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Slow slip events and flank instability at Mt. Etna volcano (Italy)

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Corresponding Author:	Mimmo Palano, PhD Istituto Nazionale di Geofisica e Vulcanologia Catania, ITALY
First Author:	Mimmo Palano, PhD
Order of Authors:	Mimmo Palano, PhD
	Federica Sparacino
	Piera Gambino
	Nicola D'Agostino
	Stefano Calcaterra
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Suggested Reviewers:	Kristy Tiampo kristy.tiampo@colorado.edu Expert on geodesy and data modelling
	Matteo Lupi matteo.lupi@unige.ch Expert on volcanoes
	José Fernández Torres jft@mat.ucm.es Expert on geodesy and data modelling
	Yo Fukushima yofukushima@rcep.dpri.kioto-u.ac.jp

Dear Editor

We are very pleased to submit our manuscript entitled "Seismic and geodetic moment-rates comparison for the Aegean - Anatolian region" in order to be considered for publication in **Tectonophysics**.

The manuscript focuses on on a sequence of slow slip events occurring at Mt. Etna since early 2006. Such a kind of aseismic events have been detected at a variety of tectonic and volcanic areas in the last decade, capturing the curiosity of seismic and geodetic communities. Hence, this submission while is of timely significance, is also of broad interest. Moreover, it provides additional constraints about the seaward flank motion of Mt. Etna volcano.

We provide you a list of 5 potential reviewers, with wide range of expertise to judge this manuscript:

- Kristy Tiampo (University of Colorado) USA, kristy.tiampo@colorado.edu
- Maurizio Battaglia (Sapienza - Università di Roma), maurizio.battaglia@uniroma1.it
- Yo Fukushima, Kyoto University, Japan (yofukushima@rcep.dpri.kioto-u.ac.jp)
- Matteo Lupi, University of Geneva, Switzerland (matteo.lupi@unige.ch)
- José Fernández Torres, Instituto de Geociencias, SPAIN (jft@mat.ucm.es)

We strongly believe that **Tectonophysics** is the best journal for sharing our efforts with the scientific community. For this reason, we really hope that you will find of interest our paper!

Yours sincerely
Mimmo Palano (on behalf all the authors)

Abstract

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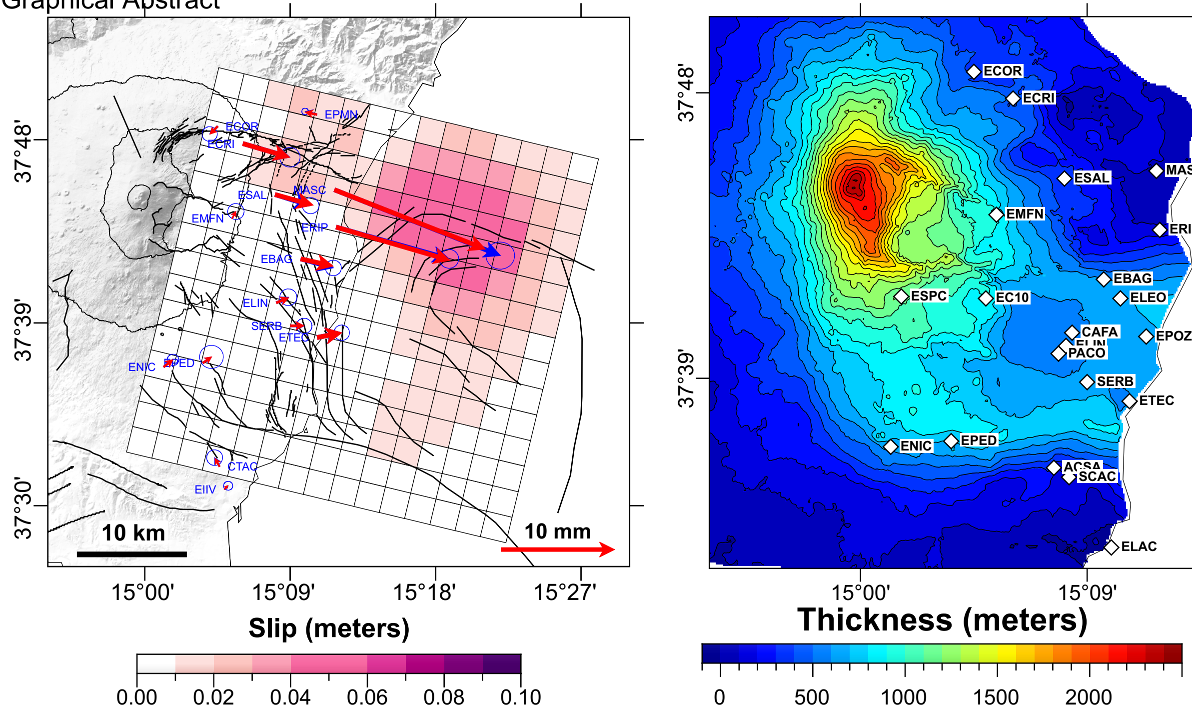
Graphical Abstract



Highlights (three to five**;** 85 characters or fewer, including space)

- A set of slow slip events occurred at Mt. Etna volcano is analyzed
- Two distinct families of slow slip events have been detected
- Most of the deformation affecting the eastern flank occurs aseismically
- Different sources temporally modulate the seaward motion of the unstable flank

Slow slip events and flank instability at Mt. Etna volcano (Italy)

Mimmo Palano[a*], Federica Sparacino[a], Piera Gambino[b], Nicola D'Agostino[c], Stefano Calcaterra[b]

[a] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Osservatorio Etneo, Catania 95125, Italy
[b] Italian Institute for Environmental Protection and Research (ISPRA), Rome 00144, Italy
[c] Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Rome 00143, Italy

[*] ***Corresponding author*:**

Mimmo Palano
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo - Sezione di Catania,
P.zza Roma 2, I-95123 Catania (Italy)
Phone: +39 0957165800
Email: mimmo.palano@.ingv.it

Abstract

We analysed a set of 11 slow slip events occurred during the 2006-2016 period and affecting the GPS stations of the unstable flank of Mt. Etna volcano. Observed surface deformation for most of the detected slow slip events, concentrates on the south-eastern edge of the unstable flank while the slow slip events involving the north-eastern edge are less frequent. Such a feature highlights the existence of two distinct families of events, involving two contiguous sectors of the unstable flank, which occasionally slip together in large slow slip events. The modelled slips also highlight that both contiguous sectors extend ~10-12 km off-shore, on areas where active tectonic lineaments such as the ESE (northward of Catania Canyon) and the N102° (along the southern slope of the Riposto Ridge) ones have been recently discovered. Equivalent seismic moments of slow slip events occurred in the last ten years (corresponding to magnitudes in the range 5.4-5.9) are larger than those associated to seismic events observed in the last 200 years, suggesting that most of the deformation affecting the eastern flank occurs aseismically.

