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FAULT RUPTURE HAZARD ALONG A SECTOR WITH ASEISMIC CREEP IN URBAN AREA (EASTERN SICILY)

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Introduction

The hazard connected with the surface propagation of a fault rupture during a seismic event is a widely discussed topic in the literature and its importance in Italy has emerged particularly after the 2009 L'Aquila (Italy) earthquake (Boncio et al., 2010; EMERGEO Working Group, 2010). The area of Mt. Etna volcano is considered as the most critical in Italy because of the high geological predisposition to surface faulting in relation to the high urbanization (Guerrieri et al., 2009).

An active fault whose coseismic displacement can intercept the ground surface is defined as capable (Machette, 2000; Galadini et al., 2012). The faults characterized by aseismic slip (creep), either episodic or constant over time, should be considered similar to the capable faults. In a largely urbanized area like the lower eastern slope of Mt. Etna also affected by high level of seismic strain release, the risk related to surface faulting (coseismic and aseismic) is very high (Blumetti et al., 2007; Guerrieri et al., 2009). The displacement between the two fault blocks can dislocate, rotate or cause structural damage to buildings and infrastructure and lifelines located along or in proximity of the fault line.

In this study we precisely map the segments associated with an active fault system in the lower eastern slopes of Etna, we characterize the damaged zone by means of several geophysical surveys (environmental noise, GPR, seismic tomography, ReMi) and, finally we try to assess the criteria for a rupture surface faulting hazard zonation, essential for any land use planning and management.

Geological and tectonic setting

A system of active normal faults with main directions trending NNW and NNE, affects the eastern slope of the volcano (Fig. 1) (Monaco et al., 1995; Bousquet and Lanzafame, 2004); these segment originated, both in recent and historical times, earthquakes with magnitude up to 4.5. Because of shallow foci depth (<2-3 km) earthquakes have often caused harsh, even though localized, damages (Azzaro, 1999). The Late Pleistocene strain rates derived from geological markers, range from 1-2 mm/a (Monaco et al., 1997).

Recent GPS and interferometric data show that the eastern flank of the volcano is rapidly moving eastwards with velocity up to several cm/a (Solaro 2010; Bonforte et al., 2011; Guglielmino et al., 2011). This extension process, accompanied by subsidence in some coastal areas (Branca et al., 2014), has been

interpreted as a sliding of the whole eastern flank (see Azzaro et al., 2013 for a complete review) driven by gravity, load of magmatic intrusions or various fluids, tectonic forcing, or a combination of these (Azzaro et al., 2013; Mattia et al., 2015; Scudero et al., under review).

Flank sliding would be confined to the north by the movement of the left-lateral Pernicana fault, while to the south it would be partially accommodated by the Trecastagni - Tremestieri – San Gregorio fault system with prevailing right-lateral kinematics (Lo Giudice and Rasà, 1992; Solaro et al., 2010; Bonforte et al., 2010; Chiocci et al., 2011); finally the differential deformation within the eastern flank is accommodated through the movements of rigid blocks outlined by the pre-existing faults. Flank sliding is thought to be a recent (last 60 years) and shallow process (Branca et al., 2014; Mattia et al., 2015).

