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# A reversed hierarchy of active normal faults: the 6 April 2009, $M_w$ 6.3, L'Aquila earthquake (Italy)

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## Abstract

Understanding the relationship between seismogenic slip at depth and surface deformation is fundamental in any seismic hazard analysis because the assessment of the earthquake potential of large continental faults relies largely on field investigations. The well-documented 6 April 2009,  $M_w$  6.3, L'Aquila earthquake affords a unique opportunity to explore the relationships between the activity of the deep source and its surface evidence.

We used available high-resolution geologic, geodetic and seismological data aided by analogue modeling to reconstruct the geometry of the seismogenic rupture in relation with surface and sub-surface faults.

We contend that the earthquake was caused by a blind fault, controlled at depth by pre-existing discontinuities and expressed at the surface by pseudo-primary breaks resulting from coseismic crustal bending.

Finally, we propose a scheme for hierarchizing normal faults that explains all surface occurrences related to blind faulting in the frame of a single, mechanically coherent, interpretative model. Failure to appreciate such complexity may result in severe over- or under-estimation of the local seismogenic potential.

## 1 Introduction

A number of recent damaging earthquakes worldwide were generated by previously unmapped, blind or hidden faults (e.g. January 2010, Haiti,  $M_w$  7.0; September 2010–February 2011, Darfield-Christchurch, New Zealand,  $M_w$  7.1–6.3; October 2011, Van, eastern Turkey,  $M_w$  7.1). The 6 April 2009 L'Aquila earthquake ( $M_w$  6.3) belongs to this category as it occurred on a previously unidentified seismogenic source. As most of the studies for investigating the earthquake potential of large continental faults are based on strictly surficial data and investigations (e.g. Wells and Coppersmith, 1994; Wesnousky, 2008), understanding how seismogenic slip at depth relates to surface

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deformation is a fundamental pre-requisite in any seismic hazard analysis. Although the L'Aquila region had long been known for its high seismicity level, the 2009 earthquake challenged the standard approach for active fault identification because (1) almost all studies carried out prior to it inexplicably failed to identify its causative source, and (2) presumed active faults showed partial or no reactivation.

The 2009 L'Aquila earthquake struck a seismically very active portion of the Apennines chain, a region undergoing NE-SW extension at  $2\text{--}3\text{ mm yr}^{-1}$  (D'Agostino et al., 2011). Due to the combined effect of tectonic stress and gravity, extended terrains often exhibit a remarkable complexity that makes the correct hierarchization of active faults – or even their mere identification – extremely challenging. In the Abruzzi Apennines (central Italy) these circumstances are worsened by the superposition of different tectonic regimes and by selective exhumation caused by vigorous regional-scale uplift at  $1\text{--}2\text{ mm yr}^{-1}$  (D'Anastasio et al., 2006). As a result, the region is criss-crossed by many 5–10 km-long normal faults mapped as active features, although their limited spacing ( $\sim 5\text{ km}$ ) is enough to suggest that they cannot all reach seismogenic depth (Vannoli et al., 2012).

Being the best documented normal faulting event worldwide, the 2009 earthquake makes a unique case for exploring the relationships between the activity of the deep source and its surface evidence. We used a wealth of high-resolution geologic, geodetic and seismological data combined with analogue modeling to reconstruct the geometry of the seismogenic rupture in relation with sub-surface and surface faults. We aimed at devising a scheme for normal fault hierarchization that explains all surface outcomes of seismogenic faulting in the frame of a single, mechanically coherent interpretative model. Proper appreciation of such complexity forms the basis for a correct assessment of the local earthquake potential.

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## 2 Tectonic and seismological setting

The complex structure of the Apennines results from subsequent tectonic phases. At the onset of the Mesozoic the region was part of the African passive margin of the Tethys Ocean; it hosted large carbonate platforms and intervening pelagic basins, subsequently broken up by Triassic-Lower Jurassic extension (Calamita et al., 2011). Since the Cretaceous the region has evolved within the framework of the convergent motion between the African and European plates; east to northeast-verging thrusts and associated foredeep/thrust-top basins progressed toward the Adriatic foreland up to the Mid-Pleistocene (Patacca and Scandone, 1989) and were subsequently dissected by strike-slip and normal faulting. Following a major geodynamic change at  $\sim 800$  ka, SW-NE extension has become the dominant tectonic style over the core of the Apennines (Hyppolite et al., 1994; Galadini, 1999), as demonstrated also by breakout and seismicity data (Montone et al., 2012).

