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Contrasting surface active faults and deep seismogenic sources unveiled by the 2009 L'Aquila earthquake sequence (Italy)

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ABSTRACT

How reliably can a seismogenic fault be identified in complex tectonic settings such as the Italian Apennines? The aftershocks of the Mw 6.3, 2009 L'Aquila earthquake developed both on the primary seismogenic fault and on a northwestern, adjacent segment. Here, the active Gorzano normal fault is exposed, and many seismogenic models are based on it. Compared with the tectonic setting, however, the 2009 aftershock sequence shows that the deep seismogenic fault does not correspond with the exposed fault plane. The latter flattens at a depth of ~4 km, and is totally hosted within a 6–7 km-thick thrust sheet. The 2009 earthquake sequence, instead, depicts an independent fault in a deeper thrust sheet. The Gorzano fault is kinematically reactivated only at the hangingwall of the deeper fault. In complex tectonic settings, seismogenic faults can be properly characterized only through the joint analysis of many independent geological and geophysical data.

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Introduction

There are places in the world where active faults superbly exposed at the surface are not directly related with seismogenic faults at depth, or, vice versa, where deep seismogenic faults do not have clear surface expression (e.g., Valensise and Ward, 1991; Yeats and Huftile, 1995; Morley, 2007; Chen *et al*., 2010). This circumstance poses a problem for the development of fault-based seismic scenarios and hazard maps. Relying only on surface fault analysis, not integrated with other independent data, this could drive to incorrect seismogenic source models.

The Central Apennines of Italy are one of these places, because SW-NE extension is affecting a region previously deformed by severe compression (Royden *et al*., 1987; Casero, 2004; Vezzani *et al*., 2010). Here, moderate to large magnitude earthquakes frequently occur (CPTI Working Group, 2004). On April 6th 2009, a Mw 6.3 earthquake struck the town of L'Aquila and surroundings causing 308 deaths. The aftershock sequence (Fig. 1A) developed both on the primary seismogenic fault (Atzori *et al*., 2009) and on an adjacent en-échelon segment, located in the Laga Mts region, culminating with a Mw 5.4 earthquake (on April 9th, 2009). In this northern area, fault mapping is extensive (e.g., Vezzani and Ghisetti, 1998; ITHACA Working Group, 2000; Boncio *et al*., 2004). The majority of the studies agree with the existence of an active, N150°-striking, 60°-70°-dipping normal fault, which bounds the western slope of Mt. Gorzano (hereinafter Gorzano fault; Fig. 1B); the clearest evidence is reported for the southernmost 10 km of the fault (Galadini and Galli, 2003; with references). Accordingly, all seismogenic models of Central Apennines refer to the Gorzano fault, extrapolating its geometry down to hypocentral depths of ~15 km (e.g., Boncio *et al*., 2004; Pace *et al*., 2006; Akinci *et al*., 2009; DISS Working Group, 2009).

The 2009 earthquake sequence poses some evidence that a direct extrapolation of surface data to depth may be misleading. Aftershock distribution striking ~N130°–135° (Chiarabba *et al*., 2009) and related focal mechanisms (Pondrelli *et al*., 2010) show that the deep seismogenic fault progressively diverges from the Gorzano fault moving towards NW (Fig. 1A). This distribution has been further constrained by recent papers that relocate more precisely the foreshock and aftershock sequence (Chiaraluce *et al*., 2011a, b).

The aim of this work was to discuss how much reliably a seismogenic fault can be identified in a complex tectonic setting such as the Apennines, where the stress field has recently changed from compression to extension (e.g., Vezzani *et al*., 2010). We use seismological, geological and geophysical data to constrain the fault geometry at depth and investigate if the apparent inconsistency between shallow and deep data might be reconciled. We integrate earthquakes distribution and geological models obtained from a joint interpretation of geological survey and seismic reflection data. This latter set of evidence takes strength from a dense grid of reflection seismic lines, calibrated with deep well logs (Fig. 3).

