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Deep reaching *versus* vertically restricted Quaternary normal faults: Implications on seismic potential assessment in tectonically active regions: Lessons from the middle Aterno valley fault system, central Italy

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ABSTRACT

We investigate the Middle Aterno Valley fault system (MAVF), a poorly investigated seismic gap in the central Apennines, adjacent to the 2009 L'Aquila earthquake epicentral area. Geological and paleoseismological analyses revealed that the MAVF evolved through hanging wall splay nucleation, its main segment moving at 0.23–0.34 mm/year since the Middle Pleistocene; the penultimate activation event occurred between 5388–5310 B.C. and 1934–1744 B.C., the last event after 2036–1768 B.C. and just before 1st-2nd century AD. These data define hard linkage (*sensu* Walsh and Watterson, 1991; Peacock et al., 2000; Walsh et al., 2003, and references therein) with the contiguous Subequana Valley fault segment, able to rupture in large magnitude earthquakes (up to 6.8), that did not rupture since about two millennia. By the joint analysis of geological observations and seismological data acquired during to the 2009 seismic sequence, we derive a picture of the complex structural framework of the area comprised between the MAVF, the Paganica fault (the 2009 earthquake causative fault) and the Gran Sasso Range. This sector is affected by a dense array of few-km long, closely and regularly spaced Quaternary normal fault strands, that are considered as branches of the MAVF northern segment. Our analysis reveals that these structures are downdip confined by a *decollement* represented by to the presently inactive thrust sheet above the Gran Sasso front limiting their seismogenic potential. Our study highlights the advantage of combining Quaternary geological field analysis with high resolution seismological data to fully unravel the structural setting of regions where subsequent tectonic phases took place and where structural interference plays a key role in influencing the seismotectonic context; this has also inevitably implications for accurately assessing seismic hazard of such structurally complex regions.

1. Introduction

The central Apennines are probably the part of Italy where seismicity and active faulting are best documented (Barchi et al., 2000; Boncio et al., 2004; Galadini and Galli, 2000; Gori et al., 2011; Roberts and Michetti, 2004; Valensise and Pantosti, 2001). Nevertheless, some issues still remain unaddressed regarding the activity, paleoseismicity and Holocene kinematics of some Quaternary faults, whose current activity is undefined or debated, and regarding some strong historical earthquakes whose causative faults are not ascertained yet.

Situated in the core of the central Apennines, the middle Aterno River valley (Abruzzi region) is an area where these open questions are all present. Here, Galadini and Galli (2000) recognised NW-SE trending active normal faults, branching into the Middle Aterno Valley fault system (MAVF), a tectonic structure potentially responsible for large magnitude earthquakes. The Quaternary kinematics of this system, including its last activation, is still largely unknown, and no historical earthquakes documented in seismic catalogues (e.g. Rovida et al., 2011) can be surely ascribed to its activity. These factors make the MAVF a seismic gap area of central Italy that deserves special attention.

The aim of this study is to document the Quaternary activity and structural evolution of the MAVF, on the basis of geological field survey and paleoseismological analyses. We also try to clarify the relation between the MAVF and the conterminous normal fault systems, whose

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fragmentation makes still uncertain the way in which adjacent segments interact during large earthquakes. We focus on the active normal faults near to the MAVF: the Subequana Valley fault (SVF), located to the south, and the Paganica fault (PF), the causative fault of the 2009 L'Aquila earthquake, located to the north (Figs. 1 and 2). Based on geologic and paleoseismology data, Falcucci et al. (2011) hypothesised a kinematic linkage between the MAVF and the SVF, while a similar relation with the PF is debated. Indeed, on the one hand, Galli et al. (2010) suggested that part of the coseismic slip during the 2009 L'Aquila earthquake took place also along the San Demetrio fault (SDF) which, according to Galadini and Galli (2000), is part of the northern strand of the MAVF. On the other hand, geologic/geodetic observations (Gori et al., 2012) attested solely sympathetic (*sensu* De Polo, 1994, and references therein) movement of the SDF during the 2009 seismic sequence.

Along with the debated coseismic activation in 2009, the structural characteristics and the long term evolution of the MAVF northern segment are still not understood. This tectonic system is made of a few km long, mainly parallel, closely and regularly spaced fault branches, distributed over a ~6 km wide belt; some of these branches displaced Early-to-Middle Pleistocene continental sequences (Bertini and Bosi, 1993). This structural complication and the ambiguous relation between the MAVF northern strand and the PF could be somehow influenced by the complex architecture of the belt resulting from the compressional phase (e.g. Chiarabba and Amato, 2003).

We try to resolve the structural complexity of this area by complementing the anomalous dense array of fault segments mapped at the surface with the distribution of seismicity generated during the 2009 L'Aquila sequence. The impressive seismological dataset of Valoroso et al. (2013) of 64k precisely located aftershocks, coupled with detailed surface geologic observations, helps us to constrain the geometry at depth of faults and their role in accommodating extension in the central Apennines, drawing a synoptic "4-D image" of the fault system.

2. Geological setting

2.1. Neotectonic framework

The Apennines formation derives from the complex interaction between westward subduction and delamination of the continental lithosphere started in the Oligocene (Chiarabba and Chiodini, 2013; Chiarabba et al., 2014). The eastward migrating compression created a thrust front that "bulldozed" Meso-Cenozoic carbonate successions, piling up different tectonic units (Figs. 1a and b). At the chain rear, extension began during the Miocene-Pliocene, chasing the advancing compressive front. This new tectonic event – associated to 1000 m chain uplift through the Quaternary (e.g. D'Agostino et al., 2001) – dismembered the structural edifice inherited by the compressional phase, by the nucleation of chain-parallel (i.e. NW-SE trending) extensional fault systems. The activity of these structures in Plio-Quaternary times formed intermontane tectonic depressions that hosted continental deposition.