The L'Aquila earthquake was generated by nearly a meter of slip over a planar,  $\sim 16$  km-long,  $45\text{--}50^\circ$  SW-dipping normal fault (for a summary see DISS Working Group, 2010; Vannoli et al., 2012). The 6 April mainshock was the culmination of a long foreshock/aftershock sequence recorded by permanent and temporary INGV seismometers (Chiaraluce et al., 2011). Due to the high quality of available data, the whole sequence has been the object of several investigations, resulting in over 100 papers published to date. Instrumental data, including high-resolution aftershock locations, GPS observations and DInSAR measurements based on Envisat and COSMO-SkyMed data, revealed coseismic slip between 9–10 to 2–3 km depth, resulting in bowl-shaped, gently-asymmetric surface subsidence up to 15–20 cm (Atzori et al., 2009; D'Agostino et al., 2012; Fig. 1). The mainshock caused faint, discontinuous surface fractures along a structural feature referred to as Paganica fault, with a maximum net throw of  $\sim 5$  cm (Emergeo Working Group, 2010). Conversely, no genuine slip was reported along a number of steep, clearly exposed, well known, presumably active faults

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lying in the epicentral area: e.g. Pizzoli, Pettino, Stabiata and Bazzano faults (Emergeo Working Group, 2010).

The large density of faults, coupled with a limited historical earthquake record, is perhaps at the basis of a sort of “L’Aquila paradox” (Valensise, 2009). In a study based on a mixed geological-statistical approach (Akinci et al., 2009) the area of the future 2009 earthquake was given a very high probability of experiencing strong ground shaking in the following 50 yr. This conclusion was supported by the many seismogenic sources included in the input model; ironically though, the corresponding surface primary active faults did not include the Paganica fault because of its weak geomorphic expression. For the same reason the Paganica fault received little attention in studies carried out prior to 2009, some of which referred to it as “uncertain or buried” (Geological Map of Italy, 2009) while others did not map it at all (Galadini and Galli, 2000).

What is the basis for this “reversed hierarchy”, such that the main seismogenic fault lies hidden beneath a blanket of clearly visible yet substantially harmless faults? What are its potential implications for seismic hazard assessment? Can we derive from this earthquake a general rule to be used in other normal faulting environments?

### 3 Seismotectonic model

The strain pattern revealed by DInSAR analyses matches well the architecture of the intramountain basin (Improta et al., 2012) overlying the main coseismic slip patch, suggesting that the long-term tectonic strain in this area is the result of sustained slip over the fault plane that ruptured on 6 April. It also shows the largest subsidence at a relatively far distance from the Paganica fault (Fig. 1), consistent with limited or no coseismic slip in the uppermost 3 km of the crust. DInSAR data also revealed sizable postseismic strains in the region above the tip of the master fault (D’Agostino et al., 2012; Fig. 1), in agreement with direct evidence from TLS observations (Wilkinson et al., 2010), but limited or no postseismic slip along deeper portions of the fault. This further suggests an effective decoupling between deep and surface deformation.

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Therefore, although most investigators agree on the primary character of the Paganica fault (to the point that the seismogenic source is called the same name), a direct connection of this surface feature with the deep fault is neither warranted by the pattern of surface strains nor by the aftershock locations, which clearly depict fault complexity at 2–3 km depth. Such conclusions are further supported by the cut-off depths of the aftershock pattern, a rather distinctive feature of the sequence (Chiarabba et al., 2009). The lower cut-off (9–10 km) has been interpreted either (a) as the bottom level of the seismogenic volume (Bianchi et al., 2010) or (b) as due to the presence of a non-optimally oriented inherited structure (Chiaraluce et al., 2011). Two competing hypotheses exist also for the upper cut-off (2–3 km): (a) the causative fault is “young” or “poorly-developed” and as such it has not yet reached the surface, or (b) pre-existing discontinuities control upward fault propagation. The alignment of several aftershocks along an interpreted sub-horizontal thrust plane running at about 3 km depth above the central portion of the seismogenic source (Chiaraluce et al., 2011) supports the latter hypothesis (Fig. 1c). It has long been known that in any fault zone the fracture propagation and arrest and the associated seismicity are largely controlled by the local stress field (e.g. Scholz, 2002). When a propagating fracture meets a mechanical discontinuity, such as a weak layer or a pre-existing fault, it may stop, penetrate it, or be deflected along it (e.g. Dyer, 1988). The structural complexity of the region hit by the 2009 earthquake guarantees that all these options are equally likely. In their turn, the scattered aftershocks located above the upper seismicity cut-off near the northern end of the fault (Fig. 1c) suggest that the mainshock triggered pre-existing complex discontinuities, although with limited displacement; a hypothesis supported by the minor post-seismic surface strain patch located above this shallow blind structure.

