# THE 2009 L'AQUILA EARTHQUAKE: FINDINGS AND IMPLICATIONS

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## Event Science Report 02

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## Executive Summary

The 6th of April 2009 *Mw*=6.3 earthquake in L' Aquila, central Italy, provides a broad range of useful outcomes and points for consideration in relation to all disciplines involved in seismic hazard assessment, planning and recovery. The event provides an important case-study, most notably because moderate magnitude earthquakes in areas of high population density, such as this, present a high risk in extensional settings (including Europe at large), where their occurrence is relatively common. The L'Aquila event resulted in the highest earthquake death toll in the EU since the 1980 Irpinia (Italy) quake and the highest economic loss due to seismic activity since the 1999 Athens earthquake.

## 1. Introduction

On Monday the 6th of April 2009 a strong earthquake struck the city of L' Aquila in central Italy and the surrounding villages, resulting in extensive damage, taking 300 lives and injuring more than a thousand people. The size of the earthquake was determined at *Mw*=6.2 ($M_L$=5.8) (INGV) or *Mw*=6.3 (USGS), with a focal depth of 9 km. A normal faulting mechanism was determined, striking at 147 and dipping at approximately 43 degrees. InSAR (Interferometric Synthetic Aperture Radar), body wave seismology and GPS data determined a SW ~50$^o$ dipping normal fault with a maximum ~0.6-0.9m slip (Walters et al. 2009, Atzori et al. 2009, Anzidei et al. 2009). The epicentre was located a few km WSW of the city of L' Aquila, which, together with the surrounding villages, hosts a population of about 100.000 (**Figures 1 and 2**).

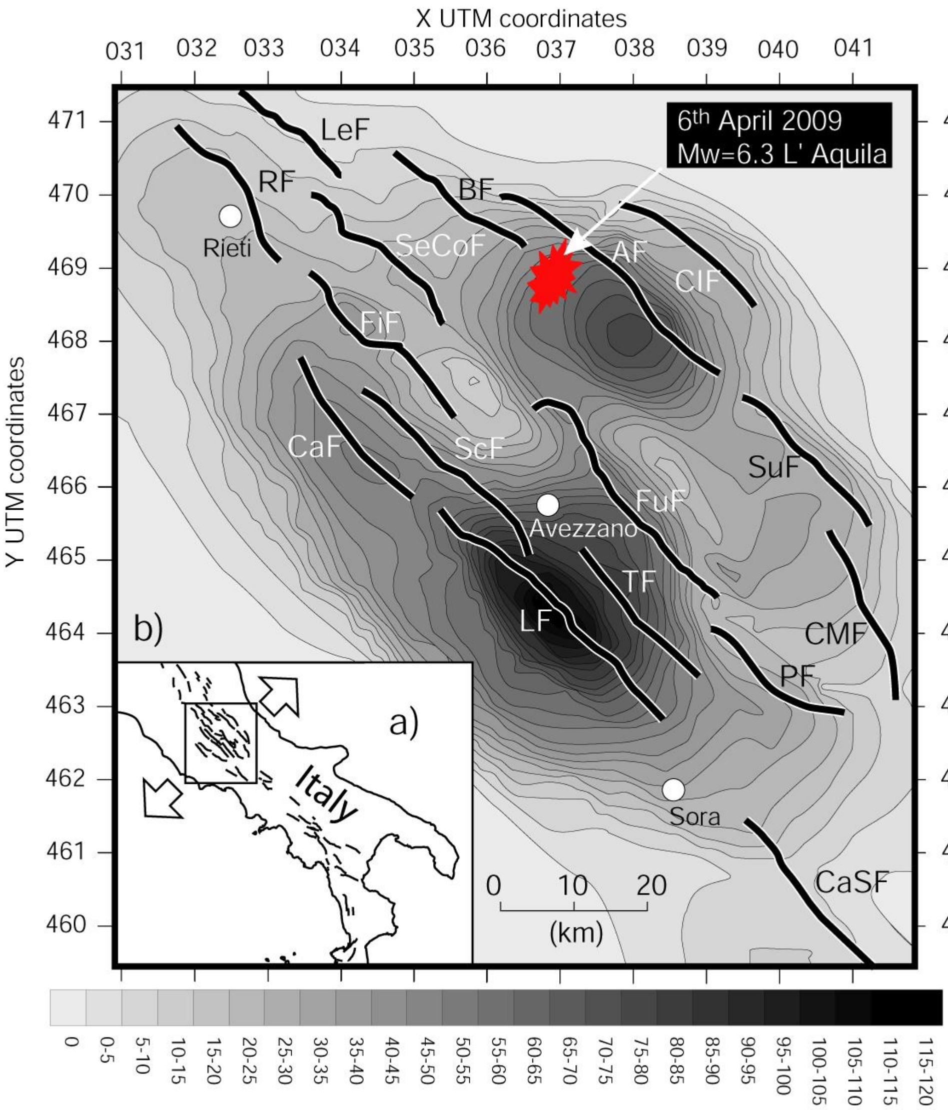



**Figure 1. a) Map of Italy showing the active faults and the NE-SW extension, b) Map showing how many times each locality receives enough energy to shake at intensities ≥ IX over the last 18.000 yrs (Roberts et al. 2004). The epicentre is located in an area that is characterized by a high frequency and lies in the hangingwall of three major faults (the L' Aquila (AF), the Barete (BF) and the Campo Imperatore (CIF) faults).**

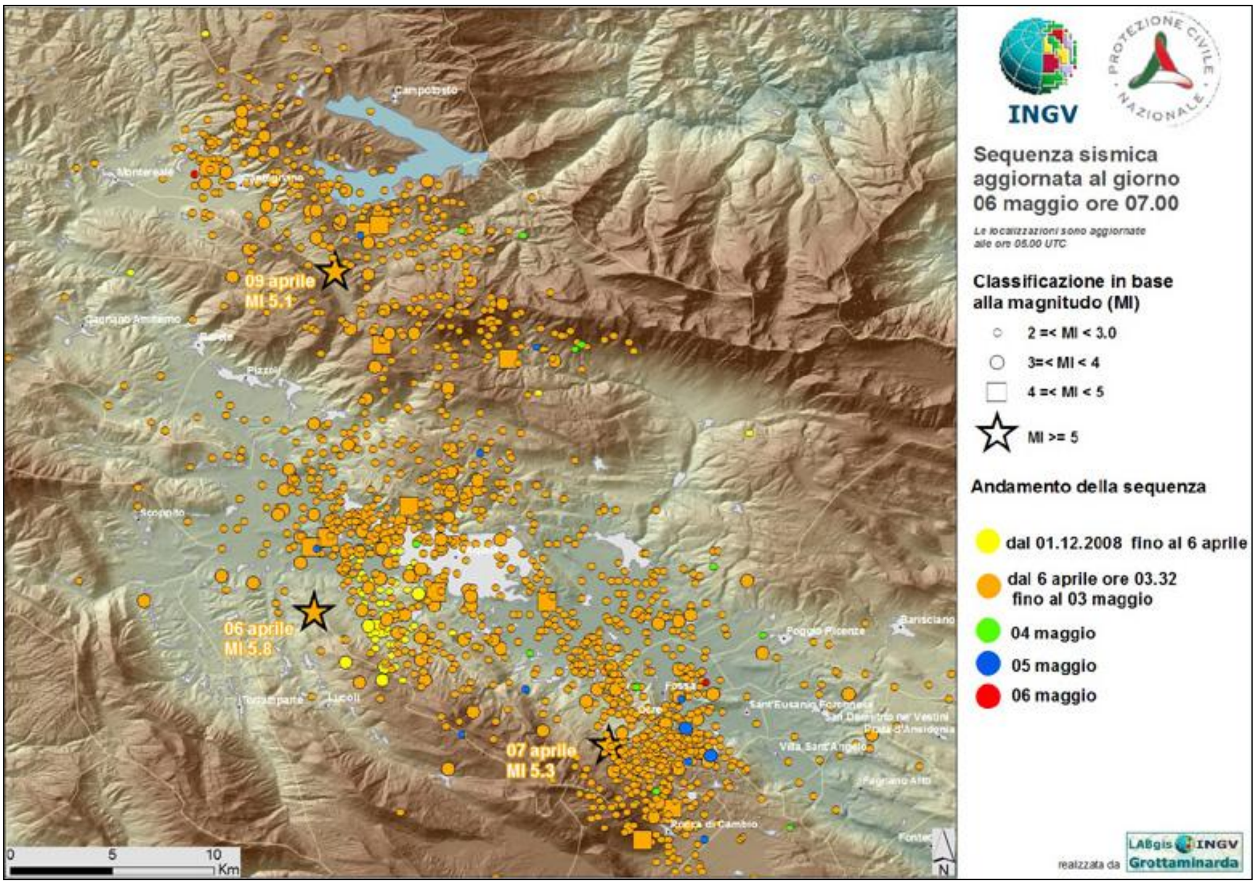



**Figure 2. View of the aftershock activity (source INGV website).**

Four hours before the mainshock, a $M_L$=3.9 foreshock occurred, spurring part of the population to evacuate buildings (Chiarabba *et al*. 2009). After the mainshock two other events above Magnitude 5 occurred, to the southeast and north of the mainshock. Most notably, about 40 hours after the mainshock, a second event of Mw=5.6 ($M_L$=5.3) struck the Valle d'Aterno, about 4 km SW of the village of Fossa, while on April 9$^{th}$ a third event of Mw=5.4 ($M_L$=5.1) occurred near Campotosto about 16 km north of L' Aquila. Initially, the aftershock activity occurred close to L'Aquila and towards the south-east of the town, whereas a couple of days later it migrated towards the northeast at Barrete and Campotosto (Chiarabba *et al*. 2009; **Figure 2**). The seismicity covers a NW-SE trending rectangular area, approximately 40 km long and 10-12 km wide (Chiarabba et al. 2009, Pondrelli et al. 2009). The earthquake occurred on one of the NW-SE trending normal faults that forms part of the 800km long segmented normal fault system (**Figure 1**) that accommodates crustal extension in the Apennine mountain range (e.g. Anderson & Jackson 1987; Roberts *et al*. 2002). In the Central Apennines, faults are characterized by pure dip-slip movements with a mean fault-slip direction of 222° ± 4° (Roberts & Michetti 2004). These faults tend to generate strong events from M=5.5 up to M=7.0 and depending on the magnitude and the earthquake depth can result in minor to severe damage, and occasionally destruction (Michetti *et al*. 1996; Galadini & Galli 2000, Roberts *et al*. 2004). It is noteworthy that in 1915, just 40 km south of the 2009 L' Aquila earthquake epicentre, Italy experienced its second most destructive earthquake. Here, in the Fucino Basin, a M=6.9 to 7.0 event caused widespread devastation, with macroseismic intensities of X and XI leading to 33,000 deaths (Oddone 1915).