Clues from instrumental seismicity

Seismologic data are well constrained by INGV national and regional permanent networks and some temporary stations deployed soon after the main event. These networks were strongly improved in the last few years and are now capable of resolving details on the active faults at depth. We selected earthquakes originally located by Chiarabba *et al*. (2009), occurred in the period April-September 2009, from a

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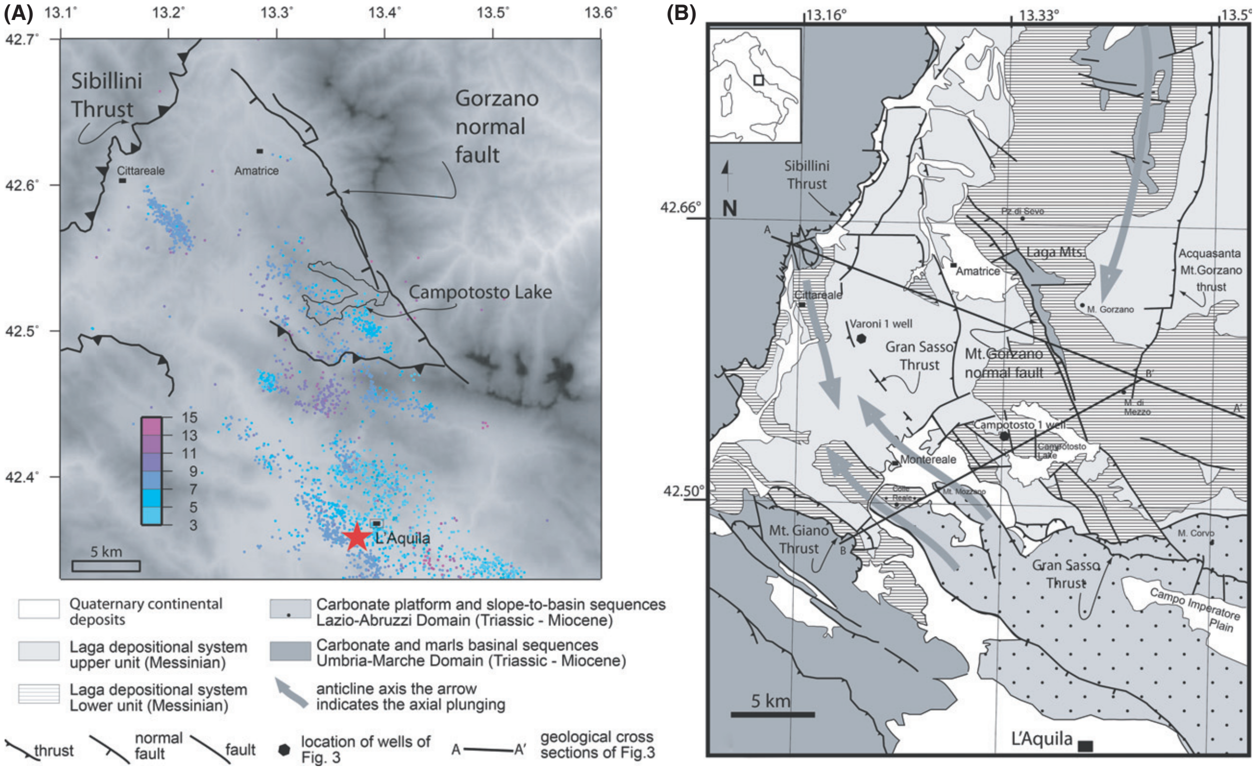

Fig. 1 (A) Northern part of the 2009 L'Aquila earthquake sequence. Numbers along the scale indicate depths in kilometres. Star: mainshock epicentre (April 6th 2009, Mw 6.3). (B) Geological setting of the study area (from Centamore *et al.*, 1992b, modified). Notice the difference between the strike of the earthquake sequence in the Campotosto area and the Gorzano fault trend.

huge set of more than 12000 events. The good consistency between the locations obtained for the whole sequence and those accurately verified for a small subset of $M_L \geq 2.3$ aftershocks occurred during the first 30 days (~4,000 events), after the refinements of P- and S-wave picks at digital recordings at three-component seismic stations, is a good indication of robustness of seismologic data. The locations used in this work have formal errors < 1.0 km and give a first order image of the ruptured fault segments.

In the Laga Mts, the aftershocks distribution shows a NW-striking elongation (Fig. 1A) with hypocentres prevalently confined between 5 and 10 km of depth. The seismicity defines two main clusters, active during different periods (April-June, June-August). The principal and southernmost cluster, located to the west of the Laga Mts, has a very clear SW-dipping plane, whereas the northernmost one has a prevalently sub-vertical geometry. The focal mechanism of the M_w 5.4 event, occurred within the principal cluster, has one of the nodal planes that strikes N136°–46° (Pondrelli *et al.*, 2010), and this is perfectly consistent with the fault geometry identified by the aftershocks distribution.