#### 4 Blind and surface faulting: an alternative model

If the causative source of the 2009 earthquake is a blind fault, what is the origin of the associated breaks (i.e. the Paganica Fault), and why is the observed surface throw so

limited in size? In view of its implications for the identification and correct hierarchization of active faults in earthquake-prone areas, we chose to test this circumstance with a simple analogue experiment. Scaled experimental models have been widely used to understand and document the evolution of faults and related folds for decades (e.g. Withjack and Schlische, 2006; Miller and Mitra, 2011). We designed a model specifically aimed at detecting brittle structures developed above a blind normal fault (Fig. 2). Our technique follows well established rules (e.g. Shellart, 2000; Bonini et al., 2011) aimed at reproducing the brittle behavior of upper crustal carbonate rocks (up to 3 km depth) similar to those that exist in the L'Aquila region. As a reference natural rock we selected a fractured limestone having the following properties: cohesion 15 MPa, coefficient of internal friction 0.53, angle of internal friction  $27.9^\circ$  (Handin, 1969). For the analogue material we used dry quartz sand having the following mechanical properties: cohesion 230 Pa, coefficient of internal friction 0.88, angle of internal friction  $41^\circ$ . The experiment took place in a normal gravity field with a geometric scale ratio of  $2 \times 10^{-4}$  (1 cm equals 0.5 km in nature).

We reproduced an asymmetric basin made up of analogue material layers using a flexing plate. The folding shape was fixed to reproduce the pattern of coseismic deformation (Fig. 1), with a basin depocenter located at the same relative position as that shown by DInSAR data at L'Aquila (Fig. 2b). During the experiment, a *forced-fold* developed above the tip of the assumed blind fault; as a result of bending, a series of crestal fractures, some showing measurable vertical throw, formed where the tensile stress is maximum, that is to say along the hypothetical up-dip prolongation of the main seismogenic fault (Fig. 2b) but not in connection with the fault itself. Overall these structures are reminiscent of the bending-moment faults observed in nature, a rare but mechanically feasible phenomenon in normal faulting environments. All the result reproduce well the data and knowledge available for the Paganica fault. Moreover, our analogue models show the mechanical feasibility of a long-lived buried extensional master fault with disconnected secondary normal faults lying along the same hypothetical plane.

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## 5 Conclusions

Our analysis of seismogenic faulting in the L'Aquila area revealed an unprecedented complexity in the interaction between coseismic slip and pre-existing structural features. In particular, it suggested that the main surface coseismic rupture, the Paganica fault, is likely a result of surface bending rather than the direct prolongation of the seismogenic fault. Under these circumstances the length of the faulted zone and the extent of surface slip would be controlled more by the rheology of shallow deposits than by slip at depth; this would ultimately prevent the surface rupture parameters from being used to derive the earthquake magnitude using empirical relationships (e.g. Wells and Coopersmith, 1994), both for the current event and for earthquakes detected through paleoseismological trenching. This conclusion justifies both the hidden nature of the earthquake causative fault prior to 2009 and the multiple divergent proposed surface rupture models (see Vittori et al., 2011; Vannoli et al., 2012, for a review). We believe the L'Aquila earthquake illustrates well the nature of the interaction between the seismogenic rupture and other pre-existing structures at depth (e.g. buried thrust planes), the partial reactivation of pre-existing surface faults (e.g. Bazzano, Mt. Stabiata and Pettino faults), and the occurrence of pseudo-primary surface ruptures (Paganica Fault).