Active extension in the central Apennines, at a rate of 3–5 mm/yr, is testified by GPS and InSAR time-series (e.g. D'Agostino et al., 2011; Devoti et al., 2011; Hunstad et al., 2009) and supported by boreholes breakout data (Mariucci et al., 2010), instrumental seismicity (e.g. Bagh et al., 2007; Chiarabba et al., 2009) and geological data, which evidenced displacement of Late Pleistocene-Holocene deposits along several normal fault systems (e.g. Barchi et al., 2000; Boncio et al., 2004; Galadini et al., 2012; Valensise and Pantosti, 2001). Some of the well exposed fault scarps have been associated to seismogenic sources able to rupture with large magnitude earthquakes (e.g., Galadini and Galli, 2000; Vannoli et al., 2012). The damage distribution of historical earthquakes read along with geologic and paleoseismological data (e.g. Galli et al., 2008) do not permit a complete association between the strongest seismic events and the central Apennine normal faults (Fig. 1c).

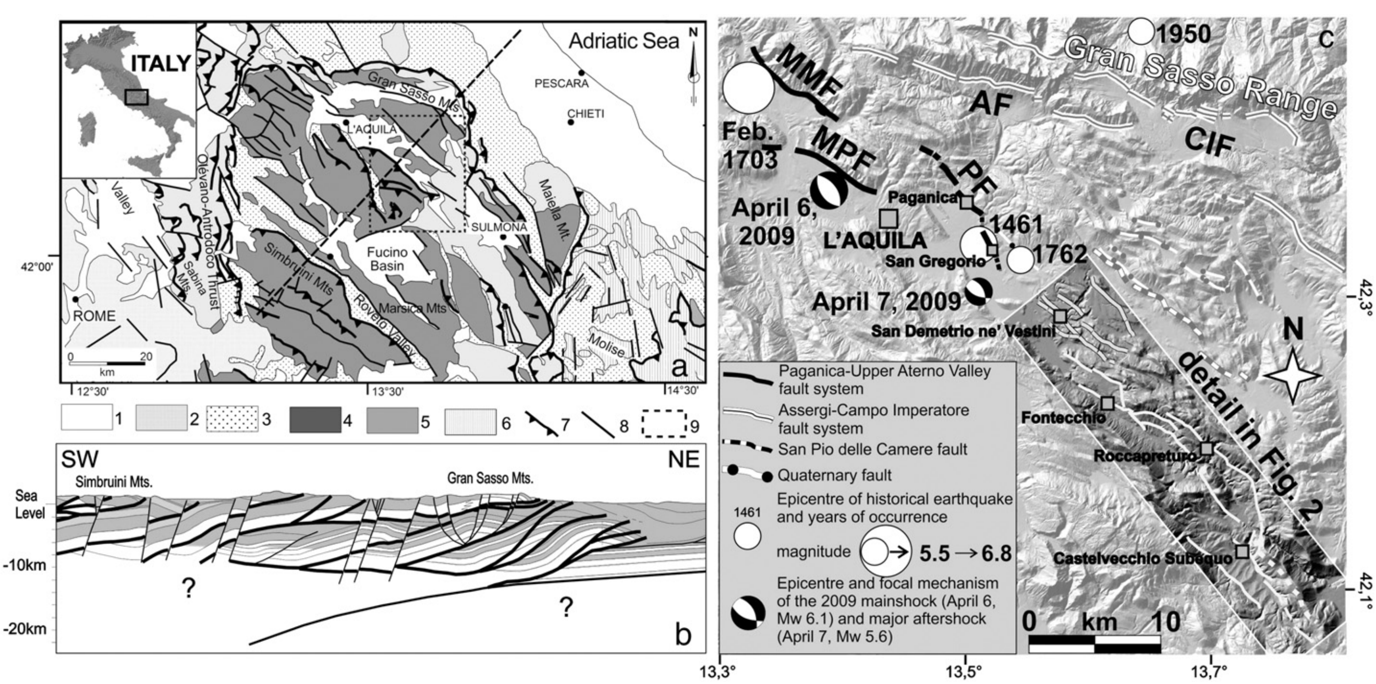

Fig. 1. a) Simplified geological map of the central Apennines. Legend: 1) Marine and continental clastic deposits (Pliocene-Quaternary); 2) Volcanic deposits (Pleistocene); 3) Synorogenic hemipelagic and turbiditic sequences (Tortonian-Pliocene); 4) Carbonate platform deposits (Triassic-Miocene); 5) Slope and pelagic deposits (Lias-Miocene); 6) Molise-Sannio pelagic deposits (Cretaceous-Miocene); 7) Main thrust fault; 8) Main normal and/or strike-slip fault; 9) Study area, shown in (c); Trace of the geological cross-section, black dashed line. b) Geological cross-section of the central Apennines (redrawn from Cosentino et al., 2010); main thrust/inverse fault planes, black bold lines; extensional faults, black thin lines. c) Shaded relief map showing the seismotectonic framework of the area under investigation, on which active faults and epicentres of large historic earthquakes are plotted. Faults: AF, Assergi Fault; MMF, Mt. Marine fault; MPF, Mt. Pettino fault; PF, Paganica fault; CIF, Campo Imperatore fault; SPF, San Pio fault; study area, in the shaded rectangle.