THE SIGNIFICANCE OF THE “HIDDEN” FAULTS OF THE EASTERN FLANK OF MT. ETNA AND THEIR SEISMOGENIC POTENTIAL: NEW GEOLOGICAL CONSTRAINTS

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Introduction. The main seismic events on the eastern flank of Mt. Etna, characterized by low to medium magnitude (M≤ 5; Azzaro et al., 2009), are generally accompanied by the development of well-defined coseismic fracture zones. Their coincidence with the elongation of the mesoseismic areas, where most of the damages are confined, suggests interpreting the fractures as the emergence at surface of capable seismogenic structures (Azzaro, 1999; Barreca et al., 2013). This hypothesis is fully demonstrated along the NNW-oriented tectonic alignments, where the historical coseismic fracturing matched oblique (dextral) normal faults, showing well defined Late Quaternary cumulative scarps (e.g. Timpa of Acireale and Moscarello; see inset in Fig. 1; Monaco et al., 1997). On the contrary, discrete NW-SE oriented fracture zones cyclically form along alignments, where neither morphological nor geological cumulative displacements can be recognized. Even if their relation with rooted faults is obscure and mostly based on their cyclical coseismic renewal, these alignments have been interpreted as seismogenic “hidden” faults (e.g. Fiandaca Fault and S. Tecla Fault), responsible for part of the main local seismicity (Azzaro, 1999). The full understanding of the origin and nature of the
coseismic fracturing associated with the hidden faults of Mt. Etna is, thus, a crucial topic in the seismic microzonation analyses to validate the location of seismogenic sources and assess their potential. In this paper we discuss the results of the geological and morphostructural investigation that has been performed across the Fiandaca, Santa Tecla and Santa Venerina hidden faults, in order to define their role in the active kinematic picture of the eastern flank of Mt. Etna.

**Seismotectonic setting.** The eastern flank of Mt. Etna is dissected by two distinct sets of active structures. The prominent NNW-oriented fault belt, representing the northern termination of the Ionian-Etnean Branch of the Siculo-Calabrian Rift Zone (inset in Fig. 1; Catalano et al., 2008), consists of a half graben that includes the Acireale-S. Alfio master fault, the synthetic San Leonardello Fault and the antithetic Trepunti Fault. The epicenters of several main earthquakes (A.D. 1881; 1911; 1971) have been located at hangingwall of the rift zone (Monaco et al., 1997; Azzaro, 1999; Azzaro et al., 2009). On the footwall of this rift zone, discrete NW-oriented fracture systems, represented by the Fiandaca, Santa Tecla and Santa Venerina faults (ff, STF and SVF in Fig. 1; Barreca et al., 2013), have been described as alignments that are usually affected by both diffuse aseismic creep (Azzaro, 1999; Monaco et al., 2012) and coseismic remobilisation. The updated models on the active tectonics and the seismicity of Mt. Etna (Azzaro, 1999; Azzaro et al., 2012; Barreca et al., 2013) refer to the Fiandaca (A.D. 1894, 1884), S. Tecla (A.D. 1865, 1914) and SantaVenerina (A.D. 1879, 2002) faults some relevant seismic events, which have been otherwise attributed to the NNW oriented faults of the rift zone (Monaco et al., 1997). The most recent episode of remobilization of a “hidden” fault has been referred to the 29th of October 2002 earthquake (Mm=4.1; Azzaro et al., 2006), which was associated to the reactivation of an historical ground fracture zone (A.D. 1879), crossing through the village of Santa Venerina (SVF in Fig. 1; Azzaro et al., 2006; Barreca et al., 2013).

