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SHORT TITLE: Surface rupture of the 2009 L'Aquila earthquake (Italy)

EMERGEO working group*

Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605 – Roma, Italia

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Corresponding Author

Paola Montone

Via di Vigna Murata, 605

00143 Rome –Italy

ph: +39 0651860419

paola.montone@ingv.it

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G. Alessio, L. Alfonsi, C.A. Brunori, F.R. Cinti, R. Civico, L. Cucci, G. D'Addezio, R. De Ritis, E. Falcucci, U. Fracassi, A. Gasparini, S. Gori, A. Lisi, S. Mariano, M.T. Mariucci, P. Montone, R. Nappi, D. Pantosti, A. Patera, S. Pierdominici, M. Pignone, S. Pinzi, S. Pucci, P. Vannoli, A. Venuti, F. Villani.

Evidence for surface rupture associated with the Mw 6.3 L'Aquila earthquake sequence of April 2009 (central Italy)

EMERGEO working group*

Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605 – Rome Italy

Abstract

An earthquake of Mw=6.3 struck L'Aquila town (central Italy) on April 6, 2009 rupturing an approximately 18 km long SW-dipping normal fault. The aftershock area extended for a length of more than 35 km and included major aftershocks on April 7 and 9, and thousands of minor events. Surface faulting occurred along the SW-dipping Paganica fault with a continuous extent of ~2.5 km. Ruptures consist of open cracks and vertical dislocations or warps (0.1 maximum throw) with an orientation of N130°-N140°. Small triggered slip and shaking effects also took place along nearby synthetic and antithetic normal faults. The observed limited extent, and small surface displacement, of the Paganica ruptures with respect to the height of the fault scarps and vertical throws of paleo-earthquakes along faults in the area, puts the faulting associated with the L'Aquila earthquake in perspective with respect to the maximum expected magnitude, and the regional seismic hazard.

Key words: *2009 L'Aquila seismic sequence; co-seismic surface effects; earthquake geology, normal faulting earthquake; Abruzzi, central Apennines.*

Introduction

At 01.32 GMT on April 6, 2009, an earthquake of Mw=6.3 occurred in the central Apennines (Abruzzi region). It caused heavy damage in the town of L'Aquila (73,000 inhabitants) and surrounding villages, and resulted in about 300 fatalities and thousands of injures. The epicenter was located close to L'Aquila and was followed by two large aftershocks on April 7 (Mw=5.6) and April 9 (Mw=5.4). The seismic sequence was confined to the upper 10-12 km, with the exception of April 7 hypocenter at about 15 km depth (Fig.1). The focal mechanisms of the main events (Fig. 1) show NW-striking normal faulting (Pondrelli et al., 2009) consistent with the NE-SW trending extensional regime (Patacca and Scandone, 1989; Galadini *et al*., 2000; Montone *et al*., 2004; D'Agostino *et al*., 2008). The aftershocks occurred in three distinct zones: 1) the area of the mainshock (Fig. 1, section AB), where seismicity is clearly confined within the Aterno river valley and images a ~50° SW-dipping fault; 2) the area hit by April 7 aftershock, and 3) the Campotosto area, hit by April 9 aftershock, which occurred on a SW-dipping fault north-east of the mainshock (Fig. 1, section CD).

The region is part of the central Apennines (Fig. 2) characterized by Quaternary extension superimposed on a NE-verging Neogene fold and thrust belt (i.e., Cipollari and Cosentino, 1995; Ghisetti and Vezzani, 1999; Meletti *et al*., 2000). On the basis of their geomorphic expression, and age of faulted sediments and geomorphic features, many workers have identified a large number of active normal faults (Figs 1, 3), mostly NW-trending, up to 15 km-long, 50°-70° SW-dipping, with a smaller number of NE-dipping faults (Lavecchia *et al*., 1994; Vezzani and Ghisetti, 1998; Galadini and Galli, 2000 and reference therein; Foglio CARG, 2009). Many historical earthquakes have hit the region (Fig. 1) however none of them could be clearly attributed to one of the mapped active faults. Paleoseismological studies on several faults (Galli *et al*., 2002; Pantosti *et al*., 1996; Salvi *et al*., 2003; Galadini *et al*., 2003) indicate average recurrence intervals for M=6.5-7 earthquakes of 1000-3000 years and average slip rates lower than 1 mm/yr. Based on historical seismicity, the presence of active faults and evidence of large surface-faulting paleo-earthquakes, the L'Aquila region was considered a high hazard seismic zone (Gruppo di Lavoro MPS, 2004; Cinti *et al*., 2004; Pace *et al*., 2006; Akinci *et al*., 2009).

We present the data collected during the post-earthquake campaigns by the Emergeo team (http://portale.ingv.it/real-time-monitoring/emergeo/; Emergeo working group, 2009) and a preliminary tectonic interpretation.

The geological co-seismic ruptures

Co-seismic surface effects were recognized during the field survey within the epicentral area, with observations recorded at about 400 sites (Fig. 3). Most of these are fractures arranged with consistent trends that cross-cut soft and hard rocks, paved and unpaved roads, and different types of man-made features. Most of the fractures occur along pre-existing fault traces. Among these, the Paganica ones most likely represent the primary rupture associated with the mainshock. The small, localized slip along the other tectonic structures (Fig. 4) may represent triggered slip or shaking effects.

We describe the most prominent tectonic ruptures along the Paganica fault, two antithetic fault strands (the Bazzano and the Monticchio-Fossa faults), and other minor features along other faults, as well as the most noticeable local shaking-induced features. No evidence for surface ruptures was observed in the Campotosto area (April 9 aftershock).

<u>The Paganica fault</u>

The Paganica fault is represented by a morphologic scarp formed by the tectonic juxtaposition of Pliocene-middle Pleistocene with late Pleistocene alluvial deposits (Bagnaia *et al* 1992; Vezzani and Ghisetti, 1998; Boncio *et al*. 2004; Foglio CARG, 2009). Co-seismic tectonic ruptures along and close to the NW-trending, SW-dipping, Paganica normal fault were found, the most clear of which coincide with the most prominent of its long-term geomorphic expression (Fig. 5). The ruptures are confined to a maximum distance of 30 m from the base of the scarp. They extend for about 2.5 km (Fig. 5), and consist of vertical dislocations or warps (~40%) and open cracks (~60%), with a persistent orientation of N130°-N140° (Fig 6). The envelope of these ruptures describes a surface trace that occurs regardless of slope angle, the type of deposits crossed, or the type of man-made features. Individual ruptures are a maximum of 25 m long, and are commonly organized as up-to-2.0 m left-steps (with rare secondary right steps), but with no overlap (Fig. 6). Many of the ruptures are associated with southwest-side down vertical throw reaching a maximum of about 0.1 m, sometimes with a slight (few millimeters) dextral component. Conversely, where open cracks are common, the vertical displacement is expressed as a ground flexure with a comparable amount of separation. Locally, the open cracks branch into a zone of deformation with a maximum width of 15 m (e.g. at the outlet of the Raiale stream, in Holocene fluvial deposits), with no appreciable vertical deformation along individual elements (Fig. 5). The amount of vertical separation and SW-NE widening of the ruptures increased slightly (twice at a few sites) in the days subsequent to the mainshock, suggesting the occurrence of afterslip on the primary fault plane. Both to the north and south of the 2.5 km alignment of ruptures along the Paganica fault, other discontinuous and sporadic breaks occurred with a trend ranging from N120° to N170°. If these features belong to the Paganica surface rupture, the total length of surface faulting may exceed 6 km (inset in Fig. 5).