Keywords: *slow slip event, unstable flank, distributed slip model, aseismic deformation, Mt. Etna*

1.0 Introduction

Episodic aseismic slip events are earthquake-like events which, releasing energy over a period of hours to months, have been detected at a variety of tectonic and volcanic environments. These particular events, termed as slow slip events (SSE hereinafter), are becoming increasingly recognized as important, due to their influence on local and regional seismicity. Indeed, recent studies have highlighted that the SSEs occur close to zones of frictional transition from velocity strengthening to velocity weakening (Liu and Rice, 2007; Rubin, 2011; Segall et al., 2010) therefore providing useful information on fault zone properties.

The first detected SSE dates December 1992 and occurred along the San Andreas fault in central California (Linde et al., 1996). This SSE was detected by two borehole strainmeters which were installed closely to the main fault and recorded a transient deformation event of about a week in duration. The rapid increase of continuous GPS (CGPS) stations has allowed to detected a large number of SSEs worldwide. The large majority of SSEs has been observed at convergent plate boundaries. Valuable examples come from Cascadia (Dragert et al., 2001;

2004; Brudzinski and Allen, 2007; Haines et al., 2019), New Zealand (Beavan et al., 2007) and Japan (Hirose et al., 1999; Obara and Hirose, 2006; Ito et al., 2013). Sometimes they are associated with seismic tremor (Dragert et al., 2001; 2004; Brudzinski and Allen, 2007; Haines et al., 2019; Beavan et al., 2007), but not exclusively. For example, it has long been recognized that detected SSEs in Cascadia are nearly always accompanied by seismic tremor (Rogers and Dragert, 2003), with a few exceptions for brief times during individual SSEs when slip appears to occur with no obvious tremor (Wech and Bartlow, 2014).

In the last two decades more than 10 SSEs have been identified from CGPS data at Kilauea volcano southern flank (see Foster et al., 2013 and references therein). These SSEs exhibit surface displacements up to a few centimeters, duration of several hours to 2 days and occur along the off-shore portion of the basal decollement (e.g. Montgomery-Brown et al., 2009).

The occurrence of SSEs has been detected also at Mt. Etna from the continuous GPS stations covering the continuous seaward moving eastern flank of the volcano (see Palano 2016 and references therein for additional details). Here, taking into account a new set of GPS data acquired at the SiOrNet network (Figure 1) we improved the results reported in Palano (2016) by extending in time (back and forward) the preexisting SSE catalog. Moreover, we performed a new modelling of the surface deformation associated to each SSE in order to better constrain the slip distribution pattern on the causative source. Achieved results are discussed in the general setting of the eastern flank of the volcano, in order to provide an improved picture about its complex kinematics and block fragmentation.

2.0 Mt. Etna background

Mt. Etna is a basaltic Quaternary volcano located on the east coast of Sicily (South Italy) at the front of the Apennine-Maghrebian chain (AMC) (Figure 1). The volcano developed over the last 500 ka over metamorphic and sedimentary rocks (belonging to the AMC) on its western and northern slopes and over Quaternary plastic clays (accumulated along the Gela-Catania Foredeep at the front of AMC; Branca and Ferrara, 2013). The different geomechanical properties of outcropping rocks coupled with the inhomogeneous long-term updoming (De Guidi et al., 2014) of the volcano have produced a complex basement topography dominated by a 17 km-wide horseshoe-shaped depression beneath the eastern flank (Branca and Ferrara, 2013). Such a complex basement topography would lead to the large-scale seaward motion of the eastern flank of Mt. Etna as clearly documented since the early 1980s (e.g. Borgia et al., 1992). At the surface, the unstable sector is defined by a 25 km-wide horseshoe-shaped region which encompassing the sedimentary one is bounded by the “NE Rift - Pernicana fault and by the “South Rift - Mascalucia - Tremestieri - San Gregorio - Acitrezza fault system”, respectively on its NE and SE half (Figure 1). In addition, the presence of compressional structures (e.g. folds) at the toe of the continental margin as well as a prominent ESE lineament with prevailing right-lateral transpressive kinematics, located northward of Catania Canyon has recently been discovered, on the Etnean off-shore (Gross et al., 2015; Figure 1). Furthermore, active tectonics also occurs over the unstable sector and is distributed on a number of shallow faults such as the Timpe, the Santa Tecla, the Santa Venerina, the Fiandaca and the Nizzeti faults (Figure 1; Azzaro et al., 2012). The Timpe fault system consists of a 20 km long and 5 km wide belt of mainly NNW to N extensional structures with well-developed morphological scarps; the Santa Tecla and Santa Venerina faults consist of two near parallel faults, which have a NW-SE trend and are characterized by right-lateral slips coupled with minor normal components. The Fiandaca fault is a NW-SE oriented right-lateral fault system with a normal component (Azzaro et al., 2012) which connects southward with the Nizzeti faults, a set of two NNE to NNW trending faults characterized by linear, up to 100 m high, cumulative scarps (De Guidi et al., 2018).

The definition of the basal sliding surface of Mt. Etna is widely debated and a number of different models have been proposed in the last 3 decades. For instance, Lo Giudice and Rasà (1992) postulate a shallow (~1.5 km) surface with a listric geometry located beneath the volcanic pile of Mt. Etna. Borgia et al. (1992) suggest an approximately 5-km-deep sub-horizontal west-dipping décollement. Tibaldi and Groppelli (2002) suggest the possibility of alternating or contemporaneous movements on both shallow and deep east-dipping slip surfaces under the effects of different source mechanisms. GPS-based models point to a sliding east-dipping surface located at a depth ranging from 0 to 5 km b.s.l. (see Palano 2016 and references therein).