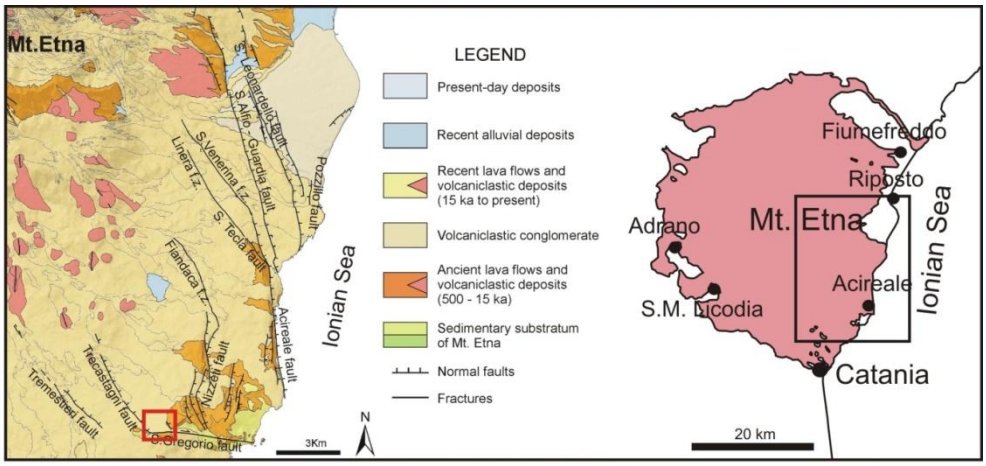

Figure 1.Geological and tectonic map of the eastern flank of Mt. Etna (modified after Monaco et al., 2010); the red box indicates the studied areas.

Ground ruptures

The San Gregorio fault extends roughly E-W for about 5 km inland (Monaco et al.2010) and continues also in the Ionian offshore (Chiocci et al., 2011). The structure is divided into three main segments with prevailing right lateral kinematics, and many other secondary segments. The absence of a sharp and defined morphology suggests that the lineament activated in more recent time with respect to the other faults, probably in response to the sliding process (Mattia et al., 2015). The fault is entirely lacking in instrumental seismicity, displacement occurs exclusively through creep episodes (Monaco et al., 2010). This study examines in detail the western segment, since it affects a large urbanized area.

Unlike other faults of Mt. Etna, whose long-term activity has produced cumulative scarps reaching tens to hundred meters, the morphological evidence of the San Gregorio fault is poor because to the lateral kinematics. The traces of the fault (or damage) zones have been mapped with precision within the urban areas

after an accurate and detailed survey of damages to artefacts and infrastructures caused by the fault displacement. The damages mainly consists of shallow to deep cracks affecting the walls of buildings (both infilling and bearing walls), fractures and rotations of retaining walls, sidewalks, curbs and paving. Fractures and cracks are usually aligned along bands with variable width ranging from 2 to more than 40 m. The maximum offset observed is ~30 cm and is probably the result of several creep episodes.

In addition to the damaged zones located along the fault trace we detected secondary damaged zones. Because of their arrangement with respect to the main fault, some of them are interpretable as Riedel's R or T type fractures in a right lateral shear zone; others are probably part of the NNW to NNE system. We mapped ground ruptures for a total length of about 3.8 km within the urban area of San Gregorio di Catania. Table 1 summarizes the geometric and kinematic characteristics of each damaged zone.

Geophysical surveys

The physical and mechanical properties of the hosting rocks are influenced by the presence of faults. To reconstruct the 3D geological structure of the fracture zones we applied different geophysical techniques: ground penetrating radar (GPR), seismic tomography, refraction microtremor (ReMi) survey and ambient noise recordings. All those methods are widely used in the investigation of active faults because they allow modelling the buried geological structure in terms of thickness of strata, geometry of discontinuities and seismic waves velocity propagation. In addition their integration allows the best possible resolution and a comprehensive interpretation (Imposa et al., under review). We performed 8 GPR sections, 1 tomographic survey, 1 ReMi section, and 533 ambient noise recordings arranged to form 26 sections. The results show features related to the occurrence of a fault: low velocity zones highly fractured areas, dislocated markers. Geophysical data always agree with field observation: damaged zone at depth is never larger than detected on the ground.

Table 1.Geometric and kinematic parameters of the mapped damaged zones.

Name	**L (m)**	**D max (m)**	**Main kinematics**	**Behaviour**	**Long term slip rate (mm/a)**	**Short-term slip rate (mm/a)**	**Ref.**
Catira - Cantarella	1600	5(v)	oblique dextral	creeping	0.3 (v; 15 ka)	5 – 7.5 (l)	Azzaro et al., 2012; this work
Salesiani	390	-	right lateral	creeping	-	-	this work
Macello	1080	3	normal	creeping	0.2 - 0.75 (15 – 4 ka)	0.4 – 0.7	this work
Morgioni	730	-	extensional (?)	creeping	-	1 - 3	this work

Surface Fault Rupture Hazard zoning

The presence of capable faults concerns two distinct topics: i) the potential interaction of the dislocation with artifacts, particularly their foundations; ii) the assessment and the zonation of the Surface Fault Rupture Hazard (SFRH; Boncio et al., 2012) and the definition of belts encompassing the potential occurrence of a ground rupture (setback). In this study we will discuss the latter issue.

