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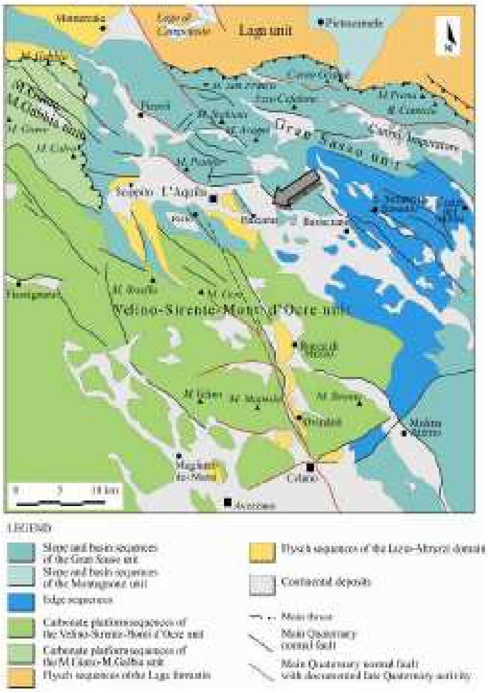

Fig. 2: Structural sketch of the L'Aquila region (from Blumetti et al., 2002). The yellow arrow shows the Paganica fault)

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In the period April 6– May 7, 2009, a total amount of 184 effects were mapped over an area of at least 1000 km^2. Their location is reported in Fig. 3.

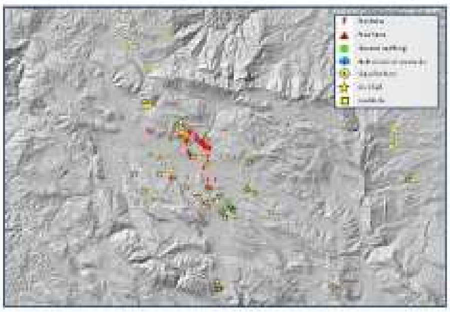

Fig. 3: Map of the geological effects accompanying the April 6, 2009, shock

Primary effects
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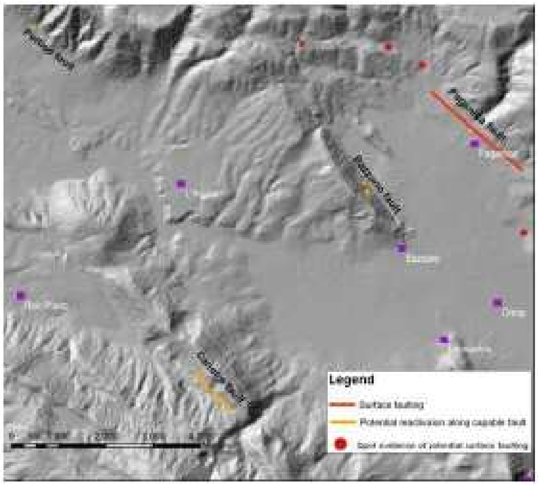

Fig. 4: Fault reactivation at Paganica and evidence of potential reactivation along other faults

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

Fig. 5: The Paganica ruptures were traced in the ground, across buildings and concrete roads, more or less continuously, for at least 2.6 km with offsets up to 7-8 cm, which locally continued to increase in the following weeks

The coseismic reactivation of the Paganica fault caused the rupture of the Gran Sasso aqueduct. The very high pressure of the water flowing from the damaged pipeline

EARTHQUAKE GROUND EFFECTS DURING MODERATE EVENTS: THE L'AQUILA 2009 EVENT CASE HISTORY

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Abstract: *On April 6th, 2009, a M_w 6.3 earthquake rocked the town of L'Aquila (Central Italy) and surroundings, inducing a noteworthy number of effects on the environment. Earthquakes with M_w between 6 and 6.5 are of relevant interest in the Mediterranean Region because of their frequency and their consequences in this densely populated area. The L'Aquila event is representative of the geological effects to be expected: ca. 200 effects on the environment have been recognized, allowing us to estimate an epicentral Intensity IX, by applying the ESI 2007 scale. The post seismic evolution of some ground fractures is under monitoring, in particular along the reactivated Paganica fault.*

Key words: *Earthquake Environmental Effects, moderate earthquakes, seismic hazard*