## 2. Historical record of seismicity and seismic hazard

The area of L'Aquila has experienced several large historical earthquakes, so that the latest event is not unexpected. Based on the historical record the town has suffered shaking at intensity IX or higher on at least three occasions in the past; in 1349 A.D., 1461 A.D. and 1703 A.D. (INGVDBM04 2004, Tertulliani *et al.* 2009). The 1703 event was part of a sequence of earthquakes that struck the area, although the damage sustained at L' Aquila during this event is not attributed to rupture of the L'Aquila Fault, but most probably to movement on the nearby Barete Fault that lies to the west (**Figure 1**). The Barete fault (also known as the Arischia Fault or Mt Marrine Fault) was activated on February 2$^{nd}$, resulting in the third and final earthquake of the 1703 sequence, causing surface ruptures and liquefaction phenomena near the village of Pizzoli (Blummeti, 1995). In light of the historical earthquake record, the L' Aquila area has been identified as having relatively high seismic hazard (Slejko *et al*. 1998; GNDT-SSN, 2001; Rebez *et al*. 2001), and allocated to seismic zone 2 (**Figure 3**). In accordance with the updated (2003) building codes, this requires that structures are designed to cope with 0.25g of peak horizontal ground acceleration.

Using a Poissonian approach, Romeo and Pugliese (2000) estimated a high probability for a peak ground acceleration of 0.25g in a 50 year period and estimated a very high time-dependent probability of 23.6 percent in the next 30 years of a *Ms*>6.3 in L'Aquila. Boncio *et al*. (2004) determined a maximum expected magnitude between 6.1 and 6.4 for the L'Aquilano Fault that bounds the Aterno basin. Moreover, based on time dependent probabilities and a BPT distribution (the Brownian Passage Time Model of earthquake recurrence) estimated for the year 2004, Pace *et al*. (2006) determined about 10 percent probability in the next 50 years of rupturing of the Paganica fault segment adjacent to L'Aquila and estimated a high probability of a peak acceleration exceeding 0.30g in a 50 year period. Finally, seismic hazard maps based solely on geological fault slip-rate data (and thus independent of the historical record) also show that the hanging-wall centre of the L'Aquila Fault is characterised by high shaking frequency for intensities ≥IX (**Figure 1b**) up to 80 times over the last 18.000 yrs, implying that the area suffers a destructive earthquake approximately every 250 ± 50 years (Roberts *et al*. 2004). This is attributed to the combined effects of three closely-spaced major active faults (the L'Aquila, Barete and Campo Imperatore faults), movement on any one of which is capable of causing extensive damage in L'Aquila. The Campo Imperatore and L'Aquila faults both exhibit high throw-rates exceeding 1 mm/yr (Giraudi & Frezzoti 1995; Galli *et al*. 2002; Roberts and Michetti 2004; Papanikolaou *et al*. 2005).

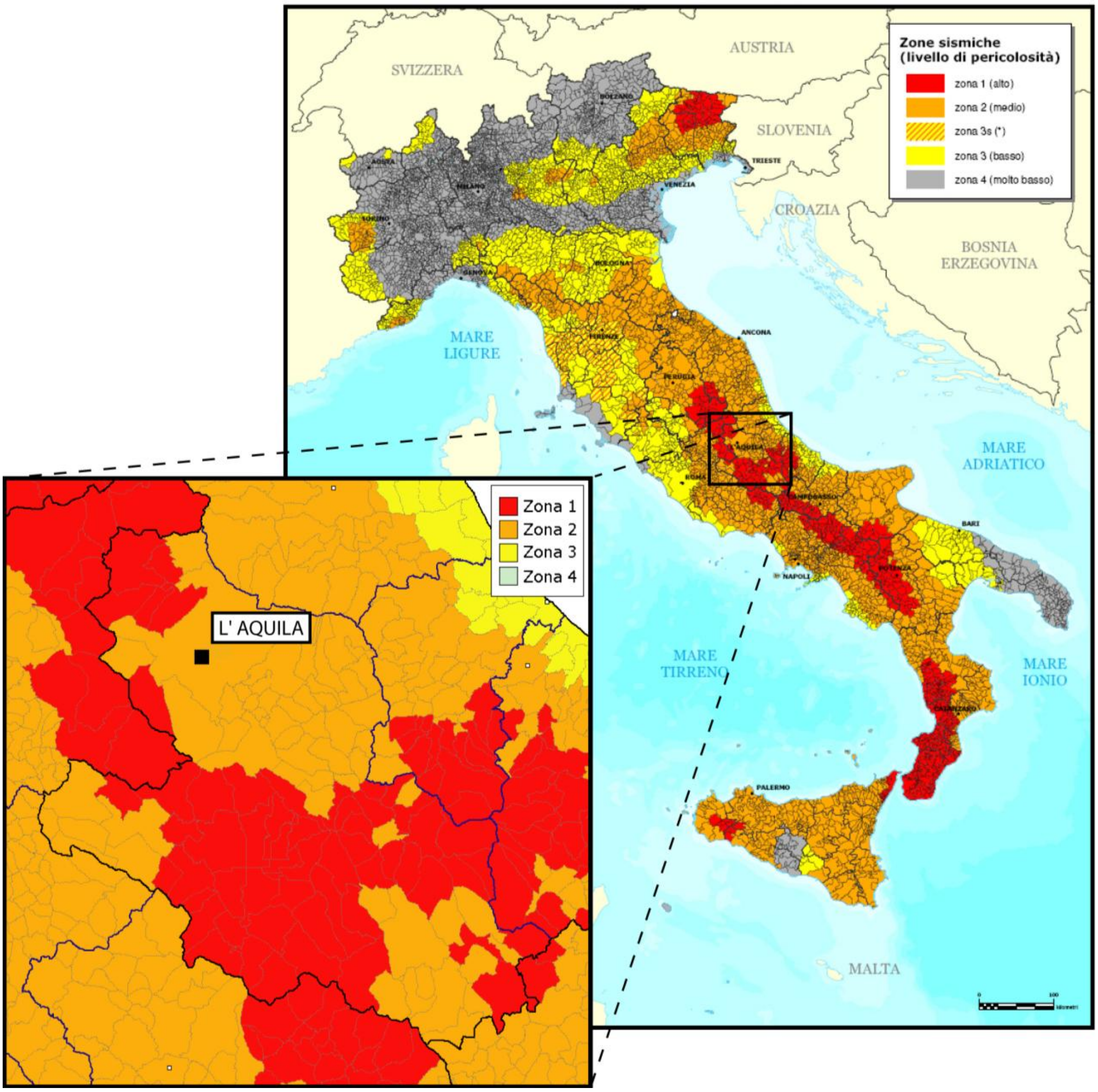



**Figure 3. Seismic hazard map of the Italian territory (Protezione Civile Nazionale, 2006). The area of L' Aquila belongs to seismic zone 2 and requires a design level value of 0.25g of peak horizontal ground acceleration.**

## 3. Active faults

The town of L'Aquila is not only surrounded by three major active normal faults, but is also located on their hanging-wall (**Figure 1b**). The hanging-wall area of a normal fault experiences higher deformation and more violent shaking, which may explain the overall high hazard at L'Aquila and in the Aterno valley. Each major fault comprises several overlapping segments, closely spaced parallel segments and antithetic structures, which, in most cases, are linked at depth. In the case of the L'Aquila Fault, this creates a complex fault structure that has led to different geological interpretations. During 2009, the greatest damage was recorded in the

Aterno valley (**Figure 4**), which is bounded to the north by the L'Aquila Fault; a 37 km long structure that strikes NW-SE and downthrows to the southwest (Roberts & Michetti 2004).


**Figure 4. View of the Aterno Valley near the macroseismic epicentre and the Campo Imperatore.**

The southern tip of the fault is located near the village of Civitaretenga (2 km east of Caporciano) and its northern tip is situated towards the western end of Mt. San Franco (**Figure 5**).

