ANALYZING SEISMOINDUCED EFFECTS AND FRAGILE DEFORMATION IN THE AVOLA VECCHIA AREA (SOUTHERN SICILY): IMPLICATION FOR ACTIVE TECTONICS AND SEISMICITY

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Introduction. Although in active areas tectonics is considered the most probable trigger mechanism of fragile deformation of the rocky masses, seismic shock is another highly probable cause (Caputo, 2005; Montenat *et al.*, 2008). Indeed, strong earthquakes can trigger several soil deformation phenomena, such as liquefaction, ground fracturing and landslides, which can often cause more damage than the seismic shaking itself. Ground fracturing, which is among the most diffuse seismo-induced effects, can also contribute to increase terrain instability. Rocks and sediments can record such effects as evidence of paleoearthquakes.

The study of these markers of seismicity can be a useful tool to obtain data on ancient earthquakes occurring in a region. Indeed, although the recognition of off-fault seismo-induced structures does not provide precise and direct information on seismogenic fault and earthquake parameters (magnitude, intensity, fault length and elapsed time), it can give important information on the epicentral distance of the site, earthquake magnitude threshold and intensity reached at the site. Moreover, the finding of features dated before historical records, can be useful to extend the seismic catalogues back in time, to assess recurrence time of earthquakes and so to better characterize the seismicity of an area.

Eastern Sicily is considered among the most seismically active area in Italy. Several strong earthquakes with Maw 6.0–7.4 (Rovida *et al.*, 2011) have occurred in the last millennium and numerous Quaternary faults modified the landform. However, the lack of instrumental data for strong historical earthquakes, and poor exposures of faulted Quaternary sediments do not allow the unambiguous identification of active, seismogenic faults. An extensional belt running, for ≈ 370 km, from eastern Sicily to South Calabria, the Siculo Calabrian Rift Zone (SCRZ), is considered responsible of the crustal seismicity of these areas (Catalano *et al.*, 2008). This belt is composed by faults up to 50 km long and some of these are considered seismogenic only on few evidence of geological and structural studies and macroseismic data (Bianca *et al.*, 1999; Catalano *et al.*, 2008). Seismicity of south-eastern Sicily is tentatively related to some tectonic structures of the northern and western Hyblean Plateau. The 1169 and the 1693 earthquakes were located off-shore and associated with Malta Escarpment fault system since the strong tsunamis triggered by these events and the lack of surface faulting evidence on-shore (e.g. Azzaro and Barbano, 2000; Monaco and Tortorici, 2000; Argnani *et al.*, 2012). The Avola Fault segment has been considered responsible of the 9th January 1693 foreshock only on the basis of the damage area that extend along a narrow belt, on land, along the eastern edge of the Hyblean Plateau (Bianca *et al.*, 1999).

The 1169, 1542, 1693, 1848 and 1990 south-eastern Sicily earthquakes caused damage, numerous fatalities and triggered several ground failures, as reported by historical sources.

Geological evidence of liquefactions, correlated to some of the strongest earthquakes, were found in the Holocene deposits of the Mascali area and in the Catania Plain, both characterized by a continental fluviatile sedimentation environment (Guarnieri *et al.*, 2009). Moreover, Pirrotta and Barbano (2011) reported seismically induced deformation structures along the rocky coast of Vendicari (southeastern Sicily). Traces of seismically induced features can be particularly significant to assess earthquake recurrence time in areas that, like eastern Sicily, have poorly defined seismogenic sources.

In this study we analyse a seismically induced landslide along with some fractures affecting archaeological structures in the ancient site of Avola Vecchia, southwest of Syracuse (Fig. 1), and correlate them with historical and prehistorical events.

