GEOLOGICAL, SEISMOLOGICAL AND GEODETIC EVIDENCE OF ACTIVE THRUSTING AND FOLDING SOUTH OF MT. ETNA (EASTERN SICILY)

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Introduction. Mt. Etna volcano is located in eastern Sicily over the front of the collisional fold and thrust belt, where it is cut by the major Aeolian-Tindari-Malta Escarpment lithospheric boundary (Fig.1, Palano et al., 2012). Accordingly, in the Mt. Etna area two distinct tectonic domains, characterized by compressive and tensional regimes, coexist (Cocina et al., 1997; Monaco et al., 2002). They are separated by a NNW-SSE trending boundary composed of en–echelon normal-dextral faults, roughly extending from the summit craters to the northern suburbs of Catania (Fig. 1a). The eastern sector is characterized by normal-oblique faults, related to WNW-ESE regional extension (Monaco et al., 1997), and flank sliding phenomena (Azzaro et al., 2013). Conversely, in the western sector, south of the volcanic edifice, contractional structures mostly occur. They are represented by a W-E trending fold belt that have deformed Pleistocene foredeep deposits in response of NNW-SSE oriented regional compression (Labaume et al., 1990; Catalano et al., 2011; Ristuccia et al., 2013). According to Lavecchia et al. (2007) this area is part a unique regional-scale, deep crustal seismogenic structure (named Sicilian Basal Thrust) whose focal mechanisms are compatible with a nearly average N–S shortening and with some field evidence of active fold-and-thrust deformation at the Sicilian chain front.

Seismological (Neri et al., 2005), geodetic data (Mattia et al., 2012) and stress in situ measurements (Ragg et al., 1999) confirm the occurrence of a still active compressional regime south of Mt. Etna, accommodated by thrusting and folding. In particular, new interferometric data recorded in the last 20 years, depict a large anticline (named the “Catania anticline”) aseismically uplifting at a rate of ~10 mm/yr in the northern outskirts of Catania (Lundgren et al., 2004; Bonforte et al., 2011). In order to verify if this aseismic frontal folding can be related to regional processes, characterized by convergence rates of about 5 mm/yr (Mattia et al., 2012), in this work we have analyzed deep crustal seismicity, geological field information and morphometric data obtained by 2x2m grid resolution DEM. Moreover, to the aim of verifying if strain accumulation is presently occurring on the growing anticline, we surveyed some benchmarks of a GPS network of the Italian Military Geographical Institute (IGMI) realized in 1994 for cartographic and geodetic purposes.

Geological setting. The geodynamic setting of Eastern Sicily (Fig. 1a) is characterized by the Neogene-Quaternary flexure of the African- Pelagian continental paleo-margin beneath the SSE-verging chain, culminating in the south-eastern sectors of the island to form the Hyblean Plateau, the foreland domain (Ben Avraham et al., 1990). Northwards, the Hyblean slab deepens under the chain, intersecting the Moho at a depth of about 30 km (Lavecchia et al., 2007 and reference therein) between the northern coast of Sicily and Mt. Etna (Fig. 1b). In such a geodynamic context, the area between the southern edge of the Mt. Etna volcanic edifice and the Catania Plain represents the remnant of a foredeep domain, filled by Pliocene-Pleistocene sediments and volcanics, and by Holocene alluvial-coastal deposits (Longhitano and Colella, 2001). This sedimentary succession is mostly deformed by an asymmetric south-facing anticline, about 10 km long and ~W-E trending (the “Terreforti anticline”, Monaco et al.,1997; Labaume et al., 1990) and other minor folds (Catalano et al., 2011). They have been interpreted as thrust propagation folds at the front of the chain, related to the lately migration of the thrust belt, as a response to the regional NNW-SSE compressive tectonic regime (Palano et al., 2012). GPS velocity fields (Ferranti et al., 2008; Mattia et al., 2012), seismological (Lavecchia et al., 2007) and interferometric synthetic aperture radar data (Lundgren et al.,
2004; Bonforte et al., 2011) suggest that contractional processes are still active and cause the growth of another large anticline (the “Catania anticline”) in the north-western outskirts of the town. Fold structures outcropping south of Mt. Etna have also been interpreted as the result of the gravitational spreading of the volcanic edifice of Mt. Etna over the sedimentary substratum (Borgia et al., 2000; Solaro et al., 2011).

