

Capable fault assessment in Seismic Microzonation of volcanic environments: fault behaviour classes and zone-based mapping from the Mt. Etna (Italy) case study

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Abstract

The volcanic region of Mt. Etna (Sicily, Italy) presents a unique challenge for seismic hazard assessment due to the interplay between regional tectonics, flank instability, magmatic processes and shallow volcano-tectonic dynamics. The area is frequently affected by shallow ($H < 5$ km), moderate-magnitude earthquakes ($M_{\max} \approx 5.0$) that generate extensive surface faulting, often disproportionate to their energy release. Standard national regulations for “Active and Capable Faults” (ACF), originally designed for tectonic environments, fail to address specific volcanic features such as “hidden” faults, aseismic creep, and diffuse fracturing fields. This paper presents the newly developed “Guidelines for the study of Active and Capable Faults in the Etna volcanic area” (GL_ACF_Etna, Version 2.1). We introduce a tailored classification system that distinguishes between Exposed and Buried ACFs, creeping faults and Active Fracturing Zones (AFZ). Furthermore, we define criteria for delimiting Respect Zones (RZ) and Susceptibility Zones (SZ) for Level 3 Seismic Microzonation (SM3). The proposed methodology integrates historical macroseismic data, high-resolution geological mapping, geophysical investigation and multi-temporal InSAR analysis to provide a robust tool for land-use planning in one of Europe’s most active volcanic areas.

Keywords: Active and Capable Faults; Surface Faulting; Seismic Microzonation; Land-use planning; Mt. Etna

1. Introduction

Seismic Microzonation (SM) aims to evaluate and mitigate local seismic hazards in urbanized areas (ISSMGE-TC4, 1999; SM Working Group, 2015; Moscatelli et al., 2020), where site effects may produce severe impacts. Permanent ground deformation caused by surface faulting is a well-known issue within the Italian regulatory framework; the national guidelines (Technical Commission on Seismic Microzonation, 2015 – hereafter GL_ACF) define Active and Capable Faults (ACF) as seismogenic structures exhibiting documented seismic activity that produces clear, cumulative morpho-structural elements at the surface. While in the first level of SM studies (SM1), identifying the precise surface trace of ACF with the Attention Zones (AZ) is a fundamental prerequisite for establishing specific hazard areas, the introduction of Respect Zones (RZ) and Susceptibility Zones (SZ) in the third level of SM studies (SM3) precisely regulates land use in strips of territory potentially subject to future coseismic effects. However, applying these standard morpho-tectonic criteria to active volcano-tectonic environments, such as Mt. Etna or Campi Flegrei, presents significant methodological challenges. Volcanic areas are typically characterized by extremely shallow seismicity ($H \leq 2-4$ km) and high earthquakes recurrence rates. Although these events generally have moderate magnitudes (e.g., $M_{\max} \approx 5.0$ at Mt. Etna), they are frequently highly destructive, resulting in high epicentral intensities (I_0 up to IX-X EMS) and severe ground deformation (Azzaro et al., 2012). Moreover, the continuous rejuvenation of the topography due to recurrent eruptive activity (e.g., lava flow invasions, ash and lapilli fallouts) and the complex rheological behavior of the crust often result in dispersed coseismic fracturing fields, making it difficult to identify cumulative long-term fault scarps. To address these regional peculiarities, this paper presents the new “Guidelines for the study of Active and Capable Faults in the Etna volcanic area” (GL_ACF_Etna v2.1), developed to properly adapt the national standards to this specific environment. The primary goal of this work is to characterize the Etnean ACF to enable accurate mapping and the subsequent delimitation of ACF Zones (Z_{ACF}) for Level 3 Seismic Microzonation (SM3). By integrating extensive macroseismic historical data, field geological-structural surveys, geophysical investigations and advanced InSAR analyses, we propose a tailored classification of active structures including exposed, buried, and creeping faults, as well as the newly defined Active Fracturing Zones (AFZ) to build reliable predictive models of coseismic surface ruptures. The GL_ACF_Etna have been developed within the “Etna ACF_SM Project” by a multidisciplinary Working Group (geologists, applied geophysicists, seismologists, remote sensing analysts) involving Public Research Institutions, Universities, and the Regional Government (Civil Protection Department of Sicily). This paper details the scientific rationale behind these new guidelines, focusing on the novel classification of volcanic faults and the associated zoning regulations for urban planning; the area of interest of the “Etna ACF_SM Project” is mostly the eastern flank of the volcano.

2. Geological and Seismotectonic Setting

In the following, we briefly recall the main geological and seismotectonic features defining the reference framework for the ACF characterization, leaving the general geodynamic context of the area (Bonforte and Puglisi, 2003; Branca and Ferrara, 2013; Catalano et al., 2004; Catalano et al., 2008; Hollenstein et al., 2003; Monaco et al., 1997; Serpelloni et al., 2007) and the flank instability processes driving the seaward sliding of its eastern sector to the extensive literature (Monaco and Tortorici, 2000; Bousquet and Lanzafame, 2004; Bonforte et al., 2011; Chiocci et al., 2011; Palano et al., 2012; Urlaub et al., 2018; Azzaro et al., 2022). In particular, the fault segments active at Etna cut through a volcanic succession spanning in age from 600 ka to the Present, including products from several successive eruptive stages (see Branca et al., 2011 and De Beni et al., 2011 for a comprehensive overview of Mt. Etna stratigraphy). The main active fault belt (“Timpe Fault System” of Azzaro et al., 2012) crosses the eastern flank of the volcano (Fig. 1), where the interaction between volcanism and active tectonics has originated clear cumulative morpho-tectonic features, varying in size according to the age of the displaced sequence. The thickness of recent volcanic products, burying and hiding the pre-existing fault scarps grown up over time, is thus the principal aspect determining the surface evidence of active faults at Etna.