Setbacks are the areas where the existing artifacts are susceptible to damage following a surface propagation of the rupture and they also define the minimum distance from the fault to build new critical infrastructures or any artefact that could suffer the rupture (Bryant and Hart, 2007). Many variables play a role in the assessment of setbacks and it is difficult to define general criteria. For a single fault system the following should be considered: fault geometry (lateral extension, dip angle, associated segments, tip or overlay zones), fault kinematics (dip, lateral or oblique slip), and the topography (Mc Calpin, 1987).

As general rule, a new rupture will tend to mark exclusively pre-existing ruptures where the greatest part of the slip is accommodated (Borchardt, 2010) and the width of the damaged zone is not strictly proportional to earthquake magnitude (or to maximum displacement) (Batatian, 2002; Boncio et al., 2012). Ground rupture could also occur at larger distances, but in any case on secondary structures that can be mapped if the scale is sufficiently detailed, so that they can be considered as independent fault in turn. (Boncio et al., 2012). It is essential to assess the scale of approach for SFRH zoning. The more detailed the scale and the fault zone is, the less are the uncertainties and the narrower could be the setback.
It is also essential to define a temporal scale for the process (Galadini et al., 2012).

The probability of a rupture on an undisturbed soil is low for rock older than the activation of the fault even for very active ones; conversely the probability of a new fracture is relatively high for young soils adjacent to moderately active faults (Borchardt, 2010). Setback should therefore follow a concept of "maturity" of the fault; Borchardt (2010) defines a statistically fault "mature" when it cumulates 30 or more slip events. In a mature fault the displacement will be always accommodated along the main rupture and the damaged zone will stop widening (Borchardt, 2010; Petersen et al., 2011); in this case, theoretically, it is not necessary to define a setback. In this study we decided to distinctly examine and characterize the detected fracture zones in order to better define the SFRH and the setbacks. We are aware that it is counterproductive to define setback unnecessarily wide, when it might be more effective to plan structural mitigation of the infrastructure where limited effects are expected (Borchardt, 2010).

In the last few years in Italy the discussion on the SRH zoningis rising (Boncio et al., 2012; Peronace et al., 2013) because of the lack of enough detailed regulation (GdL, M. S, 2008). In the literature the setback for normal faults are asymmetric based on the evidence that in normal faults the associated fracture density is wider in the hangingwall rather than the footwall. The ratio between setbacks in the two blocks varies from 1:3 to 1:5 (Boncio et al., 2012; Peronace at al., 2013; Guerrieri et al., 2014). In strike slip faulting the probability of rupture is

considered equal in the two fault block (Petersen et al., 2011), therefore setbacks are symmetric (Peronace et al., 2013; Guerrieri et al., 2014). Those authors propose setbacks depending on the level of understanding of the fault but that are never narrower than 30m even for the well assessed fault zones.