3.0 Data and modelling

3.1 Geodetic data

All available continuous GPS data on the eastern flank of Mt. Etna edifice were collected and analyzed in order to take into account the best spatially and temporally station coverage. To this aim we collected data from the following networks:

- Etn@net: this network is managed by the "Osservatorio Etneo" department of "Istituto Nazionale di Geofisica e Vulcanologia". The setting up of this network began in November 2000 reaching a configuration of 13 stations in late summer of 2001 with daily sessions of about 8 hours. The network geometry was gradually upgraded over the years in order to cover all the slopes of the volcano edifice and to replace the sites destroyed by natural (lava flows) and human (vandalism) activities or affected by local instability, reaching the current configuration of 33 stations (blue dots in Figure 1). A continuous acquisition on sessions of 24 hours at all the stations was scheduled at least since early 2005. Pillars directly founded on consolidated bedrock represent the largest monument number.
- SiOrNet: this network is currently managed by the Geodetic Group of the Geological Survey of Italy-ISPRA and consists of 5 continuous GPS stations installed on some faults segments along the SE slope of Mt. Etna (yellow dots in Figure 1). The network was established in late 2005 and discontinuously worked until mid-2016. The functioning of the network was restored in late 2018 (Pezzo et al., 2020). Monuments consist on pillars directly founded on consolidated bedrock or steel masts anchored on concrete buildings.
- Italpos: this network is currently managed by Hexagon Geosystems (https://hxgnsmartnet.com/it-it). It was developed to support commercial applications, such as mapping and cadastral purposes and stations are characterized by a wide variety of different monument types. Pillars, or steel masts, anchored to buildings represent the largest number, while monuments directly founded on consolidated bedrock are present in minor percentage. Only 2 stations are installed on the volcano edifice (red dots in Figure 1); MASC was dismissed on early 2016.
- NetGEO: this network was developed by Geotop (http://www.netgeo.it/) since early 2012. As the Italpos network, NetGEO was developed to support commercial applications. Monuments consist on pillars or steel masts, anchored to buildings. Such a network covers the volcano edifice with 2 stations installed on its eastern flank (black dots in Figure 1).

All collected data were processed using the GAMIT/GLOBK software (Herring et al., 2018) with IGS precise ephemerides. To improve the overall configuration of the network and tie the regional measurements to an external global reference frame, data coming from 15 continuously operating IGS stations were introduced in the processing. 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. Estimated GPS daily time series and displacements for specified time intervals were referred to the "Etn@ref" reference frame (a local reference frame computed to isolate the Mt. Etna volcanic deformation from the background tectonic pattern; Palano et al., 2010).

From the visual inspection on the daily-based time series, we observed that at stations located along the lower eastern flank (group 1 with red time-series in Figure 2) each SSE produces or a sudden change (e.g. ELAC and MASC), or a more gradual change with respect to the linear trend of the time-series (e.g. EPOZ). Both changes occur with a finite duration and are characterized by rates that are faster than the long-term seaward motion of the unstable flank. The stations located on the middle sector of the eastern flank (group 2 with blue time-series in Figure 2), although showing a near continuous eastward motion, are also modulated by deformation related to inflation/deflation magmatic sources. The time-series of all these stations are also locally modulated by episodic creeping of the faults dissecting and/or bordering the unstable flank (see discussion). GPS stations externally located with respect the unstable flank (group 3 with time-series colored in black in Figure 2) are characterized by time series showing no deformation to gentle eastward motion. By inspecting the time-series of ACSA, SCAC, ELAC, MASC and EPOZ (null or very little influenced by the action of the magmatic sources) we detected 11 SSEs with duration grossly ranging from 2 to 67 days (see Figure 2 and Table 1). On the analyzed time interval, the first SSE occurred in April 2006, while the last one in April 2016, therefore extending in time (back and forward) the SSE catalog previously defined in Palano (2016). Moreover, the time-series of the SiOrNet GPS stations allowed also to improve the detection of some SSEs (in term of SSE onset and related duration), leading to some differences with respect to the previous catalog. For each recognized SSE, we determine the amount of displacements by averaging site position in the 3 days preceding and following the event.

3.2 Modelling

The displacement fields were used to constrain isotropic half-space elastic inversion models. Although the faults dissecting and/or bordering the unstable flank might accommodate a fraction of deformation during each SSE, in the following we assumed that the slip occurs only along the basal sliding surface. Indeed, the current density of GPS stations on the eastern flank of the volcano doesn't allow to properly differentiate the individual contribute of the basal sliding surface and the other active faults to the total ground deformation field.

The displacement field for SSEs lasting several days could contain a significant contamination from magmatic sources contemporaneously active. In particular, considering the SSEs with duration larger than 10 days, we observed that they occurred during inflation stages of the volcano, for which magmatic source parameters are already available in literature. We therefore subtracted the calculated effects of active magmatic sources from the observed displacement field to obtain the residual field which would correspond to the SSE contribute (see Table 1). Subtracted values range on average from ~3-5 mm for the stations located on the upper eastern flank to less than 0.5 mm for stations located along the coastal belt. Estimated residual displacements are reported in Figure 3.

To determine the spatial distribution of slip for each SSE, we extended up to 36 x 36 km and divided in 15 (along-strike) by 15 (along-dip) squared patches (dimension of 2.4 x 2.4 km) a sliding surface similar to the one inferred in Palano (2016). We also fixed the dip of the sliding surface to 10° (Table 2). We used only the horizontal components of the deformation field being the vertical one too scattered among nearby stations. This choice is motivated by the lack of significant vertical variations related to each SSE on the GPS time series. To perform the elastic inversion models for each SSE we used the *GTdef* code (Feng et al., 2012) which finds the optimal model parameters by using a linear least-squares solver scheme. In particular, *GTdef* seeks to solve the linear equation system relating the unknown slips (*m*) to the observed deformation (*d*) by applying a two-dimensional second-derivative (Laplacian) operator:

$$\begin{bmatrix} \frac{w^{-1}d}{0} \end{bmatrix} = \begin{bmatrix} \frac{w^{-1}G}{k^2 D} \end{bmatrix} m \qquad (1)$$

where *w* is the diagonal matrix constructed from observation errors, *G* is the green function matrix, *D* is the second-order finite difference operator (Jónsson et al., 2002), k^2 controls the weight imposed on the smoothing. The choice of smoothing leads to different model results where increasing smoothing values generally leads to an increase of model misfit. To determine the preferred model for each SSE, a trade-off curve between model misfit and roughness has been computed. The model misfit has been quantified through the chi-square value, while the average second-order finite difference sum of each patch has been used to indicate the model roughness ρ (Jónsson et al., 2002):

$$\rho = \frac{\sum_i |p_i|}{2N} \qquad (2)$$

where $p = Dm$ and N is the number of fault patches. The units of ρ are cm/km^2, indicating the average slip gradient (Jónsson et al., 2002). Our preferred models are reported in Figure 3 and are characterized by k ranging in the 4935 - 5755 interval (Figure S1).

4.0 Results and discussion

GPS stations installed on the lower unstable flank of Mt. Etna showed significant transient displacements (namely slow slip events) in their daily time-series position during a time interval of 10 years, from April 2006 to April 2016 (Figure 2). By a simple visual inspection of these time-series, we detected 11 SSEs with duration ranging from 2 to 67 days and with a very irregular average recurrence time of 348 ± 361 days (Table 1). As above mentioned, we extended in time (back and forward) the SSE catalog previously defined in Palano (2016), improving also the definition of SSEs starting and temporal length, thank also to the GPS stations of the SiOrNet network. With respect to the previous catalog, we provided a better definition of starting and temporal length of SSE-02, SSE-03, SSE-05 and SSE-07 (Table 1).