**Stratigraphy of the eastern flank of Mt. Etna.** Along the eastern flank of Mt. Etna, the volcanostratigraphic succession includes the products of all the stages of the etnean volcanism (Gillot et al., 1994). The volcanic cover rests, as a whole, on marine deposits, consisting of a monotonous Early-Middle Pleistocene marly-clay succession (Di Stefano and Branca, 2002) that bears submarine tholeiitic lava horizons, ranging in age from 0.58 to 0.46 Ma (Gillot et al., 1994). The marine succession is capped by subaerial transitional products from tholeiitic to alkaline, ranging in age from about 225 ka B.P. to 168 ka B.P. (Gillot et al., 1994; Corsaro et al., 2002). In a large area, going from Acireale to Giarre (inset in Fig. 1), a buried clastic wedge, which was exclusively detected by geophysical data (Cassinis et al., 1970; La Delfa et al., 2007), is interposed between the top of the marly clays and the outcropping etnean volcanic cover. The clastic deposits, here designed as Basal Clastic Wedge, fill a prominent triangular shaped tectonic depression, the Giarre Basin, which is bordered by two culminations of the Middle Pleistocene marly-clay substratum: the Acitrezza Ridge and the Nunziata High (inset in Fig. 1). The sequence of the alkaline products can be divided in four distinct units, which are separated by epiclastic deposits marking first order erosion surfaces. The oldest alkaline products, showing radiometric age from 140 ka to 132 ka (Gillot et al., 1994; Branca et al., 2007) have been grouped in the pre-Tyrrhenian alkaline lavas. These are unconformably covered by huge volumes of epiclastic deposits, here named Acireale Lahars that concealed the pre-existing volcanic topography, reaching a maximum thickness of about 150 m, in the area of Acireale. The Acireale Lahars shows distinctive reddish horizons that have been drilled in different sites of the southeastern flank of Mt. Etna, indicating a wide distribution beneath the recent volcanic covers, from Acireale to Santa Venerina. On top of the Timpa of Acireale, the Acireale Lahars are capped by coastal marine deposits that form the wide terrace of the 5.5 OIS (125 ka), extending towards the Acitrezza Ridge. The marine terrace is covered by alkaline lavas, ranging in age from 120 ka to 60 ka. These have been referred to the Tyrrhenian alkaline lavas, grouping the products of several spread edifices (Branca et al., 2007). A major epiclastic horizon, here designed as Milo Formation, conceals the deeply entrenched erosion surface that models the Tyrrhenian alkaline lavas, in the whole northwestern sector of the Giarre Basin. The backbone
of the modern stratovolcano is constituted by products, ranging in age from about 40 to 15 ka, while the recent volcanic covers consist of products emitted from the active feeding systems, in the last 15 ka (Gillot et al., 1994; Branca et al., 2007). A distinction between the Wurmian alkaline lavas and the Holocene lavas is here proposed on the basis of their position with respect to the deposits of the Chiancone alluvial fan (Calvari and Groppelli, 1996). The conglomerates of the “Chiancone” actually belong to two distinct sequences, separated by an erosional surface. The older sequence, confined in age in the last 15 ka (Guest et al., 1984; Calvari and Groppelli, 1996), forms most of the alluvial fan that is unconformably draped by a thin horizon made up of the younger sequence, showing a radiometric age of 7.6 ka B.P. (Calvari and Groppelli, 1996).

**Fiandaca Fault.** The Fiandaca Fault represents a major tectonic alignment that controls the boundary between the Acitrezza Ridge and the Giarre Basin. The fault is marked by a dramatic offset of the top of the Middle Pleistocene marly-clay, from about – 500 m b.s.l. (Cassinis et al., 1970), within the basin, to 210 m a.s.l., in the Acitrezza Ridge. The fault motion was also responsible for the emergence of the 460 ka-old tholeiitic pillow-lavas, which were emitted at a minimum depth of about 400 m b.s.l. (Corsaro and Cristofolini, 2000) and for the huge vertical displacement between the pre-Tyrrhenian alkaline lavas resting on the Acitrezza Ridge and those cropping out along the Timpa of Acireale (Fig. 1). On the downthrown sector of the fault, the Basal Clastic Wedge accumulated, with a thickness of about 400 m, comparable with the depth of deposition of the underlying marly clay. The fault is concealed by the marine terrace of the OIS 5.5 (125 ka), which crosses undisturbed the structure. It directly covers the bial marly clays of the Acitrezza Ridge, while it rests on subaerial volcanic succession, including the transitional basalts (225 ka) and the overriding 190 m-thick pre-Tyrrhenian alkaline lavas (140-132 ka), on the downthrown sector. Here, the thickness of the pre-Tyrrhenian sub-aerial products constrains a minimum apparent amplitude (>210 m) of the Tyrrhenian transgression (125 ka) that is at least 70 m wider than the actual absolute rise of the sea-level (136 m; Chappel and Shackleton, 1986).