In summary we contend that the “unusual” 6 April 2009 L'Aquila earthquake in fact illustrates a common style of complex tectonic deformation, implying that the number of hidden seismogenic faults in Italy – and probably elsewhere – is larger than previously thought. Driven by the current tectonic regime such faults break through a highly complex upper crust, interacting in various ways with the existing structural fabric. This may result in limitations of their size, reactivation of older faults and generation of new surface breaks. What is absolutely crucial for the geological reconnaissance work is that in the field these highly diverse faults may exhibit a reversed hierarchy, the most obvious being the least relevant to fault-based seismic hazard assessment and vice-versa.

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bounding piggy-back basins, or more in general accompanying the progression of thrusting during the emplacement of the Apennines chain. They are generally very evident in the field and may or may not be reactivated, depending on their location and geometry relative to the coseismic strain pattern imposed by the master fault. They may be relevant to the assessment of ground shaking hazard due to fault-trapped waves (Calderoni et al., 2012), whereas due to their clear visibility they pose limited surface faulting hazard.

Full and proper appreciation of this hierarchy, to be achieved by blending surface, sub-surface, geomorphic, structural and seismological data, is mandatory for a correct assessment of the nature and extent of the associated seismic hazard.

*Acknowledgements.* This work was financially supported by Regione Lombardia, INGV and Presidenza del Consiglio dei Ministri – Dipartimento della Protezione Civile (DPC). The views and conclusions contained in this paper are those of the authors and should not be interpreted as necessarily representing official opinions and policies, either expressed or implied, of the Italian Government.

## References

- Akinci, A., Galadini, F., Pantosti, D., Petersen, M., Malagnini, L., and Perkins, D.: Effect of time dependence on probabilistic seismic-hazard maps and deaggregation for the Central Apennines, Italy, *B. Seismol. Soc. Am.*, 99, 585–610, 2009.
- Atzori, S., Hunstad, I., Chini, M., Salvi, S., Tolomei, C., Bignami, C., Stramondo, S., Trasatti, E., Antonioli, A., and Boschi, E.: Finite fault inversion of DInSAR coseismic displacement of the 2009 L'Aquila earthquake (central Italy), *Geophys. Res. Lett.*, 36, L15305, doi:10.1029/2009GL039293, 2009.
- Bianchi, I., Chiarabba, C., and Piana Agostinetti, N.: Control of the 2009 L'Aquila earthquake, central Italy, by a high-velocity structure: A receiver function study, *Geophys. Res. Lett.*, 115, B12326, doi:10.1029/2009JB007087, 2010.



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- Dyer, R.: Using joint interactions to estimate paleostress ratios, *J. Struct. Geol.*, 10, 685–699, 1988.
- Emergeo Working Group: Evidence for surface rupture associated with the Mw 6.3 L'Aquila earthquake sequence of April 2009 (central Italy), *Terra Nova*, 22, 43–51, 2010.
- Galadini, F.: Pleistocene changes in the central Apennine fault kinematics: a key to decipher active tectonics in central Italy, *Tectonics*, 18, 877–894, 1999.
- Galadini, F. and Galli, P.: Active Tectonics in the Central Apennines (Italy) – Input Data for Seismic Hazard Assessment, *Nat. Hazards*, 22, 225–268, 2000.
- Geological Map of Italy: L'Aquila sheet, no. 359, 1:50 000 scale, [http://www.isprambiente.gov.it/MEDIA/carg/359\\_LAQUILA/Foglio.html](http://www.isprambiente.gov.it/MEDIA/carg/359_LAQUILA/Foglio.html), 2009.
- Handin, J.: On the Coulomb–Mohr failure criterion, *J. Geophys. Res.*, 74, 5343–5348, 1969.
- Hyppolite, J.-C., Angelier, J., and Roure, F.: A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy), *Tectonophysics*, 230, 199–210, 1994.
- Improta, L., Villani, F., Bruno, P. P., Castiello, A., De Rosa, D., Varriale, F., Punzo, M., Brunori, C. A., Civico, R., Pierdominici, S., Berlusconi, A., and Giacomuzzi, G.: High-resolution controlled-source seismic tomography across the Middle Aterno basin in the epicentral area of the 2009, Mw 6.3, L'Aquila earthquake (central Apennines, Italy), *Italian J. Geosci.*, 131, 373–388, 2012.
- Miller, J. F. and Mitra, S.: Deformation and secondary faulting associated with basement-involved compressional and extensional structures, *AAPG Bull.*, 95, 675–689, 2011.
- Montone, P., Mariucci, M. T., and Pierdominici, S.: The Italian present-day stress map, *Geophys. J. Int.*, 189, 705–716, 2012.
- Patacca, E. and Scandone, P.: Post-Tortonian mountain building in the Apennines, The role of the passive sinking of a relic lithospheric slab: The Lithosphere in Italy, in: *Accademia dei Lincei*, edited by: Boriani, A., Bonafede, M., Piccardo, G. B. and Vai, G.G., Roma, 157–176, 1989.
- Satolli, S. and Calamita, F.: Differences and similarities between the Central and the Southern Apennines (Italy): examining the Gran Sasso vs. the Matese-Frosolone salients using paleomagnetic, geological and structural data, *J. Geophys. Res.*, 113, B10101, doi:10.1029/2008JB005699, 2008.

