Introduction. The comparison of the seismic and geodetic moment-rates can provide crucial insights for understanding fault behaviour in tectonically active zones, with obvious implications on seismic hazard assessment. It is well acknowledged that when the seismic moment-rate is lower than geodetic one, the exceeding geodetic moment-rate can be released either through earthquakes or in aseismic mode. Geodetically observed moment-rates may include both elastic and inelastic deformations, and since only the elastic component is responsible for earthquakes, comparison of geodetic and seismic moment-rate should not balance in regions affected by creeping faults or where significant amounts of deformation take place plastically. It is the case of Etna, slow aseismic slip due to fault creep being a common mode of displacement along many of the fault segments in the eastern flank. Generally, the combined moment-rate estimations based on earthquake catalogues, coupled with fault scale geological observations allow overcoming these limitations.

Taking advantage of the availability for the Mt. Etna region of extensive geophysical and geological datasets, here we propose a methodology aimed to estimate and compare in terms of seismic efficiency, i.e. the percentage of brittle deformation with respect to the overall strain observed, the scalar seismic, geodetic and geologic moment-rates of this important seismogenic zone of the volcano.

Seismic data. In order to study the seismotectonic features of the eastern flank, we analyzed seismic data recorded in the period from January 2005 to December 2013. The choice of this time-span is justified by the development of a modern seismic network, equipped with digital stations and broadband sensors. In particular, the upgrade of the seismic monitoring system operating in eastern Sicily (Fig. 1), has allowed to improve the small magnitude detection capabilities and hence the application of the latest analytical techniques for the study of seismic sources.

Over the considered period about 4,570 seismic events with a magnitude between 1.0 and 4.8 (magnitude of completeness ≥ 1.5), are located in the Etna area (Fig. 2). In general, most of seismicity is clustered in the eastern and south-eastern sectors of the volcano at a depth of 15 km or less (red in Fig. 2), confirming the instability of this sector and the continuous fault activity, while shallower events (H < 5 km) are related to the Pernicana fault to the north (green in Fig. 2) and crustal earthquakes.

Fig. 1 – Sketch map of Mt. Etna. Continuous GPS stations are reported as red points, while seismic stations are reported as blue diamonds. The highlighted boxes represents the surface projection of the prismatic bodies used for the moment-rates estimations. Abbreviations: PF, Pernicana fault; RF, Ragalna fault; TMF, Tremestieri fault; TCF, Trecastagni fault; NER: NE rift; SR: South rift. The inset reports a simplified structural map of eastern Sicily: AMC: Apenninic-Maghrebian Chain; HF: Hyblean Foreland.
(about $20 \leq H \leq 30$ km) in the north-western flank.

From the initial dataset we selected about 1,600 earthquakes located in the study areas of Timpe and Pernicana faults, (red and green in Fig. 2). In order to better define seismic clusters or epicentre alignments, the selected earthquakes have been relocated using the tomoDDPS algorithm (Zhang et al., 2009) and the 3D velocity model of Alparone et al. (2012). Compared to more simple algorithms, this code uses a combination of both absolute and differential arrival time readings, between couple of events of an earthquake cluster. This essential feature allows to considerably improve the relative locations. In fact, the use of the differential arrival times ensures that, for earthquake clusters with foci lying close to each other, travel time errors due to incorrect velocity models in the volume outside the cluster will essentially cancel out (see Scarfì et al., 2009). Preliminary results show that seismic events tend to cluster around active faults mainly in the depth range 3-10 km in the Timpe zone, and between -1 and 3 km along the Pernicana fault.

**Geodetic data.** Available GPS observations collected by the Mt. Etna Permanent GPS Network, spanning the 2005.00-2013.99 time interval and covering the eastern flank of Mt. Etna (Fig. 1), have been processed using the GAMIT/GLOBK software with IGS (International GNNS Service; http://igscb.jpl.nasa.gov) precise ephemerides. To improve the overall configuration of the network and tie the regional measurements to an external global reference frame, data coming from 10 continuously operating IGS stations were introduced in the processing (BRUS, CAGL, GENO, GRAS, GRAZ, JOZE, MATE, MEDI, NOT1 and ZIMM; http://www.epncb.oma.be). In a first step, we used daily double differenced GPS phase observations to estimate station coordinates and Earth orientation parameters. In this step, the observations were weighted according to the elevation angle, for which a cut-off angle of $10^\circ$ was chosen. In addition, we used the latest absolute receiver antenna models by the IGS and we adopted the Saastamoinen (1972) atmospheric zenith delay models, coupled with the Global Mapping Functions (Böhm et al., 2006) for the neutral atmosphere.