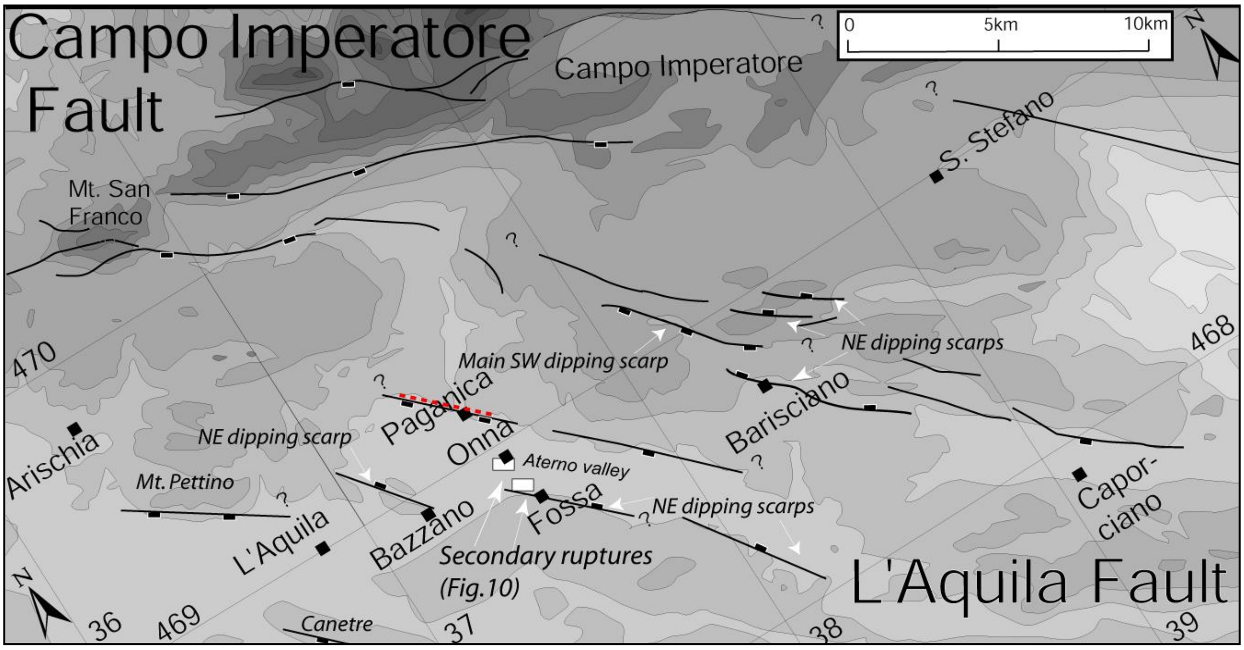



**Figure 5. Topographic map (numbers are in UTM coordinates) showing the fault segments (modified from Michetti et al. (2000), Roberts and Michetti (2004), Papanikolaou et al. (2005). Red dashed line shows the primary ground surface ruptures in Paganica.**

This fault has a rather complex structure, since it comprises several overlapping segments some of which are antithetic to the main SW dipping (**Figure 6a**) fault plane (Papanikolaou *et al*. 2005).

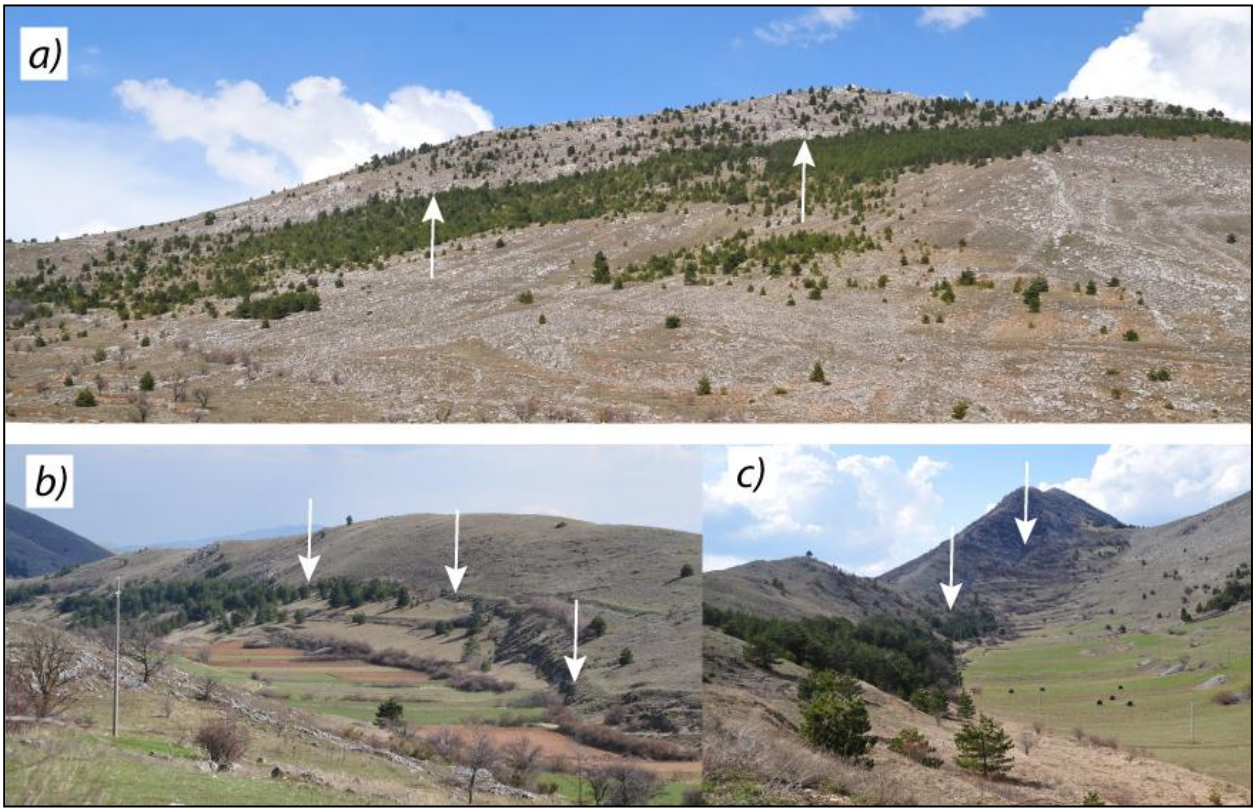



**Figure 6. View of the: a) main SW dipping and b), c) antithetic NE dipping scarps of the L' Aquila fault north of Barisciano village. These scarps have not been activated.**

These antithetic planes are nicely observed north of the village of Barisciano (**Figure 6b and 6c**), have fresh looking fault planes and are probably kinematically linked to the NE-dipping Bazzano–Fossa Fault segments in the southern part of the valley (**Figure 7**). The Mt Pettino Fault, the Paganica segment (or Aquilano Fault of Boncio *et al*. 2004) and the antithetic Bazzano-Fossa Fault crop out on either side of the valley (Michetti *et al*. 2000) and form part of the same system. The strain in the area is accommodated on multiple, closely-spaced synthetic and antithetic overlapping fault segments. Consequently, the fault zone is characterised by distributed displacement on several overlapping faults that break up the footwall and the hanging-wall into smaller blocks. The L' Aquila Fault has a reported throw-rate of 0.3-0.4 mm/yr (Galadini & Galli 2000) based on offset Quaternary terraces (Bertini & Bosi 1993) and up to 1.1mm/yr towards it's centre that decreases to 0.7mm/yr near Mt. Franco and 0.3mm/yr towards Caporciano, based on the throws of the postglacial scarps (Papanikolaou *et al*. 2005). The 2009 earthquake activated one of the segments of the L'Aquila Fault that bounds the northern part of the Aterno valley in Paganica (Michetti *et al*. 2009). Boncio *et al*. (2004) estimated a maximum expected earthquake magnitude of 6.1-6.4 for this segment in Paganica (named by them the Aquilano Fault), which is similar to the size of the 2009 mainshock. It is important to note here that other segments of the same fault system (such as the Mt. Franco, the Barisciano and the Caportiano segments), or other neighboring faults such as the Campo Imperatore and the Barete faults, are capable of producing significantly stronger events, as evidenced by their impressive postglacial fault scarps (**Figures 6 and 8**; Giraudi 1995; Papanikolaou *et al*. 2005). These faults can produce earthquakes of M≥6.5 involving extensive (15-20km) surface ruptures with maximum displacements exceeding a metre. Based upon trenching investigations, Galli *et al*. (2002) propose that the Campo Imperatore Fault, situated only 20km away from L'Aquila, can generate a Magnitude 7 earthquake. Finally, the 1703 earthquake that damaged L' Aquila (IX intensity), produced surface ruptures >10 km and a maximum displacement of 1m in the neighboring Barete Fault (Blummeti 1995).