Since the Middle Pleistocene, contractional structures have coexisted with extensional tectonics, as suggested by the occurrence of a NNW-SSE striking oblique (normal-dextral)

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Fig. 1 – a) Quaternary seismotectonic map of Mt. Etna region and stereographic projections of the principal stress axes (P-axes). Earthquakes recorded during the period 1994-2012 are also reported (http://www.ct.ingv.it/ufs/analisti/catalogolist.php). b) Crustal section with projection of the hypocentral distribution and structural interpretation [Moho depth from Lavecchia et al., (2007) and references therein].
Current tectonic activity is also responsible for the destructive historical earthquakes (M≥7) that occurred in south-eastern Sicily (e.g. 1169 AD, 1693 AD events, Boschi et al., 1995). The location of seismogenic sources is a topic still widely debated: normal faults located along the Ionian offshore (see Bianca et al., 1999 and references therein) and/or compressional structures located to the north and to the south of the Catania Plain, between the front of the chain and the northern margin of the Hyblean foreland (see DISS Working Group, 2010).

Seismicity. We analyzed distribution and kinematics of the earthquakes located in the southern and western sectors of Etna, between the chain, to the north, and the margin of the Hyblean Foreland, to the south (Fig. 1a). We excluded the events located in the eastern sector of the volcano to prevent that the shallow seismicity related to the extensional structures could complicate our analysis. About 2000 earthquakes, with a magnitude ranging between 1.0 and 4.3 and recorded by a local network between 1994 and 2012, were selected from the “Catalogo dei terremoti della Sicilia Orientale - Calabria Meridionale. INGV, Catania”, (further details about the catalogue at: http://www.ct.ingv.it/ufs/analisti/catalogolist.php). More accurate hypocentres were obtained by relocating the events with advanced techniques, by using a 3D velocity model (from Chiarabba et al., 2004; Patanè et al., 2006) and the software tomoDDPS (Zhang et al., 2009), that provide results with fewer uncertainties than those produced by the use of more simple algorithms. The distribution of earthquakes shows a clear trend of the seismic events to deepen from very shallow hypocenters in the area south of Etna, down to a depth of about 35 km to the NNW (Fig. 1b).

The analysis of the fault plane solutions (see also Scarfi et al., 2013) indicate that the majority of the events are strike-slip or oblique type. Furthermore, a careful analysis of the direction of the principal stress axes (P-axes) reveals that at the shallower and intermediate levels (down to 5 and 10 km), the stress field is inevitably influenced by the deep magmatic system of the volcano, the greater is the proximity to crater area. At greater depths, the regional dynamics is the main driving force with the P-axes NW-SE oriented (Fig.1a).

Gps data. In 1992 the IGMI (Italian Military Geographical Institute - www.igmi.org) started the GPS measuring of a network made up of 1260-bechmarks, extended over the whole Italian area. We have reoccupied three IGMI benchmarks north and south the Catania Anticline (Figs. 1a and 2) in order to calculate the velocities map of some benchmarks very close to the alignment revealed by interferometric data. The GPS survey was carried out by using Leica GX1220 receivers and AR10 antennas, while instruments used by the IGM in
1994 were Trimble 4000 SSE receivers and Trimble compact with ground plane (model 22020-00) antennas. GPS data have been processed using the GAMIT/GLOBK software (Herring et al., 2006) with IGS (International GNSS Service) precise ephemerides and Earth orientation parameters from the IERS (International Earth Rotation Service). We tied the measurements to an external global reference frame by including in our analysis the data from seven CGPS stations belonging to the IGS and EURA networks and operating since 1994 (GRAZ, HERS, JOZE, MADR, ZIMM). The quasi-observations were then combined with global solutions (IGS1, IGS2, EURA) provided by the Scripps Orbital and Permanent Array Center (SOPAC) at UC San Diego. The loosely constrained daily solutions were transformed into ITRF2005 (2005 International Terrestrial Reference Frame; Altamimi et al., 2007) and then rotated into a fixed Eurasia frame.

