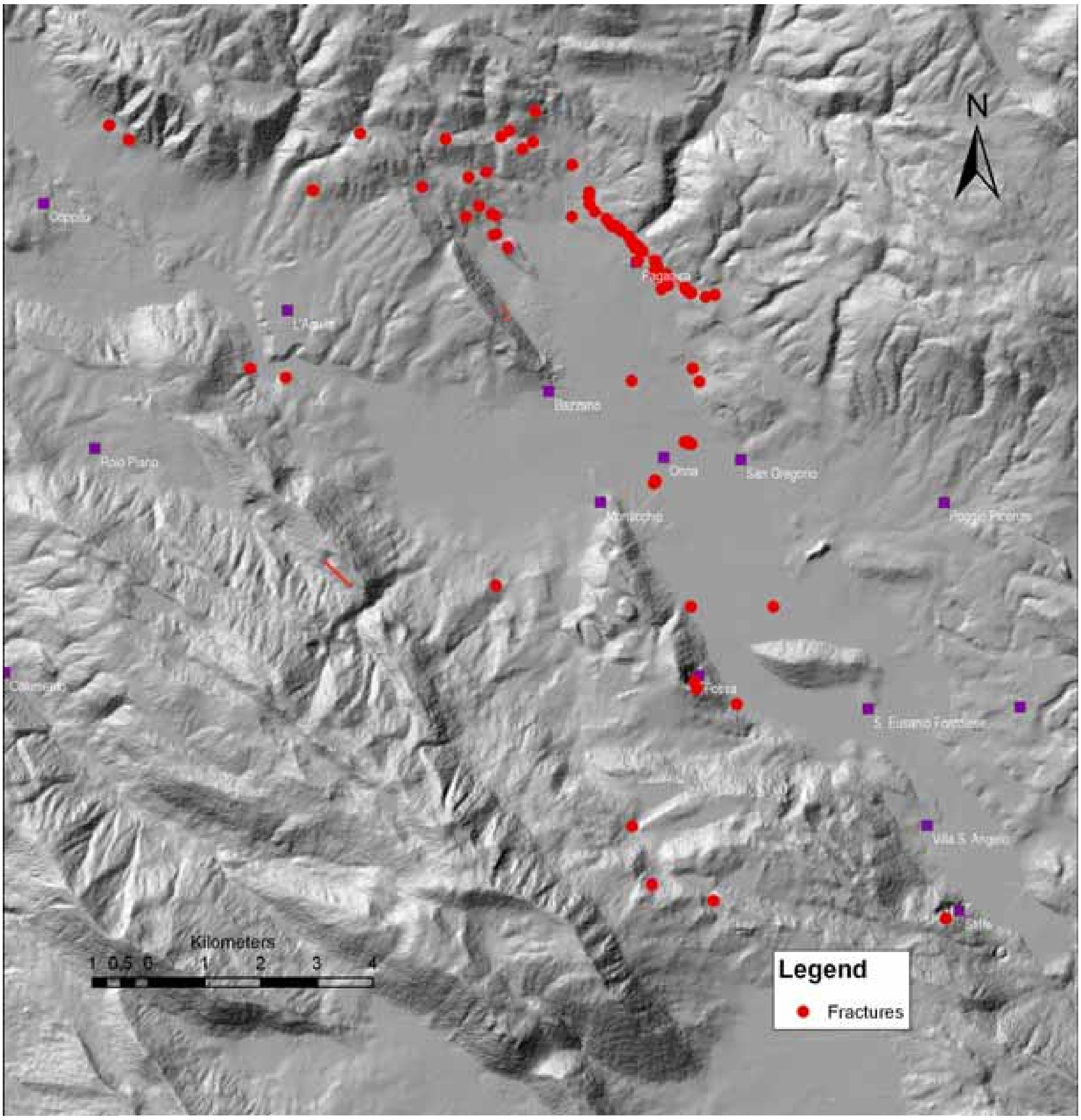
Fig. 33 – A huge block (about 7 cubic meters) fallen from the NE slope N of Mt. Bazzano

*Fig. 34 – Above: Gravitational movement affecting the SS80 Road, km. 27,4.
Below: A small landslide in artificial material along the Highway A24, between L'Aquila Est and Assergi*

Fig. 35 – Gravitational movement near Collebrincioni

Fig. 36 – Ground failures along the shorelines of Lake Sinizzo banks

Fractures



Fractures

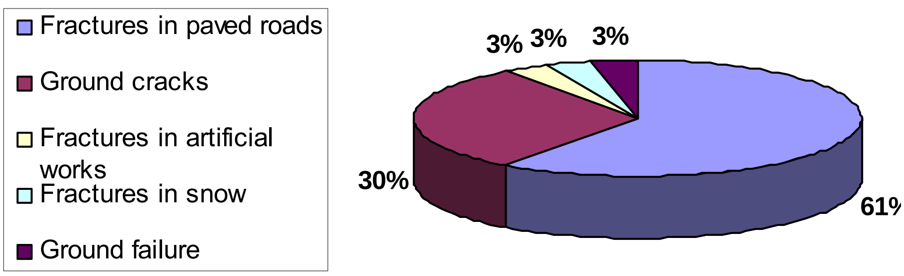


Fig. 37 – Distribution of fractures by type

Besides the fractures previously described as primary effects, many fractures have been induced by the shaking in the ground as well as in paved roads and in artificial works (Fig. 37). Two bridges on the Aterno River (near Onna, Fig. 38 and near Fossa, Fig. 39) collapsed by the progressive ground failures of the embankments.
For some of them a significant temporal evolution was monitored.