4.1 Surface deformation and modelled slip distribution

For each detected SSE, we estimated the surface deformation field which, in a successive step, was modelled to infer the spatial distribution of slip on a shallow sliding surface. Observed surface deformation (Figure 3) for most of the detected SSEs, mainly concentrates on the south-eastern edge of the on-shore unstable sector of the volcano edifice. Such a features is well evident for SSE-01, SSE-03, SSE-04, SSE-05, SSE-06, SSE-08, SSE-10 and SSE-11 (Figure 3), while SSEs involving the north-eastern edge are less frequent (SSE-07 and SSE-09). Therefore, the overall SSEs sequence highlights the existence of two distinct families of events involving the two contiguous sectors of the sliding flank as already suggested by Palano (2016), which occasionally slip together in large SSEs as observed during SSE-02. Moreover, the SiOrNet GPS stations allow to add new constrains to the deformation mode of the southern part of unstable flank of Mt. Etna. A primary key-feature is the differential motion observed along the Nizzeti faults, well captured by ACSA and SCAC stations (Figure 2 and Figure 3) and resulting in a general E-W extensional deformation. This feature is evident only in early SSEs since ACSA and SCAC worked until early 2014 and mid-2012, respectively. However, extensional deformation has been also observed by episodic measurements carried out along this sector of the volcano during November 2014 - April 2017 (De Guidi et al., 2018), highlighting a significant role of the Nizzeti faults in controlling both the long- and the short-term patterns of deformation. A similar behavior has been also observed for the Timpe faults with a general eastward increase of displacements (Palano, 2016).

Some GPS stations located along the coastal belt (ELAC, MASC and ERIP) are characterized by large displacements, suggesting a causative source located in the closest off-shore region. Conversely, EPOZ and ETEC stations showed small to moderate displacements during each SSE, which is comparable in magnitude with the ones measured at stations located in the middle eastern flank. This aspect suggests that the magnitude of deformation is not controlled only by the "station-source" distance, but requires an additional external control. Since along the coastal belt, the sedimentary basement is located at very shallow depth (Branca and Ferrara, 2013), we evaluate a possible correlation between "displacement" and "volcanic cover thickness". To this aim, for each SSE, we estimated both the daily displacement (i.e. the ratio between the total displacement and the event duration) and the volcanic cover thickness (by subtracting the sedimentary basement surface from the TINITALY digital elevation model; Figure 4a; Tarquini et al., 2007). Both estimated parameters are reported in Figure 4b: at a first glance, the average daily slip (s) is inversely correlated with the volcanic cover thickness (v) and could be described as:

$$s = -0.256 \log(v) + 1.964 \qquad (3)$$

In particular, the average daily slip of ELAC, MASC and ERIP stations appears influenced by the thin volcanic cover (lesser than 5-10 meters), while on the other stations the volcanic cover thickness doesn't significantly affect the daily slip during each SSEs. Therefore, the pattern of deformation along the coastal area seems to be controlled by the volcanic cover thickness: thinner the volcanic cover is, larger the displacement rate will be. However, the physical significance of such correlation is unclear and requires additional studies and more data to be properly quantified and understood. The establishment of new continuous GPS stations along the coastal area, especially on these sectors characterized by thin volcanic cover would represent a good starting point for these future studies.

The finer model resolution as well as the large size of the planar source used in this study allowed to get a slip distribution on the basal sliding surface much better that the one achieved in Palano (2016), where the slip was not properly constrained at the edges of the adopted source because of its small size. Looking at the new results, for SSEs occurring more frequently, the slip distribution concentrates with values up to 6 cm on the southeastern sector of the sliding surface, ~10 km off-shore in correspondence of the prominent ESE lineament (Figure 3) discovered by (Chiocci et al., 2011). Such a sector also includes the segment of the

ESE lineament where an 8-day-long SSE occurred in May 2017 (temporally outside our GPS dataset), as observed by seafloor geodetic data (Urlaub et al., 2018). Regarding the SSEs involving the north-eastern edge of the unstable flank, the slip distribution on the modelled surface concentrates ~12 km off-shore beneath the Riposto Ridge (Figure 3), a structural high related to the Apennine thrust belt (Chiocci et al., 2011). The southern slope of the Riposto Ridge is marked by a ~16-km-long tectonic lineament mapped from ~6 km from the coast up to the flat-floor depression at the toe of the continental margin with a N102° attitude (Figure 1; Chiocci et al., 2011). This lineament would represent the off-shore prolongation of the most active splay of the Pernicana fault, however the lack of clear morphological evidences, doesn't support such a connection (Chiocci et al., 2011; Gross et al., 2015). It must be noted, however, that the seaward motion measured on-land, on the northeastern edge of the unstable flank, needs to be adsorbed on off-shore structures. Since the seismic data reported in Chiocci et al. (2011) and Gross et al. (2015) also doesn't show evidences of contractional structures in the near offshore, it is more realistic that the motion is transferred/adsorbed to the east, by the N102° lineament or by a not yet discovered sub-parallel fault.

The slip distribution allows us to estimate the geodetic magnitude of each SSE (Table 1); by assuming a rigidity value of 15 GPa, estimated magnitude range between 5.4 (SSE-07) and 5.9 (SSE-01). Such a magnitude range is generally larger than the maximum magnitude (~5.2) estimated for earthquakes occurring at Mt. Etna in the last 200 years (Azzaro et al., 2015), therefore confirming the prevalent aseismic deformation of the unstable flank (Rasà et al., 1996).

4.2 General considerations and implications

Previous InSAR-based studies (Solaro et al., 2010; Bonforte et al., 2011) defined geometry and kinematics of some blocks dissecting the unstable flank of the volcano, however a set of different deformation patterns observed in the last two decades depicts a complex block fragmentation of this flank, where, beside the slow slip events analyzed in this study, other different sources/mechanisms contributed at different spatial and temporal scales to its continuous seaward motion:

- The onset of energetic volcanic events such as the October 2002 - January 2003 eruption (Andronico et al., 2005) and the 24 December 2018 dyke intrusion (Pezzo et al., 2020) activated some hidden and blind fault segments, well highlighting the mentioned above complexity. For instance, the 2002-2003 eruption was accompanied by significant ground deformation of the eastern flank mainly concentrated on its northern half, along the Pernicana fault and the Santa Tecla, Santa Venerina and Timpe faults, where few energetic seismic events (magnitude up to 4.4) also occurred (Neri et al., 2005). Conversely, the 24 December 2018 dyke intrusion led to extensive deformation of the eastern flank coupled with the occurrence of a shallow M4.9 earthquake on 26 December 2018 striking the Fiandaca fault on the southern sector of the unstable flank (Pezzo et al., 2020).