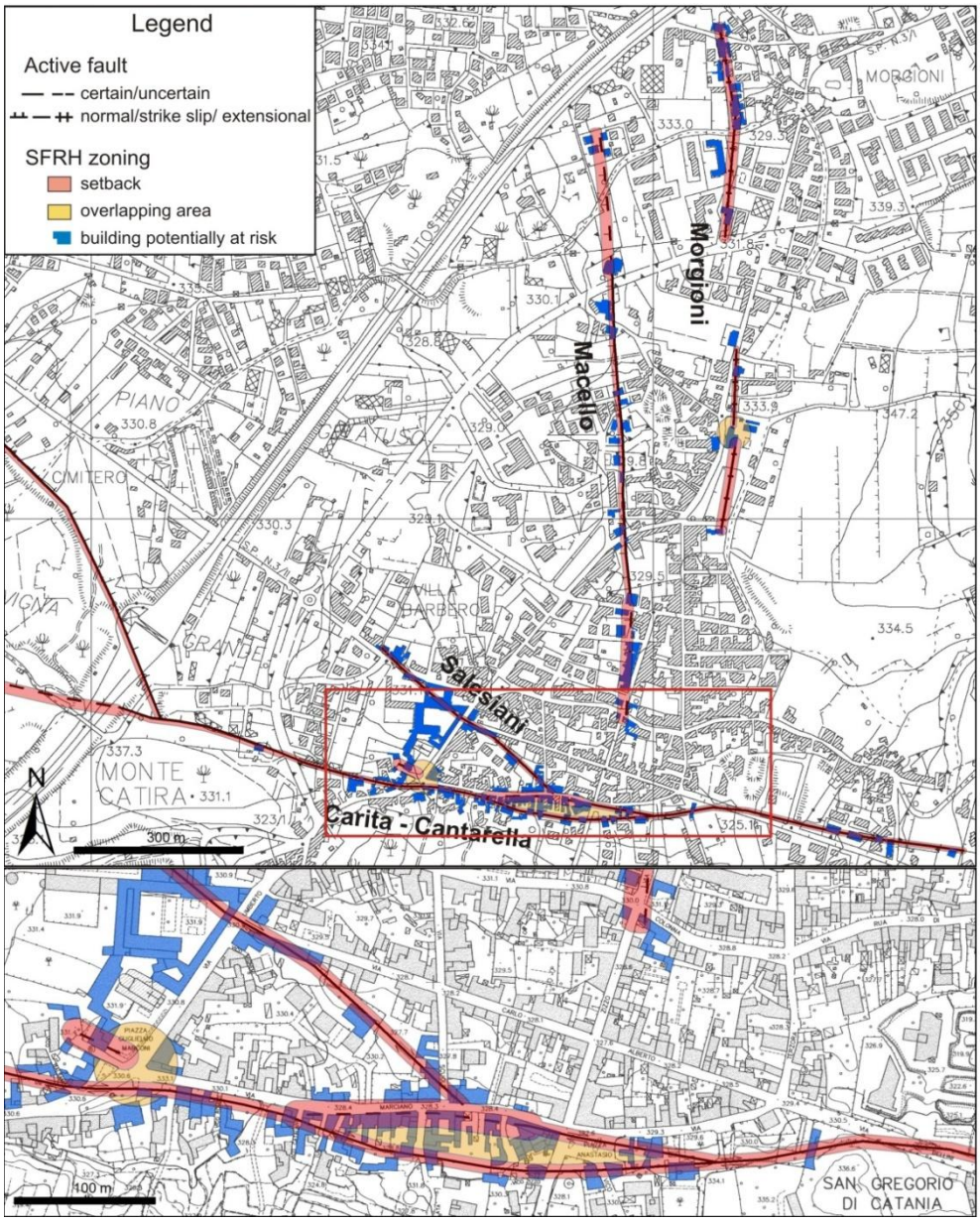

Figure 2.Example of SFRH in San Gregorio area: general view and detail.

The amount of detailed information collected on the fault makes the assessment of some general criteria for the SFRH zoning possible. We have been able to map also minor cracks or fractures associated to the main fault zone and we can consider negligible any mapping error that would be considered defining setback width. We can clearly consider the fault zone in San Gregorio area as mature because they mark pre-existing structures showing long-term activity, conversely in the Acitrezza area the fault system cannot be considered mature. For mature fault zone we propose setback of 10 m both for normal and strike slip fault extending 5m aside from the limit of the fault zones for strike slip ruptures. The same setback extends 2m in the footwall and 8 m in the hangingwall in normal fault zone, where uncertain faults were reported (dashed lines), setbacks were doubled. In the overlapping areas we propose a susceptibility zone 30 m wide.

Conclusive remarks

The multidisciplinary approach combining and integrating the classic surface survey with different geophysical methods has enabled obtaining a very accurate model of the geological structure especially in the first 15 m in depth. Therefore, we could define setbacks for the investigated fault zones. In San Gregorio area 174 buildingsintersect the setbacks and then are potentially involved in ruptures (Fig. 2). Ruptures associated with documented creep events are identified and reported. However, we cannot exclude definitively that future displacement could occur outside the assessed setback (Bryant and Hart, 2007). Ground ruptures associated to secondary effects (differential compaction, landslides, etc.) are not included in our analysis. Other potentially active faults could exist somewhere else in the mapped area and further investigations are recommended before planning any critical infrastructure.

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