Then, the GAMIT solutions were used as quasi observations in a Kalman filter (GLOBK) in order to estimate a consistent set of daily coordinates (i.e. time series) for all sites involved. Each time series was analyzed for linear velocities, periodic signals and antenna jumps by using the TSVIEW software package described in Herring (2003). To account for correlated noise during the site velocity estimation, the “Realistic Sigma” method (RSM) developed by Herring (2003) was adopted.

Finally, estimated geodetic velocities were referred to the “Etn@ref” reference frame (a...
local reference frame computed to isolate the Mt. Etna volcanic deformation from the background regional tectonic pattern; see Palano et al. 2010 for details) by minimizing, for the above mentioned 10 IGS stations, the difference between their estimated positions and those implied by their coordinates (position and velocity) in the local reference frame.

The resulting velocity field, reported in Fig. 3, illustrates the seaward motion of the eastern flank of Mt. Etna. In detail, sites close to the central sector of the unstable flank are characterized by velocities up to 35 mm/yr, while moving southward or northward the velocity field decreases to values of ca. 1-2 mm/yr.

**Geologic data.** Mt. Etna is a basaltic stratovolcano located on the east coast of Sicily, at the boundary between the external units of the Apenninic-Maghrebian Chain and the flexured margin of the Hyblean Foreland (Branca et al., 2011). This region is characterised by intense geodynamic processes at the scale of the volcano, flank instability which affects the eastern flank representing the result of interaction among regional stress regime, magma intrusion and basement geometry (Azzaro et al., 2013). A number of active faults accommodate the large dynamics of the unstable sector: the right-lateral, NNW-SSE-striking Tremestieri-Trecastagni fault system (Fig. 1) is generally acknowledged as the southern boundary (Rasà et al., 1996; Bonforte and Puglisi, 2003; Palano et al., 2008; Bonforte et al., 2011), although some authors suggest as an alternative the N-S-striking Ragalna fault system (Fig. 1) in the south-western flank of Etna (Borgia et al., 1992; Rust and Neri, 1996; Neri et al., 2007). Conversely, there is a general agreement on identifying the Pernicana fault system and the rift zones (North-East and Southern ones) as the northern and western boundaries of the unstable sector, respectively (Fig. 1). Insights into behaviour of the Pernicana fault became evident through geodetic data collected since 1997 (Azzaro et al., 2001, Palano et al., 2006), which evidenced a fairly stable slip with an average rate of about 28 mm/yr, related to the continuous long-term sliding motion of the eastern flank of the volcano toward the sea. Abrupt, even transient, increase in the seismic and geodetic strain release of the Pernicana fault has been measured during some recent flank eruptions (e.g. 2001 and 2002-03) and interpreted as a result of additional stressed induced by the magma ascent in the feeding system (Palano et al., 2008; Alparone et al., 2012; Bonaccorso et al., 2013). The central part of the eastern flank is crossed by the Timpe fault system, a 20 km long and 5 km wide belt of mainly extensional structures, striking from N to NW and consisting of well-developed morphological scarps and hidden fault segments (Azzaro et al., 2012). The relevant strain affecting this area is expressed by an intense seismicity - the largest earthquakes occurred in the past are located here - as well as fault creep, whose cumulated evidence in the long-term produces geological slip-rates varying from 1.0 to 5.3 mm/yr. The present behaviour of this fault zone has been obtained by the analysis of ground deformation decennial time series (GPS, SAR), that allowed to recognise as the faults bound kinematic domains showing different velocity and displacements, although all are characterised by discontinuous dynamics. In practise, the fairly constant mid-term (decennial) ESE seaward sliding is interrupted by sudden short-term (months to year) accelerations related to flank eruptions (Palano et al., 2008; Bonforte et al., 2011).
In order to estimate the geologic moment-rate for active faults cutting the eastern flank of Mt. Etna, we collected all fault geometric and kinematic information from published and unpublished studies (see Azzaro et al., 2013 and references therein). More in detail, for each structure we collected the following parameters: length ($L$), strike ($\theta$), dip ($\phi$), down-dip width ($H$), and slip-rate. For this last parameters, when available we used both short- and long-term estimations.