- Significant post-eruption deformations of the unstable flank, have been also documented for ~6 months after the 2002-2003 (Palano et al., 2009) and 2018 (Pezzo et al., 2020) eruption onsets.
- Co-seismic displacements along the Pernicana fault related to M>3.5 earthquakes which generally produce large surface fractures and damage to man-made features (e.g. Azzaro et al., 1998; Bonforte et al., 2007; Guglielmino et al., 2011).
- Episodic or continuous creeping of the faults dissecting and/or bordering the unstable flank (Rasà et al., 1996).
- Vigorous and long lasting inflation/deflation episodes of the volcano edifice generally produce a pattern of deformation exponentially decreasing with the increase of distance from the magmatic source (Lisowski, 2008): this results in a significant deformation at the stations located at upper and middle elevations, and a very small motion at stations located along the coast (e.g. Aloisi et al., 2011; Bruno et al., 2012; Spampinato et al., 2015).

The temporal modulation of these sources/mechanisms led to substantial changes of the displacement rates on the unstable flank. For instance, horizontal rates from ~33 mm/yr to ~61 mm/yr have been estimated for the 2003-2015 period for the southeastern and northern boundary of the sliding flank, respectively (Palano, 2016). Horizontal rates of ~28 mm/yr have been geodetically estimated during the 1997-2001 period (Palano et al., 2006) along the Pernicana fault, which are slight larger than the values estimated historically (Azzaro et al., 1998) and about an order of magnitude higher than the slip-rate estimated from geologic marker offsets (Azzaro et al., 2012). Geodetic vertical rates estimated for the 2003-2015 period depict a general subsidence with rates of ~15 mm/yr along the Pernicana fault, and of ~2-3 mm/yr along the faults bordering the southern boundary of the unstable flank (Palano, 2016). Such a general subsidence, although occurring at very low rates, can be also inferred by taking into account the available geologic estimations (Azzaro et al., 2012). Based on these observations, the complex block fragmentation of the on-shore unstable flank of Mt. Etna led to a significant partition of the seaward motion among the steep faults bordering the blocks (Figure 1), where however, i) the northern half is generally characterized by the highest deformation rates and ii) most of the SSEs concentrated on the southeastern sector of the southern half. Conversely, according to the modelled slip distribution (Figure 3), the highest deformation rates occur on the southern half of the off-shore sector.

Our approach to model the surface deformation field of the unstable flank of Mt. Etna provides a good fit of the observed deformation, assuming however that it is entirely associated to slip along the basal sliding surface. Additional sources such as the faults bordering the unstable sector and the blocks inside it have been not considered in our approach, despite their proved role on accommodating/modulating a fraction of the observed deformation. Another limitation of our approach is that it models only static deformation patterns, while as mentioned above a number of sources/mechanisms contributes over different time spans to the observed deformation. Therefore, to properly constrain and quantify all the active sources modulating the seaward motion of the unstable flank of the volcano, a time-dependent modelling approach would represent a substantial onward step for future studies. A densification of the current continuous GPS network, especially across the active faults of the unstable flank as well as along the coastal area will greatly improve the observational dataset leading to more robust model set-up and on turn, to a better definition of the active sources of deformation. In addition, the use of techniques aimed to the displacement patterns match as the one proposed in Montgomery-Brown et al. (2009) will improve the detection of small events that may be close to the noise level in the GPS time series.

The seaward motion of the unstable flank would pose a potential threat to the whole region since large submarine landslides, or subaerial landslides plunging into the sea, could trigger tsunamis which on turn can hit the densely populated coasts surrounding the eastern Mediterranean Sea. A large tsunami hitting the eastern Mediterranean in early Holocene has been correlated with the collapse of the Valle del Bove (Pareschi et al., 2006), however such a correlation is highly debated (Vigliotti, 2008). Besides this event, no other tsunamis has been triggered by volcanic and/or flank collapse episodes at Mt. Etna volcano, at least since 6150 BC (Maramai et al., 2019), therefore highlighting their very rare occurrence. This is not surprising and indeed, the occurrence of a large landslide at Mt. Etna, at least in the near future, is highly improbable because of the low slope of the volcano edifice (~10° on average) and the slow (~61 mm/yr) seaward motion of the unstable flank. The triggering of tsunamis by large

SSEs can be excluded too because of the low daily displacement rates (~2 mm/day) currently observed for each SSE from the continuous GPS stations (Figure 4).

5.0 Conclusive remarks

By inspecting the daily time series of the GPS stations located on the unstable flank of Mt. Etna we detected 11 SSEs occurred during the April 2006 - April 2016 time interval. Main conclusions can be summarized as following:

- Observed surface deformation for most of the detected SSEs, concentrates on the south-eastern edge of the unstable flank while SSEs involving the north-eastern edge are less frequent.
- The overall SSEs sequence highlights the existence of two distinct families of events involving the two contiguous sectors of the sliding flank, which occasionally slip together in large SSEs.
- The modelled slips put in evidence that both contiguous sectors extend ~10-12 km off-shore, on areas where tectonic lineaments such as the ESE (northward of Catania Canyon) and the N102° (along the southern slope of the Riposto Ridge) ones have been discovered in the last two decades.
- The faults dissecting the unstable flank control both the long- and the short-term patterns of seismic and aseismic deformation.
- The magnitude values of the SSEs sequence range in the 5.4-5.9 interval; these values are larger than the maximum observed one (at least in the last 200 years), evidencing as most of the deformation affecting the eastern flank occurs in aseismic mode.

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Figure Captions

Figure 1. Simplified tectonic map of Mt. Etna and its eastern off-shore. Bathymetry is from www.emodnet-bathymetry.eu. GPS stations covering Mt. Etna volcano are reported as colored points. Abbreviations are as follows: PF, Pernicana fault; TFS, Timpe fault system; SVF, Santa Venerina fault; STF, Santa Tecla fault; FF, Fiandaca fault; NF, Nizzeti fault system; TF, Trecastagni fault; MTF, Mascalucia-Tremestieri fault; ESEL, ESE lineament. Inset: sketch map of eastern Sicily; AMC, Apennine-Maghrebian chain; HF, Hyblean Foreland; GCF, Gela-Catania Foredeep.

Figure 2. On the right, time series of the East component of continuous GPS stations installed on the lower and middle eastern flank of Mt. Etna. GPS time series are colored according to their main features. GPS time series showing sudden change on their linear trend or a change with respect to their long-term trend are colored in red (group 1). GPS time series showing a continuous eastward motion, superposed by inflation/deflation deformation are colored in blue (group 2). GPS time series showing no deformation to gentle eastward motion and externally located with respect the unstable flank are colored in black (group 3).

