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The 2013 Lunigiana (Central Italy) earthquake: Seismic source analysis from DInSar and seismological data, and geodynamic implications for the northern Apennines. A discussion

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1. Introduction

The contribution of Pezzo et al., 2014 represents one of the first published scientific papers (see also Stramondo et al., 2014) on the 2013 Mw 5.1 Lunigiana (northern Italy) earthquake following the early-bird seismological, geodetical as well as DInSar technical reports published during the seismic sequence (http://ingvterremoti.wordpress.com/category/sequenza-in-lunigiana/). Pezzo et al. used Synthetic Aperture Radar differential Interferometry (DInSar) and seismological data to constrain the seismic source of the main shock of the 2013 Lunigiana sequence, namely, the 2013 June 21 Mw 5.1 event. Moreover, as directly referred to in the title, the authors aim at discussing the geodynamic implications of their analysis for the northern Apennines by taking into account the tectonic structures of the area, which represent fundamental input parameters for a correct seismic hazard assessment. Actually, the three-dimensional complexity of the tectonic architecture of the northern Apennines in the Alpi Apuane–Lunigiana region, if not properly taken into account, can cause deep uncertainty in the accurate determination of the source of the 2013 Lunigiana mainshock. Given the seismic hazard of the region and its social relevance (Tertulliani and Maramai, 1998; Ferretti et al., 2005; Mantovani et al., 2012; Meletti et al., 2004; Rovida et al., 2011), in the following we complement and refine the geological information provided by Pezzo et al., with the purpose of helping future work on the subject.

1. The inner northern Apennines struck by the 2013 June 21 Mw 5.1 earthquake and related seismic sequence are characterized by four recent to active regional tectonic structures Fig. 1. They include the Alpi Apuane morphostructural high and three surrounding tectonic depressions: the Garfagnana to the east, the Viareggio basin to the west (with its northern prolongation represented by the lower Lunigiana/Val di Vara) and the upper Lunigiana to the north (Fig. 1). Plio-Quaternary intramontane to marine sediments record the progressive but unsteady evolution of the tectonic depressions whose boundary faults controlled and/or displaced the basins' sediments (Bernini and Papani, 2002; Di Naccio et al., 2013; Federici, 1978; Raggi, 1985). Actually, the exposed and buried faults bounding the Alpi Apuane to the west and confining the Viareggio basin eastward show cumulative post-Early Pliocene to present vertical displacement values that are among the highest for normal fault-systems of the whole Italian peninsula (Bigot, 2010). Although Pezzo et al. quote recent seismotectonic literature (DISS working Group, 2010) reporting seismogenic sources only for the Lunigiana and Garfagnana grabens, historic seismicity, geological, morphotectonical as well as geodetical data (Bennett et al., 2012; Bigot, 2010; Federici, 1978; ITHACA, 2010; Molli, 2008, 2013; Pinelli, 2014; Rovida et al., 2011) suggest recent to present-day tectonic activity all around the Alpi Apuane high.
2. In Pezzo et al. the surface fault structure related to the seismic source of the 2013 Lunigiana event is reported to be the nearly E–W striking Minucciano Fault. In fact, the Minucciano Fault (Boncio et al., 2000; Di Naccio et al., 2013; ITHACA, 2010 and references therein) is a NW-SE trending (310°), east-dipping fault zone. Moreover, a detailed analysis of this structure has led Di Naccio (2009) to rule out its Holocene activity.
3. The fault system relevant to the 2013 Lunigiana earthquake is reported in recent geological literature as North Apuane Transfer Fault (Brozzetti et al., 2007), as Marciaso-Tenerano Fault (Scandone, 2007, where it is incorrectly reported as Marciano-Tenerano Fault) and, more recently, as North Apuane Fault System (Molli, 2013; Molli et al., 2015). This fault system includes the surface splays of a subsurface structure well defined (Fig. 2a,b) by contours of seismic basement derived from Eni regional lines across the area (Artoni et al., 1992; Camurri et al., 2001; Argnani et al., 2003).
The seismic basement extends northward from the outcropping areas of the metamorphic units in the Alpi Apuane and deep toward north/northwest with a N60E strike turning toward NE below the Garfagnana. In Fig. 2b, the locations of the 2013 Lunigiana seismic

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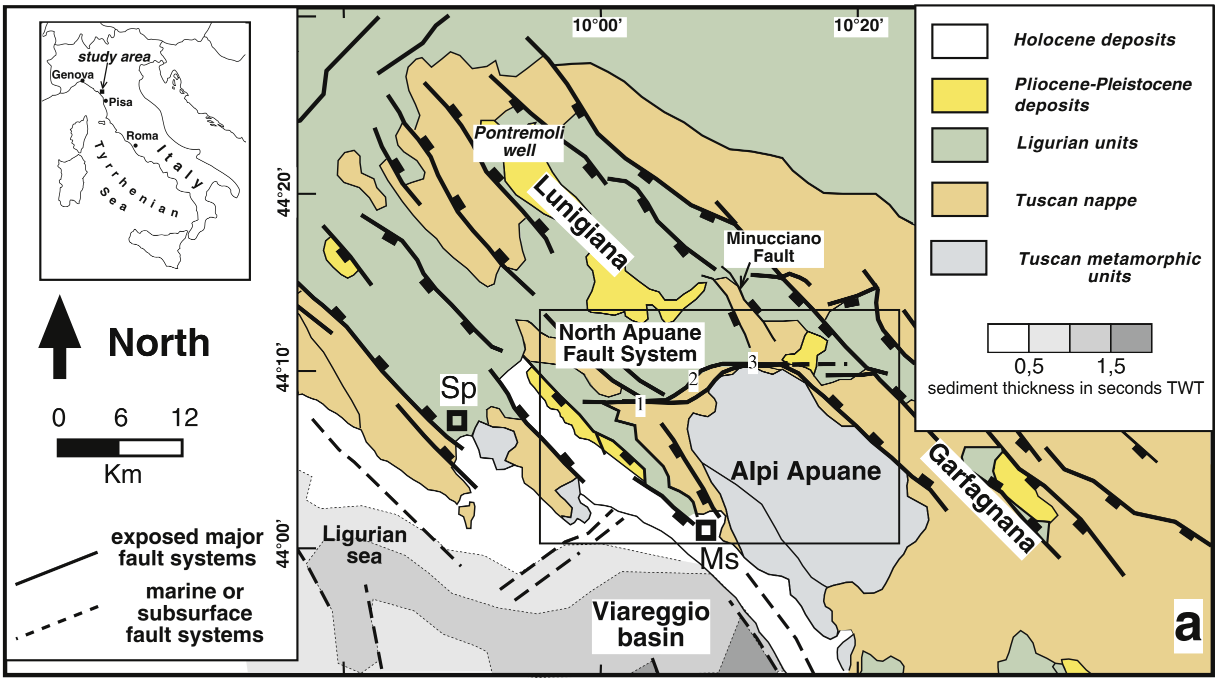