Avola Vecchia is located in the eastern coastal sector of the Hyblean Plateau, which is the emerged part of a gently deformed segment of the African continental margin representing

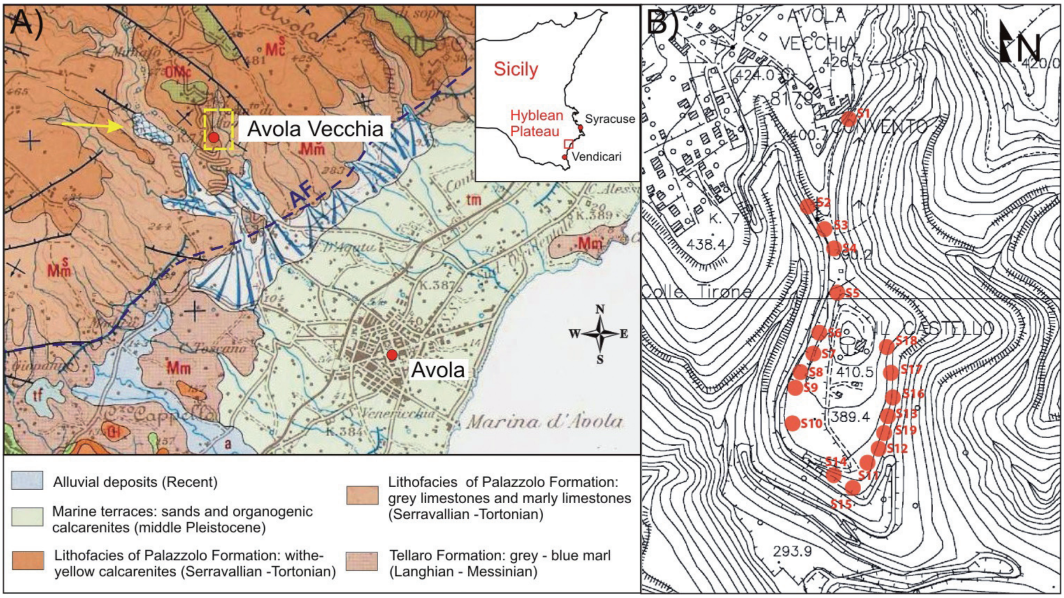

Fig. 1 – A) Geologic map (modified after Lentini *et al*., 1984) and location of the studied area; AF is the Avola Fault; the yellow arrow marks the 1693 Mt. Ginisi landslide; B) Mt Aquilone and location of the caves with the mesostructural stations.

the Tertiary foreland of the Apenninic-Maghrebian Thrust Belt. NE–SW and NW–SE trending normal fault systems affect the outcropping Miocene terrain (Lentini *et al*., 1984). In the studied area the main of these faults is the 20 km long, NE-striking E-dipping normal Avola Fault (AF in Fig. 1). The growth of this fault since 200-240 ky is hypothesized on geomorphological observation (Catalano *et al*., 2008) but its recent activity has never been constrained.

Active tectonics of the eastern sector of the Hyblean Plateau is scantly documented. The most recent evidence consist in joint sets and grid-lock fracture systems affecting Late Pleistocene terraced deposits (yellow sands and bioclastic calcarenites) documenting the existence of an extensional tectonic regime (De Guidi *et al*., 2013). However, present day active tectonics has never been documented for lacking of deformed Holocene terrains.

Historical data. The foundation of Avola, in an area previously inhabited by the Sicans, is perhaps connected to the history of the older town of Hybla Major (Di Maria, 1745) that was invaded by the Sicels in the 11th-9th centuries BC. The Greeks colonized the city in the 8th century BC. After the Syracuse domination (4th century BC), the Romans conquered Sicily in 227 BC. The Sicels' age is testified by numerous finds, especially pottery and dishes, found in the oven-shaped tombs resembling a beehive and characterizing the surroundings of Avola Vecchia and the near site of Cavagrande di Cassibile. The cave houses are a type of dwelling cave carved into the rock that marks the ancient Avola urban centre. They date back to the Byzantine-medieval period (6th-9th century AD) and people lived there until the 1693 earthquakes (Gringeri Pantano, 1996). The caves of the Sicels' necropolis along with the Byzantine-medieval cave houses are among the oldest testimony of civilization in the area. The older Hybla town disappeared in the early middle Ages, and the territory started to be repopulated during the Islamic domination of Sicily (9th-11th centuries AD). However, Avola Vecchia appeared only during the Norman or Hohenstaufen rule (12th-13th centuries), and persisted until the 1693, when two earthquakes destroyed it, as well as many of the southeastern Sicily towns. Not persisting more reasons to rebuild the city in an elevated site to protect themselves from the Saracens' incursions and to favoured maritime trade, the old city was abandoned and rebuilt in a new location along the coast (Fig. 1), following the geometrical and regular plan designed by the architect friar Angelo Italia (Gringeri Pantano, 1996).