Fig. 38 – Onna: fractures in artificial material and in paved road near a bridge on the Aterno River.

Fig. 39 – Fossa: fractures in paved road near a bridge on the Aterno River.

Ground settlements

Modest evidence of liquefaction (flat sand volcanoes less than one meter in diameter) were found in a quarry at the north-eastern border of the Bazzano industrial area (Fig. 40).
Another remarkable liquefaction feature was found in Vittorito (near Sulmona), hence relatively far from the epicenter, by the geologists of the Abruzzo Region River Basin Authority (Fig. 41).

Fig. 40 – Liquefaction in artificial material in the industrial area of Bazzano

Fig. 41 – Mud/sand volcano near Vittorito (courtesy by G. Pipponzi, AdB Abruzzo),

Hydrological anomalies

At Tempera were recorded temporary effects of turbidity, and significant changes of water discharge (Fig. 42). Springs disappeared or shifted for some hundreds of meters. A shallow well ran dry.

Fig. 42 – An increase in water discharge was recorded in local springs at Tempera

5. Preliminary ESI intensity assessment

The ESI 2007 intensity scale (Michetti et al., 2007; http://www.apat.gov.it/site/en-GB/Projects/INQUA_Scale/default.html) is a seismic intensity scale based only on earthquake environmental effects, recently developed in the frame of INQUA (International Union for Quaternary Research) initiatives. The use of this scale is recommended especially when only environmental effects are diagnostic, which is the case when effects on humans and on manmade structures are absent or too scarce, or suffer saturation (i.e., for intensity X to XII). Nevertheless, it can be applied starting already from intensity VII, paralleling the traditional Intensity scales, when some environmental effects start to become diagnostic.

The ESI epicentral intensity assessment is based on the amount of surface faulting and on the extent of total area affected by secondary effects.

Considering the maximum displacement of the ruptures along the Paganica fault in the order of 7-8 cm and the total rupture length (beyond the existing uncertainties in between 2,6 km considering only the rupture in Paganica; up to 6 km considering the spot evidence to NW and to SE) it is possible to estimate a preliminary ESI epicentral intensity = IX.

A similar result is obtained on the basis of the distribution of the mapped secondary effects (total area is equal to about 1000 km^2).

A more detailed scenario at local scale, including the evaluations of ESI local intensities and a comparison with the MCS epicentral and local intensities will be done in the next future on the basis of a complete database of environmental effects mapped by the ISPRA team and complemented with information provided by other field surveyors from other institutions.

6. Conclusions

The L'Aquila earthquake has produced a widespread set of geological effects on the natural environment.

Clear evidence of surface faulting was found along the Paganica fault, which is considered the seismogenic fault of the earthquake. The total end-to-end rupture length is still an open debate, ranging from about 2,6 km (only the Paganica fault) up to 6-7 km, considering the discontinuous aligned ruptures toward northwest (from Tempera to Collebrincioni) and toward southeast (until San Gregorio). The maximum surface displacement was in the order of 7-8 cm.

It is noteworthy that the Paganica fault was already mapped in the Sheet L'Aquila of the CARG project, the official geological map of the Italian territory (scale 1:50,000) printed by the ISPRA Italian Geological Survey. This tectonic line was also recorded in the ITHACA database, the inventory of Italian capable faults, implemented by the ISPRA Italian Geological Survey on the basis of available paleoseismological and seismotectonic studies.

Other potential reactivations along mapped capable faults (Pettino, Campo Imperatore, Bazzano and Roio faults) have been observed, but their characteristics are such that they can hardly represent the surface expression of seismogenic faulting. They could be anyhow tectonic ruptures along sympathetic and/or antithetic faults.

Secondary effects have been mapped over an area of about 1000 km^2, mostly gravitational movements and ground fissures.

Regarding slope movements, rock falls in calcareous slopes and artificial cuts have been the most common type of effect. Sliding phenomena have also occurred, threatening in some cases the viability of important roads. Numerous ground cracks, especially in loose unconsolidated sediments, and fractures in paved roads have been surveyed, mostly induced by shaking.

The scenario of environmental effects includes also some minor liquefactions, hydrological anomalies and some local peculiar effects (e.g., the ground failures along the shores of the Lake Sinizzo).

The general picture of geological effects induced on the natural environment is typical for M~ 6 earthquakes. Preliminary assessments with the ESI intensity scale indicate that the epicentral intensity was equal to IX. This assessment will allow a more objective comparison, in terms of scenario of geological effects, with historical earthquakes occurred in the same area (e.g. 1703 earthquake).

The post seismic evolution of these effects, especially the ruptures along the Paganica fault, is still an open debate. In fact, it was noted a significant increase in offsets and width of some fractures. The ruptures have been monitored with high precision instruments (e.g. LIDAR) in order to understand the phenomenon in the frame of an international collaboration among several academic and research institutes, which includes the ISPRA Italian Geological Survey, the University of Insubria, the National Research Council of Italy, the Geological Survey of Trento Province, the Birkbeck/UCL – University College of London, the University of Durham and the Geological Survey of Israel.

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