Traces of the active Capitignano and San Giovanni faults (Abruzzi Apennines, Italy)

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ABSTRACT
We present a 1:20,000 scale map of the traces of the active Capitignano and San Giovanni faults in the area of the Montereale basin (central Apennines, Italy) covering an area of about 80 km\textsuperscript{2}. Detailed fault mapping is based on high-resolution topography from airborne LiDAR imagery validated by extensive ground truthing and geophysical prospecting. Our analysis allowed the recognition of several features related to fault activity, even in scarcely accessible areas characterized by dense vegetation cover and rugged terrain. The identified fault traces run at the base of the NW-SE striking Montereale basin-bounding mountain front and along the base of the southwestern slope of the Monte Mozzano ridge, and have a length of about 12 and 8 km, respectively. Improving the knowledge of fault geometry is a critical issue not only for the recognition of seismogenic sources but also for surface fault hazard assessment and for local urban planning. The knowledge of the exact location of the fault traces is also crucial for the seismogenic characterization of the active faults by means of paleoseismological trenching.

1. Introduction
We present a 1:20,000 scale map of the traces of the active Capitignano and San Giovanni faults in the area of the Montereale intermontane basin (Abruzzi region, Italy – hereinafter referred to as MB). The Main Map comprises an area of about 80 km\textsuperscript{2} including the villages of Montereale, San Giovanni Paganica and Capitignano.

The study area (Figure 1) is located within the central Apennines, one of the most seismically active areas in the Mediterranean that was repeatedly struck by $M \geq 6$ destructive earthquakes both in recent and historical times. Major events, with local Intensity ranging from VIII to X, occurred during the 1703 seismic sequence with mainshocks in Norcia (January 14), Montereale (January 16) and L’Aquila (February 2) (Chiarabba, Jovane, & DiStefano, 2005; Rovida, Camassi, Gasperini, & Stucchi, 2011). Recently, the area experienced strong shaking during the Mw 6.1 2009 L’Aquila earthquake (Herrmann, Malagnini, & Munafò, 2011; ISIDe working group, 2016; Scognamiglio et al., 2010), located about 20 km to the SE.

The Capitignano Fault (hereafter referred to as the CF) and the San Giovanni Fault (SGF) belong to a very dense array of NW–SE striking, mainly SW-dipping, normal faults accommodating the present-day 2–4 mm/yr regional NE–SW extension (D’Agostino et al., 2011; Hunstad et al., 2003). According to Galadini and Galli (2000), both faults are part of the Alto Aterno Fault system, whereas according to Lavecchia et al. (2012), they form the Montereale Fault that behaves as an individual source capable of releasing strong earthquakes.

The CF occurs mainly in the syn-orogenic siliciclastic deposits of the Laga formation, with a stratigraphic offset ranging from 400 to 600 m (Chiarini et al., 2014). It bounds the MB to the northeast and is characterized by a normal slip kinematic with a minor left lateral component (Lavecchia et al., 2012). It runs at the base of a prominent fault-generated mountain front characterized by wine-glass valleys and well expressed triangular facets (Figure 2). In the piedmont belt three generations of Middle Pleistocene to Holocene in age alluvial fans have been recognized (Chiarini et al., 2014). At the hangingwall the oldest ones (orange-colored in the 3D view of the map), possibly of Middle Pleistocene age on the basis of their weathering degree, are tilted toward the CF.

The SGF bounds the southwestern slope of the Meso-Cenozoic basin-to-slope carbonate succession of Mt. Mozzano, giving rise to a straight fault scarp with well exposed bedrock fault planes. The stratigraphic offset ranges from 500 to 700 m. Early Pleistocene in age stratified alluvial/slope breccias (yellow-colored on the 3D view of the map) cropping out at the hangingwall significantly tilted towards the
fault. In the northern portion, the fault offsets colluvial deposits Late Pleistocene in age (Chiarini et al., 2014).

The knowledge on these faults is currently limited and no data on their seismic behavior is available, therefore their contribution to the local and regional seismic hazard is not constrained. Geological data for a reliable seismic hazard assessment should include detailed information on fault characteristics, including location, complexity, kinematics, slip, and fault-zone length and width.

LiDAR (Light Detection And Ranging) is a robust tool for active fault identification and mapping.