The Fiandaca Fault is buried beneath the Tyrrhenian alkaline lavas and the overriding recent lava flows. However, its trace has been reconstructed taking into account the distribution of the outcrops of the Early-Middle Pleistocene marly-clays, representative for the extent of the upthrown sector, and the isopachs of the lava succession (Cassinis et al., 1970), significant to discriminate the volcanic cover accumulated on the downthrown sector. The resulting fault trace matches the location of the historical coseismic fracture zones which has been referred to the Fiandaca “hidden” fault (Azzaro, 1999). The relations of the fault with the different stratigraphic units are illustrated along a NNE-SSW oriented cross-section (profile 1 in Fig. 1). The profile shows that the Tyrrhenian alkaline lavas and the overriding recent lava flows, being very thick on the top of the Basal Clastic wedge within the Giarre Basin and thinner on the Acitrezza Ridge, have obliterated a tectonic scarp that cumulated before the Tyrrhenian. Considering all the described geological constraints, we can conclude that the fault activity along the Fiandaca Fault was confined in the 460-125 ka interval, during which it accommodated the whole relative vertical motions along the southwestern margin of the Giarre Basin.

**Santa Tecla Fault Zone.** Adjacent to the Fiandaca Fault, the Santa Tecla Fault Zone (Fig. 1) consists of two main left-stepping NW-oriented segments. The southeastern segment, showing a length of about 6 km, splays from the Acireale Fault, to the north of Acireale. Along a short length of the fault, at its southeastern termination, a tectonic scarp as high as 160 m is exposed. Along the scarp, the fault offsets a volcanic succession that includes the pre-Tyrrhenian and the Tyrrhenian alkaline lavas. The scarp is clearly bypassed by the Holocene lava flows, that cross undisturbed the structure, obliterating every morphological evidence of the fault motion. The trace of the fault has been, thus, reconstructed following the trend of historical coseismic ground fractures (Azzaro, 1999). The northwestern segment, showing a length of 4 km, developed in the area of Zafferana. This segment is marked by a
Fig. 1 – Geological map of the lower south-eastern flank of Mt. Etna (for location see dotted frame in the inset) and geological profiles across the ff, STF and the north termination of Acireale Fault. The inset shows the main tectonic features of the region.
cumulative scarp, which is completely draped by the Holocene lava flows. Along this segment, the stratigraphy of the volcanic products on the two sides of the structure is well exposed, providing several constraints for determining the age and the displacement-rate of the fault (Profile 2 in Fig. 1). The cross-section evidences that most of the total vertical displacement (180 m), corresponding to the offset of the top of the pre-Tyrrhenian alkaline lavas (> 125 ka), pre-dates the emplacement of the Tyrrhenian alkaline lavas of the Valle del Bove centers, showing radiometric age of about 93 ka (Branca et al., 2007). They unconformably cover the Acireale Lahars (132-125 ka) that reach a maximum thickness of about 200 m on the hangingwall of the fault, while they are reduced to a few meters preserved by erosion in the footwall of the fault. The later vertical displacements affect the Tyrrhenian alkaline lavas and the deposits of the Milo Formation (60-40 ka). At the northern termination, the fault segment, as well as the southeastern segment, shows a 160 m-high tectonic scarp. Also in this case, the scarp offsets a volcanic succession that includes the pre-Tyrrhenian and the Tyrrhenian alkaline lavas, ranging in age from 128 to 93 ka. The tectonic scarp is by-passed by the 40 ka-old basal levels of the Wurmian alkaline lavas, that cross undisturbed the fault. The field evidence, collected along the entire Santa Tecla Fault Zone would constrain, thus, an activity of the fault that must be confined in the 125-40 ka.