**Figure 7. View of the surface ruptures on the antithetic northeast dipping Bazzano fault (courtesy E. Vittori).**

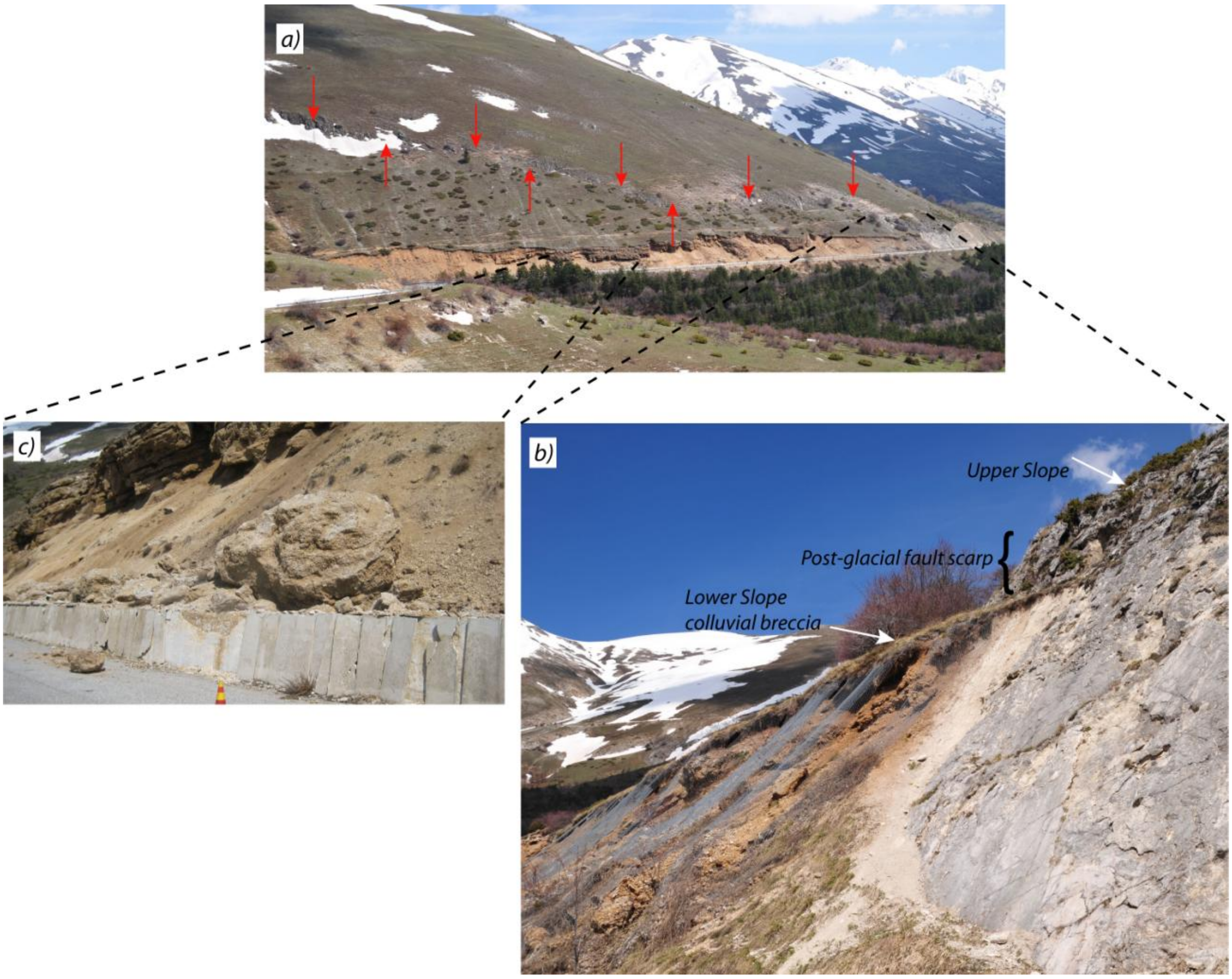



**Figure 8. View of the rockfalls and the postglacial scarp at Mt. Franco. This is an impressive post-glacial scarp, indicating that this fault can generate strong surface rupturing events whose displacement can exceed 1 metre. It has not been activated during the 6th of April 2009 event. a) Distant view of the postglacial scarp, b) Close up view of the postglacial scarp at the road section, showing the upper and the lower slopes. c) The rockfalls involved cemented glacial debris in the immediate hanging wall of the fault.**

# 4. Field observations and earthquake impacts

The broader, environmental effects of the L'Aquila earthquake involved primary and secondary surface ruptures, rockfalls, landslides and liquefaction phenomena across an area of almost 1,000km$^2$ (Blummeti *et al.* 2009). A large number of surface ruptures were recorded at several locations, both on pre-existing fault planes and within the Aterno Basin. These ruptures were all NW-SE trending, parallel to the activated fault plane, and have throws ranging from a few up to several centimetres. A number of reports describe surface ruptures that occurred on pre-existing fault planes, including the Paganica Fault and the Roio – Canetre Fault, on the NE dipping Bazzano Fault, where a 5-8cm white stripe at the base of the limestone fault scarps was observed (**Figures 7 and 9**), and locally on the Mt. Pettino segment and the Campo Imperatore

Fault (Blummeti *et al*. 2009; Falcucci *et al.* 2009; DST Working Group – Uni CH 2009; INGV-Emergeo Group 2009; Michetti *et al*. 2009). Researchers agree that the surface ruptures traced in Paganica were primary and form the surface expression of the activated fault. This conclusion is reached partly because the ruptures correlate well with the focal mechanism and the position of the epicentre, but mainly due to the DInSAR (Differential Interferometric Synthetic Aperture Radar) analysis (see following Section). Most notably, the analysis predicted fault surface ruptures coinciding with the ground surface ruptures observed in Paganica. Additionally, these ruptures broke a 0.7m diametre high pressure water pipeline in Paganica. Ruptures were discontinuous, but well aligned and could be traced up for at least 2.6 km with maximum displacements not exceeding 10cm (Michetti *et al*. 2009, **Figures 5 and 9**).

**Figure 9. View of the primary surface ruptures in Paganica (courtesy E. Vittori).**

Tens of secondary surface ruptures occurred widely across the Aterno Basin, reaching up to several tens of metres long (**Figures 5 and 10**); most recorded near the villages of Onna and Fossa. The village of Onna was the focus of maximum shaking intensity (IX - X MCS Mercalli-Cancani-Sieberg intensity). As a result, it suffered the greatest damage and recorded the highest death toll (losing 10 percent of its population). These secondary ruptures are several tens of metres long and up to 30cm wide and are all strictly NW-SE trending (150° ± 20°), parallel to the activated fault plane and the existing fault segments. They are mostly observed near the river as well as on artificial road embankments (**Figure 10**). Overall, these secondary ruptures appeared in artificial and natural structures that are prone to rupturing. Most were aligned transverse to the road network, producing cracks in paved roads several metres long and having offsets, both horizontal and vertical, of up to 6cm). This is important because such secondary ruptures are usually disregarded in seismic hazard assessment studies for planning and design purposes. Many Pleistocene palaeo-landslides of tectonic origin are reported for the L' Aquila Fault (Demangeot 1965; Bagnaia *et al*. 1992), no significant landslide activity was recorded, however, as a result of the 2009 earthquake. Rockfalls were widespread, but generally small scale (e.g. see **Figure 6c**). More extensive rockfalls were observed towards the southern boundary of the Fossa village, where steep limestone cliffs are a feature of the topography.

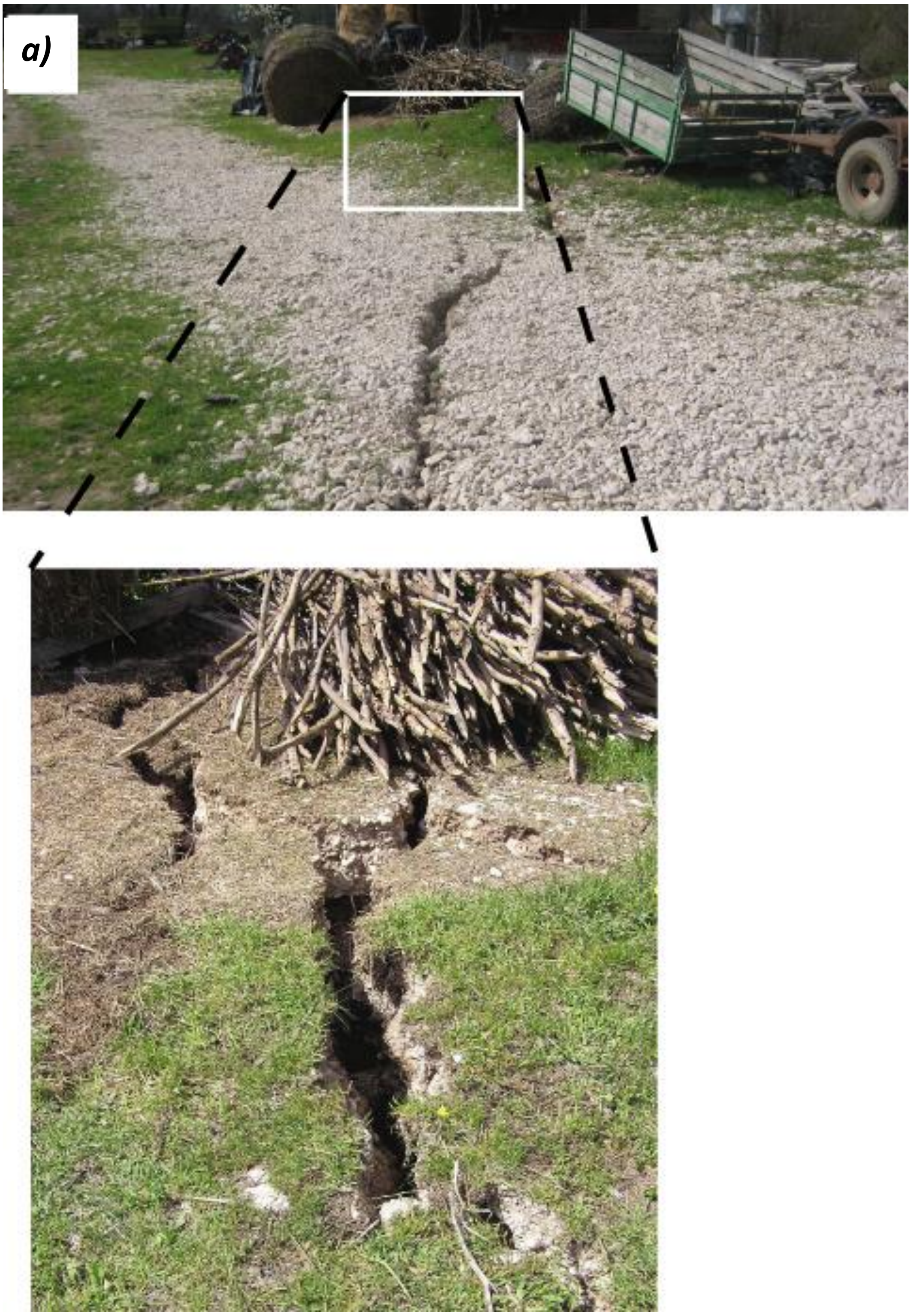
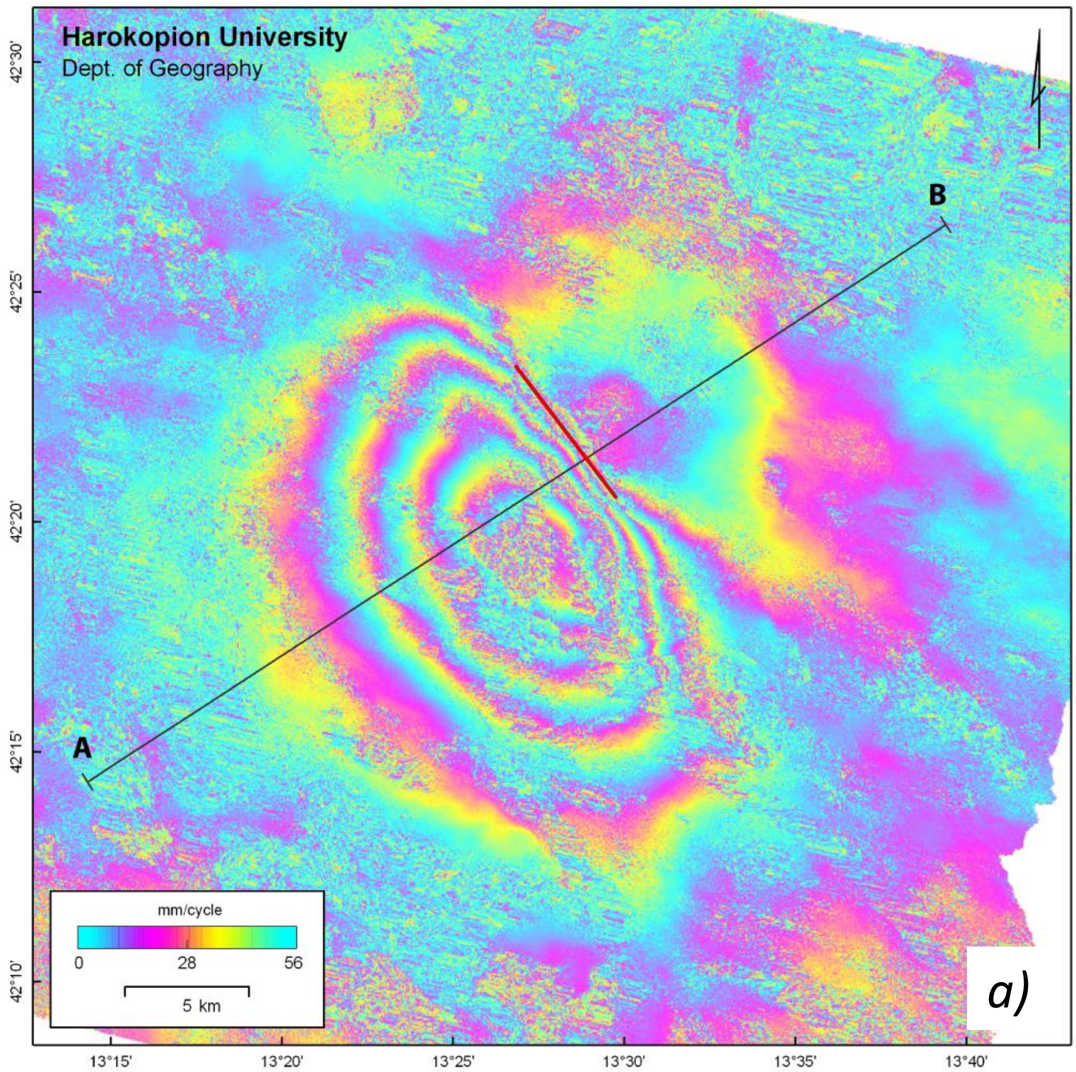