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Schellart, W. P.: Shear test results for cohesion and friction coefficients for different granular materials: scaling implications for their usage in analogue modeling, *Tectonophysics*, 324, 1–16, 2000.

Scholz, C. H.: *The Mechanics of Earthquakes and Faulting*, 2nd Edn., 471, Cambridge, New York, Melbourne: Cambridge University Press, 2002.

Scognamiglio, L., Tinti, E., Michelini, A., Dreger, D. S., Cirella, A., Cocco, M., Mazza, S., and Piatanesi, A.: Fast determination of moment tensors and rupture history: What has been learned from the 6 April 2009 L'Aquila earthquake sequence, *Seismol. Res. Lett.*, 81, 892–906, 2010.

Valensise, G.: Faglie attive e terremoti: Tempo di cambiare strategie, *Geoitalia*, 28, 12–17, [http://www.geoitalia.org/upload/home\\_page/geoitalia/n28.pdf](http://www.geoitalia.org/upload/home_page/geoitalia/n28.pdf) (last access: September 2009), 2009.

Vannoli, P., Burrato, P., Fracassi, U., and Valensise, G.: A fresh look at the seismotectonics of the Abruzzi (Central Apennines) following the 6 April 2009 L'Aquila earthquake (Mw 6.3), *Italian J. Geosci.*, 131, 309–329, 2012.

Vezzani, L., Festa, A., and Ghisetti, F.: Geological-structural map of the Central-Southern Apennines (Italy), 1 : 250 000 scale (S.E.L.C.A. ed., Firenze, 2009), 2009.

Vittori, E., Di Manna, P., Blumetti, A. M., Commerci, V., Guerrieri, L., Esposito, E., Michetti, A. M., Porfido, S., Piccardi, L., Roberts, G. P., Berlusconi, A., Livio, F., Sileo, G., Wilkinson, M., McCaffrey, K. J. W., Phillips, R. J., and Cowie P. A.: Surface Faulting of the 6 April 2009 Mw 6.3 L'Aquila Earthquake in Central Italy, *B. Seismol. Soc. Am.*, 101, 1507–1530, 2011.

Wells, D. L. and Coppersmith, K. J.: New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *B. Seismol. Soc. Am.*, 84, 974–1002, 1994.

Wesnousky, S. G.: Displacement and geometrical characteristics of earthquake surface ruptures: Issues and implications for seismic hazard analysis and the earthquake rupture process, *B. Seismol. Soc. Am.*, 98, 1609–1632, 2008.

Wilkinson, M., McCaffrey, K. J. W., Roberts, G. P., Cowie, P. A., Phillips, R. J., Michetti, A., Vittori, E., Guerrieri, L., Blumetti, A. M., Bubeck, A., Yates, A., and Sileo, G.: Partitioned postseismic deformation associated with the 2009 Mw 6.3 L'Aquila earthquake surface rupture measured using a terrestrial laser scanner, *Geophys. Res. Lett.*, 37, L10309, doi:10.1029/2010GL043099, 2010.

Withjack, M. O. and Schlische, R. W.: Geometric and experimental models of extensional fault-bend folds, *Geol. Soc. Sp.*, 253, 285–305, 2006.