The Mt. Bazzano fault

The north-east dipping Mt. Bazzano fault (antithetic to the Paganica fault) is clearly expressed by a bedrock fault plane along a NW-SE 3 km-long limestone ridge, located between L'Aquila and the Paganica alluvial fan (Fig. 3). At the base of the bedrock fault plane, we observed a whitish fault ribbon (Fig. 7a) with a constant height of about 50 mm. Fresh north-east facing scarps are present in the unconsolidated slope deposits at the foot of a main 1.5-3.0 m high pre-existing scarp. These discontinuous scarps extend for about 1 km with an average strike of N320°, suggesting co-seismic vertical displacements of 0.1-0.3 m (Fig. 7b).

The Monticchio-Fossa fault

The north-east dipping Monticchio-Fossa fault runs along the eastern slope of the Mt. Ocre ridge (Foglio CARG, 2009) and is aligned with the south-eastward continuation of the Mt. Bazzano fault (Fig. 3). The long-term surface expression of the Monticchio-Fossa fault consists of a fault scarp in cemented breccias, with a more recent, parallel scarp running along the base of the slope. Surface ruptures at least 300 m-long occurred on and close to the recent geomorphic scarp, particularly near Fossa village. Here, an excavation across the scarp exposed part of the fault zone in unconsolidated colluvial and slope wash deposits, with evidence of dip-slip paleo-offset (NE side down). At this site, newly-formed 10-20 mm wide fissures, without appreciable vertical displacement, had formed along the pre-existing fault planes (Fig. 8a). Along the lower scarp at the base of the ridge we mapped N130° striking left-stepping fractures, with 50 to 150 mm of north-east facing vertical offset at some locations (Fig. 8b).

The Roio-Canetra, Colle Praticciolo, Valle del Macchione, and Mt. Pettino faults

Ruptures with small offsets and of limited and discontinuous extent were observed along other faults within the area (Fig. 3). A fresh free-face scarp with a constant height up to 30 mm, associated with local fissuring and detachment of the soil and loose debris, was mapped along the bedrock plane of the SW-dipping Roio-Canetra fault (Fig. 9a), for a minimum length of 1 km. A 10 mm free-face scarp was also observed along the SW-dipping Colle Praticciolo fault, in the vicinity of Collebrincioni (Fig. 9b). Local ground ruptures occur along the NE-dipping Valle del Macchione fault extending for about 100 m at the base of a pre-existing scarp. Similarly, vertical offsets in soil and debris of 0.1 to 0.2 m, mostly parallel to the slope, were observed along the SW-dipping Mt. Pettino fault (Fig. 9c) on discontinuous strands, each with a length of several tens of meters.

Shaking effects

Within the Aterno River valley there were many features that we interpret as being induced by the intense seismic shaking, not associated with tectonic structures but related to gravitational or differential compaction phenomena (Fig. 3). Among the significant failures and sediment compaction features was a 150 m long, NW-SE striking, set of open cracks affecting the alluvial sediments near to Onna (Fig. 10a). Also, numerous ruptures occurred parallel to the youngest terrace risers in the alluvial plain of the Vetoio stream (west of L'Aquila), (Fig. 10b). The karstic Sinizzo lake, near S. Demetrio ne' Vestini village, was affected by a large collapse expressed by open failures encircling the shore (Fig. 10c). The highly fractured and weathered bedrock in the epicentral area and the steep fault-related slopes contributed to the formation of seismically induced small-scale gravitational failures as along the steepest slopes of the Mt. Ocre range (Fig. 10d). Landslides of medium size, debris slides and broken trees occurred in the area of the Campotosto Lake (Fig. 10e) and along the SW-Campotosto and Mt. Laga faults, which were strongly shaken by the April, 9 aftershock (Fig. 1).

Discussion

We found evidence of co-seismic tectonic ruptures in the epicentral area. The alignment of ruptures along the Paganica fault shows a spatial continuity not observed along any other structure within the area. These ruptures are located at the base of the most evident long-term geomorphic expression of the Paganica fault and are particularly clear along a ~2.5 km section of the scarp. To the north and to the south, they fade out and are difficult to follow. The Paganica fault ruptures cut across loose and cemented deposits, buildings, and structures, always with a constant N130°-140° strike and irrespective of local slope direction.

The continuity and the consistency of the ruptures leads us to interpret them as the surface rupture of the fault responsible for the Mw 6.3 earthquake. This interpretation is in agreement with the seismological data as well as with GPS and DInSar modelling (Anzidei *et al.*, 2009; Atzori *et al.*, 2009; Chiarabba *et al*., 2009). Seismicity recorded by INGV permanent and temporary stations shows that the 9 km deep mainshock and the aftershocks (generally deeper than 2 km) clearly image a ~50° SW dipping normal fault whose projection to the surface coincides with the Paganica fault (Fig. 1). Moreover, based on seismological and geodetic models, the most shallow slip patch (with ~1 m of displacement) is located below the 2.5 km-long surface ruptures (Atzori *et al.*, 2009; Cirella *et al*., 2009). Thus, we interpret the main 2.5 km-long Paganica fault ruptures to represent the propagation to the surface of the slip at depth on the mainshock fault. The ruptures observed along the Bazzano and Fossa antithetic faults can be interpreted as triggered slip considering: (1) their geometrical arrangement, these faults are shallow-rooted on the Paganica fault, accommodating the extension on its hanging-wall without reaching seismogenic depth; (2) their regular throw, and that ruptures are consistent with the long-term fault expression; (3) they occur both on gentle and steep slopes thus independently from gravitational effects; (4) they currently contribute to the graben growth along with the Paganica fault as suggested by its long-term geomorphic expression. All the other ruptures appear to be related to shaking or gravitational movement.

The small surface displacement observed on the Paganica fault associated with Mw 6.3 earthquake raises questions about the range of seismogenic behaviour of the fault. On the Paganica fault itself, on the antithetic Monticchio- Fossa fault, and also on other faults in the region (*eg.*, Mt. Marine, Campo Imperatore, Cerasitto-Campo Felice-Ovindoli-Pezza faults - see Galli *et al.* 2008 and references therein) there is evidence for large cumulative displacements (average scarp heights of several m) and for individual events of surface faulting with vertical throws of 0.25-1.0 m (Fig. 5). Historical seismicity in the region has also recorded earthquakes in the M~7 range, the latest of which occurred in 1915 ~40 km to the south. Thus, if during previous events the Paganica fault has ruptured with larger displacement at the surface, and assuming that surface displacement is scaled with earthquake magnitudes, then this fault may have produced events with larger magnitude than the 2009 event. The dense array of surface ruptures associated with the L'Aquila earthquake also begs the question of the connectivity of the surface faults at seismogenic depth. Do they connect at depth so that the surface array represent active splays of the 2009 seismogenic plane, or are the surface faults merely accommodating the deformation induced by the deep fault? The complex surface deformation observed recently requires us to reconsider the seismogenic model built for this region on the basis of historical and paleoseismological evidence, and suggests a range of seismogenic behaviour (*c.f.* characteristic earthquake) may be more typical of this area.