Fig. 1. Tectonic frame of the inner northern Apennines north of the Arno river with location of the area interested by the Lunigiana 2013 EQ. Box shows the area of Fig. 2; (1) Fosdinovo, (2) Tenerano-Marciaso, and (3) Aiola-Equi Terme faults, parts of the North Apuane Fault system.

sequence are reported with projection of the main shock and aftershocks over the depth contours.

As concerns the surface splays of the North Apuane Fault (Figs. 1 and 2), they are striking for nearly 20 km with a SW–NE trend and include three interconnected segments: the westernmost E–W trending Fosdinovo Fault, the central NE/SW trending Marciaso-Tenerano Fault and the northeasternmost, nearly E–W trending, segment represented by the Aiola-Equi Terme Fault. The Aiola-Equi Terme Fault shows evidence (bedrock fault scarps, triangular facets, hydrothermal springs) of recent activity (Di Naccio, 2009; ITHACA, 2010; Molli et al., 2015) and has a primary seismogenic role in the 2013 June 21 Mw 5.1 main shock. In fact, the Aiola-Equi Terme Fault (for details see Molli et al., 2015) has a transcurrent component compatible with a direction of maximum shortening (P axis) plunging at a low angle approximately SE–NW and a sub-horizontal maximum extension (T axis) SW–NE oriented (Fig. 2a). The coupled system of normal fault zones and/or normal/oblique faults is associated with a sub-vertical direction of maximum shortening and an approximately NS sub-horizontal direction of maximum extension (Fig. 2a). As a whole, the kinematic analysis suggests a dextral transtensive setting for the Aiola-Equi Terme Fault, which is well compatible with the focal mechanism of the main shock reported by Pezzo et al. as well as by previous INGV reports (http://ingvterremoti.wordpress.com/category/sequenza-in-lunigiana/) (Fig. 2b). It follows that the structure relevant for the discussion of the main shock of June 21st is not the Minucciano Fault but the Aiola-Equi Terme Fault, i.e., the easternmost surface splay of the North Apuane Fault.

4. The line-drawing of Fig. 3, modified from Camurri et al. (2001), crosscuts the North Apuane Fault at depth and its Aiola-Equi Terme segment at the surface, allowing to better constrain the seismic source of the 2013 Lunigiana EQ. The fault is well imaged down to a depth of 5 km (ca. 2 s in TWT, Fig. 2b) where it separates a metamorphic footwall domain (Apuane unit in subsurface) from non-metamorphic cover units of the Northern Apennines nappe stack (Ligurian, sub-Ligurian, and Tuscan units). The dip angle of the subsurface Equi Terme Fault appears slightly steeper than reported in Pezzo et al. (ca.. 50° instead of 44°) and basically shows the same dip modelled by Stramondo et al. (2014). A first-order correlation between nappe stack units in surface and subsurface between the footwall (Alpi Apuane) and hanging-wall (Lunigiana) blocks reveals an along strike variation of the thrust sheet stack with an extra non-metamorphic unit (XX-cover unit) underlying the reflector b in Fig. 3 (basal contact of the Tuscan Nappe in surface exposure), which is absent in the footwall block. This major feature may be related to a setting in which the North Apuane Fault reworked a previous lateral ramp and/or transfer zone of the contractional wedge and an early system of low angle normal faults. This hardly fits a simplistic interpretation of the North Apuane fault system as part of the transfer zone of an extensional framework formed by two major low angle east-dipping extensional structures (the Lunigiana and Garfagnana Low Angle Normal Fault, part of the Etrurian Fault System of Boncio et al., 2000; Basili et al., 2008; Meletti et al., 2008) as reported in Pezzo et al., nor does it suit the similar frame of a breached-relay ramp proposed by Stramondo et al. (2014).
5. Finally, the presence of a high velocity Apuane structure (metamorphic units) juxtaposed against low velocity units all around the Alpi Apuane with a complex 3D subsurface architecture, in particular across the area of the 2013 Lunigiana earthquake, calls for a general reconsideration of the whole seismic sequence at least in terms of depth of the events using a 3D velocity model instead of a simple 2D one (Barani et al., 2013; Scognamiglio et al., 2009). After the relocation of the main event and aftershocks, it will be possible to discuss in detail the seismotectonics of the 2013 Lunigiana earthquake and test the kinematic and tectonic role of the North Apuane Fault.

In conclusion, as correctly underlined by Pezzo et al., the seismic source of the 2013 Lunigiana earthquake was not listed among the