**Figure 10. View of the secondary ruptures near the village of Onna. All secondary ruptures are NW-SE (150$^{o}$ ± 20$^{o}$) trending parallel to the activated fault plane and the existing active faults and appear in artificial and natural structures that are prone to rupturing. a) Secondary ruptures several tens of metres long and up to 30cm wide, near the river embankments. b),c),d) transverse ruptures in paved roads that are several metres long and having offsets of several cm (up to 6cm) both horizontal and vertical. e) NW-SE trending ruptures in a nonpaved road that links the village of Onna with the village of Fossa. The cracks were so violent that they ruptured also the asphalt pebbles.**

## 5. DInSAR and surface deformation pattern

The Differential Radar Interferometry (DInSAR) technique has been used to detect surface displacements in the order of a few centimetres. The technique combines and merges two radar images acquired before and after the earthquake in order to trace the differences caused by the earthquake, providing a detailed view of the deformation pattern. **Figure 11a** shows the differential interferogram with well constrained fringes extending both on the foot-wall and the hanging-wall, covering the periods between April 2008 and April 2009. A cross section across the strike of the activated fault plane, shows the uplifted and subsided area, from which the fault trace can be easily traced with high precision (**Figure 11b**). The ground deformation pattern is asymmetrical since the deformed area is significantly expanded to the southeast. The deformed area is about 460 $km^2$ with a maximum length of 24km, trending NW-SE along the direction of the rupture plane, and a maximum width of 22km, trending NE-SW (**Figure 11c**).



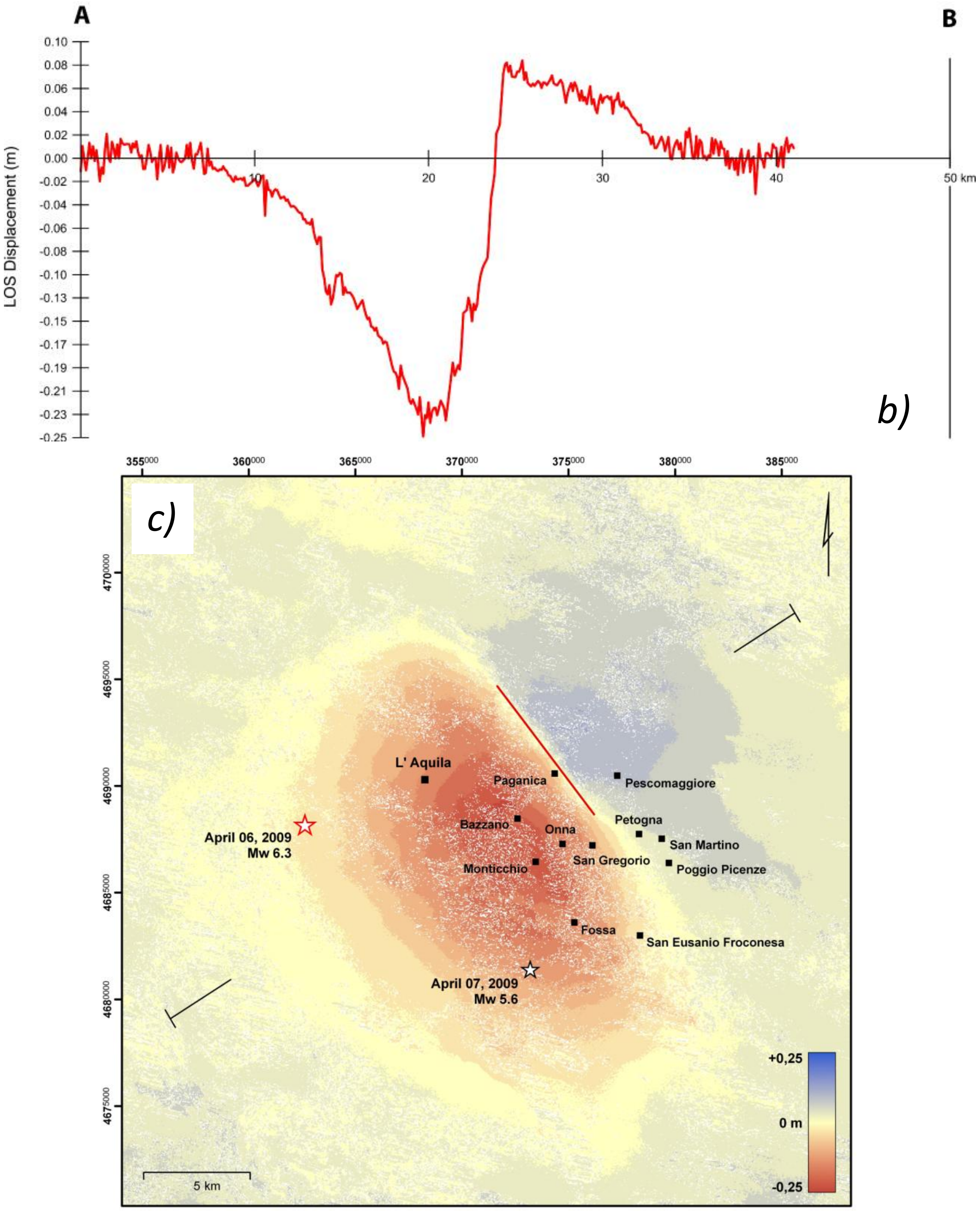



**Figure 11. a) Coseismic differential interferogram of the April 2009 L' Aquila earthquake sequence, covering the period from April 2008- April 2009. b) Cross section constructed across strike the activated fault plane on the interferogram, showing the uplifted and subsided area, from where the fault trace can be easily traced with high precision. c) Displacement field of the 6$^{th}$ and 7$^{th}$ of April 2009 L' Aquila earthquakes (Papanikolaou et al. 2010).**

This area is shorter in length, but much wider compared to the aftershock distribution. About 66 percent (305 km$^2$) of the deformed area has subsided, while the remaining 34 percent (155 km$^2$) has been uplifted (Papanikolaou *et al*. 2010). The maximum observed uplift was about 10 cm, recorded a couple of km northeast of the Paganica surface ruptures in the immediate footwall of the fault, while the maximum subsidence was 25 cm, and observed about 2 km southwest of the NE-dipping Bazzano Fault. Based on the interferogram, the approximately 7km long, DInSAR-predicted, fault surface ruptures coincide with localities where surface ruptures are observed in the field, confirming that the ruptures observed near Paganica are primary. This is an important outcome because this earthquake produced both primary and secondary ruptures, many of which occurred on pre-existing fault planes. Due to the moderate magnitude of the event, primary surface ruptures had small displacements that did not exceed 10cm, making it difficult to distinguish between primary and secondary ruptures. Consequently, the interferogram has proved invaluable in terms of providing a clear picture of the surficial deformation pattern and the ruptured fault geometry.