Conclusion

The 2009 earthquake sequence was associated with an extensive and complex set of surface features. A NW-SE orientation of the ruptures is persistent throughout the whole area (Fig. 3: see rose diagram A), with a particularly consistent trend of N130°-140° along the Paganica, Bazzano, Monticchio-Fossa faults (Fig. 3: rose diagrams B, C and D).

The continuity of the ruptures, the consistency between the average trend of these ruptures and focal plane solutions, seismicity distribution, geodetic and DInSar observations, and the coincidence of the ruptures with the late Quaternary trace of the Paganica fault, lead us to interpret these ruptures as the surface expression of the seismogenic fault. Our data indicate that rupture of the Paganica fault to produce the Mw 6.3 earthquake propagated to reach the surface, causing minor, but detectable surface faulting. The limited extent and the small throw of the surface rupture, in comparison to the cumulate size of late Quaternary Paganica fault scarp, and with other well-expressed active faults in the region, suggests the Paganica fault is capable of rupture with a larger maximum magnitude earthquake than the 2009, Mw 6.3 event. Thus, although the L'Aquila earthquake and associated faulting caused major damage and loss of life, it does not fully characterize the seismic hazard associated in this area.

* INGV prompt geological survey team - http://portale.ingv.it/real-time-monitoring/emergeo/

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A photo gallery is available at http://portale.ingv.it/produzione-scientifica/quaderni-di-geofisica/quaderni-di-geofisica-2009 (Emergeo working group, 2009).

References

Akinci, A., Perkins, D., Lombardi, A.M. and Basili, R., 2008. Uncertainties in probability of occurrence of strong earthquakes for fault sources in the Central Apennines, Italy. *J. Seismol*., doi10.1007/s10950-008-9142-y.

Anzidei, M., Boschi, E., Cannelli, V., Devoti, R., Esposito, A., Galvani, A., Melini, D., Pietrantonio, G., Riguzzi, F., Sepe, V. and Serpelloni, E., 2009. Coseismic deformation of the destructive April 6, 2009 L'Aquila earthquake (central Italy) from GPS data. *Geophys. Res. Let.*, **36**. Doi:10.1029/2009GL039145.

Atzori, S., Hunstad, I., Chini, M., Salvi, S., Tolomei, C., Bignami, C., Stramondo, S., Trasatti, E. and Antonioli, A., 2009. Finite fault inversion of DInSAR coseismic displacement of the 2009 L'Aquila earthquake (central Italy). *Geophys. Res. Let.*, **36**, L15305. Doi:10.1029/2009GL039293.

Bagnaia, R., D'Epifanio A. and Sylos Labini, S., 1992. Aquila and sub- aequan basins: An example of Quaternary evolution in central Apennines, Italy. *Quat. Nova*, **II**, 187 – 209.

Barchi, M., Galadini, F., Lavecchia, G., Messina, P., Michetti, A.M., Peruzza, L., Pizzi, A. and Tondi, E. (eds.), 2000. Sintesi delle conoscenze sulle faglie attive in Italia Centrale: parametrizzazione ai fini della caratterizzazione della pericolosità sismica. *GNDT, Gruppo Nazionale per la Difesa di terremoti*, spec. publ., Roma, 62. pp.

Boncio P., Lavecchia G. e Pace B. (2004). Defining a model of 3D seismogenic sources for Seismic Hazard Assessment applications: the case of central Apennines (Italy). *Journal of Seismology*, **8**/3, 407-425.

Calamita, F. and Pizzi, A., 1994. Recent and active extensional tectonics in the southern umbro-marchean Apennines (central Italy). *Memorie della Società Geologica Italiana,* **48**, 541–548.

Chiarabba, C., Amato A., Anselmi M., Baccheschi P., Bianchi I., Cattaneo M., Cecere G., Chiaraluce L., Ciaccio M.G., De Gori P., De Luca G., Di Bona M., Di Stefano R., Faenza L., Govoni A., Improta L., Lucente F.P., Marchetti A., Margheriti L., Mele F., Michelini A., Monachesi G., Moretti M., Pastori M., Piana Agostinetti N., Piccinini D., Roselli P., Seccia D. and Valoroso L., 2009. The 2009 L'Aquila (central Italy) Mw6.3 earthquake: main shock and aftershocks**.** *Geophys. Res. Lett*., in press.

Cinti, F.R., Faenza, L., Marzocchi, W. and Montone, P., 2004. Probability map of the next large earthquakes in Italy. *G cubed*, **5**, 1. Doi:10.1029/2004GC000724.

Cipollari, P. and Cosentino, D., 1995. Miocene unconformities in the Central Apennines: geodynamic significance and sedimentary basin evolution. *Tectonophysics,* **252**, 375-389.

Cirella A., Piatanesi A., Cocco M., Tinti E., Scognamiglio L., Michelini A., Lomax A. and Boschi E., 2009. Rupture history of the 2009 L'Aquila (Italy) earthquake from non- linear joint inversion of strong motion and GPS data. *Geophys. Res. Lett*.. Doi: 10.1029/ 2009GL039795.

CPTI working group, 2004. Catalogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04), INGV, Bologna, http://emidius.mi.ingv.it/CPTI04/.

D'Agostino, N., Mantenuto, S., D'Anastasio, E., Avallone, A., Barchi, M., Collettini, C., Radicioni, F., Stoppini, A. and Fastellini, G., 2008. Contemporary crustal extension in the Umbria–Marche Apennines from regional CGPS networks and comparison between geodetic and seismic deformation. *Tectonophysics*, in press. Doi:10.1016/j.tecto.2008.09.033.

Emergeo working group, 2009. Field geological survey in the epicentral area of the Abruzzi (central Italy) seismic sequence of April 6th, 2009. *Quaderni di Geofisica*, **70**, Istituto Nazionale di Geofisica e Vulcanologia, ISSN 1590-2595 http://portale.ingv.it/produzione-scientifica/quaderni-di-geofisica/quaderni-di-geofisica-2009.

Foglio CARG 1:50,000, 2009. Cartografia geologica ufficiale Foglio CARG 1:50,000 N. 359, L'Aquila.

Galadini, F. and Galli, P., 2000. Active tectonics in the Central Apennines (Italy)-input data for Seismic Hazard Assessment. *Natural Hazards*, **22**, 225–270.

Galadini, F., Meletti, C. and Rebez, A. (eds.), 2000. Le ricerche del GNDT nel campo della pericolosità sismica (1996-1999). *CNR-Gruppo Nazionale per la Difesa dai Terremoti* - Roma, 397 pp.

