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Active faults in the epicentral and mesoseismal Ml 6.0 24, 2016 Amatrice earthquake region, central Italy. Methodological and seismotectonic issues

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Abstract

The August 24, 2016 Amatrice earthquake (Ml 6.0) struck a region of the central Apennines (Italy) where several active faults were known since decades, most of which are considered the surface expression of seismogenic sources potentially able to rupture during earthquakes with M of up to 6.5-7. The current debate on which structure/s activated during the mainshock and the possibility that conterminous faults may activate in a near future urged us gathering all the data on surface geological evidence of fault activity we collected over the past 15-20 years in the area. We then map the main tectonic structures of the 2016 earthquake epicentral and mesoseismal region. Our aim is to provide hints on their seismogenic potential, as possible contribution to the national Database of Individual Seismogenic Source (DISS) and to the Database of the active and capable fault ITaly HAzard from CApable faults (ITHACA).

I. INTRODUCTION

The Ml 6.0 August 24, 2016 Amatrice earthquake occurred on a NW-SE trending normal rupture, manifestation of the extensional tectonic regime ongoing in the central Apennine chain since the Late Pliocene. The active NE-SW trending stress generated sets of chain-parallel normal fault systems, arranged as two-to-three tectonic rails, along which major historical and instrumental seismicity concentrates. Some of the outermost active normal faults of the central Apennines are considered as "*silent*", that is seismic gaps (Galadini and Galli, 2000). The Amatrice earthquake occurred in the sector between two of these silent faults, the Laga Mts. and Mt. Vettore normal faults. The former affects the base of the western slope of the Laga Mts. Its surface expression is represented by a NW-SE ~26 km-long fault-scarp carved onto clayey-arenaceous Miocene flysch sequences. The Mt. Vettore fault, NW-SE to NNW-SSE trending, is made of different splays and segments whose scarps are carved onto Meso-Cenozoic limestone sequences, exposed along the SW slopes of Mt. Vettore, Mt. Le Porche and Mt. Bove. These compose an about ~27 km-long (at surface) tectonic structure.

Seismological, geodetic, remote sensing and geological investigations currently underway seem to indicate that parts of these two structures played a primary role in the seismogenic process of the August 24 mainshock. The aftershock sequence is distributed in the territory affected by the Laga Mts. and Mt. Vettore faults, and beyond the area of maximum coseismic deformation (Gruppo di Lavoro INGV sul terremoto di Amatrice, 2016).

Since researches are still ongoing about the causative fault(s) and considering the inherent variation of static stress in the regions nearby, we here review data we collected over the past 15-20 years of geological field surveys in the epicentral and mesoseismal areas, to describe and map the major active faults of the region, basing on critically selected geological criteria for active faulting definition in terms of both chronology and surface evidence. Finally, we will propose some hypotheses about the characteristics of the related seismogenic sources, as possible contribution to the national Database of Individual Seismogenic Sources (Basili et al., 2008) and to the Database of the active and capable fault ITaly HAzard from CApable faults (ITHACA) (http://www.isprambiente.gov.it/it/progetti/suolo-e-territorio-1/ithaca-catalogo-delle-faglie-capaci).

II. GEOLOGICAL "RATIONALE" FOR ACTIVE FAULT DEFINITION AND MAPPING

The vast geological literature on the Apennine active extensional tectonics provides numerous evidence of active normal faulting that allow to derive a conceptual model for defining an active and capable fault as the primary expression at surface of a seismogenic source.

As for fault capability, i.e. a fault able to rupture the surface, we adopt the 6.0±0.2 threshold magnitude for surface faulting, on the order of that proposed by Michetti et al. (2000) for the Apennine faults. We therefore consider the faults we map as the surface expression of seismogenic sources able to rupture with $M \geq 6.0 \pm 0.2$ earthquakes. We also map other normal faults but with different symbology to mark that, based on several geological observations, we consider them as not (or no more) able to nucleate seismic events larger than M 6.0±0.2.

As for the time interval to assess active and capable faulting, we adopt the criteria provided by Galadini et al. (2012), for the Italian extensional domain: a fault should be considered as active and capable if it displays evidence of activation in the last 0.8 Myr, unless it is sealed by deposits or landforms not younger than the Last Glacial Maximum. This definition has been basically adopted by seismic microzonation regulatory in force in

Italy (Commissione tecnica per la microzonazione sismica, 2015).
Hence, to assess and map an active and capable extensional fault/ fault system as primary expression of a deep seismogenic source, we define conceptual and factual criteria based on Quaternary geological, geomorphological and structural field evidence. From these criteria we derive "requisites" that a fault must all have:
1) the fault must show evidence of displacement of deposits and/ or landforms (derived from field observations and paleoseismological trenching across fault traces) in diverse sectors of its trace, for different ages (Middle Pleistocene-Holocene interval), with offsets that must increase with the age of displaced features (Fig. 1). The latter issue is to avoid to consider as primary those secondary ruptures such as extrados or bending fractures, not primarily connected with the seismogenic fault at depth, as they inherently close at certain depth. This can be only unraveled by considering the displacement of deposits and/ or landforms over long time spans.