Figure 3. Observed (blue arrows) and modelled (red arrows) surface displacements related to each detected SSE. Slip distributions on modelled decollement surface are also reported. See Table 1 for additional details.

Figure 4. a) Estimated volcanic cover thickness computed as the height difference between the TINITALY digital elevation model (Tarquini et al., 2007) and the sedimentary basement surface (Branca and Ferrara, 2013). b) Correlation between volcanic cover thickness and daily displacement (see text for details).

Figure S1. Trade-off curve between roughness and chi-square misfit (see text for details) for each modelled SSE. The preferred model is chosen in the inflection corner of the curve (yellow star). The corresponding *k* value is also reported.

Table Captions

Table 1. Catalog of slow slip events identified in this study. For each SSE, the duration, the geodetic moment (GM) and the estimated magnitude (M_w) are also reported. The deformation related to active magmatic sources has been removed from the displacement field of SSE-01,

SSE-02, SSE-03, SSE-05 and SSE-09 by adopting the source parameters available in literature (Pal17, Palano et al., 2017; Alo11, Aloisi et al., 2011; Spa15, Spampinato et al., 2015; Can18, Cannata et al., 2018).

Table 2. Parameters of the modelled sliding surface. The position (latitude, longitude and depth) indicates the top-center of the modelled surface. Depth (positive downward) is referred to the mean elevation of GPS stations used in this study, namely 1100 m above sea level.

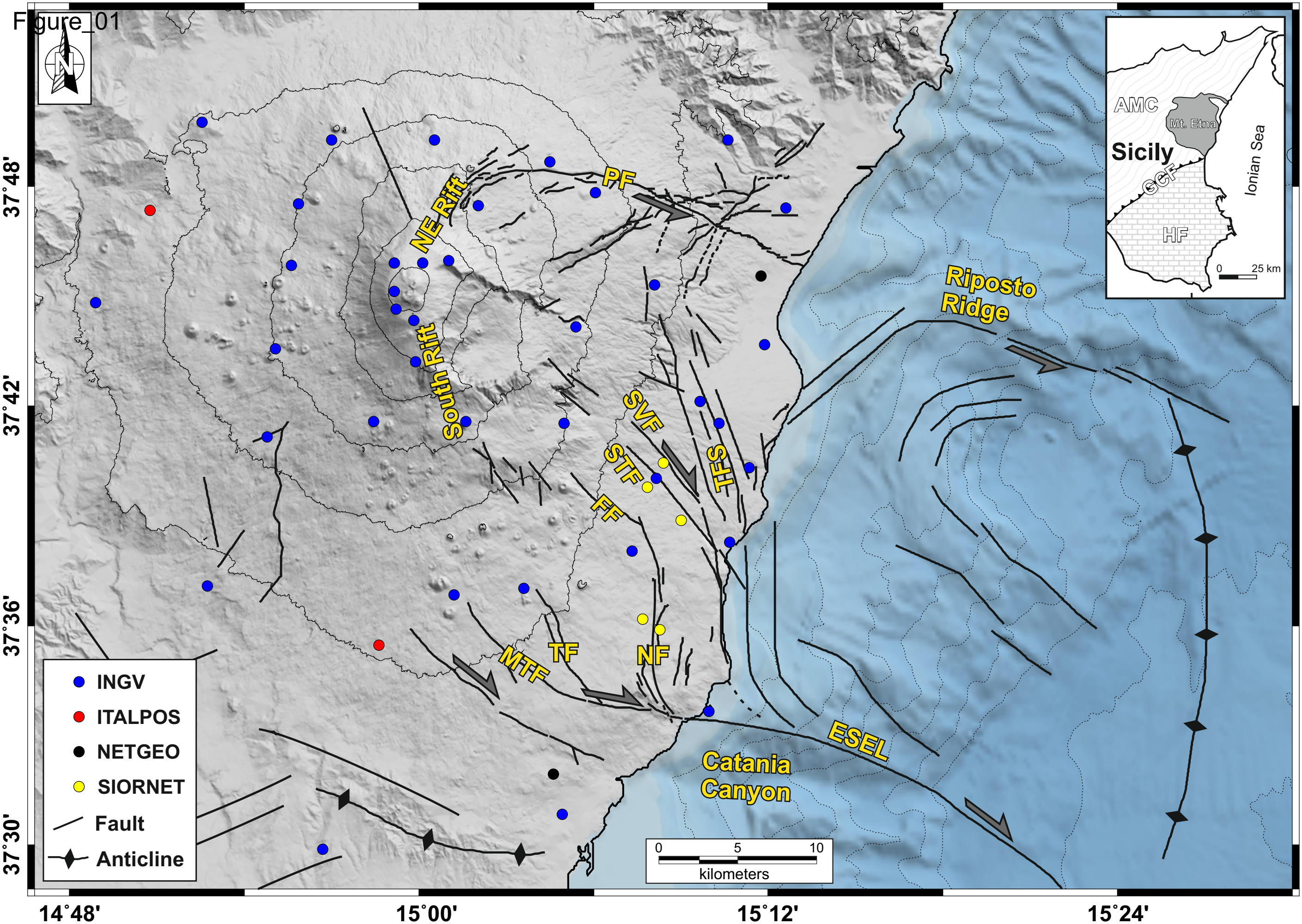
Longitude (°)	15.03
Latitude (°)	37.70
Depth (m)	500
Length (km)	36.0
Width (km)	36.0
Azimuth (°)	13.5
Dip (°)	10.0

Table 2. Parameters of the modelled sliding surface. The position (latitude, longitude and depth) indicates the top-center of the modelled surface. Depth (positive downward) is referred to the mean elevation of GPS stations used in this study, namely 1100 m above sea level.