Contrasting structural evidence

The Campotosto area is located in the western sector of the Laga basin, which is one of the widest foredeep basins of the Central Apennines (Messinian age; Centamore *et al.*, 1992a,b; Casero *et al.*, 1991; Bigi *et al.*, 1999; Mazzoli *et al.*, 2002; Bigi *et al.*, 2009). We analysed this area through a dataset of seismic lines, calibrated by borehole data, which comprises profiles acquired in the years 1983–1985. This dataset allowed reconstructing the geometry of the whole Laga basin substratum (Bigi *et al.*, 2011). We used part of this dataset to define at depth the detailed geometry of the Gorzano fault (Fig. 2).

The Campotosto area is at the footwall of the Sibillini thrust, which is exposed with a SW–NE trend to the west of the study area (Fig. 1). Moreover, this area forms part of the footwall of the Gran Sasso thrust, which displays here a NNW–SSE trend. Immediately to the east, in the footwall of the Gran Sasso thrust, the contractional structures of the Acquasanta-Gorzano thrust show a main N–S trend. In the Mt. Gorzano area, the thrust displacement at the front of the structure is very limited, and the westward dipping Gorzano fault offsets the backlimb of the hangingwall anticline.

Differing from the strike of the earthquake sequence in the Campotosto area, the Gorzano fault trends NNW-SSE and is ~30 km-long. The hangingwall of this normal fault hosts the Amatrice basin, filled by Quaternary continental deposits (Cacciuni *et al.*, 1995). The maximum offset reaches the value of ~1500–1800 m where the fault places the upper unit of the Laga Depositional Sequence (late Lower Messinian) onto the bottom of the same sequence, i.e. the

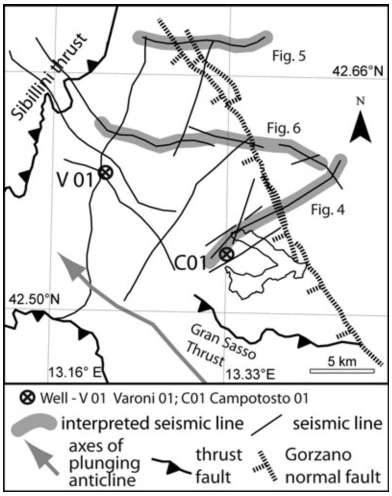

Fig. 2 Dataset of reflection seismic lines and deep wells used in this work. Trace of profiles in Figs 4–6 are also shown. The fault geometry reconstructed in this work was obtained by interpreting the entire dataset shown in figure to reconstruct in 3D the upper crustal volume of the study area.

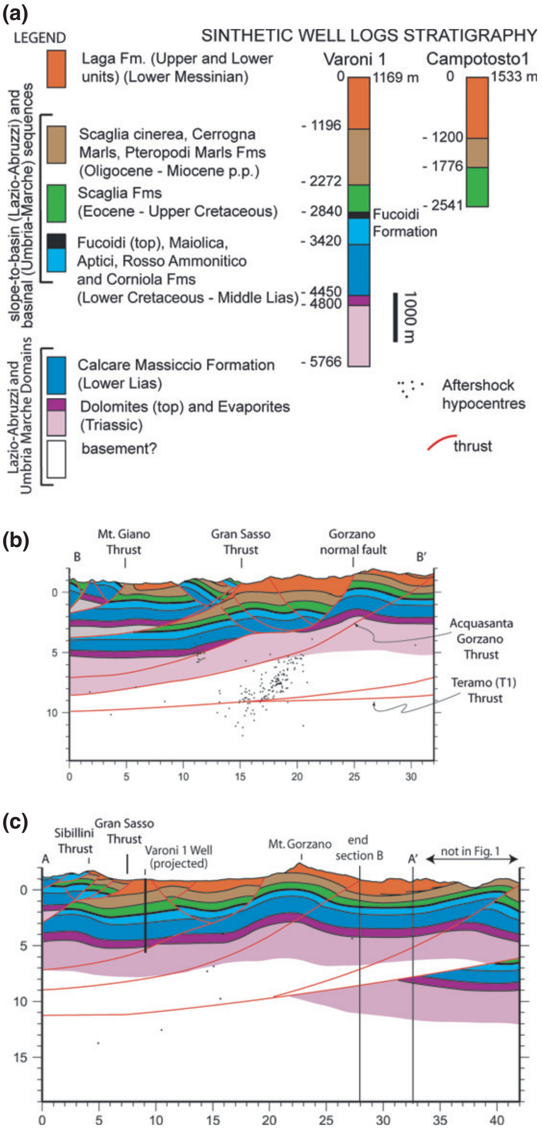

Fig. 3 Simplified well logs (a), and geological sections (b) and (c) across the Gorzano fault (modified from Bigi *et al.*, 2011). The scale for the Fucoidi marls and Evaporites in the Varoni 1 well stratigraphy is not respected to make them visible. The 2009 earthquake sequence is also projected. Cross-sections location is in Fig. 1B. The Gorzano fault is entirely confined in the upper thrust sheet, whereas the earthquake sequence, that is a direct expression of the stress field presently acting in the study area, is located within a deeper thrust sheet.