Among the numerous historical sources, reporting the effects of the 1693 earthquakes in Avola Vecchia, we selected the two witness contemporary and reliable accounts by Dell'Arte (1699) and Di Maria (1745), who described in detail the effects of earthquakes on the city and on the territory.

"In Avola Vecchia, the January 9 at four-thirty (Italian time, used in the XVII century in Sicily) in the night (~21 GMT), a strong earthquake destroyed almost the whole quarters known as di Sopra and Marchi, ruining houses since foundations with the loss of 500 citizens. 40 hours after the first shock, on January 11 at 20 hours and a quarter (~13 GMT), the earthquake was so proud and terrible that destroyed the entire city. No stone remained upon stone, including caves, and people was not able to distinguish one house from the other houses" (Dell'Arte, 1699). The earthquake "has unhinged stones above which Avola was built; then destroyed throughout the whole city" (Di Maria, 1745). Five hundred people died for this shock. In Avola, the whole fatalities (9 and 11 January shocks) were 1,000 out of 6,225, in minor percentage than other Sicilian cities, because most of the inhabitants, were outdoors, having felt another slight shock at 16 hours (~9 GMT). The fortified castle, located on the acropolis of Mt Aquilone, was destroyed, although it had been rebuilt a first time after the December 10, 1542 earthquake, "which had ruined the castle and many houses" (Gallo, 1966). "The Mount called Gisini split, and almost half Mount, breaking away with fury, sank in the bed of the Valley called Carnevale, remaining under the portentous mass three mills with many people inside them" (Di Maria, 1745). The Mt Gisini landslide is further documented by an archive plan concerning the construction of a canal system to bypass the occlusion and provide water to the plantations and factories (Gringeri Pantano, 1996).

Data analysis. Aerial-photos interpretation, field survey and mesostructural analysis near Avola Vecchia allowed us to observe some devastating effects of the 1693 earthquakes still evident on the surface.

Mechanical discontinuities with decimetric spacing affect the calcarenites, marly limestones and limestones of Miocene age, outcropping at Mt Aquilone. Numerous of these fractures affect both the cave-tombs of the Sicels' necropolis and the Byzantine-medieval cave houses (Figs. 2A and 2B). Since they can give an evidence of active tectonics, we performed systematic and mesostructural analyses (stereographic projections and rose diagrams) of 137 fractures disturbing 19 caves of Mt Aquilone (Fig. 1B). These fractures are up to several metres long, often opened from few millimetres to several centimetres (Figs. 2B and 2C) and sometimes filled by re-crystallized calcite deposit. They show no, or few, evidence of shear motion, being originated as purely extensional fractures. This type of brittle features is known as "extensional joints" and they have been recognized as one of the most common deformational structures in every tectonic environment (Caputo, 2010 and references therein).

The joints are grouped in two orthogonal sets with main directions N45 and N140 (Fig. 2D). According to Caputo (2005), two orthogonal joint sets are due to stress swap mechanisms between σ_2 and σ_3 stress axes that occur locally causing stress field deformation. However, the prevalence of fractures with direction NE-SW indicates that the local tectonic maximum extension is almost NW-SE oriented (Fig. 2E), which is compatible with the regional stress field. This stress field is also responsible of the Avola fault (AF in Fig. 1A). It is worth noting that the study site is located on the footwall of the Avola Fault, which according to some authors may be active and could be the source of the 9 January 1693 earthquake (Monaco and Tortorici, 2000).

Nevertheless, other mechanisms such as seismic shacking can have triggered the fractures. Indeed historical accounts describe damage in the cave houses and "unhinged stones" during the 1693 earthquakes.