2.1 Stratigraphy

The backbone of Mount Etna consists of the succession of the modern central stratovolcano that has grown in the last 60 ka (Stratovolcano Supersynthem of Branca et al., 2011). This edifice expanded on a highly articulated

topography composed of remnants of a “Primitive Shield Volcano” (Branca et al., 2008) and other edifices scattered east of the modern summit areas (C.C. in Fig. 1) and located in the same areas affected by the ACFs. In the last

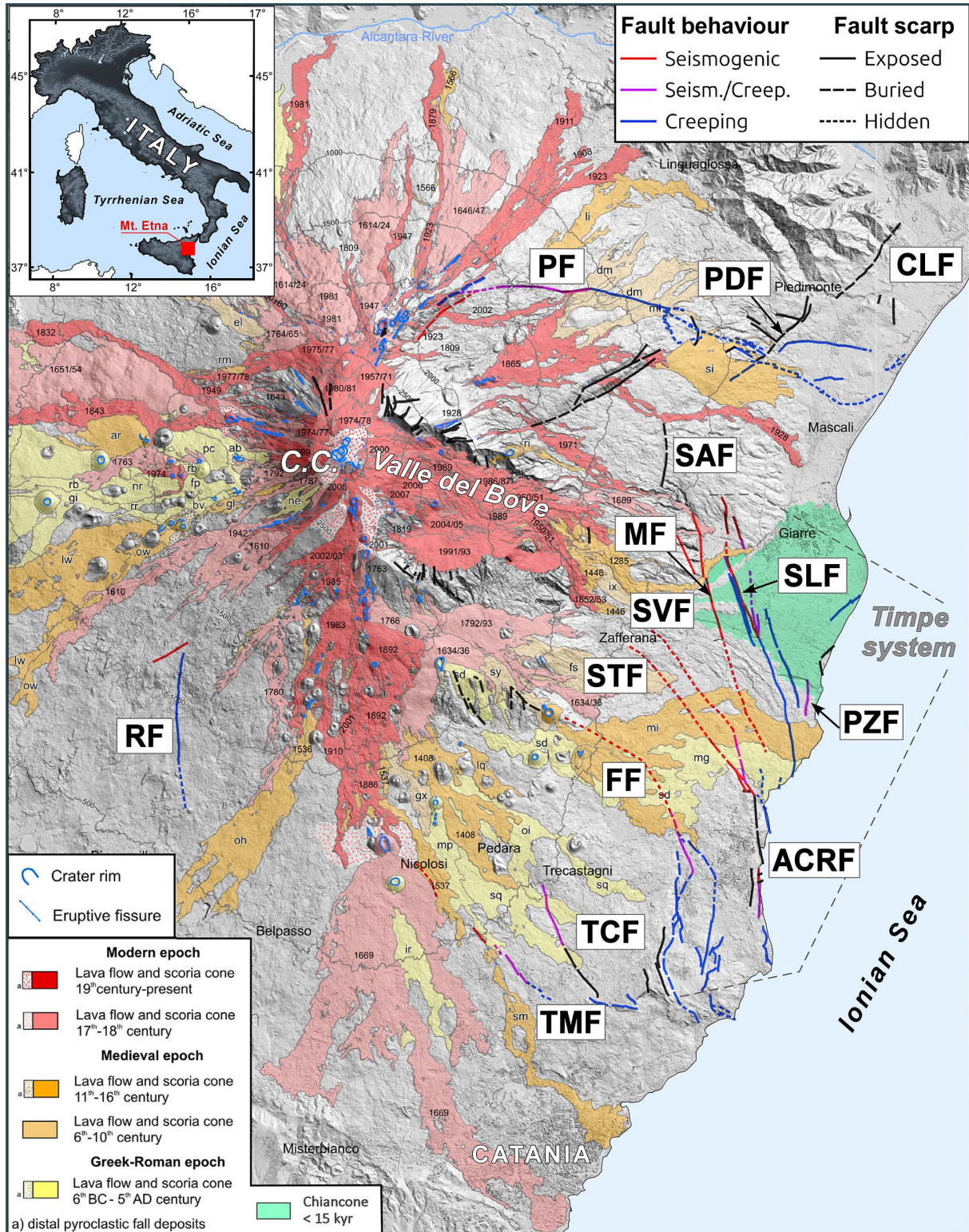


Figure 1. Geological and tectonic framework of Etna. Base map with dates and abbreviations of historical and ancient lava-flows from Branca and Abate (2019); fault types and behavior from Azzaro et al. (2012). Fault abbreviations: ACRF, Acireale; CLF, Calatabiano; FF, Fiandaca; MF, Moscarello; PDF, Piedimonte; PF, Pernicana; PZF, Pozzillo; RF, Ragalna; SAF, Sant'Alfio; SLF, S. Leonardello; STF, S. Tecla; SVF, S. Venerina; TCF, Trecastagni; TMF, Tremestieri. Black lines indicate inactive faults. C.C., Central Craters.

