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.

Terra Nova, 00, 1–9, 2012

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 echelon 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
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 $M_\text{L} \geq 2.3$ aftershocks occurred during the first 30 days (~4000 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 southermost 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 $M_\text{w} 5.4$ event, occurred within the principal cluster, has one of the nodal planes that strikes $\text{N}136^{\circ}-46^{\circ}$ (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 Acqua-santa-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
marks of the “Marne a Pteropodi” and “Marne con Cerroagna” 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 Cerroagna” 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; Caccioni 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 se-
quence comprises a thick pile of are-
aceous beds which correspond to the
depocenter of the Laga basin and
appear as well defined seismogenic facies.
In the fault hangingwall, it is difficult
to recognize a facies with the same
characters and thickness. This sug-
gest 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 sev-
eral seismic profiles (both confidential
and public; ViDEPI, 2010), which
were calibrated and interpreted based
on borehole data (Varoni-I and Cam-
potosto-I wells; Figs 2 and 3). Seismic
interpretation was carried out by
identifying several seismic markers
corresponding to the top of the for-
mations: “Marne con Cerrognà”
(marls; Tortonian), “Scaglia Rossa”
(marly limestone; Eocene), “Marne
con Fucoidi” (marls; Aptian-Albian),
“Calcarea Massiccio” (limestone; Sin-
emurian) 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-
I well).

We reconstructed the Gorzano fault
geometry by picking the marker sur-
faces at both the hangingwall and
footwall of the fault plane (Figs 4–6).
At the hangingwall, these markers
depict a rollover anticline, as sug-
gested 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 reconstruc-
tion 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 re-
ferred to the top of the “Marne con
Fucoidi” Fm. (Aptian-Albian;
Bigi et al., 2011) shows that at depth
the Gorzano fault progressively be-
comes 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-
Monteareale area are shown: the Sibili-
lini, Gran Sasso and Gorzano-Acqua-
santa thrust sheets. The low angle
geometry of the Gorzano fault shows
a main décollement in correspondence
with the top of the Burano Fm. anhy-
drites, at a depth of ~3000 m (Fig. 3b).
The normal fault plane remains con-
fined above the Mt. Gorzano-Acqua-
santa thrust, reaching the deeper
décollement far in the west, under the
Gran Sasso thrust sheet.

The projection of the 2009 earth-
quake 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-Gorz-
zano 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 pro-
files show that the Triassic dolostone
markers in between are continuous
(Figs 4–6). This implies that the Gorz-
zano 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 anithetic segment, whose activa-
tion has been triggered by the motion
of the SW-dipping fault. If this inter-
pretation is correct, the anithetic 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 re-
lated to two different thrust sheets
superposed. The Gorzano fault is
entirely confined in the upper unit,
and flattens on a horizontal décolle-
ment inherited from the previous
compressional phase of chain build-
ing. 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 kine-
matically dependent: not by chance,
the sole part of the Gorzano fault that
has been proved to be active is the
southernmost one (Galadini and Gal-
li, 2003, with references), which falls at
the hangingwall or on the projection
along the plane of the deeper seismo-
genetic fault. We therefore interpret
the Gorzano fault activity as a sympa-
thetic reactivation induced by the
motion of the deeper, seismogenic
normal fault.

This result poses an intriguing ques-
tion about the relationship between
surface active faults and deep seismo-
genetic faulting in areas of complex
geology, such as the Italian Apen-
nines, where:

• the current extensional regime is
  very recent, acting since the Pleis-
tocene (Pantosti et al., 1993; Hipp-
oyte 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 (Cal-
amita 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 sce-
narios, 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-
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

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**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.
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. 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.
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.

Acknowledgements

We thank the anonymous Reviewers and Editor for their valuable reviews of the manuscript. This research benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri – Dipartimento della Protezione Civile (DPC). Scientific papers funded by DPC do not represent its official opinion and policies.

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Received 2 March 2011; revised version accepted 18 July 2012