Preliminarily, the Eurasian velocity field shows that the two GPS stations south of the anticline (UNIG, S114) move with velocities ranging from about 4 to 7 mm/yr along NNW to NNE directions, whereas the station located north of the structure (TIRI) move to the SSW with velocity of about 2 mm/yr (Fig. 2). This results are consistent with NNW-SSE vectors obtained by permanent stations (Mattia et al., 2012), related to the Africa-Europe convergence process (with the exception of the TIRI benchmark that could be affected by the dynamics of the volcano).

Morphostructural data. New field surveys were performed with the aim to verify if ground deformation provided by satellite data agree with geological and morphological features. The Catania Anticline is located in a volcanic and strongly anthropized area. So, field evidence of active thrusting and folding is difficult to observe. However, preliminary results indicate that the differential ground motion provided by interferometric data (Lundgren et al., 2004; Bonforte et al., 2011) matches with the vertical deformation of the drainage network along the hinge of a large WSW-ENE trending anticline west of the urban area of Catania. Moreover, high resolution topographic profiles obtained by 2x2 m grid DEM show the occurrence of bulging coaxial with the hinge zone (Fig. 2).

Information on geometric relationships between the growing anticline and the underlying thrust is lacking. However, thrust-related anticlines can be described by three end-member geometries, depending on the relationships between thrusts and the overlying anticlines: fault-bend folding, fault-propagation folding and detachment folding (see Storti and Poblet, 1997 and references therein). Combining the 5-6 mm/yr shortening across the anticline with the 10 mm/yr of the corresponding uplift, the hypothetical slip on a unique shear surface would result on a >60° dipping plane. Such attitude is unrealistic for a thrust ramp, therefore we exclude fault-propagation folding or fault-bend folding models (Fig. 3). Conversely, kinematic models have shown how detachment fold model can account for uplift rate greater than shortening, in particular in the early stages of the anticline (Storti and Poblet, 1997). An incipient sub-horizontal detachment within the clayish foredeep deposits or at the top of the buried foreland sequence is clearly showed by seismic profiles (Torelli et al., 1998).

**Discussion and conclusion.**
Geological and morphological analysis, compared with seismological and geodetic data, suggest that a compressive regime currently occurs in the western sector of Mt.
Etna, accommodated by aseismic folding at the front of the chain, south of the volcanic edifice, and seismogenic oblique thrusting at crustal depth under the northwestern sector of the volcano. Moreover, the NNW-SSE direction of the axis of compression obtained by seismological data is consistent with that suggested by geological and geodetic data.

In particular, a large WSW-ENE trending anticline is growing west of Catania (the Catania anticline). For its location, within a middle-late Pleistocene fold system, and growth rates, consistent with detachment fold models, we exclude that this structure have only developed in response to volcanic spreading, as proposed by previous authors. Moreover, the gentle slope of the southern flank of the volcano (5-6° on average) would not be a sufficient gradient to drive the process and, mainly, the steady deformation growth rate is in contrast with the episodic magmatic injections that are invoked as another promoting mechanism of the spreading. We therefore propose the occurrence of detachment folding at the chain front, as response of a shallow thrust migrating within the clayish foredeep deposits or at the top of the buried foreland sequence.

In conclusion, our analysis confirms that, besides the activity related to the volcanic feeding system, the seismic pattern under Mt. Etna edifice can be certainly related to the regional dynamics. The compressive stress is converted into elastic accumulation and then in earthquakes along the ramps to the rear of the chain, whereas along the frontal detachment it is accommodated by aseismic ductile deformation. In fact, despite the high rates of convergence, the seismicity is moderate at the front of the chain and the “seismic efficiency” of the Sicilian Basal Thrust is greater in correspondence of ramps at the rear, where strong earthquakes can occur.

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**References**


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