15 ka, the piling up of the active edifice (Mongibello of Branca et al., 2011) has been coincident with a profound re-shaping of the entire eastern flank. In the upper part, the horseshoe-shaped Valle del Bove depression formed due to the impressive dismantling of a series of ancient edifices developed in the region, whose relics form the wall of the depression (Valle del Bove Supersynthem of Branca et al., 2011). The huge volumes of epiclastics remobilized from the Valle del Bove have been deposited in the lower eastern flank, to form the wide, 15 to 7 ka old, Chiancone Alluvial Fan (CAF; Calvari and Groppelli, 1996), extending from the village of Zafferana to the Ionian coast of Giarre (light green in Fig. 1). The resulting topography played a decisive role in the distribution of the younger lava flows around the principal ACFs of Mt. Etna. Lavas emitted from the summit areas (C.C. in Fig. 1) and other scattered vents have been mostly captured by the Valle del Bove and/or diverted further east along the southern flank of the CAF, isolating large portions of the eastern flank where the primary topography, imprinted by cumulative fault scarps, has been largely protected from resurfacing by successive lava flows. In these regions, the very impressive scarps (“Timpa”) cumulated on the remnants of ancient “Primitive Shield Volcano” (>110 ka; Timpe Supersynthem of Branca et al., 2011) and the linear sharp scarps cumulated on ACF (Fig. 1) are still exposed. On the contrary, the morphological expression of the ACFs sharply disappears in the adjacent areas subject to protohistoric and historical lava invasions, where the repeated re-surfacing processes have been faster than the fault-scarp growth-rate.

2.2 Active faults Framework

The eastern sector of Mt. Etna is affected by a complex network of active faults involved in the flank instability processes driving the seaward sliding of this part of the volcanic edifice (Urlaub et al., 2018 and references therein). The seismotectonic characteristics of these structures exhibit a wide spectrum of features ranging from different rupture mechanisms (coseismic slip vs creep) to heterogeneous morphological evidence (exposed, hidden and buried scarps) (for details, see Azzaro et al., 2012). These elements play a primary role in delimiting Respect Zones (RZ) and Susceptibility Zones (SZ) or Active Fracturing Zones (AFZ).

Figure 1 shows the complex tectonic framework of interest for the ACF characterization (see Azzaro et al. and Brooks et al., this volume).

Without describing in detail the individual faults, here we briefly recall that they appear segmented, with sections of the same structure characterized by either stick-slip (earthquake-related slip) or stable-sliding behaviour (aseismic creeping), albeit in some cases they can coexist, for example along the Pernicana Fault (PF; Acocella and Neri, 2005; Bonforte et al., 2007). This has to be taken into account when delimiting RZs or SZs, since the impact of the associated surface faulting effects is completely different. While creep produces localised ground ruptures, damage effects affecting only the man-made features astride the dislocation lines (Rasà et al., 1996), coseismic displacements cause significant ground deformations along strike, affecting fault length up to 6-8 km (Azzaro, 1999), and widths up to 300 m across the fault trace, with fracture fields prevailing in the hangingwall (see the features produced by the 2018 earthquake in Tortorici et al., 2021; Azzaro et al., 2022; Tringali et al., 2023).

Similarly, the grade of morphological evidence also has a significant impact on the ACF characterization. The three tectonic landforms recognised by Azzaro et al. (2012) – exposed and buried scarps, and hidden faults – intrinsically imply a decreasing level of precision in mapping the fault trace, and this produces RZs or SZs more or less wide to be defined.

The implications of the above characteristics to define ACF classes for Etna and the related criteria adopted to delimit the zones, are discussed in Section 4 and 5.

3. Reference data for ACF zoning

The characterization of Etna ACFs relies on a multidisciplinary approach combining a huge amount of data of different nature, spanning from historical to instrumental and field observations. Here, we briefly recall the main components considered to constrain, at best, the definition and mapping of the ACF zones discussed hereinafter.

The first source of information comes from historical seismology. Seismic activity at Etna has been extremely well documented since the 1600s and provides a clear view of seismotectonic activity especially in the urbanized areas of the volcano. We referred to the Macroseismic Catalogue of Mt. Etna Earthquakes (CMTE, Azzaro and D’Amico, 2026a),

a specific compilation which reports 1,874 events, including fore- and after-shocks. In particular, our attention focused on the distribution of the mainshocks – i.e., the damaging earthquakes with epicentral intensity I_0 larger than VII EMS – capable of producing significant effects of coseismic surface faulting (Azzaro, 1999). Importantly, CMTE allows for the reconstruction of the “Seismic Fault Histories,” that is the association between a causative fault and the relevant earthquakes.