INTRODUCTION

The growing threat posed by geological effects of earthquakes to ever-expanding human settlements and infrastructures has been made more and more evident by the large events that have rocked various regions of the earth in the last years (Turkey 1999, Taiwan 1999, Indonesia 2004, Kashmir 2005, Sichuan 2008). Concern is therefore eventually growing for those urban areas where a rapid economic growth has often lead to neglect even in the recent past the historical and paleoseismic evidence. However, far from negligible hazard can be also posed by environmental effects following moderate earthquakes, as proven by several examples, among which the April 6, 2009, Mw 6.3 L'Aquila event is the most recent one. Moderate events in the range of Mw 6.0 to 6.5 are of special importance in the Mediterranean Region, since A) they are relatively frequent in most of the Mediterranean countries and B) the damage expected from similar events is relatively large, due to the local historical and cultural setting, and increasing vulnerability of the anthropic environment. The relevant geological effects and strong societal impact from moderate seismic events has been also recently illustrated by the July 16, 2007, Mw 6.6, Kashiwazaki – Kariwa earthquake in Japan, that damaged the largest Nuclear Power Plant site in the world. The 2009 L'Aquila earthquake is used here to illustrate the type and size of geological effects to be expected, strongly dependent on local geology and morphology, and their impact on human structures.

SEISMICITY DATA ON THE APRIL 6 2009 L'AQUILA EARTHQUAKE

After several months of anomalous seismic activity in the Abruzzo region of Central Italy, on April 6th, 2009, at 01:32 GMT the Central Apennines were rocked by a moderate-size earthquake (Ml 5.9, Mw 6.2, depth around 9 km). The epicentre was located near the historical town of L'Aquila (Fig. 1), which was severely damaged together with many villages in the surroundings. The death toll was of 307 casualties. Two M > 5 shocks followed on April 7th (Ml=5.3; epicentre about 10 km SE of L'Aquila) and on April 9th (Ml = 5.1; epicentre near Campotosto, about 15 km NW of L'Aquila). The seismic sequence, still far from its end in July 2009, being M > 4 events still present (Fig. 1), has affected to date an about 40 km long zone, elongated in the NW-SE direction. The focal mechanisms clearly define a NW-SE trending normal faulting mechanism, in good agreement with the tectonic setting of the region (Fig. 2), characterized by a "Basin and Range" landscape due to a segmented belt of capable normal faults (e.g., Blumetti and Guerrieri, 2007).

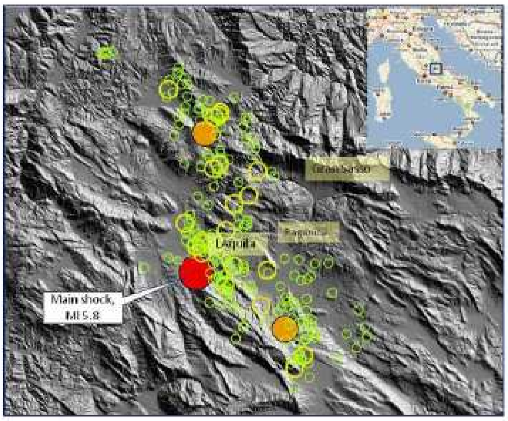

Fig. 1: The Basin and Range morphology of the epicentarl region and the 2009 seismic sequence: orange circles: main aftershocks = Ml>5, yellow circles = Ml>4, green circles = Ml>3. The Quaternary intermountain basins, among which that of L'Aquila (Middle Aterno Valley), and fault-generated mountain fronts, including the highest peak of the Apennines (Gran Sasso, 2912 m), are quite evident

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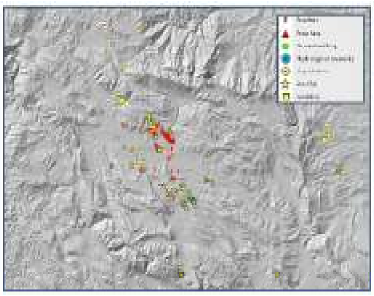

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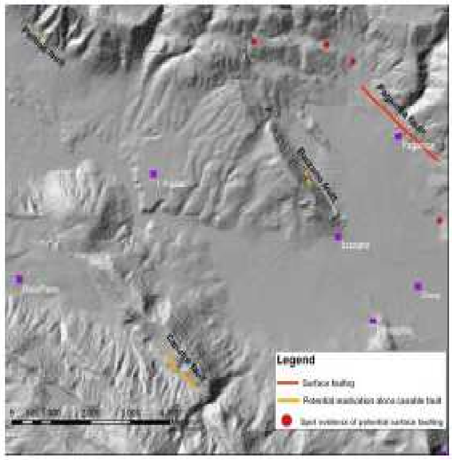

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Fig. 5: The Paganica ruptures were traced in the ground, across buildings and concrete roads, more or less continuously, for at least 2.6 km with offsets up to 7-8 cm, which locally continued to increase in the following weeks

The coseismic reactivation of the Paganica fault caused the rupture of the Gran Sasso aqueduct. The very high pressure of the water flowing from the damaged pipeline excavated a deep trench, thus providing extraordinary exposures of faulted sediments and unquivocal evidence of previous, larger, coseismic surface faulting events.