Galli, P., Galadini, F., Moro, M. and Giraudi, C., 2002. New paleoseismological data from the Gran Sasso d'Italia area (central Apennines). *Geophys. Res. Lett.*, **29** (7). Doi 10.1029/2001GL013292, 38.1-38.4.

Formattato: Italiano (Italia)

Galadini, F., Galli, P. and Moro, M., 2003. Paleoseismology of silent faults in the Central Apennines (Italy): the Campo Imperatore Fault (Gran Sasso Range Fault System). *Annals of Geophysics*, **46** (5), 793-813.

Galli, P., Galadini, F. and Pantosti, D., 2008. Twenty years of paleoseismology in Italy, *Earth-Science Reviews*, **88** (1-2), 89-117. Doi:10.1016/j.earscirev.2008.01.001.

Ghisetti, F. and Vezzani, L., 1999. Depth and modes of Pliocene–Pleistocene crustal extension of the Apennines (Italy). *Terra Nova*, **11**, 67–72.

Ghisetti, F. and Vezzani, L., 2000. Modalità di riattivazione, circolazione dei fluidi e rottura sismica di alcune delle principali faglie normali nelle zone esterne dell'Appennino centrale, In: *Le Ricerche del GNDT nel Campo della Pericolosità Sismica (1996-1999)*, (F. Galadini, C. Meletti, and A. Rebez, eds.). *GNDT, Gruppo Nazionale per la Difesa dai Terremoti,* Roma, 193-202.

Gruppo di Lavoro MPS, 2004. Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM del 20 marzo 2003. Rapporto Conclusivo per il Dipartimento della Protezione Civile, INGV, Milano-Roma, aprile 2004, 65 pp. + 5 appendici. http://zonesismiche.mi.ingv.it/

Lavecchia, G., Brozzetti, F., Barchi, M., Menichetti, M. and Keller, J.V.A., 1994. Seismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformations and related stress fields. *Geological Society of America Bulletin*, **106** (9), 1107–1120.

Meletti, C., Patacca, E. and Scandone, P., 2000. Construction of a seismotectonic model: The case of Italy. *Pure Appl. Geophys*., **157**, 11– 35.

Montone, P., Mariucci, M. T., Pondrelli, S. and Amato, A., 2004. An improved stress map for Italy and surrounding regions (central Mediterranean). *J. Geophys. Res*., **109**, B10410. Doi:10.1029/2003JB002703.

Pace, B., Peruzza, L., Lavecchia, G. and Boncio, P., 2006. Layered Seismogenic Source Model and Probabilistic Seismic-Hazard Analyses in Central Italy. *Bulletin of the Seismological Society of America*, **96**, 107-132.

Patacca, E. and Scandone, P., 1989. Post-Tortonian mountain building in the Apennines; the role of the passive sinking of a relic lithospheric slab. In: *The Lithosphere in Italy. Advances in Earth Science Research.* (A. Boriani, M. Bonafede, G.B. Piccardo, and G.B. Vai, eds.). *Atti Conv. Lincei*, **80,** 157–176.

Pondrelli, S., Salimbeni, S., Morelli, A., Ekström, G., Olivieri, M. and Boschi E., 2009. Seismic moment tensors of the April 2009, L'Aquila (Central Italy), earthquake sequence. *Geophys. J. Int*., in press.

Formattato: Italiano (Italia)

Salvi, S., Cinti, F.R., Colini, L., D'Addezio, G., Doumaz, F. and Pettinelli, E., 2003. Investigation of the active Celano–L'Aquila fault system, Abruzzi. *Geophys. J. Int.*, **155**, 805-818.

Formattato: Italiano (Italia)

Speranza, F., Adamoli, L., Maniscalco, R. and Florindo, F., 2003. Genesis and evolution of a curved mountain front: paleomagnetic and geological evidence from the Gran Sasso range (central Apennines, Italy). *Tectonophysics*, **362**, 183– 197.

Vezzani, L. and Ghisetti, F., 1998. Carta Geologica dell'Abruzzo, scala 1:100,000. S.EL.CA., Firenze.

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Captions

Figure 1 - Seismicity map of the L'Aquila region from April 6th to May 11th, 2009 (http://portale.ingv.it/primo-piano-1/news-archive/2009-news/april-6-earthquake/copythe-l-aquila-seismic-sequence-april-2009/view?set_language=en). The historical earthquakes (CPTI Working group, 2004) are scaled by magnitude, and the main active faults are from Galli *et al*. (2008) and references therein. The two cross sections below (locations shown on the map), perpendicular (AB) and parallel (CD) to the belt axis, define the aftershock distribution and the mainshock location at depth. The location of faults along the topographic profile is approximate.

Figure 2 - Geological and structural map of the central Apennines, modified from Speranza *et al*. (2003). Legend: 1. Mesozoic-Cenozoic slope-basin sediments; 2. Mesozoic-Cenozoic Latium-Abruzzi shelf carbonates; 3. Mesozoic-Cenozoic Apulian shelf carbonates; 4. upper Miocene-lower Pliocene foredeep siliceous turbidites; 5. Messinian– lower Pliocene thrust-top sediments; 6. buried Pliocene marine sediments; 7. middle–upper Pleistocene volcanics; 8. Pliocene-Pleistocene and Holocene marine and continental deposits; 9. thrusts; 10. undifferentiated faults. The rectangular area includes the 2009 earthquake sequence.

Figure 3 - Map of the surveyed co-seismic effects. Sites of measurements are distinguished between tectonic ruptures and shaking effects. The purple box includes the Paganica ruptures which are interpreted to be primary surface faulting (shown in detail in figure 5). We also show the sites along faults where no ruptures or other effects were observed. Stars indicate the three main events. Rose diagrams of the tectonic surface ruptures: A) total data; B) Paganica fault; C) Mt. Bazzano fault and D) Monticchio-Fossa fault. We do not report rose diagrams when the data are less than 5 measurements. Active normal faults are numbered as follow: 1 - Paganica, 2 - Poggio Picenze-S. Demetrio, 3 - Mt. Bazzano, 4 - Monticchio-Fossa, 5 - S. Angelo-Tione, 6- Roio-Canetra, 7- Mt. Pettino, 8 - Mt. Stabiata, 9- Colle Praticciolo, 10 - Valle del Macchione, 11 - Mt. Marine, 12 - Gran Sasso-Mt. Corvo, 13 - Campo Imperatore, 14 - Mt. Laga, 15 - SW Campotosto, 16 - Mt. S. Franco, 17 - Mt. Ocre system, 18 - Campo Felice, 19 - Ovindoli-Pezza, 20 - Mt. Orbetello.

Figure 4 - View from the NW of the eastern side of the Middle Aterno valley. The Paganica and Bazzano faults are in the foreground of the picture, the Monticchio-Fossa Fault is in the background. Onna is the village most damaged by the 6th April earthquake (10 on the MCS scale). The distance between the Paganica and the Bazzano Faults is ~ 2.5 km.