A further step in the knowledge of the characteristics of the coseismic faulting has been obtained with the recent online publication of the “Etnan Active Faults Database” (DFAE; Azzaro and D’Amico, 2026b). DFAE is based on a revised and updated dataset of earthquake ruptures, and it reports the interactive mapping of the tectonic elements linked with the relevant metadata such as: seismotectonic behaviour, morphological evidence, kinematics, location and extension of ruptures along strike. As for CMTE, it is possible to analyze in detail the characteristics of the coseismic faulting through the “Seismic Fault histories”, which show the chronological sequence and spatial distribution of the ruptures along a specific fault (for details, see Azzaro et al., this volume). This historical perspective is vital for identifying fault segments potentially active during different events as well as the “hidden” faults, such as the Santa Venerina Fault (SVF in Fig. 1), identified in the field only after the 2002 earthquake (Azzaro, 2004).

The above framework has been validated and improved through specific field surveys. In particular, we integrated data from the “Geological Map of Etna Volcano” (1:50,000 scale; Branca et al., 2011) and the “Volcano-tectonic map of Mt. Etna” (1:100,000 scale; Azzaro et al., 2012) with inspections aimed at verifying some traces of the “Exposed” and “Buried” faults in order to transpose these categories in terms of SM3 guidelines. In this phase, special attention was devoted to discarding some purely volcanic elements such as eruptive fissures or flow channel levees introduced in Level 1 SM, which have to be not considered in the ACF zoning.

Another important and innovative source of information derives from the application of Differential SAR Interferometry (DInSAR). In the framework of the “GL_ACF_Etna”, Brooks et al. (this volume) developed an original approach to investigate the spatio-temporal evolution of ground deformation using Sentinel-1 data over the 2015-2020 period. This analysis represents one of the first attempts, in this context, to apply the SBAS approach using a dense interferogram network specifically aimed at fault-scale investigation on Mt. Etna. Results show that the differential fault-slip analysis across fault traces can isolate the fault-related component, highlighting a significant variability along strike – both in terms of slip rate and kinematic segmentation (locked fault segments and creep sectors) – useful for better constraining the definition of Respect Zones and Susceptibility Zones.

Finally, we have to recall the extensive campaign of targeted geophysical surveys to define the geometry of faults in the subsurface (Caielli et al., this volume). Depending on the logistic and geological conditions of the sites of interest, the geophysical teams tested different methods, spanning from Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR), seismic refraction (SR), and Horizontal-to-Vertical Spectral Ratio (HVSr) measurements. These investigations were critical for reducing the uncertainty of positioning the “Buried” faults, allowing for the refinement of the Susceptibility Zones.

4. Results: Classification of Etnan ACF

A comprehensive database (DB_ACF_Etna) cataloguing some fault segments and associated zoning relevant to SM level 3 studies accompanies the guidelines (Fig. 2). The active lineaments at Etna, identified as capable faults in national and local archives (ITHACA Working Group, 2019; Azzaro and D’Amico, 2026b), were classified based on their surface expression into categories, some aligning with the classical national guidelines (GL_ACF, 2015) definitions. Only the faults with documented seismic history and observed ground displacement/fracturing were considered in the database and relevant for SM studies. Eligible ACF must demonstrate cyclic seismic activity with morpho-structural evidence, sufficient to identify either the principal fault trace (ACF_a, certain) or its probable location when buried (ACF_b, uncertain), critical for establishing Respect Zones (RZ) or Susceptibility Zones (SZ) as defined in GL_ACF (2015).

A central assumption of this framework is that surface deformation relevant to SM may occur through different mechanisms, not all of which are directly associated with coseismic slip on a single, well-defined fault plane. Consequently, capable fault assessment must distinguish between exposed and buried structures, between seismic and aseismic deformation, and between localized faulting and spatially distributed deformation zones. We also had to consider that the categories “exposed” and “buried” may have very different meaning from the perspective