marls of the ‘‘Marne a Pteropodi’’ and ‘‘Marne con Cerrogna’’ Formations (Tortonian p.p.–Messinian; Centamore *et al*., 1992a; b; Milli *et al*., 2007; Bigi *et al*., 2009, 2011; Fig. 3b and c). Despite its straight trace on the map, which would suggest a high dip angle at surface, neither is the fault plane exposed, nor can we assess its dip angle on the basis of available seismic lines, whose resolving power is typically low at shallow depth. The fault zone, about 3–4 m thick, is characterized by the disrupted strata of the Laga sandstone, and by sheared clays within the ‘‘Marne a Pteropodi’’ and ‘‘Marne con Cerrogna’’ Formations, where shear fractures showing dip slip kinematics can be observed. The fault trace extends further to the south and cuts the main thrust front of the Gran Sasso unit, at the base of Mt. Corvo (Fig. 1B). The displacement, however, is difficult to be measured here, because the fault offsets a pre-existing contractional structure.

The age of the main activity of the Gorzano fault is quite debated (e.g., Centamore *et al*., 1992a; b; Marsili and Tozzi, 1992; Cacciuni *et al*., 1995; Vezzani and Ghisetti, 1998; Ghisetti and Vezzani, 2000). The Amatrice basin developed during the Early Quaternary in response to the fault activity; moreover, Lower Pleistocene deposits that fill this depression show a displacement of ~30 m. Finally, activity along the southernmost ~10 km of the Gorzano fault is dated to the Holocene, therefore younger than the Amatrice basin age (Cacciuni *et al*., 1995; Galadini and Galli, 2003). Being the total displacement measured in the Messinian siliciclastic succession much higher than that observed in the overlying Quaternary deposits, we can conclude that large part of the fault activity occurred in Pliocene times. During this time interval, still characterized by compressional tectonics, the kinematics along this fault plane was quite complex. Although the total displacement is always normal along the fault, the correlation between the hangingwall and the footwall stratigraphic sequences suggests the occurrence of a reverse slip along the same plane, at least in its very early phase of deformation. In the fault footwall, the Mt. Gorzano sequence comprises a thick pile of arenaceous beds which correspond to the depocenter of the Laga basin and appear as well defined seismic facies. In the fault hangingwall, it is difficult to recognize a facies with the same characters and thickness. This suggests an inversion of the present-day topography in correspondence with the bottom of the basin (Bigi *et al.*, 2009). The rising of the Mt. Gorzano thrust could have induced the collapse of the Amatrice basin.

Reconciling different pieces of information

The Gorzano fault is crossed by several seismic profiles (both confidential and public; ViDEPI, 2010), which were calibrated and interpreted based on borehole data (Varoni-1 and Campotosto-1 wells; Figs 2 and 3). Seismic interpretation was carried out by identifying several seismic markers corresponding to the top of the formations: "Marne con Cerrogna" (marls; Tortonian), "Scaglia Rossa" (marly limestone; Eocene), "Marne con Fucoidi" (marls; Aptian-Albian), "Calcare Massiccio" (limestone; Sinemurian) and "Burano" (anhydrites; Rhaetian). The Burano Fm. is also characterized by a typical couple of reflectors at a distance of 200 ms TWT one from one other, due to ~400 m-thick dolostones located in the upper part of this formation (5100–5500 m interval in the Varoni-1 well).