We have also compared the trend of the NE-SW fractures, with that of the slope at the location of each mesostructural station. A similitude between the two directions was observed

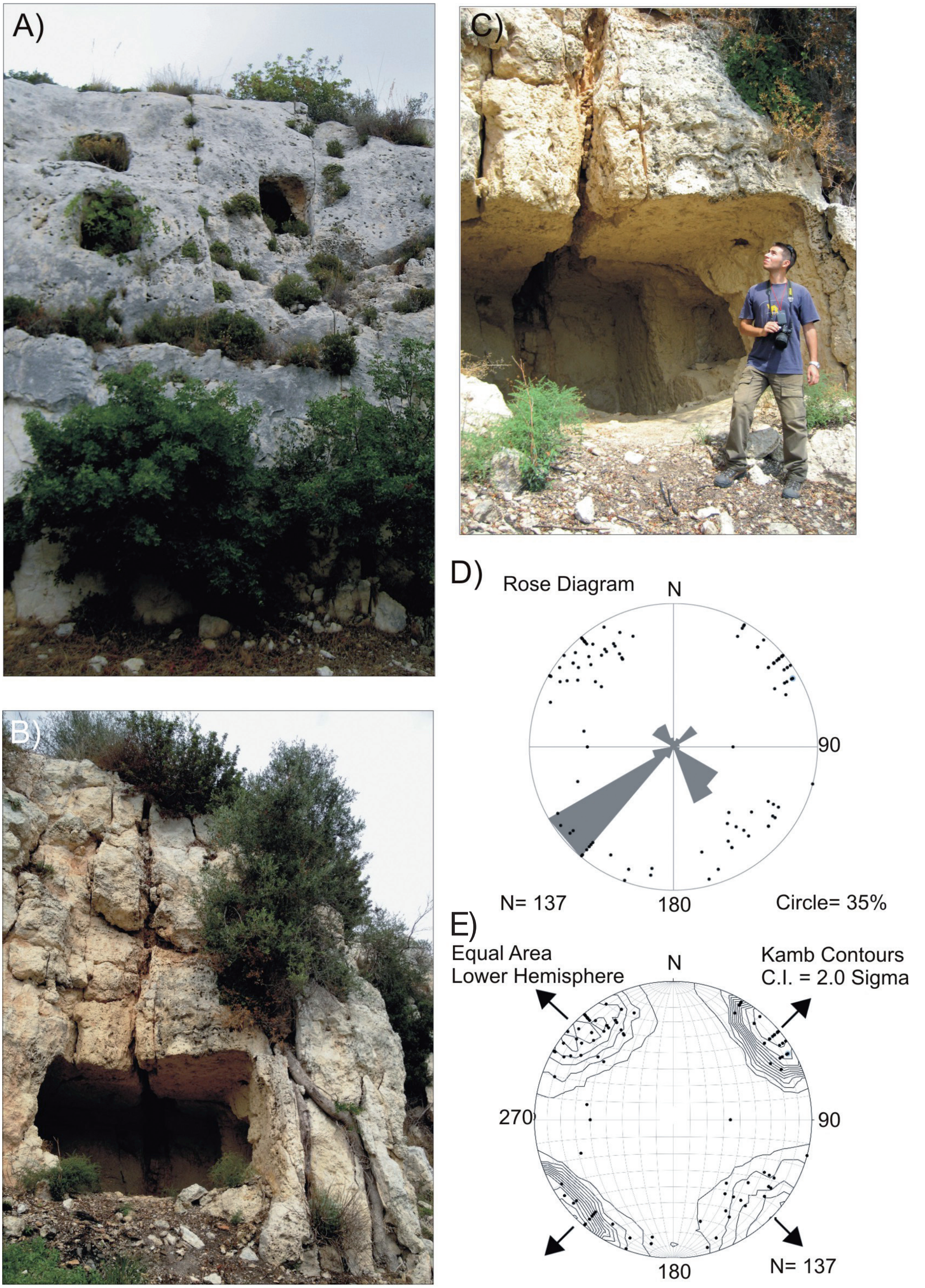

Fig. 2 – A) Fractures in the limestone affecting oven-shaped tombs in the Sicels' necropolis (11th-9th centuries BC); B) and C) open fractures in the calcarenite affecting cave houses dated back to the Byzantine-medieval period (6th-9th century AD); D) stereographic projections of the joints in the surveyed stations and rose diagram; E) stress inversion.

for the most of the stations indicating that the NE-SW set represents potential failure surfaces for future rockfalls. Moreover, the weakening of the rocky slope, along with the enlargement of the fractures, is likely enhanced by water circulation dissolving the limestone and by the presence of the caves. Therefore, seismic shaking, which in turn can drive slope instability, can be considered a cause for the rock fracturing superimposed on tectonic stress.