Figure 1. Seismotectonic sketch of the Montereale basin and surrounding region (Central Apennines, Italy). Historical and recent earthquakes ($M > 5.0$; http://emidius.mi.ingv.it/CPT11, http://iside.rm.ingv.it/), focal mechanism of the 2009 L’Aquila mainshock and Quaternary normal faults are shown (LMF: Laga Mountain Fault; CF: Capitignano Fault; SGF: S. Giovanni Fault; AF: Assergi Fault; MMF: Monte Marine Fault; MPF: Monte Pettino Fault; SF: Stabiata Fault; PSDFS: Paganica-San Demetrio Fault System; modified after Galli, Galadini, and Pantosti (2008) and ITHACA database (Comerci et al., 2013 – http://sgi1.isprambiente.it/geoportal/catalog/content/project/ithaca.page). The black-dashed ellipse encloses the study area. The lower right inset shows the location of the area with respect to Italy and the direction of extension across the central Apennines (black arrows).
because it allows accurate detection of the bare-earth surface even in densely vegetated and urbanized areas, yielding high-resolution topographic information about the ground surface. For this reason, we have used high-resolution topographic data from an airborne LiDAR survey, complemented by field data, to compile a 1:20,000 scale map (Main Map) of the fault traces and fault-related geomorphic features of the CF and the SGF in the area of the MB. By providing a detailed reconstruction of the CF and SGF surface geometry (location, complexity, kinematics, and fault-zone length and width), this map (Main Map) represents a valuable contribution to seismic hazard assessment because, (1) the exact location of the active fault traces provides first-hand information on where surface faulting can occur during a moderate to large earthquake, (2) provides a minimum length of the potential seismogenic source at depth and (3) provides the necessary background for starting further studies on the fault seismogenic characterization (e.g. reconstruction of geomorphic piercing points for slip rate estimates, paleoseismological trenching, etc.).

2. Data and methods

Our approach in mapping traces of active faults in the MB area includes a combination of office-based and field-based methods. Our strategy was to first identify and digitally map fault traces (e.g. lineaments) on-screen, on the basis of geomorphology interpreted from airborne LiDAR-derived imagery. As a second step, LiDAR-derived data were compared with data from ground truthing and extensive field survey, including shallow geophysical prospection, in order to verify the tectonic origin of the identified lineaments and of the fault-related geomorphology.

2.1. LiDAR data

Airborne LiDAR is an optical remote sensing technology that uses multiple returns of a laser beam aimed at the ground to measure distances with high accuracy and high resolution (sub-metric), allowing rapid measurement of topography over large areas. In more detail, this technology permits a laser signal to penetrate the forest canopy and ultimately yield an image of the ground surface as if the forest were stripped away. This allows geoscientists to undertake detailed geomorphic and tectonic mapping to identify faults scarps, displaced geomorphic features, and other tectonic landforms, even in highly vegetated areas (e.g. Arrowsmith & Zielke, 2009; Brunori, Civico, Cinti, & Ventura, 2013; Cunningham, Grebby, Tansey, Gosar, & Kastelic, 2006; Haugerud et al., 2003; Hilley, DeLong, Prentice, Blisniuk, & Arrowsmith, 2010; Hunter, Howle, Rose, & Bawden, 2011; Lin, Kaneda, Mukoyama, Asada, & Chiba, 2013).

Our mapping was performed using an airborne LiDAR dataset acquired in the framework of the Progetto Abruzzo (http://progettoabruzzo.rm.ingv.it/en) with a RIEGL LMS-Q680i sensor. The coverage includes an area of about 80 km² that encompasses scarcely accessible and densely forested areas. Vertical and horizontal errors associated with the LiDAR acquisition are less than 0.2 and 0.5 m, respectively. We processed the original point cloud to create digital elevation models (DEMs) of the bare-earth surface, virtually stripping the trees from the land, and several derivative digital maps (shaded relief, slope, aspect, etc.). The DEMs have a resolution of 1 m, better resolving the topography with respect to conventional data (e.g. 10 m DEM of Italy; Tarquini et al., 2007).

Figure 3 compares shaded relief images of a 5 m-pixel DEM derived from orthophotographs (panel a) and high-resolution (1 m-pixel) LiDAR-derived Digital Surface Model (DSM) and Digital Terrain Model.
(DTM)s (panels b, c and d) and highlights how LiDAR data can be an effective tool in detecting the bare-earth surface even in densely vegetated and rugged areas.

We should mention that the actual resolution is variable across the study area. In regions of especially dense cover and/or rugged topography, the number of laser returns decreases considerably compared to less vegetated, less steep areas, resulting in lower resolution. This is visible in shaded relief images of the DEMs, where the lower density of ground returns results in triangles that obscure some topographic details. Fortunately, this issue does not affect fault trace recognition because of their preferential location at the base of slopes.

### 2.2. Fault location from geomorphic expression and field truthing

Within the study area the CF and the SGF traces are defined through the recognition of: (1) classical assemblages of geomorphic features related to fault activity and (2) fault plane outcrops. Classification of features was performed according to the available literature (Lienkaemper, 2012; Zachariasen, 2008 and references therein).

The fault traces are included on the Main Map as a line coverage. The different degree of certainty on the fault trace location is highlighted on the map by different line types: certain, good fault identification; inferred, extrapolated trace location; uncertain, faint fault identification. Other tectonic lineaments within the study area are reported too as olive green lines. They are predominantly normal faults occurring mostly in bedrock (Centamore et al., 1992; Vezzani & Ghisetti, 1998) and likely inactive based on their geomorphic expression.