We reconstructed the Gorzano fault geometry by picking the marker surfaces at both the hangingwall and footwall of the fault plane (Figs 4–6). At the hangingwall, these markers depict a rollover anticline, as suggested by the dip towards the fault plane of the whole sequence (both carbonate and siliciclastic deposits). The back limb of the rollover anticline dips progressively to the west, under the Gran Sasso thrust, following the ramp geometry of the more external Mt. Gorzano-Acquasanta thrust, which dips southwestward. This monocline is offset by an array of back thrusts that are splays of the Gorzano fault and balance part of the deformation in the hangingwall of the normal fault. The full reconstruction of the fault geometry, based on the available seismic lines, shows a lateral variability of the fault dip, which appears as relatively steeper to the north than to the south. The analysis of a map of isochrones referred to the top of the "Marne con Fucoidi" Fm. (Aptian-Albian; Bigi *et al.*, 2011) shows that at depth the Gorzano fault progressively becomes a low angle normal fault completely confined within the Mt. Gorzano-Acquasanta thrust sheet. This geometric relationship can be easily recognized in the geological sections obtained by converting our seismic profiles from time to depth (Fig. 3b and c). In these sections the main tectonic units of the Campotosto-Montereale area are shown: the Sibillini, Gran Sasso and Gorzano-Acquasanta thrust sheets. The low angle geometry of the Gorzano fault shows a main décollement in correspondence with the top of the Burano Fm. anhydrites, at a depth of ~3000 m (Fig. 3b). The normal fault plane remains confined above the Mt. Gorzano-Acquasanta thrust, reaching the deeper décollement far in the west, under the Gran Sasso thrust sheet.

The projection of the 2009 earthquake sequence onto the geological cross-sections described allows observing that, in the southern part of the study area, the hypocenters depict a fault plane dipping ~45° to the SW (Fig. 3b). It is located at a depth between 5 and 11 km, therefore totally below the Acquasanta-Gorzano thrust, in the deeper thrust sheet. In spite of the fact that, in this zone, the deep fault plane seems to be in geometrical continuity with the exposed Gorzano fault, seismic profiles show that the Triassic dolostone markers in between are continuous (Figs 4–6). This implies that the Gorzano fault has a dip angle progressively lower, and flattens westward at a depth of about 4 km.

In Fig. 3b, the secondary seismic cluster has a sub-vertical geometry that we tentatively infer to occur on an antithetic segment, whose activation has been triggered by the motion of the SW-dipping fault. If this interpretation is correct, the antithetic fault develops through two thrust sheets and cuts the western part of the Gorzano fault, therefore irrespective of the preexisting tectonic features.

Discussion

The deep and surface faults are found to be genetically independent but kinematically dependent. They are genetically independent because related to two different thrust sheets superposed. The Gorzano fault is entirely confined in the upper unit, and flattens on a horizontal décollement inherited from the previous compressional phase of chain building. On the contrary, the seismogenic fault responsible for the earthquake sequence, that is a direct expression of the stress field presently acting in the study area, is definitely deeper. The two faults, however, are in part kinematically dependent: not by chance, the sole part of the Gorzano fault that has been proved to be active is the southernmost one (Galadini and Galli, 2003, with references), which falls at the hangingwall or on the projection along the plane of the deeper seismogenic fault. We therefore interpret the Gorzano fault activity as a sympathetic reactivation induced by the motion of the deeper, seismogenic normal fault.

This result poses an intriguing question about the relationship between surface active faults and deep seismogenic faulting in areas of complex geology, such as the Italian Apennines, where:

- the current extensional regime is very recent, acting since the Pleistocene (Pantosti *et al.*, 1993; Hippolyte *et al.*, 1994; Cavinato and DeCelles, 1999);
- the previous compressional regime is responsible for the most evident tectonic features of the fold-and-thrust belt (Bally *et al.*, 1986; Casero *et al.*, 1991; Ghisetti and Vezzani, 1991; Bigi *et al.*, 1999);
- inherited faults are known to have been repeatedly reactivated through times by different stress fields (Calamita *et al.*, 2002; Bigi and Costa Pisani, 2005; Scisciani, 2009).

In this perspective, our results have important consequences for the assessment of seismic hazard and scenarios, because they suggest that the identification of seismogenic faults in areas of complex geology may be incorrect and severely affect strain rate estimations if exclusively based on the surface analysis of fault activ-