Figura 5 - Detail of the Paganica surface faulting. Red lines are the mapped rupture strands (see purple box in Figure 3 for location), and the white line is the long-term Paganica fault trace. The inset in the upper left shows the fault setting in this sector of the Aterno valley (dashed red line is the inferred NW-prolongation of the surface ruptures). Photos with white frame show details of the long-term expression and displacements of the Paganica fault. In particular, a natural trench originated by collapse of a major aqueduct in the village of Paganica which exposed a complex fault structure. The upper photo is the aqueduct excavation before repair where the cutting exposed the Paganica fault zone (red arrows point to faults). Photos with the red frame show details of the April ruptures (red arrows) crossing man-made features in the urbanized area.

Figure 6 – Surface ruptures along the Paganica fault. The breaks consist of vertical dislocations, or warps and open cracks, with a persistent orientation of N130°-N140°. The ruptures cross different type of deposits and man-made features.

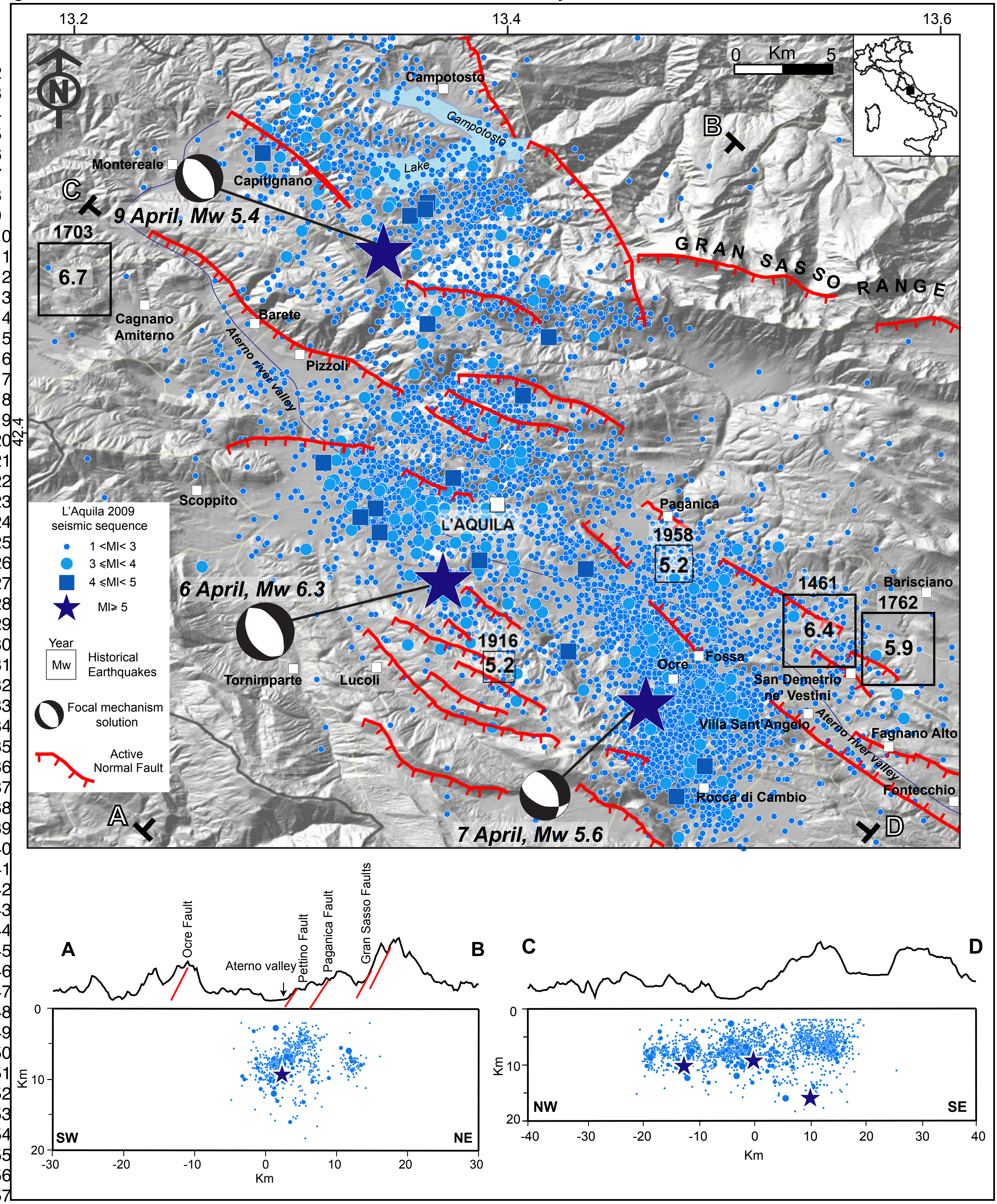
Figure 7 – Surface ruptures along the Mt. Bazzano fault: a) free face at the base of the bedrock fault plane; b) NE-facing scarp in slope deposits.

Figure 8 – Surface ruptures along the Monticchio-Fossa fault: a) newly-open crack along pre-existing fault plane; b) fractures with cm-scale north-east facing vertical offset (red arrows).

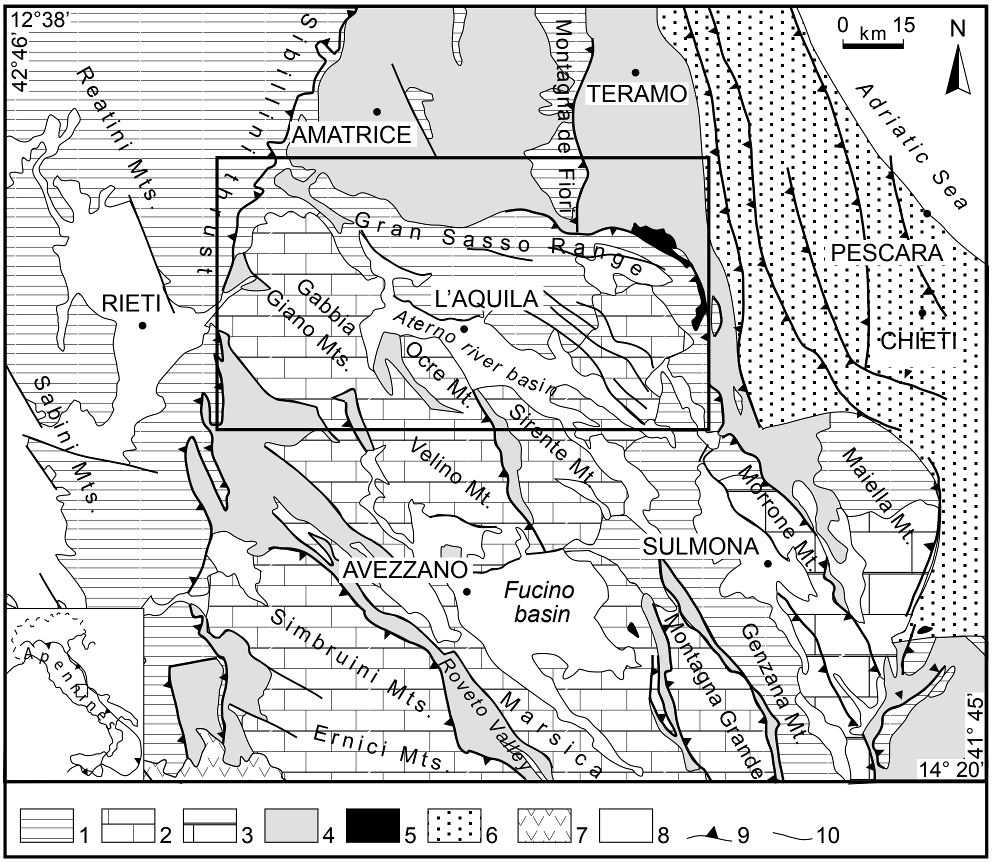
Figure 9 – Surface ruptures on: a) Roio-Canetra fault, showing fresh free-face and soil detachment on the bedrock fault plane and fissuring in the loose debris (red arrows); b) Colle Praticciolo fault, showing fresh free-face along the bedrock fault plane; c) Mt. Pettino fault, with soil and debris offset along the fault scarp.