### Table 1. Morphotectonic features used in map compilation.

| Morphotectonic feature | Description |
|------------------------|-------------|
| Fault (strike, dip)    | Fault plane outcrop |
| Deflected stream       | Deflection in the natural drainage system |
| Hanging valley         | Tributary valley higher than the main valley |
| Stream knickpoint      | Sharp change of stream gradient |
| Saddle                 | Lowest point on a mountain ridge between two peaks |
| Tilted deposits        | Quaternary continental deposits tilted by fault activity |
| Linear valley          | Linear-shaped fluvial valley |
| Scarp (facing direction)| Step or offset on the ground surface where one side of the fault has moved vertically with respect to the other |
| Triangular facet (base)| Inverted V face with a broad base and an apex pointing upward, remnant of a fault plane |
Fault-related geomorphic features relevant for fault recognition are drawn on the **Main Map** as a point coverage with different symbols (Table 1), although some of them extend laterally. These latter are fault scarps (with facing-direction identified), triangular facets and linear valleys. Point features include fault outcrops (shown on the map with strike and dip), deflected streams, stream knickpoints, hanging valleys and tilted deposits (Figure 4). Triangular facets or faceted spurs are one of the most striking features of mountain fronts produced by active normal faulting. Facets are considered to be eroded fault scarps and usually increase in complexity through time because of erosion of the mountain front. Knickpoints can develop in response to normal faulting when the downthrown (hanging-wall) block is in the downstream direction: this causes a sharp change (knickpoint) of the stream gradient in the longitudinal stream profile. Vertical motion and tilting that accompany normal faulting can influence the drainage in faulted regions by creating hanging valleys and by influencing the drainage pattern (e.g. linear zones of weakness, such as faults, cause streams to cut down linear valleys).

2.3. **Fault location from shallow geophysical investigations**

To provide additional information on the subsurface location and geometry of the faults, we integrated ground truthing with high-resolution electrical resistivity tomography (ERT) investigations. Electrical resistivity data were collected at three key sites of the previously recognized fault traces using a Syscal R2 (IRIS Instrument) with 64-electrode dipole-dipole and Wenner–Schlumberger array geometries. Data inversion was performed by using the smoothness-
constrained least-squares algorithm of Loke, Acworth, and Dahlin (2003). We acquired 6 ERT profiles setting different electrodes spacing, respectively, of 2 and 5 m in order to obtain very shallow resolution while at the same time recover resistivity data at depth (about 30 m maximum).

Figure 5 shows an example of an ERT profile performed in the area of San Giovanni. The ERT model exhibits a net resistivity contrast which ranges from lower resistivity (10 Ωm) to the west to higher resistivity values (700 Ωm) to the eastern sector that was effective in confirming the tectonic nature of previously identified morphological scarps. Red dashed lines with arrows indicate the location of two possible fault splays inferred from abrupt lateral resistivity changes.

3. Conclusions

New high-resolution topographic data from LiDAR imagery analysis complemented by ground truthing and newly acquired field data (including shallow geophysical prospections) resulted in the compilation of a 1:20,000 scale map of the traces of the active CF and the SGF in the MB. The CF and the SGF define a complex fault setting at surface for a total extent of about 12 km with an average strike N145°. Both the CF and the SGF surface expression comprise 200 to 800 m-wide deformation zones with multiple sub-parallel, locally overlapping traces.

The map presented here represents a significant refinement of the location of the active faults in the study area resulting in the detailed knowledge of the faults surface complexity. LiDAR data proved to be an invaluable tool that substantially increased the confidence in identifying and mapping most of the fault traces. However, a combined approach integrating office-based LiDAR interpretation with ground truthing is necessary because of possible inconsistencies in the interpretation.

By providing a detailed map of the faults at surface, the Main Map represents a valuable contribution to surface faulting hazard assessment, helps in defining the minimum length of the seismogenic structure, and supplies the necessary background (i.e. precise fault trace location) for the development of detailed paleoseismological studies that would shed light on the surface rupture history of these faults.

Software

LiDAR data processing and analysis and field surveying used a range of software. LAStools suite (http://rapidlasso.com/lastools) was used for LiDAR processing and DTM production. Rocklogger (http://rockgecko.com/), for Android smartphones, was used to measure fault dip and strike. Google Maps for mobile (https://www.google.com/intl/en/maps/about/) was useful for geolocation and visualization of outcrops and sites while in the field. We organized and analyzed all the collected field data and remotely sensed imagery using Esri ArcGIS 10.2.1, Esri ArcGIS Pro 1.1 and Google Earth Pro. Adobe Illustrator CS6 was used for final map production.

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