**Santa Venerina Fault.** The Santa Venerina Fault was described by Azzaro (2004); Azzaro et al. (2009) as a NW-SE oriented, 5 km long seismogenic fault responsible for at least two main historical shocks (1879, Mm=4.3; 2002, Mm=4.1), associated with ground fracturing. Because of the absence of any surface evidence of the structure, the fault has been traced on the basis of the distribution of the coseismic ground fractures that are cyclically renewed. These outline an alignment that splays from the northern tip of the NNW-SSE oriented Acireale segment of the Acireale-S.Alfio fault (Azzaro et al., 2009; 2012; Monaco et al., 2010; Barreca et al., 2013). The last episode of reactivation of the Santa Venerina Fault, which occurred during the 2002 event, was characterized by the development of two distinct discrete fracture zones: the former originated at the southeastern end of the structure, in the localities of San Giovanni Bosco and Dagala Canne, the latter developed at the northeastern termination of the “hidden” fault, across the village of Santa Venerina (Fig. 2).

The southern fracture zone was composed of two distinct clusters of closely spaced N-S to N170° oriented fractures, ranging in length from few hundreds to about 500 m that flanked a discrete segment of the northern termination of the Acireale Fault. This latter, characterized by oblique (dextral) motion (Monaco et al., 1997) clearly cut through very recent lava flows, forming a buried fault scarp by-passed by historical (1329) lavas (profile 3 in Fig. 1). The two clusters of coseismic fractures developed parallel to the main structure, on both the hangingwall and footwall of the fault, showing kinematics consistent with that of the major structure.

The northern fracture zone reactivated a length of 1 km of the termination of the “hidden” fault, along which closely spaced N10°-20° oriented fractures, ranging in length from 100 to 300 m, originated. The fracture zone crossing Santa Venerina has been investigated in detail through a grid of 9 cross-sections, based on integration of field data, from 1:5000 geological mapping, and several logs from bore-holes. The collected data provided sufficient information to outline a 3D geometry of the topography that have been concealed by the recent alkaline lava flows, related to the modern activity of Mt. Etna (< 15 ka; Recent Mongibello; Gillot et al., 1994)(Fig. 2). In the 3D reconstruction, a sharp 20 m-high scarp marks the trace of a buried NE-SW normal fault, separating the western and eastern sectors of the village (profile 1 and 2 in Fig. 2). The shallow stratigraphic horizons characterising the hangingwall of the structure have been analysed by three aligned, 90 m-deep bore-holes (profile 2 in Fig. 2) that are aligned from the buried fault line towards the east. The borehole S1, located immediately to the southeast of the fault trace, crosses the fault, thus constraining the southeast-dipping geometry of the structure. The deeper portion of the log, related to the horizons uplifted in the footwall of the fault, is represented by the pre-Tyrrhenian alkaline lavas that rest on a paleosol draping
Fig. 2 – 3D model of the substratum of the Holocene lava flows in the surroundings of Santa Venerina and distribution of the coseismic ground fractures related to the seismic event of 2002. Two geological profiles across the SGF and the ground fracture zone are reported.
epiclastic deposits. These have been correlated with the top of Basal Clastic Wedge of the Giarre Basin that, in the hangingwall, has been detected by geophysical data (Cassinis et al., 1970) at an elevation of about 150 m lower. The entire stratigraphic succession encountered in the boreholes S2 and S3, located more to the east, can be clearly referred to the volcanic succession that accumulated on the hangingwall of the fault, on top of the Basal Clastic Wedge. The stratigraphy and the geometry of the successions involved on both the footwall and the hangingwall of the fault, here designed as Santa Venerina-Giarre Fault (SGF in the inset of Fig. 1), are illustrated by the two cross-sections (Fig. 2). They show that the base of the Tyrrhenian alkaline lavas was vertically displaced by the fault for about 150 m and that the accommodation space due to motion along the SGF has been mainly filled with the Milo Formation that forms a wedge widening towards the fault. Finally, the structure appears to be bypassed by huge volumes of the volcanic products of the Recent Mongibello (< 15 ka) and the associated deposits of the two cycles of the Chiancone alluvial fan, which cross undisturbed the structure. The bore-hole data, combined with field information, thus suggest an age of the fault, starting from 125 ka B.P.. The end of the fault activity pre-dates the 15 ka and more probably was confined at the age of the top of the Milo Formation (40 ka). However, the buried fault played a major role in the evolution of the paleotopography reproduced in Fig. 2. The structure controlled the pre-15 ka river entrenchment that was confined at the footwall of the structure, while in the hangingwall was dominating the deposition. This topography has influenced the distribution of the volcanic products of the last 15 ka. In the western sectors of the village, where the coseismic fractures developed, the recent volcanic cover, alternating with several alluvial horizons, are channelized within WNW-oriented valleys that are modeled on a succession including the Acireale Lahars, the Tyrrhenian alkaline lavas and the Milo Formation (profile 1 in Fig. 2). The subsurface data, fitting well the surface evidence, show a clear continuity of the different stratigraphic units, which exclude the existence of a rooted fault beneath the surface coseismic fracture zone. The data rather point out that the fracture zone affects the volcanic products and the alluvial deposits infilling the axis of a buried valley.