Fig. 6: The site where the aqueduct was broken by coseismic faulting

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) could be interpreted as the possible NW extension of the Paganica ruptures. Furthermore, coseismic fractures opened in cultivated fields N of Onna and, with a length of some hundred metres and direction N140-N160. 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 all the active faults known in the area (Fig. 4). Along the Pettino fault only local ground ruptures, some tens of meters in length with offsets up to 10 cm were found, without evidence 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. 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. 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.

Secondary effects
Secondary effects (basically gravitational movements and fractures) induced by the ground shaking had a widespread distribution.

Gravity movements
Numerous rock falls (78% of gravitational movements, Fig. 7) occurred especially from calcareous slopes. Among them, one of the most impressive falls took place above the village of Fossa, which was directly damaged by huge boulders (Fig. 8). Residual risk of rock falls caused the temporary closure of some important roads.

Other important rock falls were seen within the Gran Sasso mountain range (rock avalanches), along the NE slope of Mt. Bazzano and on the north-facing cliffs of Stiffe (several cubic meters in size).

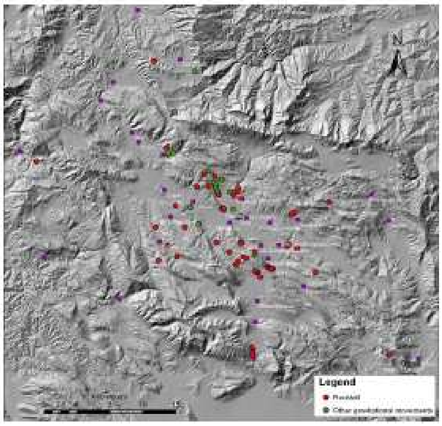

Fig. 7: Distribution of slope movements by type

Other types of slope movements, generally affecting artificial fills, occurred along several roads, including the highway A24. Around the Lake Sinizzo, near San Demetrio ne' Vestini, impressive ground failures along the whole shoreline were observed (Fig. 9). In the other sinkholes of the area (generally empty of water) no remarkable effects were found.

Fig. 8: Fossa rockfall: huge boulders on a paved road

Fractures
Besides the fractures previously described as primary effects, many fractures were induced by shaking in the bare ground as well as in paved roads and in artificial works. Two bridges on the Aterno River (near Onna, and near Fossa) were severely damaged by the failures of the supporting embankments. Also some of these fractures showed a significant temporal evolution (widening).

Liquefaction
The only remarkable liquefaction feature was found by the geologists of the Abruzzo River Basin Authority at Vittorito (near Sulmona), hence relatively far from the epicenter (Fig. 10).

Fig. 9: Ground failures along the shore of lake Sinizzo

Hydrological anomalies

At Tempera (W of Paganica) the springs of Capo Vera experienced temporary effects of turbidity, and significant changes of water discharge. Some springs disappeared or shifted for some hundreds of meters. A shallow well ran dry.

Fig. 10: Mud/sand volcano near Vittorito (courtesy by G. Pipponzi, AdB Abruzzo)

CONCLUSIONS

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

Clear evidence of surface faulting was found along the Paganica fault, which is regarded as the causative structure of this earthquake. The maximum surface displacement was ca. 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; and 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. Nevertheless, it was considered a secondary element when compared to several nearby more prominent capable faults. The same fault also exhibits evidence of larger surface faulting events in the past. This pinpoints the need to pay the due attention also to "minor" structures and also leaves open the question about the real seismic potential of the area.

Other potential reactivations along mapped capable faults (Pettino, Campo Imperatore, Bazzano and Fossa faults) were observed but they can hardly represent the surface expression of seismogenic faulting. Anyway, they could still represent tectonic ruptures along sympathetic and/or antithetic faults.

Secondary effects were mapped over an area of ca. 1000 km², mostly gravity movements and ground fissures. Regarding slope movements, rock falls in calcareous slopes and artificial cuts were the most common type of effect. Sliding phenomena also occurred, threatening in some cases the road infrastructures. Numerous ground cracks, especially in loose unconsolidated sediments, and fractures in paved roads were 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 environmental effects is typical for earthquakes of magnitude around 6. Preliminary assessments with the ESI 2007 scale indicate that the epicentral intensity was equal to IX. This provides an objective calibration, in terms of scenario of geological effects, for a better intensity assessment of historical earthquakes occurred in the same area (e.g., the 1703 earthquake sequence). The post seismic evolution of these effects, especially the ruptures along the Paganica fault, is still going on. A significant increase in offsets and width of some fractures was noted in the weeks after the mainshock. A monitoring is being carried out with high precision instruments (e.g. LIDAR) in order to understand the phenomenon in the frame of a 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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