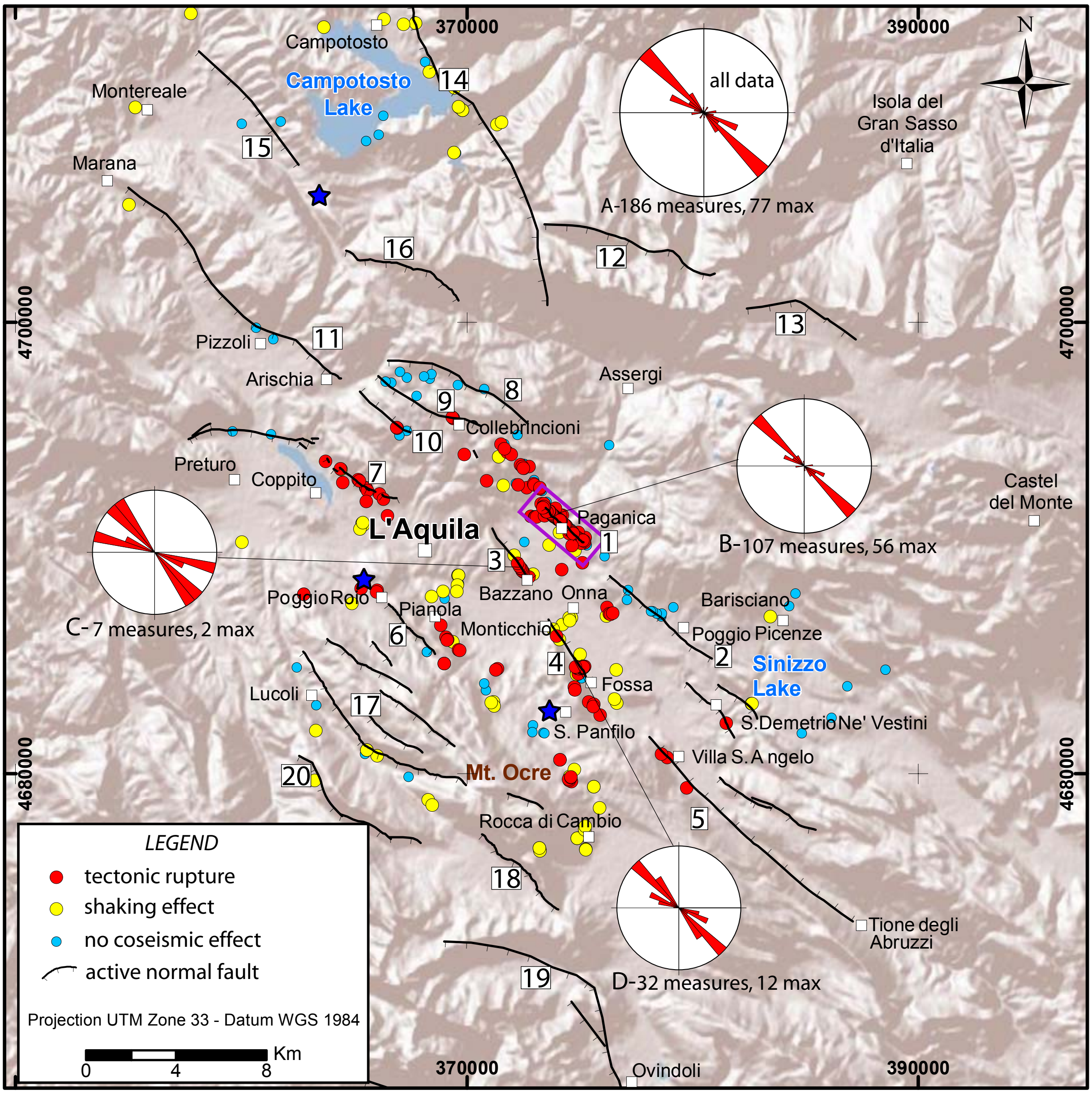
Figure 10 – Shaking effects: a) open cracks (red arrow) in alluvial sediments beside the Aterno River, close to the village of Onna; b) ruptures in the alluvial plain of the Vetoio stream (west of L'Aquila); c) open fissures (up to 2.0 m wide, and up to 1.5 m deep) in the banks of the Sinizzo Lake; d) landslide surface of detachment along the eastern slope of Mt. Ocre range; e) landslide in slope deposits in the Campotosto area.

Figure 11 – GPS and DInSar data modelling with respect to the active faults of the area. The arrows represent the GPS data (Anzidei *et al*., 2009): black and white arrows are the observed horizontal and vertical displacements, respectively; red arrows are the modelled horizontal and vertical displacements. A blue box marks the surface projection of the modeled source. DInSar data (Atzori *et al*., 2009): the different colour fringes define the displacement field (almost vertical) due to the earthquake from the ENVISAT Interferogram. The maximum lowering is about 0.25 m between L'Aquila and Fossa village (each fringe corresponds to 25 mm). The heavy red line shows the envelope of the surface fractures identified in the field.