SSE_Id	Event date	Duration (days)	GM (Nm)	M_w	Notes
SSE-01	16/04/2006	13	$1.84 \cdot 10^{17}$	5.48	Pal17
SSE-02	13/04/2009	42	$8.60 \cdot 10^{17}$	5.92	Alo11
SSE-03	27/03/2010	67	$3.86 \cdot 10^{17}$	5.69	Alo11
SSE-04	16/03/2012	5	$2.15 \cdot 10^{17}$	5.52	
SSE-05	15/05/2012	29	$2.42 \cdot 10^{17}$	5.56	Spa15
SSE-06	24/06/2012	4	$1.56 \cdot 10^{17}$	5.43	
SSE-07	10/08/2012	4	$1.49 \cdot 10^{17}$	5.42	
SSE-08	10/02/2014	2	$1.95 \cdot 10^{17}$	5.49	
SSE-09	26/10/2015	12	$2.52 \cdot 10^{17}$	5.57	Can18
SSE-10	14/01/2016	3	$2.45 \cdot 10^{17}$	5.56	
SSE-11	28/04/2016	5	$2.34 \cdot 10^{17}$	5.55	

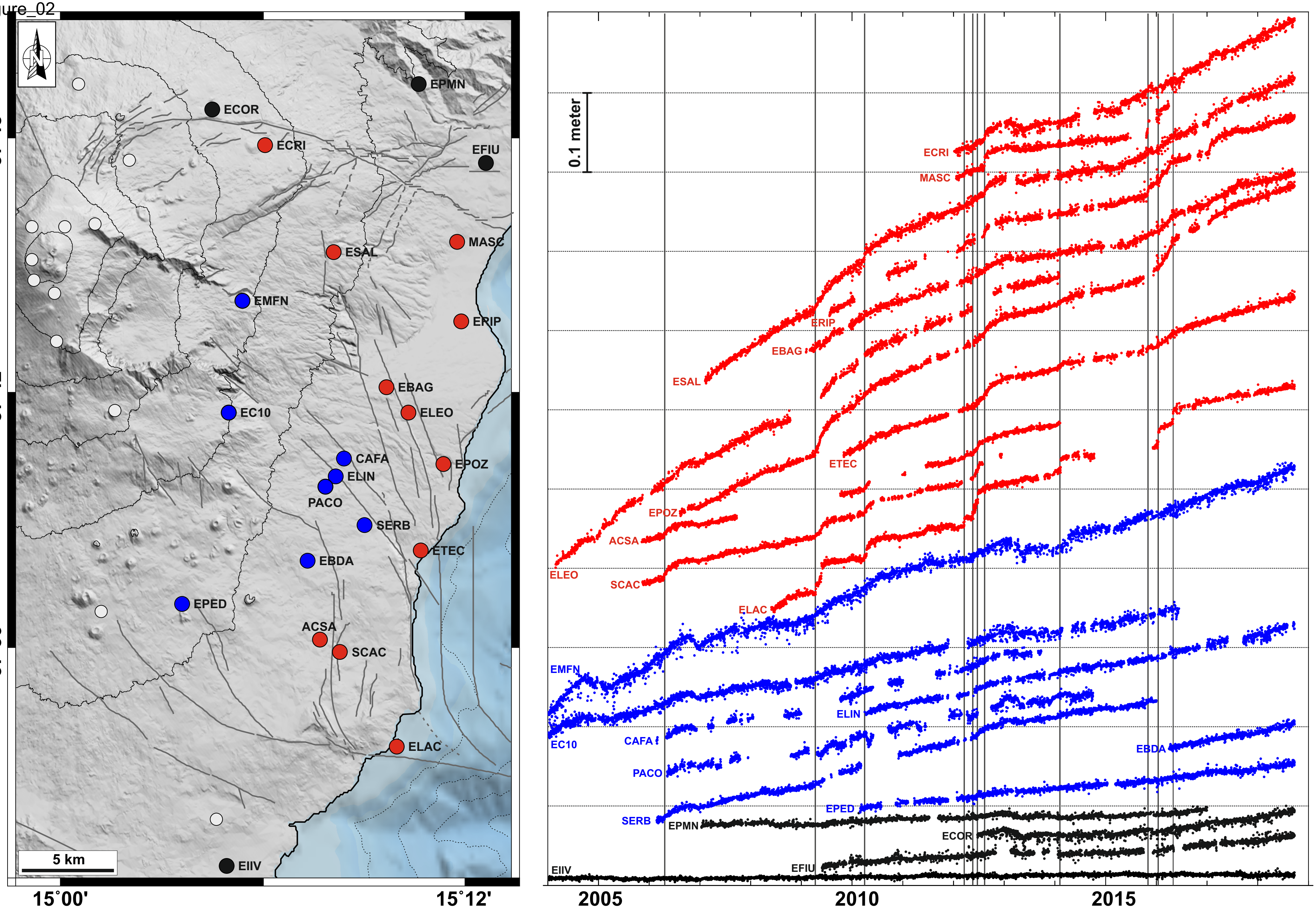
Table 1. Catalog of slow slip events identified in this study. For each SSE, the duration, the geodetic moment (GM) and the estimated magnitude (M_w) are also reported. The deformation related to active magmatic sources has been removed from the displacement field of SSE-01, SSE-02, SSE-03, SSE-05 and SSE-09 by adopting the source parameters available in literature (Pal17, Palano et al., 2017; Alo11, Aloisi et al., 2011; Spa15, Spampinato et al., 2015; Can18, Cannata et al., 2018).

Figure_01



N
NE Rift
South Rift
PF
SVF
STF
FF
TFS
MTF
TF
NF
Riposto
Ridge
ESEL
Catania
Canyon
AMC
Mt. Etna
Sicily
GCF
HF
Ionian Sea
0
25 km
INGV
ITALPOS
NETGEO
SIORNET
Fault
Anticline
0
5
10
kilometers
37°48'
37°42'
37°36'
37°30'
14°48'
15°00'
15°12'
15°24'

Figure_02


EPMN
ECOR
ECRI
EFIU
MASC
ESAL
EMFN
ERIP
EBAG
EC10
ELEO
CAFA
ELIN
PACO
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EBDA
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SCAC
ELAC
EIIV
5 km
37°48'
37°42'
37°36'
15°00'
15°12'
0.1 meter
ELEO
SCAC
ACSA
EPOZ
ESAL
EBAG
ERIP
ECRI
MASC
ETEC
ELAC
EMFN
EC10
CAFA
PACO
SERB
ELIN
EBDA
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EFIU
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2005
2010
2015