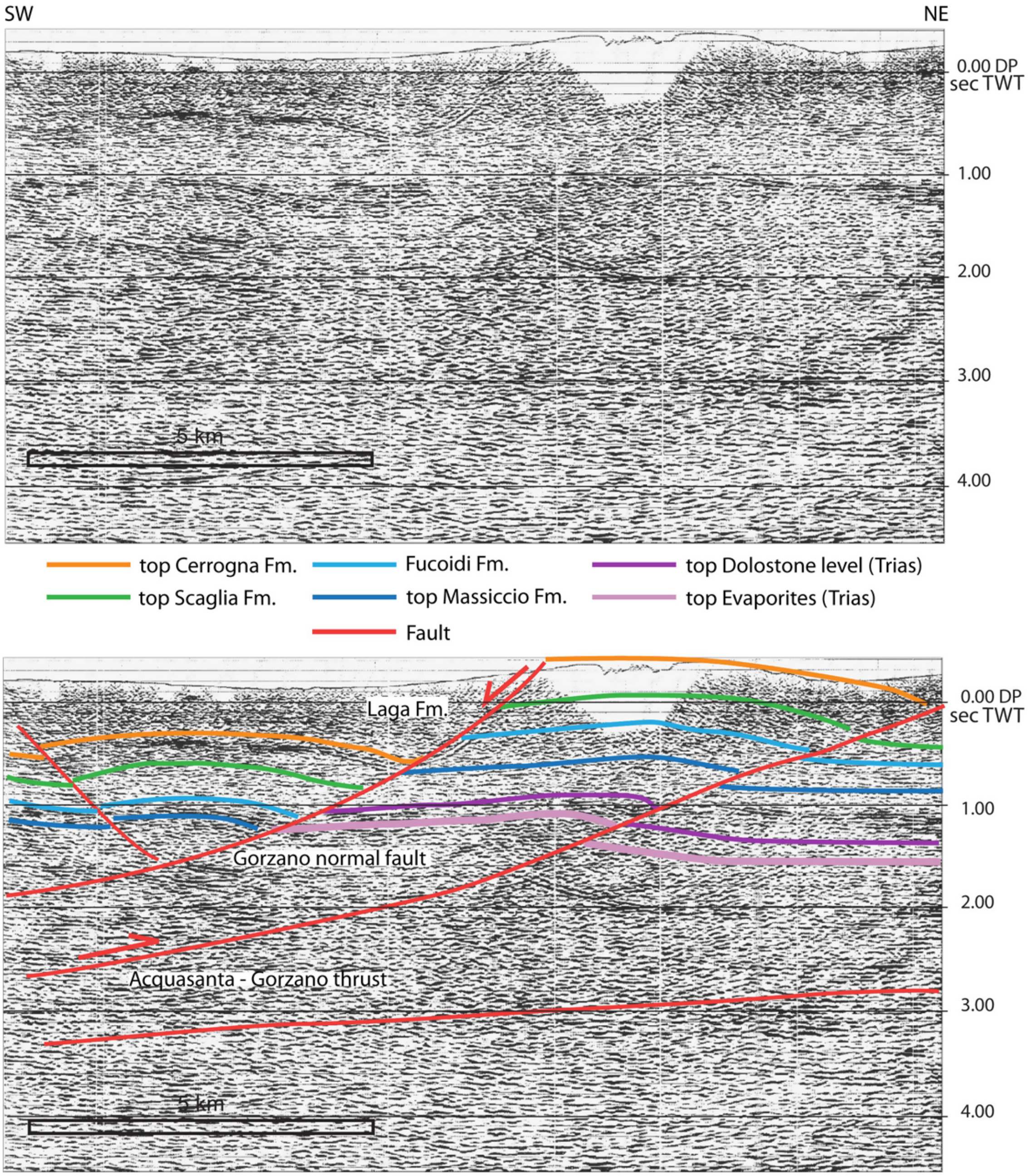

Fig. 4 Detail of one of the seismic lines (top figure) used to draw the cross-section of Fig. 3, and related interpretation (bottom figure). Notice the Triassic dolostone layer, which extends uninterruptedly below the Gorzano fault. The total displacement measured in the Messinian siliciclastic succession is much higher than that observed in the field in the overlying Quaternary deposits, suggesting that large part of the fault activity occurred in Pliocene times.

ity. As already proved for other parts of the Italian Apennines, observed active faults can be inherited from previous tectonic phases and thus have attitude and length that do not correspond with the associated seismogenic fault, whose motion can induce their coseismic slip simply as kinematic effect (Di Bucci *et al.*, 2005, 2006; Bonini *et al.*, 2011). Therefore, the seismogenic faults can be properly characterized only on the ground of many further and independent pieces of information jointly analysed, among with:

1. the deep geological setting based on geophysical data (reflection seismic profiles, deep well logs, magnetotelluric profiles, instrumental seismicity, seismic tomography);
2. the detailed geological survey, morphotectonic and structural analysis, also including the pre-Quaternary geology;
3. the long-term tectonic evolution of the study area, also supported by