Seismically induced brittle deformation on rock, usually found close to active fault zones worldwide (Montenat *et al*., 2008), is documented locally at Vendicari (10 km south from the study site) (Pirrotta and Barbano, 2011).

The Mt. Gisini landslide (Figs. 1 and 3) occurred to the west of Avola Vecchia. It was a planar translational rockslide, with a steep slip surface, involving a volume of 2 x 106 m^3 of sub-horizontally bedded Tortonian and Messinian calcarenite and marly limestone (Gringeri *et al*., 2002). The accumulation, about 250 m wide and 370 m long, is around 60 m high above the valley bottom. Despite the high degree of fracturing, the rock stratification remains sub-horizontal. The landslide produced the obstruction of the Miranda river causing a dam belongs to type II (spanning the entire valley) according to the classification of landslide dams by Costa and Schuster (1988) (Nicoletti and Parise, 2002). Nowadays the landslide body is re-incised by the Piscitello stream that creates a V valley on it. The erosion processes on the downstream face have triggered a secondary landslide on the downstream side of the same landslide body. The Mt. Gisini landslide seems to have reached the position of minimum potential energy and, therefore, the probability of a further failure seems low (Nicoletti and Parise, 2002).

Discussion. The Avola Vecchia area shows several effects of active tectonics and earthquake shaking. We have observed brittle deformational structures and seismically induced features such as the Mt. Gisini landslide.

Fig. 3 – The Mt. Gisini landslide that dammed the River Miranda on 11 January 1693, and destroyed three mills killing people.

The occurrence of landslides and ground fracturing during strong earthquakes in eastern Sicily is also illustrated both by the historical accounts, reporting the observation of such phenomena in several places of this region, and by previous field works that studied similar seismically induced structures (Nicoletti and Parise, 2002; Guarnieri *et al.*, 2009; Pirrotta and Barbano, 2011).

The large and inactive landslide occurred near Avola Vecchia is described by historical accounts as related to the 1693 earthquake. Other landslides were surveyed in the same area and in southeastern Sicily. Since this is a seismic region but commonly considered no prone to slide failure, these landslides are considered earthquake-triggered (Nicoletti and Parise, 2002). The landslides testify the occurrence of seismic events with magnitude greater than 5 and intensity greater than IX, that are the thresholds for which these seismo-induced features may develop in a site (e.g. Pirrotta and Barbano, 2011). According to empirical relationship between source parameters and epicentral distance of the site where landslides developed during historical earthquakes in eastern Sicily, the triggering earthquakes occurred at a distance lower than 20 km, considering the threshold parameters, or at a longer distance but with a higher magnitude than the threshold (Pirrotta *et al.*, 2007).

The study of joint sets and grid-lock fracture systems, allows documenting the existence of an extensional tectonic regime, which is still active since fractures affect historical and archaeological man-made structures. The obtained stress orientations are in good agreement with the regional extensional tectonic stress field and support the recent activity of the Avola fault located close to Mt. Aquilone (Fig. 1A). Since the joints can be related and reopened either because of coseismic shaking, or for slope instability, additional surveys and analysis need to validate their connection to the recent stress field.

Conclusion. Coeval sources describe with certainty a landslide triggered by the January 11, 1693 Sicilian earthquake near Avola Vecchia. The landslide occurred west of the town, at Mt. Ginisi, along the Miranda river, which was the economic and productive focus of the territory hosting five mills. The landslide destroyed three mills and dammed the river. Near Avola Vecchia, at Mt. Aquilone, we have recognized several fractures in rock masses as well as in anthropogenic caves (the so-called cave houses) and oven-shaped tombs, dating back to the Byzantine period and Sicels' age, respectively. The mesostructural analysis of the rock masses showed that fractures are mainly classifiable as joints and that some of them are due to the tectonic stress field. The fact that fractures affect man-made structures confirms that in southern Sicily a WNW-ESE extensional regime is still active. Some fractures are due to seismic shaking and slope gravity effects, suggesting that several earthquakes have affected the area. Therefore, with the aim to provide new and useful information on ancient earthquakes, we plan to extend structural and morphometric analyses in other site of the Avola area and to date landslides and fractures. This data can help to better define the seismic framework in Sicily having a strong seismic activity but poorly defined seismogenic sources.

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