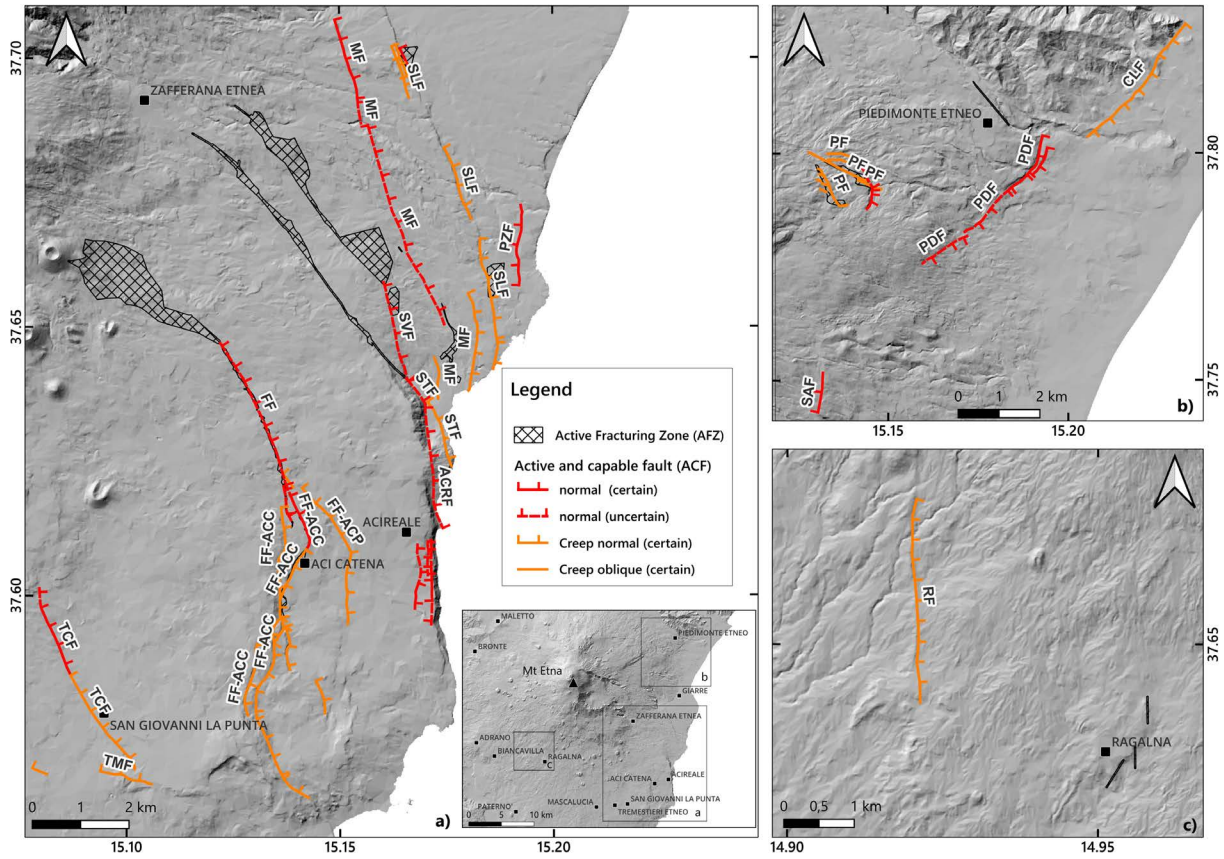


Figure 2. Details of the structures considered in the DB_ACF_Etna. Faults: ACC, Acicatena; ACRF, Acireale; ACP, Aciplatani; CLF, Calatabiano; FF, Fiandaca; MF, Mascareello; PDF, Piedimonte; PF, Pernicana; PZF, Pozzillo; RF, Ragalna; SAF, Sant’Alfio; SLF, S. Leonardello; STF, S. Tecla; SVF, S. Venerina; TCF, Trecastagni; TMF, Tremestieri.

of SM studies, referring to the exposure of fault scarp or of the fault trace. According to this latter connotation, the two terms can be transposed in the classification for SM studies as synonyms of “certain” (ACF_a) and “uncertain” (ACF_b). However, our categorization included all the “exposed” active faults as “certain”, using cautelative width of the susceptibility zones, taking into account also potential residual uncertainties about the exact location of fault traces. These distinctions are made explicit for the Etna volcanic area through the definition of four fault behaviour classes (Fig. 3): exposed capable faults (ACF_E), buried capable faults (ACF_{E_s}), creeping faults (ACF_{E_c}), and Active Fracturing Zones (AFZ).

4.1 Exposed capable faults (ACF_E)

The Exposed capable faults (ACF_E) correspond most directly to the strict definition of a capable fault, in that they display clear and unambiguous evidence of activity at the surface, corresponding to classical concept of a capable fault explained in the national guidelines (GL_ACF, 2015). These structures are characterized by a clear and mappable surface expression, typically in the form of fault scarps, offset geomorphic markers or displaced stratigraphic units. Geological and geomorphological evidence indicates recent activity, and the fault trace can be identified with sufficient confidence to allow a reliable cartographic representation at detailed operational scale (1:5,000-1:10,000).

In the Etna area, ACF_E structures are commonly expressed through offset lava flows, fractured surfaces and linear scarps affecting volcanic and sedimentary units of different ages. However, even within this class, fault traces may exhibit segmentation, changes in orientation or variations in surface expression due to volcanic resurfacing and erosion. For this reason, the mapping of ACF_E structures is supported by the integration of geomorphological analysis, stratigraphic observations, seismological data and, where available, geophysical constraints.

4.2 Buried capable faults (ACF_{E_s})

The Buried capable faults (ACF_{E_s}) include segments of ACF covered by recent lava flows that locally mask the geological and morphological evidence of tectonic structures. This category includes fault segments classified in the literature as buried faults (Azzaro et al., 2012). ACF_{E_s} segments are often located in continuation of ACF_E segments abruptly interrupted at the intersection of detrital deposits and/or the edge of historical lava flows that overlie the fault. The trace of the ACF_{E_s} can be reconstructed by interpolating between adjacent exposed segments (ACF_E), taking into account the generally recognizable morphological bend in the lava covering the structure, at the location of the buried fault scarp.

Areas affected by ACF_{E_s} segments, in the event of seismic reactivation, may still be subject to intense faulting/fracturing, also linked to the deformation of the recent lava cover, i.e. footwall flexure with related extrados extensional fractures.

4.3 Creeping faults (ACF_{E_c})

This category includes faults or segments of active faults with a clearly identifiable trace that produce, within a narrow zone surrounding the structure, deformation and/or surface faulting – whether continuous or episodic – without any significant associated seismicity.