## 6. Macroseismic intensities, ground accelerations and damage pattern

According to the Italian Department of Civil Protection approximately 18.000 buildings were judged as unsafe for occupancy (Akinci *et al.* 2010), indicating that they needed either major repair or had to be demolished. The highest macroseismic intensities were recorded at the village of Onna (MCS intensity IX-X) located about 12km east of the earthquake epicentre. In contrast, the town of L'Aquila experienced intensity VIII-IX shaking (Quest, 2009). **Figure 12** shows the MCS intensity values that have been determined by the Quest team.

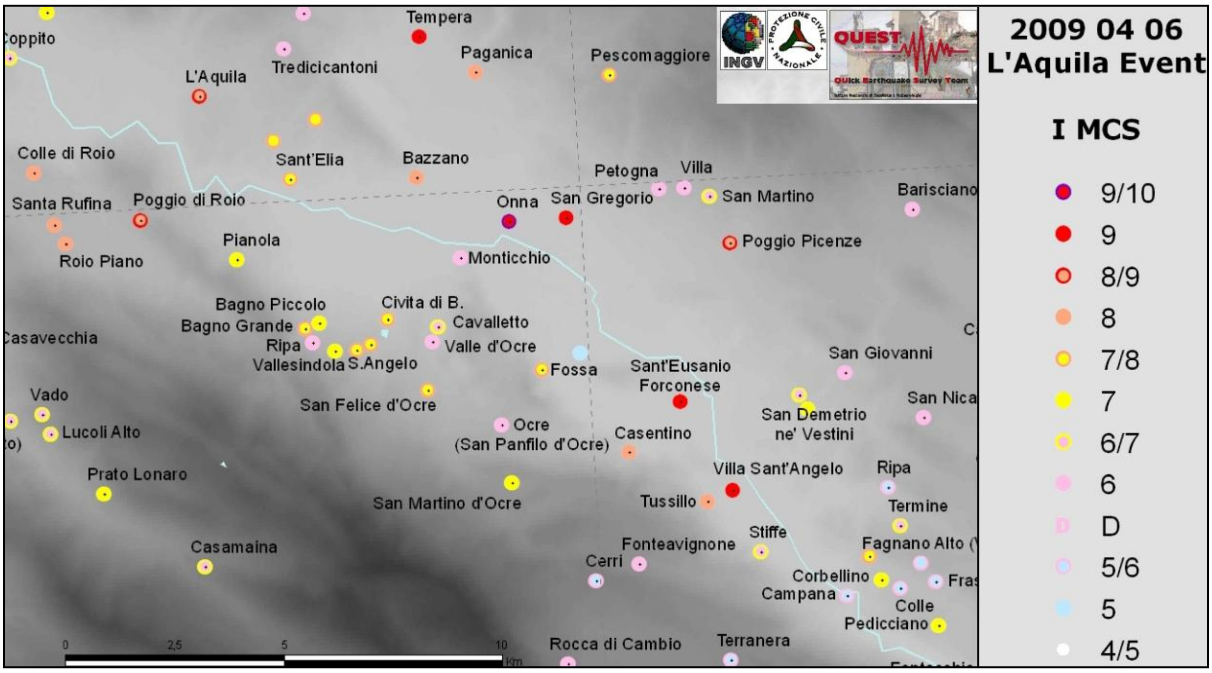


**Figure 12. View of the macroseismic intensities expressed in MCS (Mercalli-Cancani-Sieberg) values (Quest 2009).**

In **Figure 13**, these intensities have been superimposed on the official 1:50.000 scale geological map of the area. Despite the fact that the fault plane ruptured up to the surface near Paganica village, it is interesting to note that the village suffered only moderate damage (intensity VIII shaking). Several neighboring villages in the immediate footwall of the rupture plane, such as Pescomaggiore, Petogna and San Martino, experienced minor to moderate damages (VI up to VII-VIII shaking).

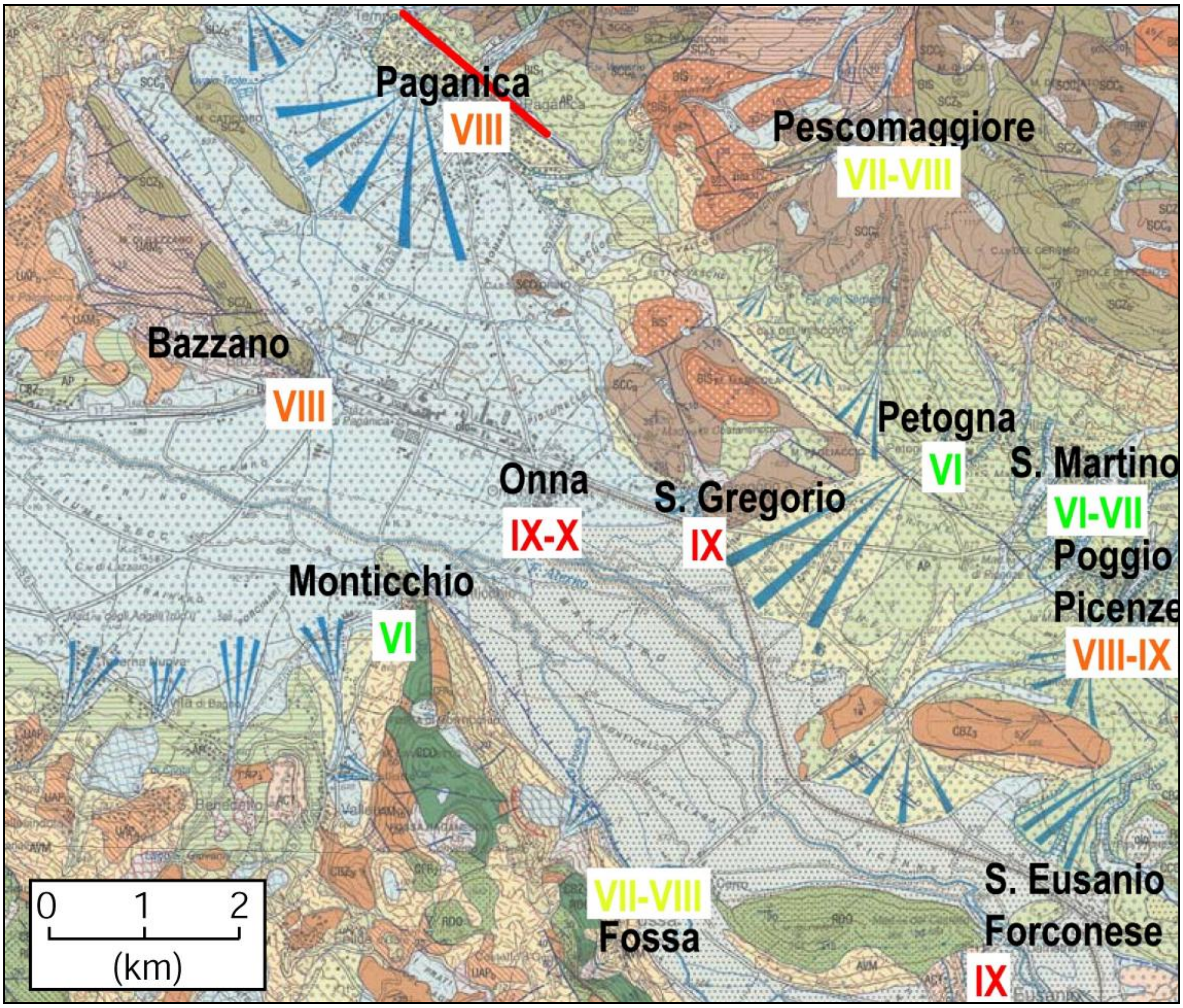



**Figure 13. View of the official geological map (CARG N. 359 L' Aquila) in the epicentral area. Superimposed are the ground observed surface ruptures and the intensities recorded by the Quest 2009 team. Intensities are highly influenced by the bedrock geology. For example, the villages of Onna (founded on recent alluvial sediments underlain by 100m thick lacustrine sediments) and Monticchio (founded on limestones) are only 1.5km apart, but their MCS recordings differ up to 3.5 intensity values (Quest 2009).**

On the other hand, villages located within the Aterno Basin, suffered significant damage (Onna, intensity IX-X, **Figure 14;** San Gregorio, intensity IX; Villa Sant' Angelo, intensity IX; Sant' Eusanio Forconese, intensity IX). North-west of L'Aquila, damage was negligible and shaking did not exceed intensity VII. In broad terms, the damage pattern is distributed along a NW-SE direction with the highest damages shifted about 10-15km eastward from the earthquake epicentre and within the floor of the Aterno valley compared to lower damage on the valley slopes. This elongation and shift probably reflects the location of the activated fault plane, the elongated geological structure of the recent sediments of the Aterno valley and possibly also involves some rupture directivity effects. The damage pattern also varies over short distances due to changes in bedrock geology. The most striking example involves the villages of Onna and Montticchio. These are only 1.5km apart, but shaking intensity varies by 3.5 (Quest 2009). Monticchio is located on bedrock (limestones) and recorded intensity VI, whereas the village of Onna is founded on recent alluvial sediments underlain by 100m of thick lacustrine sediments, contributing to elevated shaking intensities of IX-X (**Figure 13**). Most damages in these villages is a consequence of the impact of strong shaking on old masonry buildings (**Figure 14**).