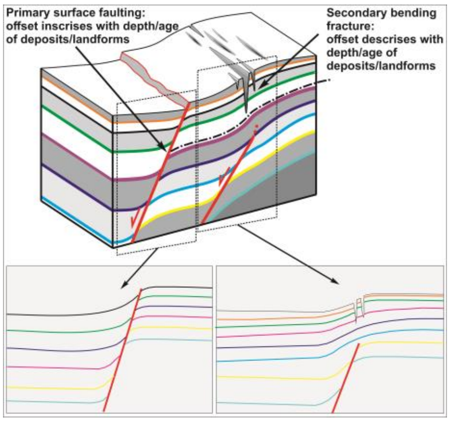

Figure 1. Structural scheme of the different displacement features related to primary surface faulting and secondary (extrados) displacement.

We preferentially consider the displacement of the base of a given stratigraphic unit across the considered fault. Indeed, the top surface could be affected by erosional/ depositional processes that may alter its actual shape and morpho-stratigraphic significance. As best practice, geological/ geomorphological data must ascertain that the considered displaced top surface is primary (or sub-primary) and/ or ascribable to a depositional/ erosional specific order. This aspect is fundamental to avoid to erroneously correlate across a fault surfaces (erosional/ depositional) pertaining to different orders or having different morpho-stratigraphic significance.
2) the scarp of a major normal fault has to be continuously detectable for several kilometres. This relates to the observations that faulting occurs and maintains on the discrete structural elements for long time periods, and structural features must hence be geologically and geomorphologically recognisable in the field. Minor synthetic or minor antithetic structures, or secondary faults may provide evidence for detecting primary active faulting in the field. But as these faults may not accommodate a large amount of slip and, therefore, may not be representative of the major fault behaviour, we have not reported these secondary faults.
3) a several km-long normal fault segment, splay or branch for which evidence of displacement of deposits and/ or landforms are not specifically available has to be considered as primarily connected to the seismogenic fault if it either displays overlap with or is parallel to other structural features for which these evidence are available, unless spacing exceeds ~4 km (for synthetic splays) in map view (Wesnousky, 2006); if so, the faults may indeed have different kinematic history and behaviour and could be related to different seismogenic structures.

At the same time, major cautions must be taken before defining an active fault as primarily linked to a deep seismogenic structure:

a) It must be considered if normal faulting hypothesised on the lateral contact of different sedimentary bodies or of sedimentary bodies with the bedrock, could be instead due to morpho-sedimentary processes, that could be misleadingly interpreted. For instance, sedimentary units embedding, fluvial entrenchment and terracing. At this purpose, detailed geomorphic and sedimentological analyses, characterisation of the mechanism of transport and sedimentation, and (paleo)environment assessment of deposition are crucial aspects.

b) It must be evaluated the possible occurrence of any other non-tectonic morphogenetic process that could imitate surface faulting, especially when occurring along fault-scarps. Among these factors, local and areal landsliding (i.e. of sediments/ rocks at the base of a fault-scarp), large scale gravitational mass movements (superposing on a fault-scarp), local sediment compaction (resembling fault displacement), local erosion (e.g. of the debris deposited at the base of the fault-scarp), morpho-selection processes and differential erosion (i.e. due to differential erodibility of deposits/ rocks across a fault-scarp), local ground subsidence or collapses (e.g. sinkholes or karstic features), human activity (quarrying, excavations, debris accumulations) must be thoroughly acknowledged. A number of studies discussed about this (Bucci et al., 2007; Fubelli et al., 2009; Kastelic et al., 2015). Most of these studies defined that active faulting only based on the recognition of supposed morphotectonic features, such as the sole local exposition of the fault plane at few places at the base of a given fault-scarp, or the recognition in the field of geomorphic features (e.g. triangular facets) supposed to be fault-related, cannot be considered satisfactory when taken alone.

III. DISCUSSION

Data collected through the past 15-20 years in the area affected by the 2016 Amatrice seismic sequence and surroundings allow us to trace series of normal fault systems, that we consider as the primary expression at surface of seismogenic sources.