Figure_03

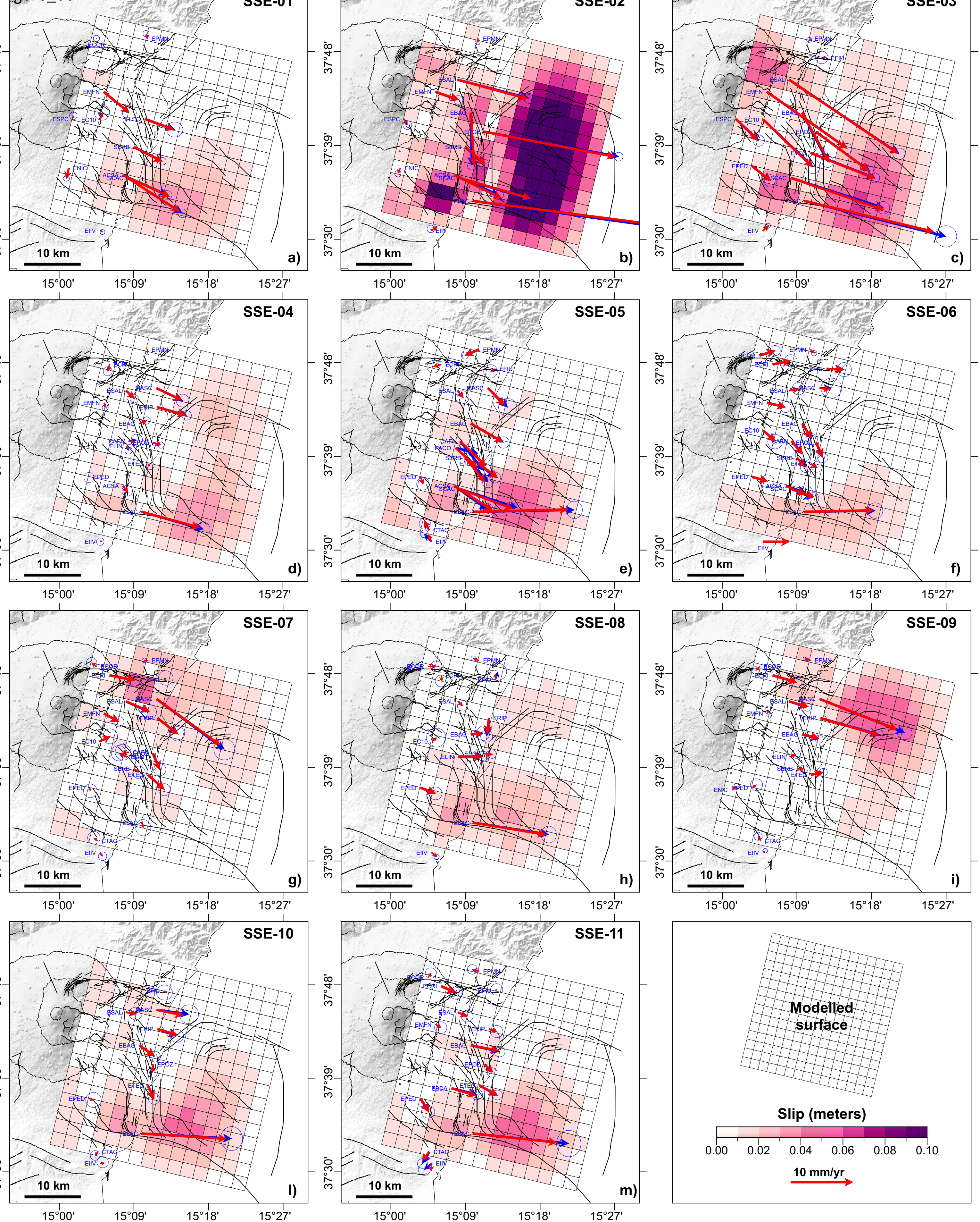
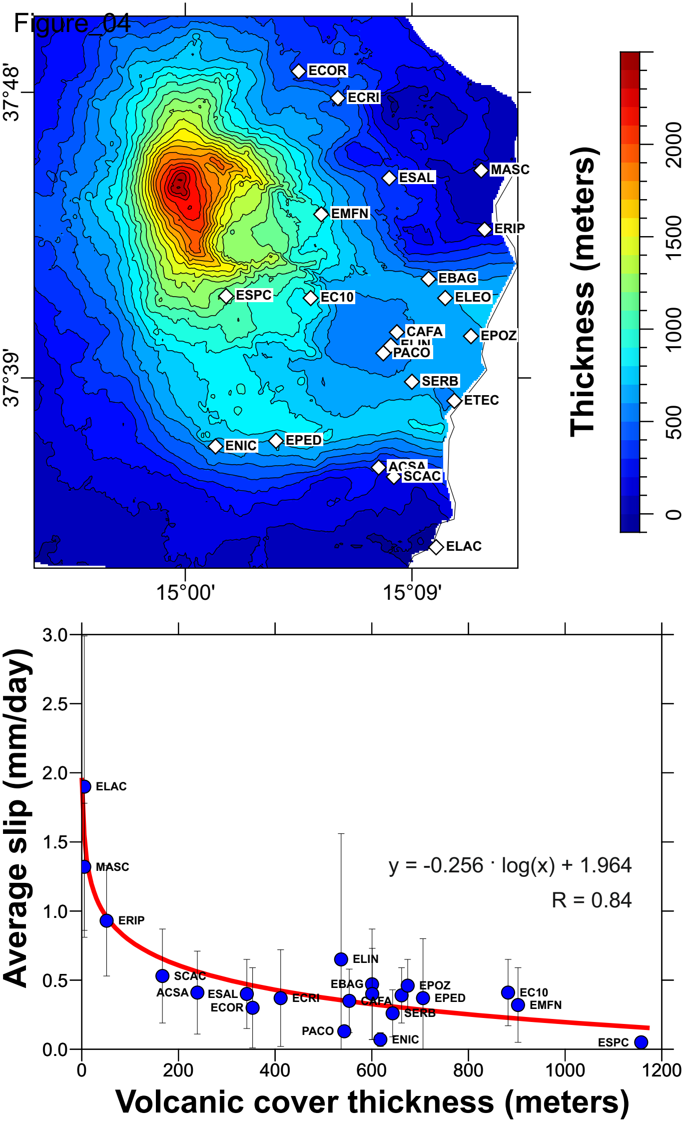

SSE-01
a)
SSE-02
b)
SSE-03
c)
SSE-04
d)
SSE-05
e)
SSE-06
f)
SSE-07
g)
SSE-08
h)
SSE-09
i)
SSE-10
l)
SSE-11
m)
10 km
37°48'
37°39'
37°30'
15°00'
15°09'
15°18'
15°27'
Modelled surface
Slip (meters)
0.00
0.02
0.04
0.06
0.08
0.10
10 mm/yr

Figure_04



ECOR
ECRI
MASC
ESAL
EMFN
ERIP
EBAG
ESPC
EC10
ELEO
CAFA
ELIN
PACO
EPOZ
SERB
ETEC
ENIC
EPED
ACSA
SCAC
ELAC
37°48'
37°39'
15°00'
15°09'
Thickness (meters)
0
500
1000
1500
2000
y = -0.256 · log(x) + 1.964
R = 0.84
Average slip (mm/day)
Volcanic cover thickness (meters)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
200
400
600
800
1000
1200

All the authors know and concur with the submission of this manuscript to **Tectonophysics** journal and declare no conflict of interests.

Mimmo Palano (on behalf all the authors)