During energetic earthquakes (also in case of shallow hypocenters), some portions of these faults may experience an acceleration in creep movement, with the coseismic reactivation of previous dislocations. The trace of ACF_{E_c} corresponds to the interpolation of evidence of surface deformation recognizable on the ground, where deformations and consequently damage to structures also occur. Such alignments may be associated with cumulative morpho-structures along segments characterized by a prevailing vertical component of movement.

4.4 Active Fracturing Zone (AFZ)

The Active Fracturing Zone (AFZ) is introduced to address a distinctive characteristic of the Mt. Etna volcanic area, namely the frequent absence of stable and cumulative surface fault traces associated with active and capable structures. In fact, AFZs envelop coseismic fracturing effects identified over the last two centuries, even if they cannot be associated with a fault trace clearly supported by geological and geomorphological evidence. The lack of cumulative morpho-structures suggests a spatial dispersion of coseismic fracturing, which prevents the definition of classic ACF Zones as defined by GL_ACF (2015). AFZs can also be permanently confirmed using geodetic data after events (GPS and InSAR – Azzaro et al., 2013; 2020).

This category includes most of the hidden faults described in the literature (hidden faults in Azzaro et al., 2012), the latest occurring on 26 December 2018 (Civico et al., 2019; Villani et al., 2020; Romagnoli et al., 2021; Tortorici et al., 2021; Azzaro et al., 2022; Tringali et al., 2023), the lineaments reported in the DRPC Sicily database and classified as “historical and observed seismic fractures,” as well as the seismic fracture fields associated with them. In these cases, surface fracturing may also occur at significant distances from the vertical projection of the main buried fault, making it impractical for the longitudinal zoning of surface rupture.

Historical and macroseismic observations indicate that periodic reactivations of capable faults at Mt. Etna do not necessarily produce localized and cumulative topographic offsets indicative of a single surface rupture. Rather, different seismic events may activate secondary structures located in different positions along the inferred structural alignment, preventing the identification of a single reference trace suitable for conventional fault zoning. This behaviour is consistent with the presence of surface-hidden structures, often referred to as hidden faults, which do not reach the ground surface but generate extensive fields of coseismic fracturing.

One of the priorities in the implementation of the Guidelines was to distinguish among tectonic features – those actually related to growth, by repeated seismic cycles, along stabilized dislocation lines, feasible for a predictive SM scenario – from volcano-tectonic coseismic features related to single eruptive episodes not necessarily subject to predictable future reactivation. These last dispersed volcanic features have been explicitly excluded from the ACF database and the SM zonation framework, for the objective difficulty to predict eventual location of future eruptive fissures opening at the detailed scale required by SM3 studies.

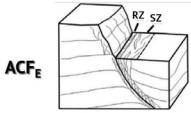
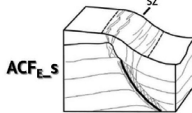
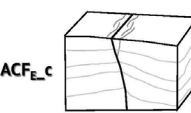
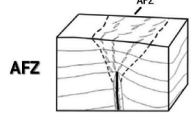
	Exposed Active and Capable Fault	Buried Active and Capable Fault	Active Fault by Aseismic Creep	Hidden Fault (Active Fracturing Zone)
				
Definition	A fault with a clearly identifiable morphological scarp or an exposed fault plane.	A fault covered by recent volcanic deposits (e.g., historical lava flows or pyroclastic/epiclastic covers) where the scarp is masked. The trace is inferred by linearly interpolating between exposed segments.	Faults exhibiting continuous displacement without significant seismicity associated. During energetic earthquakes, some portions of these faults may experience an acceleration in creep movement, with the co-seismic reactivation of previous dislocations.	Areas characterized by distributed coseismic fracturing rather than a single rupture plane and trace. This category covers "hidden faults" and historical fracture fields (e.g., the 2018 Fiandaca rupture) where no cumulative morphology exists.
Mapping	Classified as ACF_a (certain).	Classified as ACF_b (uncertain).	Classified as ACF_a (certain).	Defined by the envelope of historical fractures plus a buffer.
Behavior	Ruptures are expected to occur at the base of the scarp.	Rupture may propagate diffusely through the overburden.	Ruptures are concentrated in a narrow zone bordering the fault.	Distributed coseismic fracturing.

Figure 3. Classification of Etnean ACF typologies.

5. Discussion.DB_ACF_Etna and zoning criteria for Seismic Microzonation (SM)

The operational core of the new guidelines is represented by DB_ACF_Etna, a comprehensive database that systematically catalogues some of the active and capable fault (ACF) segments in the Etnean volcanic area and defines their associated hazard zonations required for SM3 studies (Fig. 4). This archive serves as a regulatory tool designed to standardize the active lineaments of Mt. Etna already identified as capable faults within national and local archives (such as ITHACA or the DFAE – Azzaro and D’Amico, 2026b). The inclusion criterion for DB_ACF_Etna is highly rigorous: it considers exclusively those structures demonstrating a documented cyclic seismic history and direct evidence of surface dislocation or coseismic fracturing.