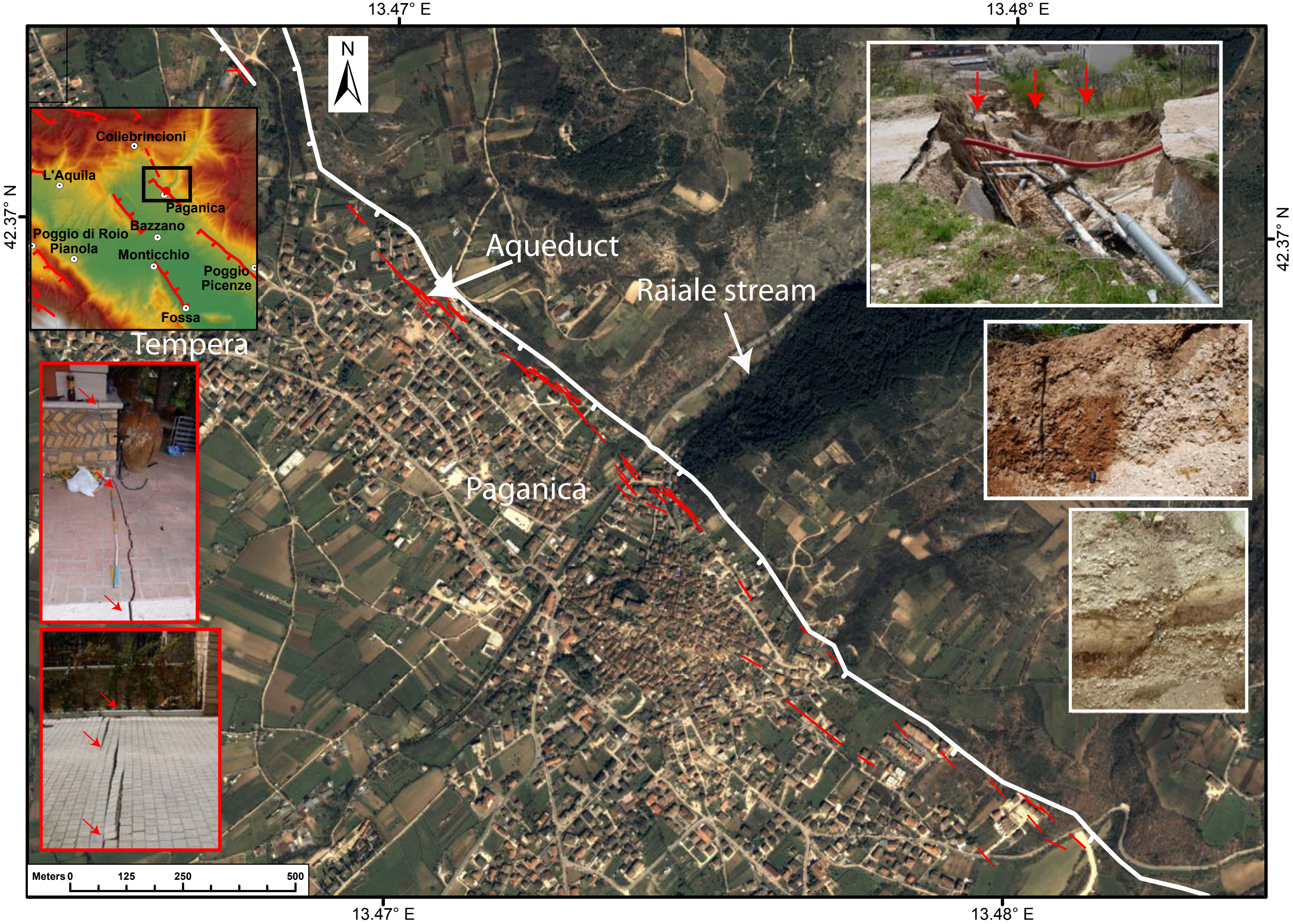


13.2
13.4
13.6
42.4
N
0 Km 5
Campotosto
Campotosto Lake
Montereale
Capitignano
9 April, Mw 5.4
1703
6.7
Cagnano Amiterno
Barete
Pizzoli
Aterno river valley
GRAN SASSO RANGE
B
C
Scoppito
L'AQUILA
Paganica
1958
5.2
6 April, Mw 6.3
1916
5.2
Tornimparte
Lucoli
Ocre
Fossa
1461
6.4
1762
5.9
Barisciano
San Demetrio ne' Vestini
Villa Sant'Angelo
Fagnano Alto
Rocca di Cambio
Fontecchio
7 April, Mw 5.6
A
D
L'Aquila 2009 seismic sequence
1 <Ml< 3
3 ≤Ml< 4
4 ≤Ml< 5
Ml≥ 5
Year
Mw
Historical Earthquakes
Focal mechanism solution
Active Normal Fault
Ocre Fault
Aterno valley
Pettino Fault
Paganica Fault
Gran Sasso Faults
SW
NE
NW
SE
Km
0
10
20
-30
-20
-10
0
10
20
30
-40
40


12°38'
42°46'
0 km 15
N
TERAMO
AMATRICE
Adriatic Sea
PESCARA
CHIETI
Reatini Mts.
Sibillini thrust
Montagna dei Fiori
Gran Sasso Range
RIETI
Gabbia
Giano Mts.
L'AQUILA
Aterno river basin
Ocre Mt.
Sirente Mt.
Velino Mt.
Sabini Mts.
Morrone Mt.
Maiella Mt.
SULMONA
AVEZZANO
Fucino basin
Simbruini Mts.
Roveto Valley
Marsica
Ernici Mts.
Montagna Grande
Genzana Mt.
Apennines
41° 45'
14° 20'
1
2
3
4
5
6
7
8
9
10


Campotosto
Campotosto Lake
Montereale
Marana
Isola del Gran Sasso d'Italia
all data
A-186 measures, 77 max
370000
390000
4700000
4680000
Pizzoli
Arischia
Assergi
Collebrincioni
Preturo
Coppito
L'Aquila
Paganica
Castel del Monte
B-107 measures, 56 max
C-7 measures, 2 max
Poggio Roio
Pianola
Bazzano
Onna
Barisciano
Poggio Picenze
Monticchio
Sinizzo Lake
Fossa
Lucoli
S. Panfilo
S.Demetrio Ne' Vestini
Villa S. Angelo
Mt. Ocre
Rocca di Cambio
Tione degli Abruzzi
D-32 measures, 12 max
Ovindoli
LEGEND
tectonic rupture
shaking effect
no coseismic effect
active normal fault
Projection UTM Zone 33 - Datum WGS 1984
0 4 8 Km