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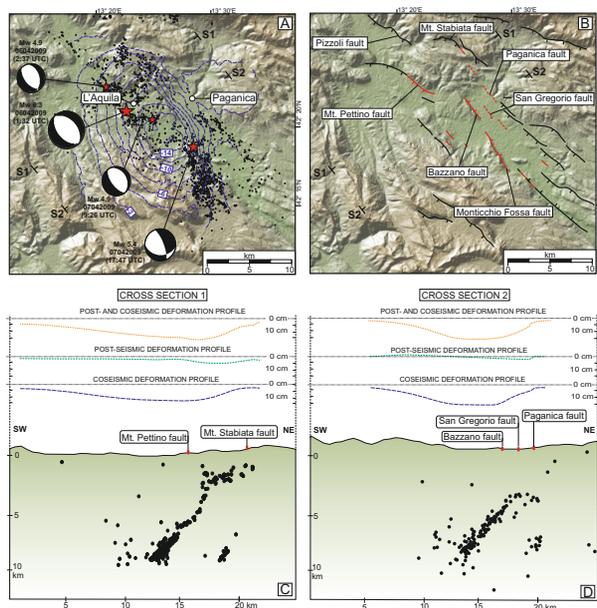
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**Fig. 1.** (A) Map view of the L'Aquila area showing the location (red stars) and focal mechanism of the largest events of the 2009 sequence (Scognamiglio et al., 2010). Blue dashed lines are contours of the elevation changes observed between 4 and 12 April 2009 (D'Agostino et al., 2012). (B) Mapped active faults, shown by black lines; those shown in red were reported reactivated in 2009 (Emergeo Working Group, 2010). S1, S2 indicate the traces of cross Sects. 1 and 2. (C) and (D) cross sections, showing dominantly coseismic (D'Agostino et al., 2012) (4 April 2009–12 April 2009; blue dashed line), post seismic (D'Agostino et al., 2012) (12 April–5 October 2009; green dotted line) and cumulative elevation changes (orange dotted line) measured along the section trace. In all figures black dots indicate relocated aftershocks (Chiarabba et al., 2009; Chiaraluce et al., 2011).

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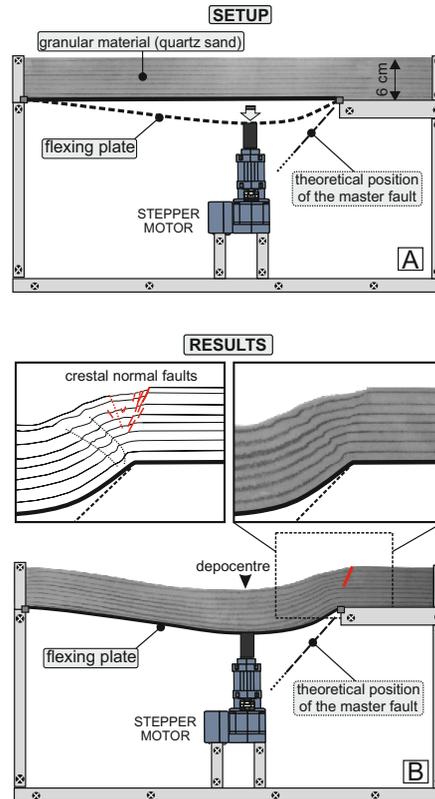
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**Fig. 2.** Analogue modelling setup and results. **(A)** Sketch of the experimental modelling apparatus. The granular material (quartz sand) is deformed above a flexing plate pulled by a stepper electric piston. A dashed line indicates the theoretical position of the master (seismogenic) fault. **(B)** Detail of the results of the experiment; thick black lines represent newly formed faults (Category #3 faults, see text).