*a)*

b)

c)

**Figure 14. a) View of the extensive damage and building collapses towards the village of Onna. b) Collapsed bridge about 1km southwest from the village of Onna. c) View of the Monticchio village that is situated approximately 1.5km southwest from the village of Onna. Even highly vulnerable structures remained intact. Monticchio is founded on bedrock and experienced intensity VI, whereas the neighboring village of Onna is founded on recent alluvial sediments, overlying about 100m of lacustrine sediments.**

In L' Aquila itself, however, which suffered intensity VIII-IX shaking, some modern buildings also collapsed and hundred others sustained severe damage (**Figure 15**), suggesting that construction quality is not the only determinant of the level of damage. Several modern, multi-storey, buildings displayed crumbling masonry and collapsed fill walls, even though their frames remained intact. This is systematically observed towards the ground and first floors of the buildings, which probably experienced greater stresses than the higher floors (**Figure 15**).

a)

b)

c)

**Figure 15. a) View of the damage in the town of L' Aquila. Collapses in reinforced concrete buildings were few in number, but produced a high death toll. b) Several modern multi-store buildings were characterized by crumbling masonry and collapsed fill walls, but their frame remained intact. This is particularly observed towards the ground and first floor of these buildings, which probably experienced greater stresses than the higher floors. c) Several public and historical buildings such as churches (photo from Paganica) and municipality buildings (photo from L' Aquila) suffered significant damage.**

The L' Aquila sedimentary basin is characterised by unfavourable site specific conditions (**Figure 16**). The basin is filled with a few hundred metres of lacustrine sediments that overlie the bedrock (Blumetti *et al*. 2002), resulting in significant ground motion amplification effect at low frequencies (~0.6 Hz); as demonstrated by De Luca *et al*. (2005) using weak motion and ambient noise data. This amplification is mostly attributed to the thick lacustrine basin in-fill. This situation should be considered by civil authorities in future planning, in particular because the faults in the area have the capacity to generate stronger earthquakes than the recent Mw=6.3 event.

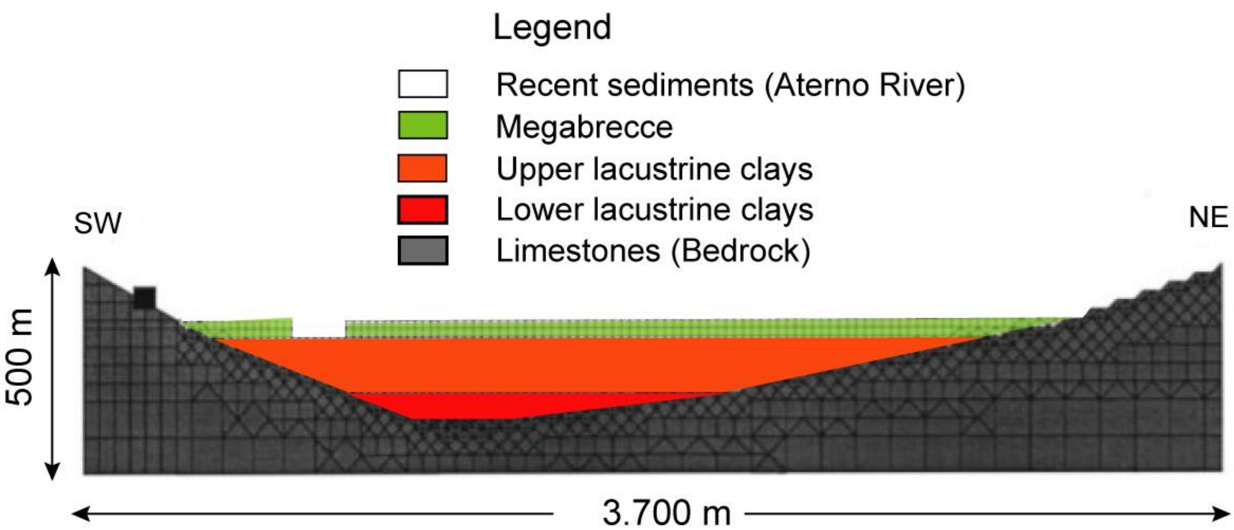



**Figure 16. Geological section across the L' Aquila basin (modified by De Luca et al. 2005, based on the geological data from Blumetti et al. (2002)).**

Displacement values that were extracted from the DInSAR analysis were tested against the macroseismic intensity MCS values (Quest 2009) recorded for all villages in the epicentral area (**Table 1**). One would expect that the greater the recorded displacement (subsidence or uplift), the greater would be the expected damage.

**Table 1. DInSAR Displacement in cm (Papanikolaou et al. 2010) and intensity MCS values (Quest 2009) in the epicentral area.**

| Locality | DInSAR (cm) | Mercalli (MCS) |
|---|---|---|
| Paganica | - 6.5 | VIII |
| Pescomaggiore | + 6.4 | VII-VIII |
| Bazzano | - 18.7 | VIII |
| Onna | - 17.0 | IX-X |
| Monticchio | - 20.6 | VI |
| San Gregorio | - 10.4 | IX |
| Fossa | - 14.6 | VII-VIII |
| Petogna | + 1.4 | VI |
| San Martino | + 2.2 | VI-VII |
| Poggio Licenze | + 1.2 | VIII-IX |
| S. Eusanio Froconesa | - 2.0 | IX |
| **Positive values (+) correspond to uplift. Negative values (-) to subsidence.** | | |

**Figure 17** shows, however, that there is no correlation between the amount of recorded uplift or subsidence and the intensity of shaking (Papanikolaou *et al*. accepted). The majority of damage in these villages occurred to old masonry buildings so that the building stocks are of comparable construction quality. It is noteworthy that the community of Paganica in the immediate hanging-wall of the activated fault, where the primary surface ruptures were recorded, subsided by only 6.4cm and experienced intensity VIII shaking. On the other hand, the community of Onna, the macroseismic epicentre, founded on recent alluvial sediments, experienced intensity IX-X shaking and subsided by 17 cm, whereas Monticchio, built on bedrock only 1.5 km from Onna and 4 km from the primary surface ruptures, subsided by 20.6 cm but experienced macroseismic intensity shaking of only VI (**Figure 13**). Overall, it is interesting to note that the amount of the DInSAR recorded displacement does not correlate with the intensity of shaking, implying that bedrock geology is the predominant factor

governing the damage pattern; overwhelming all other effects of the earthquake. It is also evident that communities that recorded uplift are characterized by less damage than those in the hanging wall of the fault. This is expected because damage on the footwall is usually lower, since secondary effects are fewer and in most cases bedrock is exposed in the footwall.

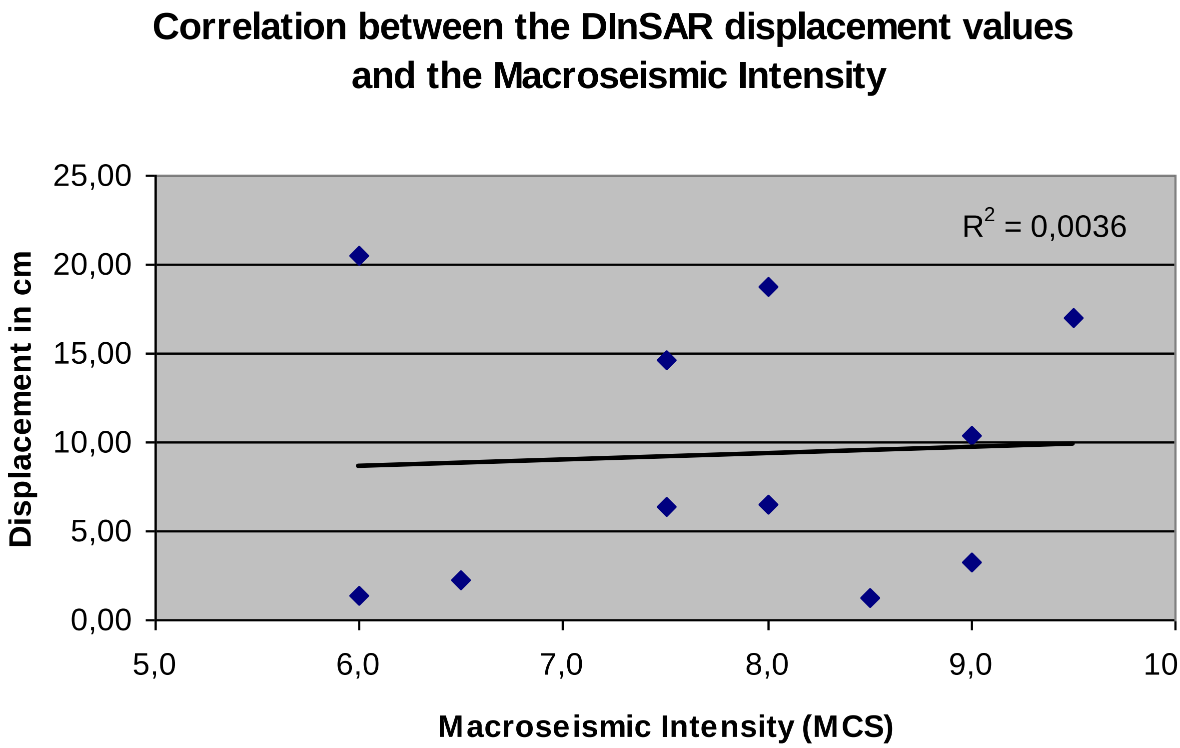



**Figure 17. Values of Table 1 are plotted in this diagram, showing that no correlation exists between the amount of displacement values and the macroseismic intensity (Papanikolaou *et al.* accepted).**