As for the Laga Mts. fault, evidence of Late Pleistocene-Holocene activity was reported (Galadini and Galli, 2003). The fault can be splitted into two segments, the ~18 km-long southern segment, bounding the Campotosto *plateau*, and the ~8 km-long northern segment, bounding the Amatrice basin. The Campotosto segment shows a continuous surface fault-scarp and displays geological and geomorphological evidence of Late Pleistocene-Holocene movements; surface faulting episodes were identified by paleoseismological trenching. Conversely, no evidence at surface of late Quaternary fault activity was found along the Amatrice segment. Galadini and Galli (2003), therefore, considered this segment as inactive or that the fault would not be no more able to generate earthquake large enough to rupture the surface. Noteworthy, this is consistent with the surface observations made after the August 24 mainshock, as no evidence of surface rupture occurred along the Amatrice fault segment (Emergeo Working Group, 2016). Interestingly, the deep portion of the Campotosto segment activated in its lowermost portion during the 2009 seismic sequence (Bigi et al., 2013).

As for the Mt. Vettore fault, Galadini and Galli (2003) defined that the 18 km long surface expression of the seismogenic structure is made of different segments and splays. Evidence for the Pleistocene-Holocene activity of the structure was obtained by paleo-seismological investigations. The Mt. Vettore faults therefore shows geological evidence at surface of recent activity, differently from the Amatrice segment. Therefore, the about 5 km long surface rupture along the easternmost splay of the Mt. Vettore fault following the August 24 mainshock (Emergeo Working Group, 2016) would corroborates surface faulting potential of the Mt. Vettore fault. Our analyses revealed that the fault should be lengthen northward for ~8 km.

IV. Conclusions

The Ml 6.0 August 24, 2016 Amatrice earthquake struck a region of central Italy where several normal active normal faults were already known. Debate on the seismotectonics of the 2016 event, the presence of many other nearby active normal faults and the fact that some of these underwent increase of static stress after the 2009 L'Aquila earthquake (Falcucci et al., 2011) and likely after the 2016 seismic sequence, urged us to gather and sum up the results of field investigations we performed in this region and to map in detail the active normal faults we consider as the primary expression at surface of seismogenic sources able to rupture during earthquakes with magnitude of up 6.5-7. In this perspective, as for the maximum depth reached by the considered faults, the analysis of the seismological data related to the 2009 L'Aquila earthquake (e.g. Valoroso et al., 2013) and 2016 Amatrice seismic sequence (Gruppo di Lavoro INGV sul terremoto di Amatrice, 2016) suggest that major seismogenic faults in the central Apennines can reach ~10 km depth. Figure 2 sums up all the active faults we mapped, and the related seismogenic sources, as possible contribution to the Italian Database of the active and capable faults (ITaly HAzard from CApable faults, ITHACA) and to the Italian Database of Individual Seismogenic Sources (Basili et al., 2008).

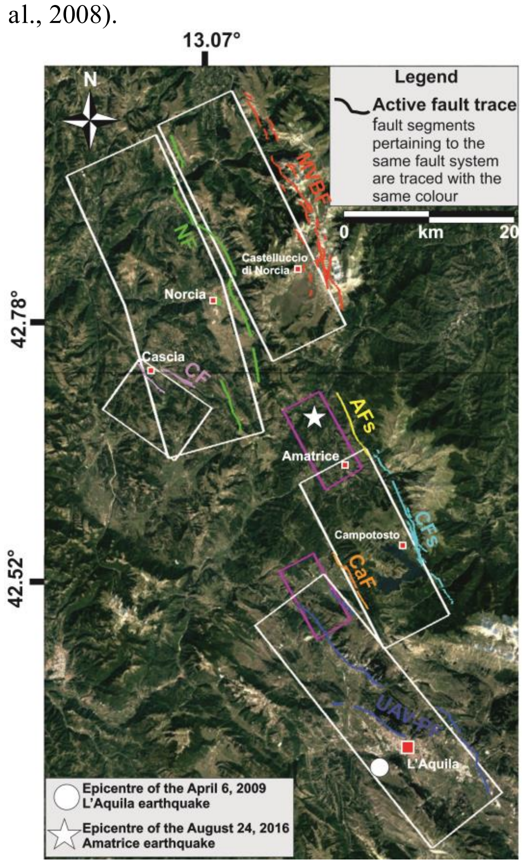

Figure 2. Map of the active faults of the region (coloured lines). Faults: Mt.Vettore-Bove fault, MVBF; Norcia fault, NF; Cascia fault, CF; Amatrice fault segment, AFs; Campotosto fault segment, CFs; Capitignano fault, CaF; Upper Aterno Valley-Paganica fault ststem, UAV-PF. Seismogenic sources, white boxes; Purple boxes indicate seismogenic sources not able to generate surface faulting earthquakes.

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