The contribution of airborne LiDAR data to the assessment of surface faulting hazard

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Surface faulting is the breaking of the ground surface directly related to coseismic slip along a fault in case of moderate to strong earthquakes (generally for M > 5.5) and is commonly confined to a relatively narrow zone a few meters to few tens of meters wide. However, in some cases a fault can rupture the surface along multiple splays, distributing the deformation across a zone hundreds of meters wide (BONCIO *et alii*, 2012 and references therein).

As the other natural hazards, although scarcely considered, the surface faulting hazard can have a relevant societal impact because it determines a substantial risk where urban areas and/or important infrastructures, facilities and lifelines are developed or planned in correspondence of an active fault trace.

In central Italy, although a significant number of active faults able to produce surface ruptures were recognized and mapped at different scales and with variable accuracy, the assessment of surface faulting hazard is often a difficult task because of: a) lack of detailed map of active faults at a national level; b) the frequent complex geometrical pattern of active tectonic structures related to inherited structural and deformational style.

By a practical point of view, the exact identification of active fault traces is the first task to be accomplished for assessing surface faulting hazard. This is done by means of the direct observation of geomorphic and tectonic features that are related to the present tectonic activity.

The occurrence of the 6 April 2009 Mw 6.3 2009 L'Aquila earthquake strongly highlighted how critical is a deep knowledge of the location and characterization of the active faults and also of their secondary splays to prevent damage directly related to surface faulting.

In fact, during the April 6 mainshock, coseismic surface ruptures occurred along several splays that are part of the complex fault system that is the expression of the earthquake causative fault at the surface (Paganica fault – PF thereinafter). Buildings and lifelines located across or near the coseismic surface ruptures suffered significant damage (e.g. the Paganica-Tempera aqueduct pipe broke because crossed by coseismic surface faulting). Even secondary splays had a role in the damage distribution in the area. (EMERGEO WORKING GROUP 2009; FALCUCCI *et alii* 2009; BONCIO *et alii* 2010).

Prior to the 2009 earthquake, the PF was reported in the official geological maps as a single, simple fault trace affecting Middle to Late Pleistocene continental deposits (Geological Map of Italy, scale 1:50.000, sheet 359, L'Aquila, APAT, 2005).

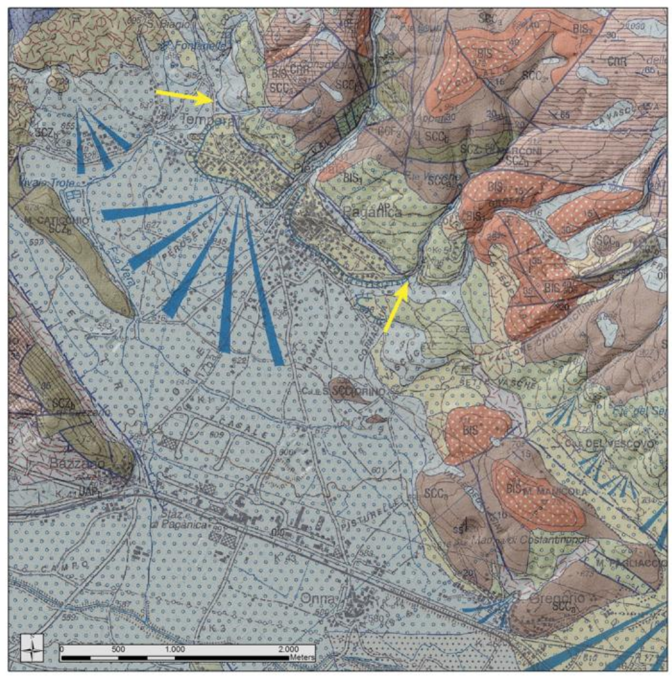

Fig. 1 – Trace of the Paganica Fault (blue line between yellow arrows) as reported by the Geological Map of Italy, scale 1:50.000, sheet 359, L'Aquila (APAT, 2005).

The complexity of the 2009 coseismic surface breaks highlighted the need for a substantial refinement of the PF mapping, including minor and hidden active fault traces despite they have or have not ruptured in 2009. This with the aim of defining all the fault splays capable of displacement in the future earthquakes and especially to pinpoint those that have a higher potential to slip.

In doing this, we took advantage of the availability of an airborne LiDAR (light detection and ranging) survey performed in the area hit by the 2009 earthquake.

LiDAR is an optical remote sensing technology that uses laser light to measure distances with high accuracy and high resolution and that is capable of revealing the ground surface even in highly vegetated areas. Moreover, the high-resolution topographic data stored in the LiDAR-derived Digital Elevation Models (DEMs)

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may be digitally manipulated to enhance and reveal subtle topographic features, something not possible with most aerial photographs, satellite imagery, or lower-resolution digital elevation data.

High-resolution topographic data such as airborne LiDAR have recently been deployed to qualitatively and quantitatively analyze landscapes resulting from tectonic, hillslope, fluvial, biologic, and anthropogenic activity. Earth-science applications of LiDAR include identification of faults (HAUGERUD *et alii* 2003, CUNNINGHAM *et alii* 2006, KONDO *et alii* 2008, ARROWSMITH and ZIELKE 2009, HUNTER *et alii* 2011), characterization of the geometry of fault scarps (BEGG and MOUSLOPOULOU 2010, DELONG *et alii* 2010, HILLEY *et alii* 2010, BRUNORI *et alii* 2012) and estimates of slip-rate of active faults (FRANKEL *et alii* 2007, AMOS *et alii* 2010).