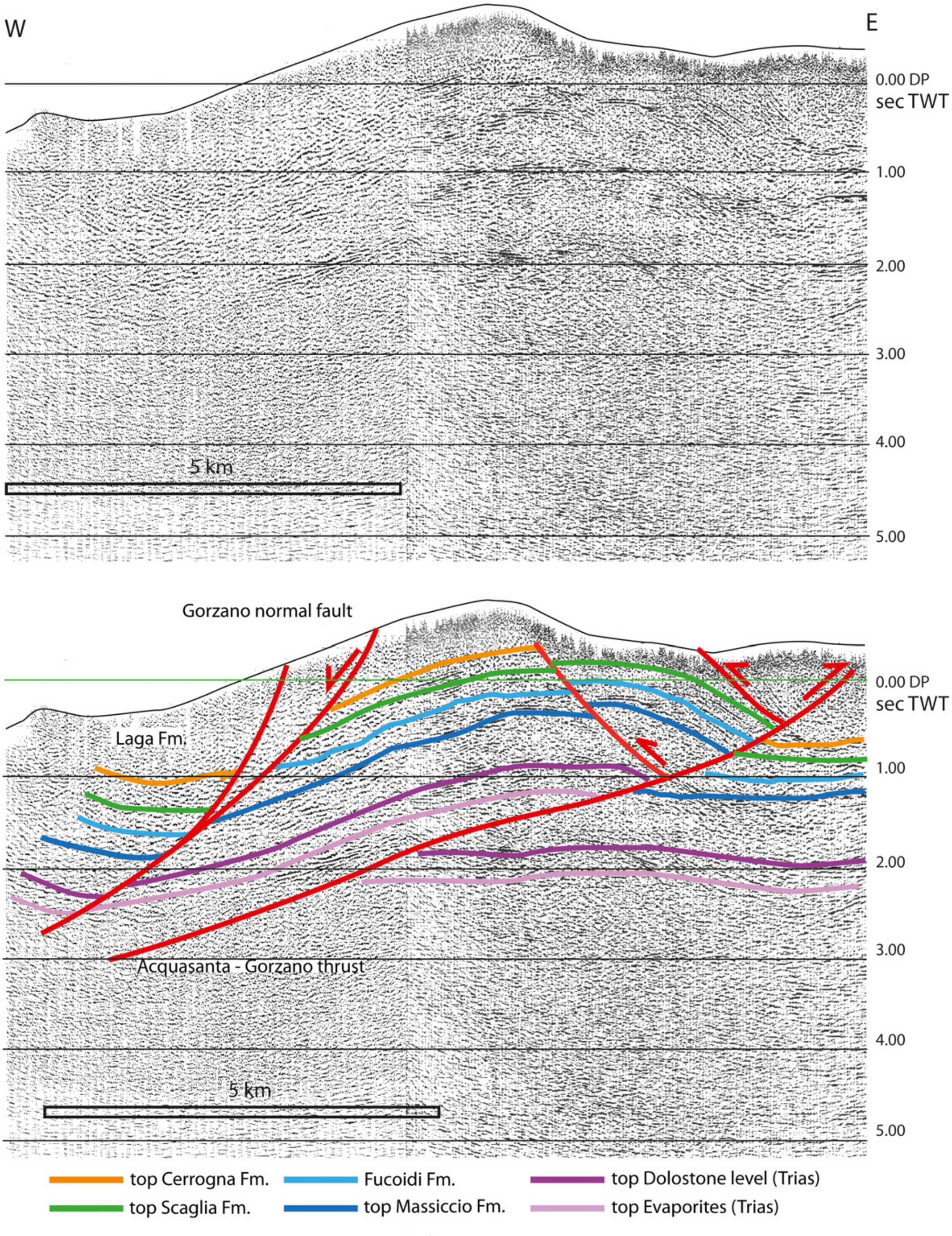

Fig. 5 Detail of the Gorzano fault as shown in one of the seismic lines used in this work. This section illustrates the northern termination of the fault, where two splays characterize its shallower part.

restoration of balanced cross-sections, analogue and numerical modelling, etc.

The comparison of what obtained from this integrated analysis with the historical seismicity and the detailed knowledge of the current stress field finally allows a reliable identification and parameterization of a seismogenic fault.