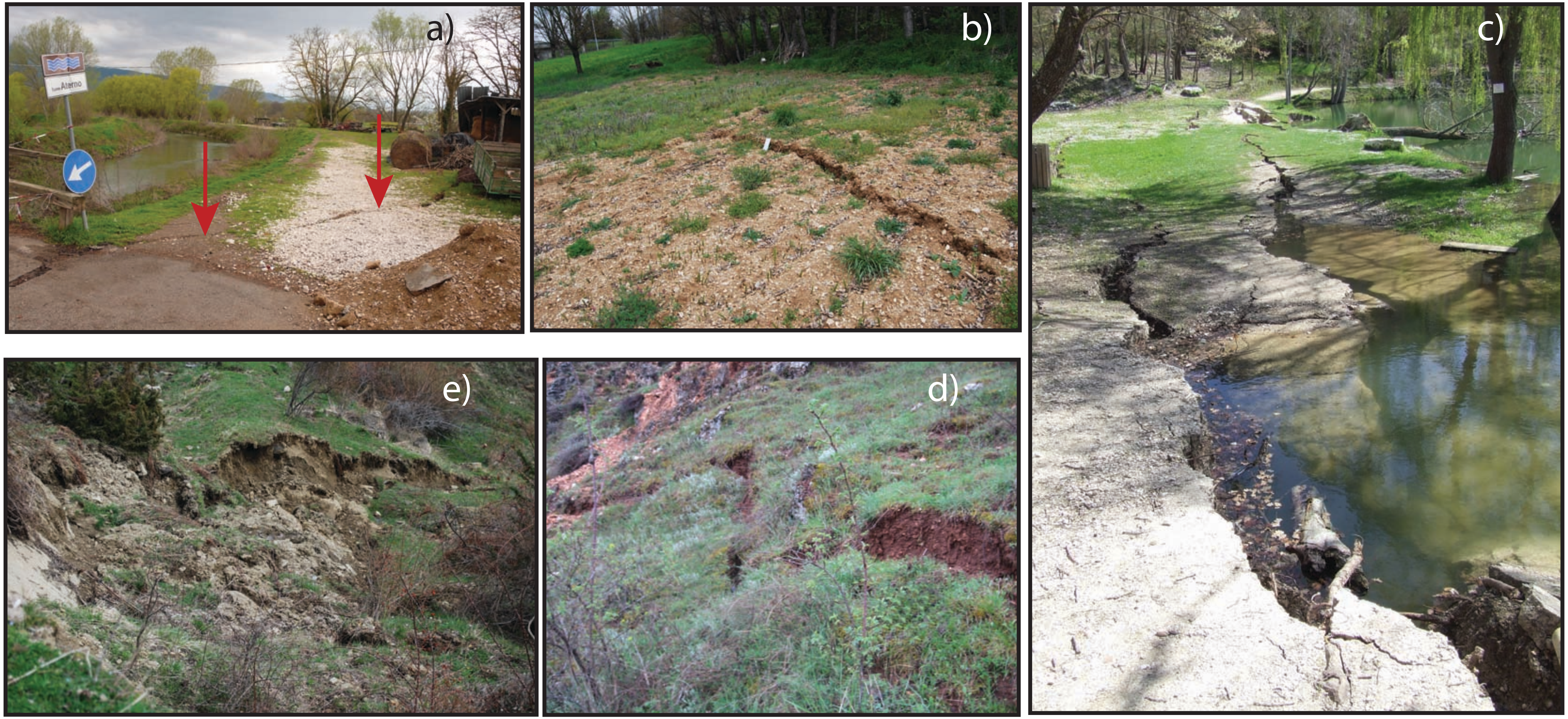

Ocre Range
Monticchio-Fossa Fault
Paganica Fault
Onna
Bazzano Fault

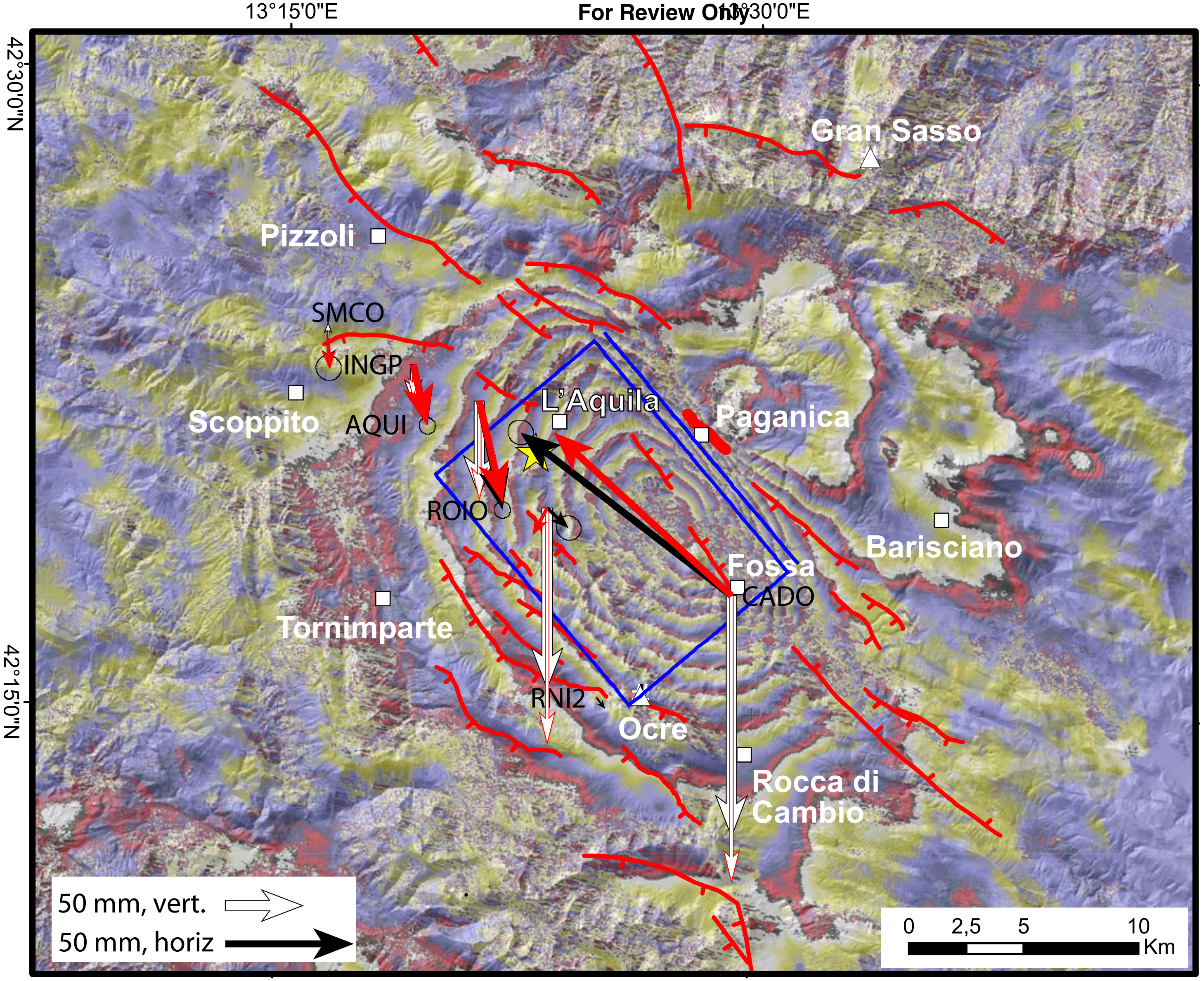

13.47° E
13.48° E
42.37° N
N
Collebrincioni
L'Aquila
Paganica
Poggio di Roio
Bazzano
Pianola
Monticchio
Poggio Picenze
Fossa
Tempera
Aqueduct
Raiale stream
Paganica
Meters 0 125 250 500


a)
b)


a)
b)


a
b
c


a)
Aterno
b)
c)
e)
d)


13°15'0"E
13°30'0"E
42°30'0"N
42°15'0"N
Gran Sasso
Pizzoli
SMCO
INGP
Scoppito
AQUI
L'Aquila
Paganica
ROIO
Barisciano
Fossa
CADO
Tornimparte
RNI2
Ocre
Rocca di Cambio
50 mm, vert.
50 mm, horiz
0
2,5
5
10
Km