The airborne LiDAR survey of the study area was commissioned by the Italian Civil Protection Department and was performed a few days after the 6 April 2009 mainshock by the Civil Protection of Friuli Venezia Giulia (Italy) using an Optech ALTM 3100 EA Airborne Laser Terrain Mapper System, with vertical errors <0.2 m and horizontal errors <0.54 m. The original LiDAR bare-earth point cloud was processed in order to obtain a regular 1 x 1 m DEM and several derivative digital maps (shaded relief, slope, aspect, etc.).

Figure 2 compares the resolution of traditional photogrammetry-generated (5 m resolution - figure 2a) and LiDAR-generated shaded reliefs (figure 2b) and highlights how the very high-resolution (1m) LiDAR-derived data can be an effective tool in representing the landscape morphology with unprecedented detail.
In figure 2, the LiDAR-derived shaded relief allows to display, among others, some subtle landforms like fault-related scarps and peculiar drainage patterns (e.g. fluvial entrenchment that may testify the location of uplifted fault footwall) of an area close to the San Gregorio village.

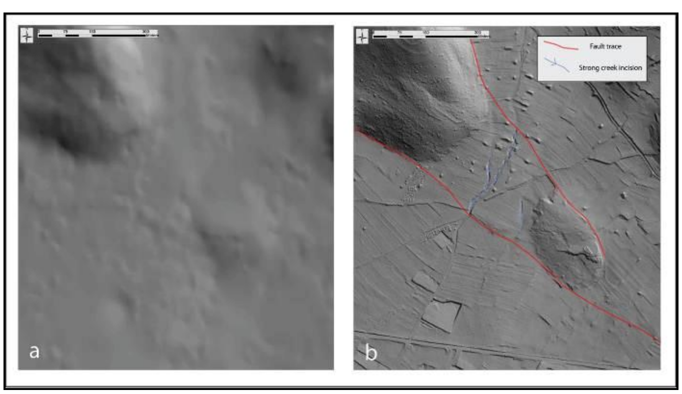

Fig. 2 – Comparison between 5m resolution (a) and 1-m resolution (b) shaded reliefs.

By extensively using the LiDAR-derived high resolution topographic data, we performed morphological analysis and mapping at a 1:10.000 scale, to identify and map all the existing active tectonic structures in the study area, as well as to characterize their predominant behavior.

Figure 3 encompasses the same area of figure 1 and highlights how the LiDAR-derived data can substantially increase our confidence in locating and tracing most of the active fault traces.

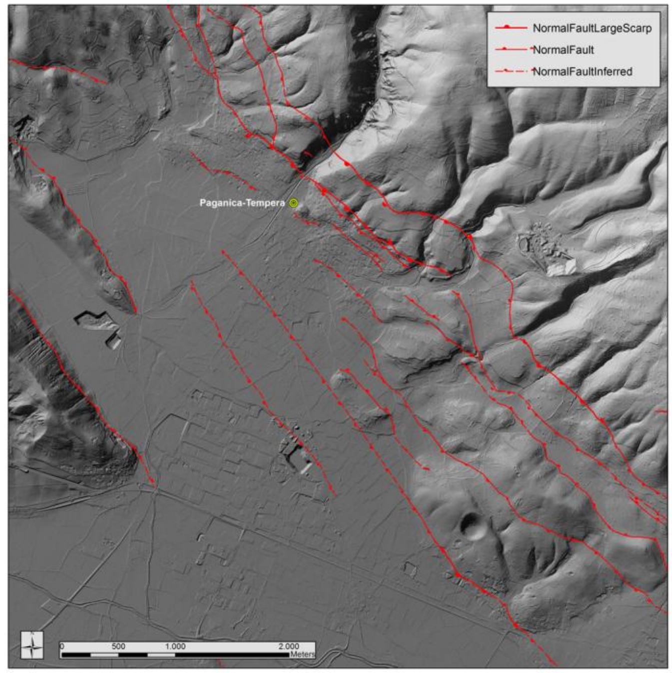

Fig. 3 - LiDAR-derived shaded relief showing the surface structural setting of the Paganica fault (same area of figure 1).

At the LiDAR resolution, the surface structural setting of the PF appears to be much more complex than expected from the geological map (figure 1) but also from previous detailed works (BAGNAIA *et alii* 1992, VEZZANI and GHISETTI 1998, BONCIO *et alii* 2004), being characterized by the presence of several normal parallel fault splays both synthetic and antithetic.

The L'Aquila experience, as well as those developed from other parts of the World, shows that LiDAR data offer a unique opportunity to improve our knowledge about the location of fault splays related to an active structure, the reconstruction of its overall geometry and extent, and for its characterization. Under this light, fault mapping integrating LiDAR to the other traditional approaches, is certainly an innovative and effective tool that represents the first input for starting, in Italy too, a reliable assessment of surface faulting hazard following standardized or regional methodologies (e.g. Eurocode 8, 2003; BONCIO *et alii* 2012).

In this paper we are going to present some key areas where LiDAR data analysis contributed to a better imaging of the location of the active fault splays relevant to existing and developing urban centers, industrial areas and main infrastructures (roads, railways, pipelines, etc.) in the area hit by the April 6 2009 earthquake.

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