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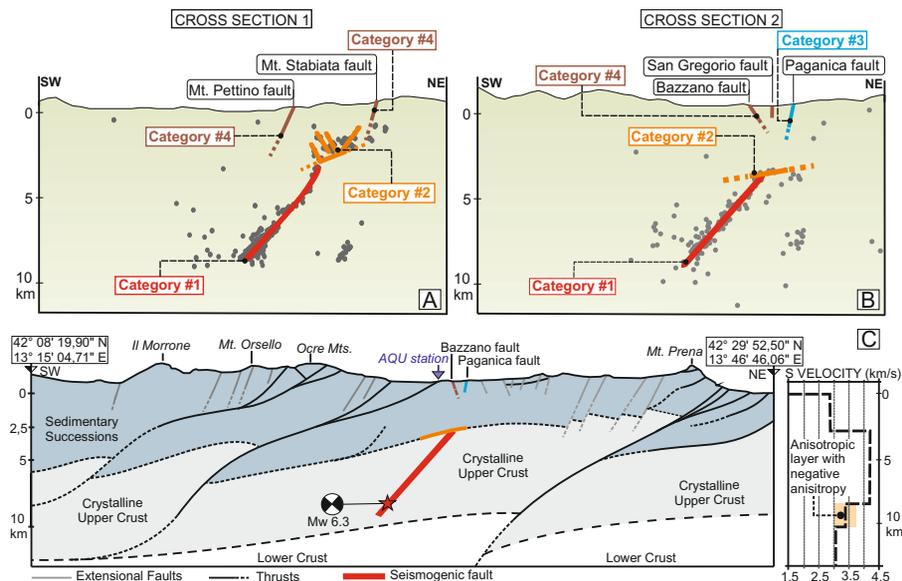
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**Fig. 3.** (A) and (B) are Sect. 1 and Sect. 2 across two portions of the seismogenic fault. Red lines delineate the mainshock rupture. Orange lines identify secondary blind faults whose activity was triggered by the mainshock. A blue line marks the Paganica fault. Brown lines describe the geometry of the active faults not directly connected to the main seismogenic fault. (C) Regional cross-section showing the main tectonic features of the area (modified after Satolli and Calamita, 2008; Vezzani et al., 2009). The main seismogenic rupture is shown in red along with the focal mechanism and rupture nucleation. The small diagram to the right shows the S velocity model (black dashed line) for seismological station AQU from Bianchi et al. (2010).

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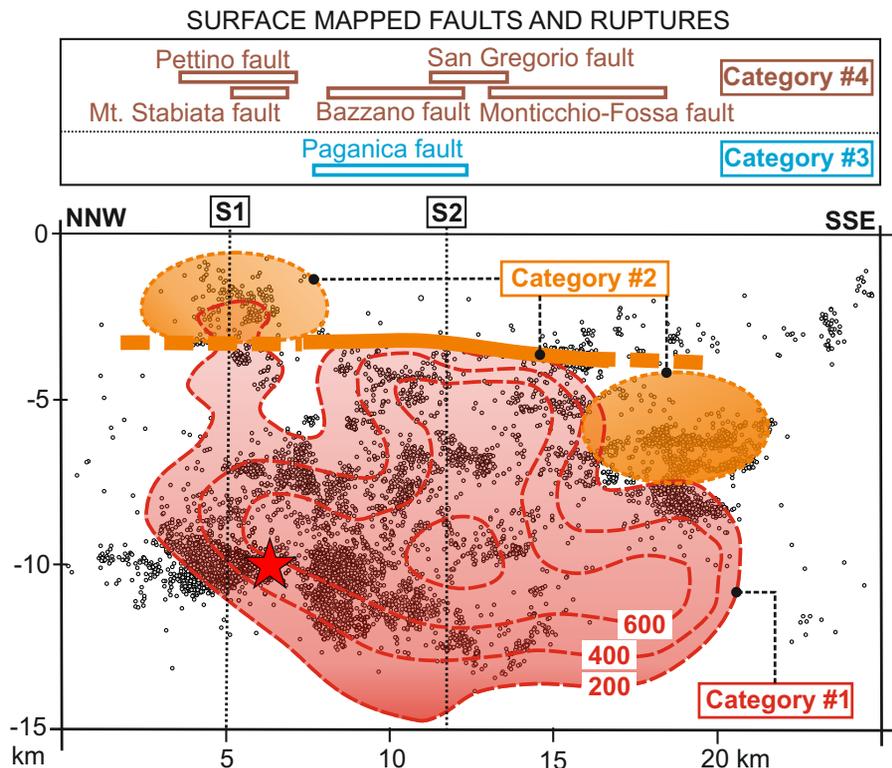
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**Fig. 4.** Down-dip section along the L'Aquila master fault (strike N135E; dip 50° to the SW), showing the mainshock location (red star); black dots are aftershocks located within 0.5 km of the fault plane (Chiaraluze et al., 2011); red dashed lines show the coseismic slip pattern (contours in mm; Atzori et al., 2009) and the location of the secondary faults (orange line and ellipses). The box above shows the categorization of surface faults and their relative location along strike of the master fault.

**A reversed hierarchy of active normal faults: L'Aquila earthquake (Italy)**

L. Bonini et al.

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