The considered faults have length typically in the ~5-8 km range and down-dip width in the 1.6-4.5 km range. Long-term slip-rate estimations range from 1 up to 5.2 mm/yr while short-term slip-rate values for the last decades range from 2 up to 28 mm/yr. Higher slip-rate values are observed along the Pernicana fault, especially on its easternmost segment (Palano et al., 2006).

**Method and preliminary results.** The methodology applied in the southern Apennines (Palano et al., 2011) to estimate and compare the scalar seismic, geodetic and geological moment-rates has been used in the eastern sector of Mt. Etna. In particular, taking into account the spatial distribution of the active faults and their seismogenic thickness $H_s$, as a first step we divided the volume into prismatic bodies. Then, by adopting the classical formulations below reported, for each prismatic body we estimated and compared the aforementioned moment-rate scalar values as follows.

The seismic moment rate was calculated according to the Kostrov (1974) general formulation where $N$ is the number of events occurred in the selected interval in the volume $A \cdot H_s$ ($A$ and $H_s$ represent the surface area and the seismogenic thickness of the selected prismatic body), $M_{seis}$ is the seismic moment of the $n$-th earthquake from the $N$ total earthquakes, and $\Delta T$ represents the considered time interval (in our case 8 years). To perform the computation we considered all earthquakes with magnitude $M \geq 1.5$ - i.e. the value of the completeness magnitude - selected for the investigated area (see Fig. 1). Earthquake magnitudes were converted into scalar moments through the relationship proposed by Giampiccolo et al. (2007). Our preliminary estimations range in the interval $5.82 \cdot 10^{14} - 7.21 \cdot 10^{14}$ Nm/yr.

The geodetic moment rate was estimated by taking into account the observed horizontal velocity field and associated covariance information; in a first step we computed the expected velocity values at the nodes of the selected area (i.e. at the top surface of each prismatic body) and as a second step we derived the average 2D strain-rate tensor at the center of each selected area. Then, by adopting the previous formulation, we computed the geodetic moment-rate using the Savage and Simpson (1997) formulation, where $\mu$ is the shear modulus of rocks within the focal volume, with assigned value of 10 GPa, $H_s$ is the seismogenic thickness, $A$ is the surface area of the selected prismatic body and are the principal horizontal geodetic strain-rates. We found that our preliminary geodetic moment-rate estimations range between $3.18 \cdot 10^{18} - 1.03 \cdot 10^{19}$ Nm/yr.

Lastly, the geological moment rate was computed using the Brune (1968) formulation, where $\mu$ is the shear modulus of the rocks involved in faulting with assigned value of 10 GPa, $L$ and $H$ are length and down-dip width, respectively, of the dislocation along which faulting and $u$ is the average displacement, which corresponds to the estimated geologic slip-rate (see Azzaro et al., 2013 and references therein). Our preliminary estimation of the geological moment rate ranges in the interval $4.92 \cdot 10^{14} - 2.81 \cdot 10^{16}$ Nm/yr.

As already observed by Azzaro et al. (2013) comparing the short- vs. long-term slip-rates of active faults in the Etna region, also the geodetic moment-rate estimations computed in this work are generally larger than the seismic and the geologic ones. In general, a number of reasons may account for the observed discrepancy among the estimated moment-rates, such as: i) uncertainties of the geologic slip-rate estimations; ii) poorly defined geometry of modeled faults, especially for down-dip width; iii) role of buried/hidden fault segments in accommodating deformation; iv) limited length of the instrumental earthquake catalogue. Despite this, it is well evident that a large amount of the deformation affecting the eastern flank occurs aseismically,
confirming field observations that creep at Etna is a common mechanism of faulting (Rasà et al., 1996).

This implies that quantifying the deficit of seismic moment-rate with respect the geodetic one in terms of spatial distribution and temporal variations is an important task to characterize the potential for seismic slip of contiguous fault segments. In fact, creep may be viewed as a proxy of loading processes on locked fault segments leading to seismic failure during subsequent earthquakes.

Acknowledgments. This study has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri - Dipartimento della Protezione Civile (DPC), in the frame of the 2014-2015 Agreement with Istituto Nazionale di Geofisica e Vulcanologia - INGV, project V3: “Multi-disciplinary analysis of the relationships between tectonic structures and volcanic activity “. This paper does not necessarily represent DPC official opinion and policies.

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