Collapses in reinforced concrete buildings were relatively few in number (a couple of dozens) and preliminary reports tend to agree that these were associated with poor construction methods. The main problems seem to have been: insufficient transversal reinforcement of the column-beam connections; poor distribution of fine aggregates and cement in the concrete with a very porous core of disconnected larger aggregates; inadequate confinement steel (EERI 2009, EEFIT 2009). Broadly, reinforced concrete buildings behaved fairly well, especially considering the limited seismic design requirements and the severe ground shaking that exceeded their design level (EERI 2009). Despite the moderate magnitude of the quake, large peak ground accelerations (PGA) values were recorded by the Italian Accelerometric Network (Rete Accelerometrica Nazionale - RAN). Four stations within 6 km from the epicentre in the hanging-wall of the fault recorded high horizontal PGA values ranging from 0.37g up to 0.67g and peak ground velocity (PGV) values higher than 32cm/s (source PCN Protezione Civile Nazionale). There are no recordings between 7 and 18 km distance from the epicentre, but 12 recordings between 18 and 50 km (**Figure 18**), making the L'Aquila earthquake one of the best recorded normal faulting events. The attenuation of PGA with distance is asymmetric with a higher decay rate towards the west (Ameri *et al*. 2009). Overall, the area of higher PGA is stretched to the south east, indicating directivity effects in the rupture propagation (Ameri *et al*. 2009; Akinci *et al*. 2010). This strong directivity effect and the heterogeneous slip distribution (Cirella *et al.* 2009), favors an inherent asymmetry of the mainshock. Reports clearly show that the recorded PGA values are in disagreement with the prediction obtained using different ground motion prediction equations (Ameri *et al*. 2009; EERI 2009; Akinci *et al*. 2010). These equations tend to underestimate PGA values near the surface ruptures and the location of greatest macroseismic intensity, overestimating the acceleration for distances further than 20km from the epicentre. L'Aquila and its environs belongs to seismic zone 2 (**Figure 2**), for which the building requirements of the 1996 and the 2003 updated regulations of the modern building code imply peak horizontal ground accelerations of 0.23 and 0.25g, respectively. It is clear that the 2009 L'Aquila earthquake exceeded these design levels, since none of the four accelerometres in the epicentral area recorded values lower than 0.35g.

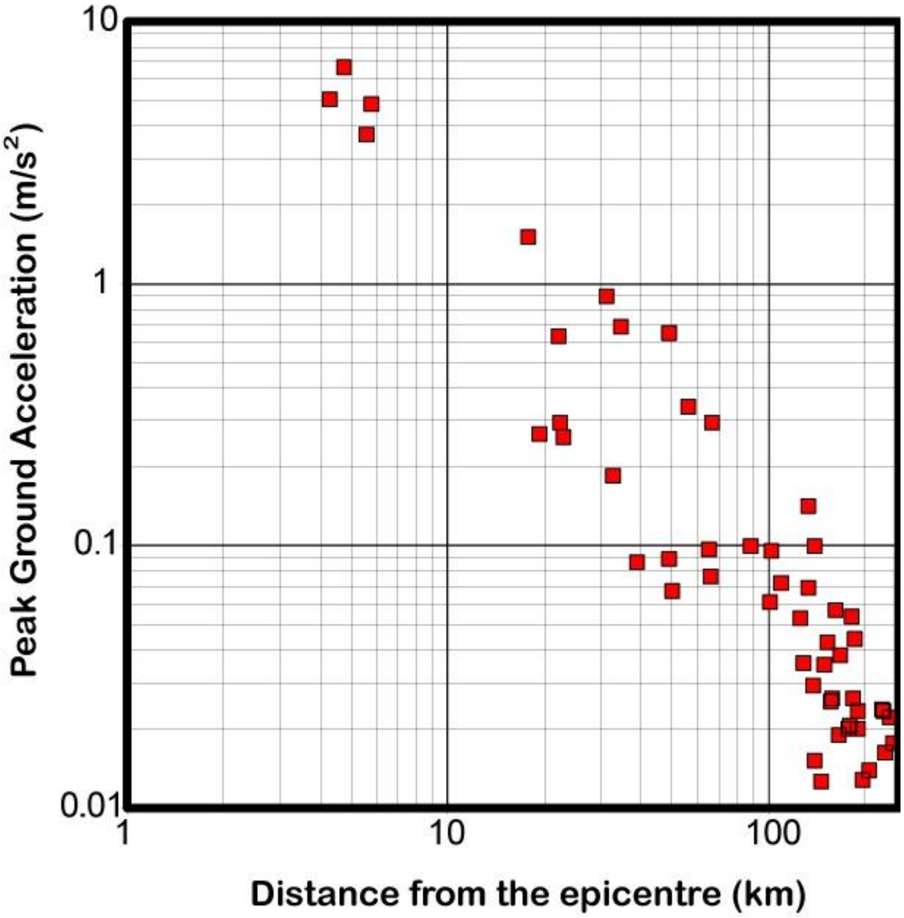



**Figure 18. Diagram showing the PGA values versus distance in the epicentral area.**

# 7. Conclusions

Several conclusions can be drawn as a consequence of observations of the 2009 L'Aquila earthquake:

- Unlike many other earthquakes, this event was not a surprise. It occurred in an area characterized as having high seismic hazard based on traditional seismic hazard maps and the historical record as well as on seismic hazard maps based on longer term geological fault slip rate data.

- The event ruptured a small segment of the fault system and not one of the major postglacial fault scarps that crop out in the area. This explains the minor primary surface ruptures that have been reported. These ruptures do not exceed 4km in length, are discontinuous, and do not exceed 10cm in displacement. Other surrounding faults, however, can produce much stronger earthquakes that can generate primary surface ruptures of 15 to 20km long and maximum displacements exceeding 1 metre. One example is the 1703 event, which caused severe damage to L' Aquila due to intensity IX shaking. These ruptures are almost one order of magnitude larger than those produced by the 6th of April 2009 earthquake, implying that the surrounding faults have the capacity to generate significantly stronger events. In light of the 1980 Mw=6.9 Irpinia earthquake, which claimed close to 3.000 lives, such an event could have increased the number of casualties almost 10 fold. Consequently, the 2009 L' Aquila event can be regarded as a lower end member in relation to the damaging capacity of seismic sources of the area.

- The large number and extensive spatial distribution of secondary surface ruptures occurred not only within the recent sediments of the Aterno basin, but also on pre-existing fault planes was another characteristic of this earthquake. These ruptures are usually disregarded in seismic hazard assessment planning and design studies, but can produce significant damage.

- The interferogram provides valuable input to the understanding of this earthquake, through presenting a clear view of the associated deformation pattern. It has also permitted comparison between predicted fault surface ruptures and those observed in the field, confirming that the ruptures observed near Paganica are indeed primary. The DInSAR analysis also demonstrated that the earthquake resulted in a maximum subsidence of 25cm and uplift of 10 cm.

- Fault geometry significantly influenced the damage pattern, with communities located on the hanging wall of the fault experiencing higher intensity shaking, compared with those located on the footwall. This is also verified by the DInSAR analysis, which shows that the hanging-wall area was more deformed. On average, the amount of subsidence was two and a half times greater than that of uplift, leading to more violent shaking.

- Basin effects and the bedrock geology played decisive roles in relation to the damage pattern, even over short distances. It is interesting to note that communities that were only 1.5 km apart, recorded differences in shaking intensity of up to 3.5 degrees. In particular, Monticchio, located on bedrock recorded intensity VI shaking, whereas Onna, built on recent alluvial sediments overlying another *ca*. 100 m of lacustrine sediments, recorded intensity IX-X shaking. The unfavorable site effects of the Aterno basin were not a surprise since they were known from previous smaller magnitude earthquakes. A more detail knowledge of the stratigraphy and geological characteristics of the basin would, however, have provided a better and more accurate picture of the likely variability in shaking intensity.

- The amount of the DInSAR recorded displacement does not correlate with the intensity of shaking, implying that bedrock geology is the predominant factor that governs the damage pattern and overwhelms all other effects in the earthquake.

- Accelerometres in the epicentral area recorded values of horizontal peak acceleration ranging from 0.37 to 0.67g; significantly higher than the 0.25g design level incorporated into the existing seismic code. Recorded PGA values contradict estimates made using different ground motion prediction equations, which tend to underestimate PGA values close to surface ruptures and the macroseismic epicentre area, while tending to overestimate ground acceleration for distances greater than 20km from the epicentre.

- Collapses in reinforced concrete buildings were relatively few in number and preliminary reports point to poor construction being the principle contributory factor in those that did collapse. Several modern, multi-storey, buildings also, however, experienced crumbling masonry and collapsed fill walls, even though their reinforced concrete frames remained intact. This was observed to occur systematically towards the ground and first floors of multi-storey buildings, suggesting that the nature of the infill walls and their attachment to the frame of the buildings should be re-examined.

- Given the moderate size of the earthquake, the high level of structural damage and the sizeable casualty figures should concern governmental agencies, public bodies, and insurance and construction companies, particularly in the context of the fact that significant larger earthquakes are possible. In mitigating the impacts of future, more powerful, earthquakes, particular emphasis needs to be placed on ensuring that the historical centres of villages and towns of central and southern Italy, which sustained significant damage during this event, are better prepared next time. In a wider context, the moderate 2009 L'Aquila earthquake has highlighted the vulnerability of such historic centres, both in Italy and across much of the Mediterranean region, and provides a valid argument for the establishment of major retrofitting programmes in order to avoid far worse seismic disasters in future.

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