Discussion and conclusions. According to the new geological data on the eastern flank of Mt. Etna, the coseismic fracture zones that have been referred to “hidden” faults developed in almost two distinct conditions. The fracture zones aligned along the Fiandaca and the Santa Tecla faults are actually connected to buried tectonic structures. In both the cases, along the rooted faults, huge Late Quaternary vertical displacements can be recognised, even if the end of their activity can be referred to 125 and 40 ka B.P., respectively. This implies that there is no a direct connection between the active coseismic ground deformation with the long-term evolution of the two structures. This is also demonstrated by the evidence that the lava flows of the last 40 ka by-passed the two faults, obliterating their older morphological expression. Moreover, none new morphotectonic feature generated and cumulated on these recent volcanic products. The cyclical renewal of the active fracture zones, thus, did not produce an appreciable cumulative permanent ground deformation. On the other hand, the explanation of the active fracture zones developed along the Santa Venerina fault is even more problematic, as our data would exclude a connection between the ground deformation and a deep seated NW-SE oriented fault. Paradoxically, the most unclear situation could provide the explanation for the genesis of the “hidden” faults at Mt. Etna. If the development of the coseismic fracture zones of the 2002 event is considered, we can distinguish along an apparent single NW-SE alignment, designed as Santa Venerina “hidden” fault, two distinct sets of structure. The former consists of the N170° fractures that, being developed in the San Giovanni Bosco area with the same trend and kinematics of the main Acireale Fault, can be referred to the remobilization of a discrete length of the major structure. The latter set of fractures, in the area of Santa Venerina, developed where the geological data inhibit to locate a rooted fault. A genesis of the fractures different from tectonics is also suggested by their unusual geometry that deviates from that of the modeled shear zones, because of the high angle orientation of the single fractures (N 10-20°) compared to the trend of their alignment (N 150°). The detailed
subsurface investigation have evidenced that the ground fracture zone is aligned with the axis of a buried paleovalley, whose flanks represent sharp lateral discontinuities between an alternation of lavas and clastic deposits, infilling the valley, and the more homogeneous epiclastic sequences of the substratum. In this context, the coseismic fractures originated at almost right-angle to the valley orientation, being centred on its axis, and extend for a length which is consistent with the reconstructed width of the valley at depth. Finally, the fracture alignment abruptly interrupts at the mouth of the valley, which is controlled by a NE-SW oriented buried fault zone. The direct connection between their geometry and that of the buried valley strongly suggests interpreting the coseismic fracture zones of Santa Venerina as a site effect of the ground motion, determined by major lateral mechanical discontinuities of the substratum that likely produced a differential ground motion between the valley infilling and the surrounding terrains. As well, the active coseismic ground deformation along the Fiandaca and Santa Tecla faults, where cumulative features are absent, could be explained in terms of differential site response, due to the sharp lateral discontinuities of the rock mechanics on the opposite sides of the two major structures. The two faults, located at the southwestern border of the prominent Giarre Basin, can represent mechanical barrier along which the ground motion generated by seismic events located along the main seismogenic faults of the SCRZ, cutting through the Giarre Basin, concentrate their effects.

References
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