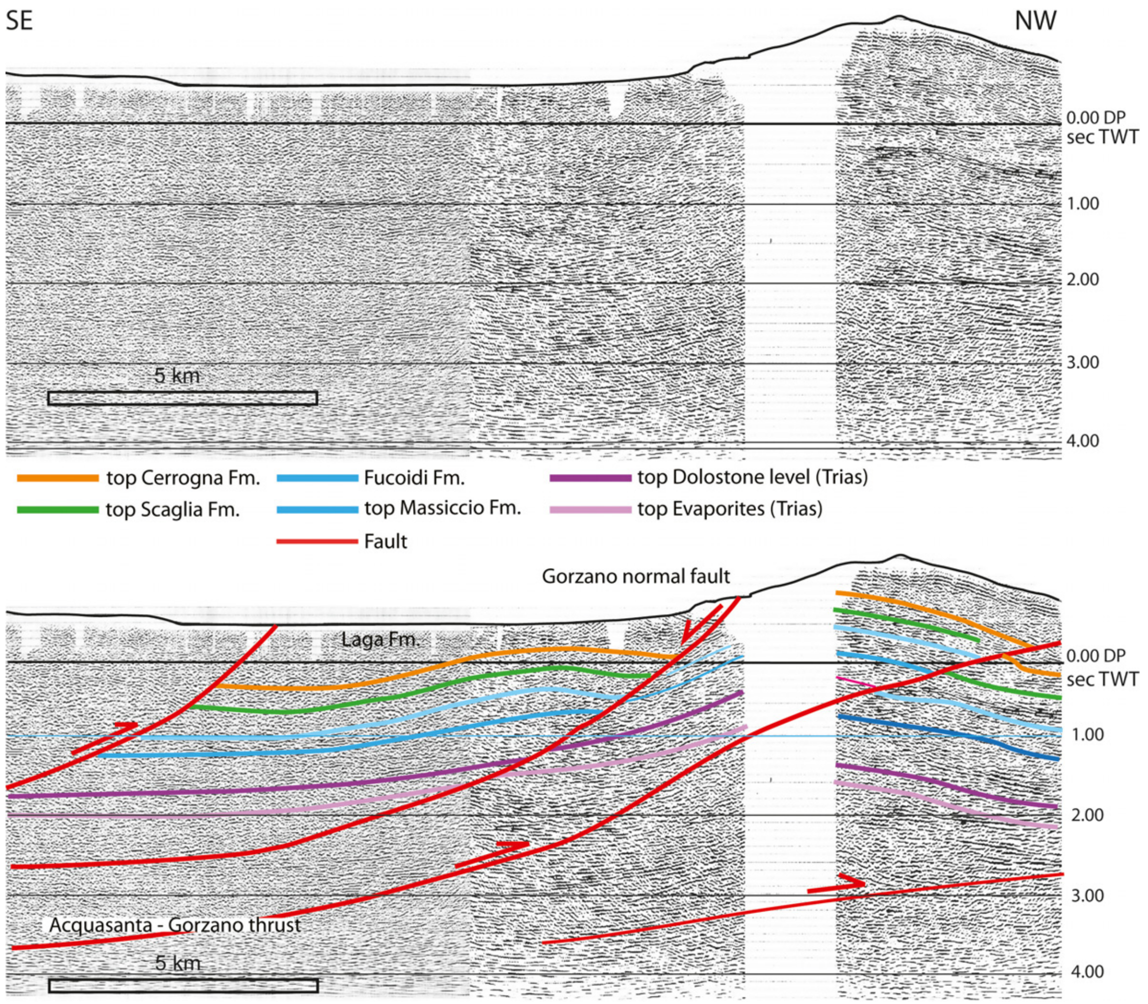

Fig. 6 Detail of the Gorzano fault as shown in one of the seismic lines used in this work. This section illustrates the fault setting in an intermediate location between Figs 4 and 5. To the SE, the Gran Sasso thrust is also shown.

Conclusions

The integration of seismicity distribution and structural setting characterizing the first 10 km of crust, obtained through the independent analysis of different datasets, allowed us to unveil the relationship between active fault observed at surface and seismogenic fault at hypocentral depth.

1. The Gorzano fault plane flattens at a depth of 4 km and plunges 2–3 km deeper further to the west; it is thus totally hosted within a 6–7 km-thick thrust sheet.
2. The 2009 earthquake sequence developed in a deeper thrust sheet on a fault plane independent from the Gorzano fault.
3. The Gorzano fault appears as kinematically reactivated by the deeper fault only where it falls in the hangingwall of such fault.

Our results (i) indicate that our approach provides an innovative and more comprehensive interpretation of the possible relationships between surface active faults and deep seismogenic sources in areas of complex geology, (ii) give us a tool to evaluate the reliability of the seismogenic sources available in literature and (iii) allow defining a procedure to best constrain seismogenic faults before the occurrence of strong earthquakes.

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