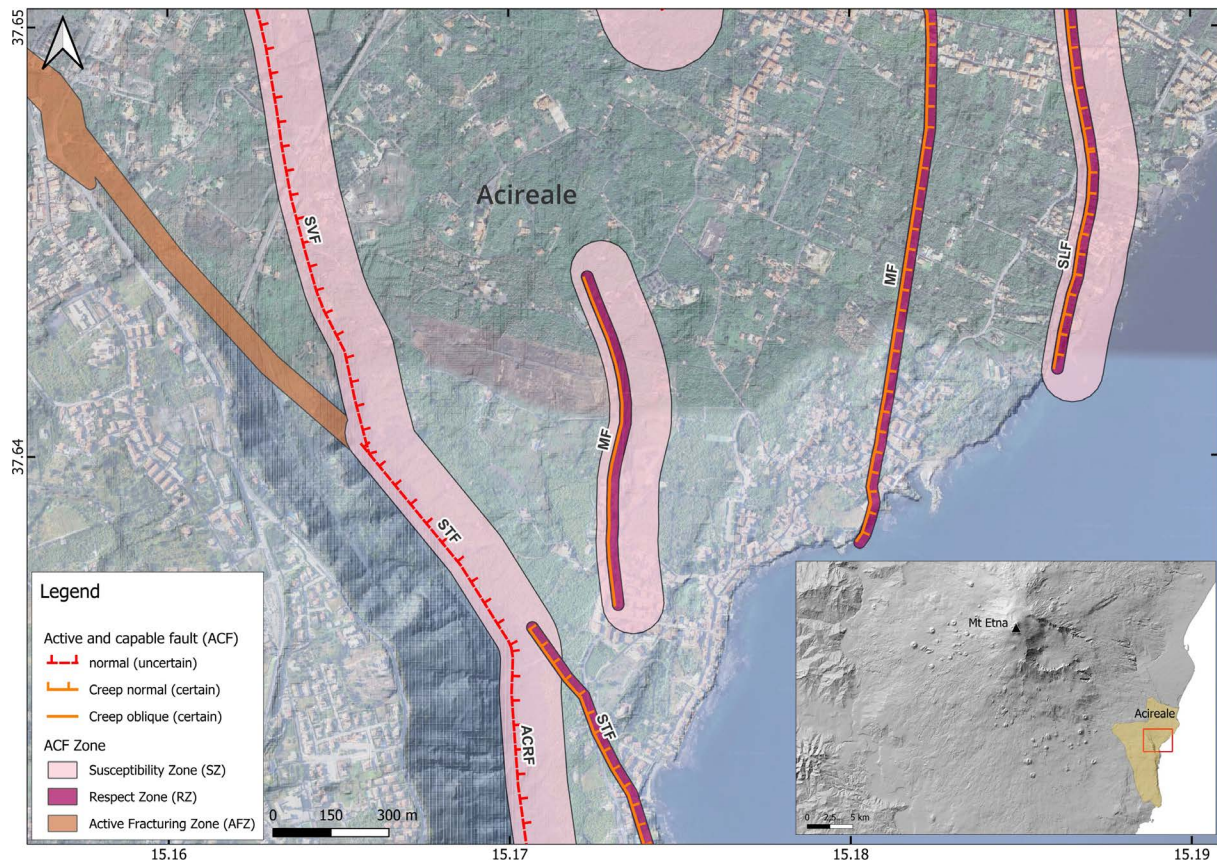


Figure 4. Example of zonation of ACF types in a portion of Acireale municipality. Fault name: SVF, Santa Venerina; STF, Santa Tecla; ACRF, Acireale; MF, Moscarello; SLF, San Leonardello.

The implementation of this database overcomes the limitations of the traditional morpho-tectonic approach, which is often inapplicable in active volcanic environments due to the continuous rejuvenation of topography by lava flows and pyroclastic deposits masking long-term cumulative fault scarps. Below, we outline the detailed geometric and operational criteria utilized within the database to delimit the different fault zones, mapping them directly to the corresponding fault behavior classes.

The translation of the DB_ACF_Etna behavior classes into cartographic constraints for land-use planning is achieved through two main levels of urban protection, applied differentially based on the degree of trace certainty:

- The **Respect Zone (RZ_{ACF})** represents an area of absolute exclusion for new construction. It is defined exclusively for faults whose surface trace is classified as “certain” (ACF_a – Fig. 4 and Table 1), including both exposed structures (ACF_E) and those characterized by aseismic creep (ACF_{E_c}). The standard width is established at 30 m total, centered on the fault trace. However, to reflect the structural physics of dip-slip normal faulting prevalent in the regional extensional belt, the RZ_{ACF} can be applied asymmetrically. For normal faults, a footwall (FW) to hanging wall (HW) ratio of 1:4 is established to mitigate the broader deformation field typically expected on the downthrown block (Fig. 4). Conversely, a symmetric 1:1 ratio is retained for purely strike-slip segments (such as the Pernicana Fault boundary).
- The **Susceptibility Zone (SZ_{ACF})** identifies the area where future surface ruptures or distributed ground cracking are likely to occur, mandating detailed high-level investigations for any localized urban deployment. For ACF_E and ACF_{E_c}, the reference width of the SZ_{ACF} ranges from 0 to 160 m (Fig. 4 and Table 1). This envelope can be deleted only if paleoseismological trenches or site-specific geophysical campaigns (e.g., ERT, GPR) confirm the absolute absence or precise spatial confinement of the main deformation band. For the ACF_{E_s} which are always classified as uncertain (ACF_b – Table 1) are assigned a more conservative and wider SZ_{ACF} of 300 m. Due to the unpredictability of how a seismic rupture can propagate diffusely through fractured volcanic cover, this zone can only be optimized down to a strict minimum of 160 m and can never be completely reduced to zero. Furthermore, the SZ_{ACF} can be asymmetric following the same principles as the RZ_{ACF}.
- The **Active Fracturing Zone (AFZ)** is the most important novelty from standard national planning (GL_ACF, 2015) introduced within the DB_ACF_Etna framework. This polygonal zone is applied where the presence of deeply buried structures or the complex mechanical layering of basaltic and pyroclastic successions generate wide, spatially dispersed fields of coseismic ground cracking and secondary fracturing, making it mathematically and operationally impractical to identify a single, continuous reference fault trace suitable for conventional linear buffers (Table 1). The extension of the AFZ in the database is not determined by an idealized linear centerline but rather encompasses the actual geometric envelope of all historically observed and documented coseismic fracturing effects compiled over the last two centuries (such as the extensive surface data collected following the 26 December 2018 Fiandaca earthquake or data collected in the DRPC Sicilia database), expanded outwardly by a 30 m safety buffer (Table 1). This 30-m dimension was defined as a precautionary measure and is highly representative of the extensive dataset available for the Etna area, in accordance with the requirements of Seismic Microzonation (SM) studies, while also accounting for potential mapping uncertainties.

Table 1. ACF zonation and criteria of Etnean ACF; ACF_a, certain; ACF_b, uncertain.

SM3		
	Susceptibility Zone (SZ _{ACF})	Respect Zone (RZ _{ACF})
Exposed Active and Capable Fault (ACF _E)	ACF _a = 0-160 m	ACF _a = 30 m
Buried Active and Capable Fault (ACF _{E_s})	ACF _b = 160-300 m	n.d.
Active Fault by Aseismic Creep (ACF _{E_c})	ACF _a = 0-160 m	ACF _a = 30 m
Active Fracturing Zone (AFZ)		
Hidden faults	Envelope of historical and observed fractures +30 m buffer	

6. Conclusions

The development of the Guidelines for the study of Active and Capable Faults in the Etna volcanic area (GL_ACF_Etna, 2025) represents a critical advance in the mitigation of seismic risk in active volcanic settings. This work highlights that standard regulatory frameworks designed for tectonic environments – specifically the national GL_ACF (2015) – cannot be applied uncritically to volcanic areas like Mt. Etna, where the interplay between shallow magmatism, flank instability, and rapid resurfacing creates a unique morpho-tectonic landscape.

The primary contribution of this study is the formalization of a new classification system that addresses the “hidden” nature of many Etnean faults. By introducing the Active Fracturing Zone (AFZ), we provide a regulatory solution for areas affected by diffuse coseismic fracturing – such as those observed during the December 2018 earthquake – which lack a single, continuous fault plane and were previously difficult to zone under standard protocols. This ensures that hazard maps reflect the true physical reality of rupture propagation through complex volcanic overburden.

From a methodological perspective, the guidelines establish that a single diagnostic method is insufficient. The integration of historical seismology (CMTE data) has proved to be indispensable for identifying active structures masked by recent lava flows, while multi-temporal InSAR analysis is essential for quantifying aseismic creep, a phenomenon that contributes significantly to cumulative damage in the absence of major earthquakes.

Finally, the operational criteria defined for Level 3 Seismic Microzonation (SM3) – specifically the dimensioning of Respect Zones (30 m) and Susceptibility Zones (up to 300 m for buried faults) – provide local authorities with clear, actionable tools for land-use planning. The adoption of these protocols will lead to more resilient urban development in the densely populated flanks of Mt. Etna, bridging the gap between scientific knowledge and civil protection requirements. Future applications of these guidelines to other volcanic areas could further refine our understanding of faulting in active magmatic systems.

Data and sharing resources. Data used in this study were obtained from the following online resources:

- CMTE: Azzaro, R. and S. D’Amico (2026a). Macroseismic Catalogue of Etnean Earthquakes (CMTE2), version 2.0, 1633-2026 [Data set], Istituto Nazionale di Geofisica e Vulcanologia (INGV), doi:10.13127/cmte.2.
- DFAE: Azzaro, R. and S. D’Amico (2026b). Etnean Active Faults Database, [Data set], Istituto Nazionale di Geofisica e Vulcanologia (INGV), <https://www.ct.ingv.it/macro/dfae/main2.html>.
- GL_ACF_Etna: ETNA ACF Working Group (2025). Guidelines for the study of Active and Capable Faults (ACF) in the Etna volcanic area v2.1. The book will be published by the end of 2026 in the “BookMS” series (a collection of volumes by CNR Edizioni dedicated to Seismic Microzonation, edited by the Center for Seismic Microzonation and its Applications - CentroMS), and made available under a Creative Commons Attribution-ShareAlike 4.0 International license at the following link: <https://www.centromicrozonazioneismica.it/it/strumenti/bookms/>.

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