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Mt. Etna Supersite: June 2022 – June 2024

History	***https://geo-gsnl.org/supersites/permanent-supersites/mt-etna-volcano-supersite/***
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1. Abstract

Mt. Etna is one of the most active volcanoes on Earth that in the past few decades has erupted virtually every year. The current Etnean volcanism results from the interaction between magma ascent in the rather complex plumbing feeding system and the local tectonic regime controlled by the volcano edifice's eastern flank instability, whose driving conditions (e.g., structural setting, tectonic forces) and cause-effect relationships are not completely understood yet. At the surface, the combination of the two factors produces eruptions along fissures that open on the flanks (e.g., in 2001, 2002-03, 2004-05, 2018) or at the one or more of the four summit craters (e.g., in 2011-'13; 2015; 2021-'22). Eruptions might be either strongly explosive (e.g., in 2002; 2011-'13; 2015; 2021-'22) or quietly effusive (e.g., in 2004-05). Explosive eruptions have produced volcanic ash plumes, sometime reaching also the stratosphere, that likely disrupt air traffic for hours to weeks (e.g., 5 January 2012), whereas effusive eruptions have fed lava flows capable of invading the populated areas of the volcano edifice, thus threating human property and vital infrastructures. Flank eruptions are often linked to seismic swarms with thousands of earthquakes having maximum magnitude of medium intensity (Mw = 4-5) and local severe damages to artifacts.

During the reporting period, the dynamic of the volcano was dominated by the activity at the summit craters, although from June 2022 to February 2023 brief effusive episodes occurred from vents opened in the upper north-western flank of the Valle del Bove. On 2023, four paroxysmal episodes occurred at the New South East Crater (NSEC) characterized by lava flows, strombolian explosions, often evolving to lava fountains and forming sustained volcanic plumes. In June 2024 the resumption of the activity at the Voragine Crater (VOR), after more than three years, was observed.

In this context the scientific production was focused on the analysis and interpretation of EO data (both SAR and optical) related to these events and their effects (e.g. the morphological variation in the summit area). Beside the scientific objective, Mt. Etna Supersite data (both EO and in-situ) were largely used to support the volcano surveillance and the activity of the Italian Civil Protection (both at local and regional level).

This report has been implemented with the contributions of: Lucia Cacciola, Annalisa Cappello, Francesco Guglielmino, Gaetana Ganci, Enrico Indovina, Danilo Reitano, Letizia Spampinato, Francesco Zuccarello.

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Scientists/science teams issues

The science team is largely a legacy of the EC-FP7 MEditerranean SUpersite Volcanoes (MED-SUV) project, and some others joint the group through the last years.
Indeed, most of the participants listed above had declared the interest in using the Supersite data and thus, they have been registered users of the MED-SUV portal. The main issue concerns the capacity to maintain an adequate level of cooperation and scientific benefit in the future, and possibly to enlarge the number of users, although the lack of steady financial support. To face this issue, the team has encouraged the exploitation of the Mt. Etna Supersite resources and the use of the MED-SUV data portal in the framework of international and national projects and initiatives. This point will be detailed in section 7 of this report.

3. Data Portal

The activities related to the upgrading of the Mt. Etna Supersite Data Portal followed two parallel lines: one is relevant to the implementation of the Data Portal s.s., and the second concerns the implementation of the Mt. Etna Supersite Portal. As reported in the 2020-2022 reports, both entities stopped to be maintained during the previous biennial period due to the expiration of the agreement among the institutions managing the portal of the EC FP7 MED-SUV project. These activities are strictly linked to the implementation of the EPOS Volcano Observations Thematic Core Service (VOLC-TCS) Gateway.

The first objective is to keep alive the legacy of the EC FP7 MED-SUV in term of data. To this aim, continuing the activity started during the previous biennial period, the contents and the data belonging to the EC FP7 MED-SUV project moved in the VOLC-TCS Gateway Data Portal, now in an advanced stage of development. Indeed, during the two-year period (2022 -2024) a new version of the Gateway has been designed and started to be implemented. The actual Gateway beta version, contains all useful information concerning the Supersite project initially collected during the EC FP7 MED-SUV Project; they are discoverable at the link https://vo-tcs.ct.ingv.it/gateway/. For the next future a new domain name will be adopted by the VOLC-TCS, which will replace the actual one. All of data and products refer to specific end points available both in the VOLC-TCS Gateway Data Portal and in the EPOS Data Portal.

In the framework of the EPOS Italia JRU, the team involved into Mt. Etna Supersite decided to propose the development of a specific Mt. Etna Supersite Web Portal, able to expose general information as well as a continuous updated list of in-situ and satellite data focused on Mt. Etna. The first stage of the work has been conducted by collecting all necessary information and planning the best way to provide information to the users. Then a specific tech group was formed in order to create the Web site and all references to the main Data Portal in the form of specific data bases. At the time of this report the process is still ongoing but, for the sake of clarity, the actual version of the Mt. Etna Supersite web portal can be found at the following url: https://vo-tcs.ct.ingv.it/gateway/EtnaSupersite/.

4. In-situ data

The in situ data are recorded from the INGV monitoring networks of Mt. Etna, which are listed below (Table 1).

Seismic	Permanent:	42 stations	Mobile:	12 stations
Accelerometric	Permanent:	6 stations		
Infrasonic	Permanent:	12 stations		
GPS	Permanent:	37 stations	Periodic surveys:	80 benchm.
Leveling			Periodic surveys:	38 benchm.
Tilt & strainmetric	Permanent:	19 stations		
Gravimetric	Permanent:	7 stations	Periodic surveys:	106 stations
Magnetic and SP	Permanent:	7 stations		
Dilatometric	Permanent:	4 stations		
Geochemical	Permanent:	16 stations		
Visible & Thermal IR Imagery	Permanent:	14 stations		

Table 1. In-situ available data and the access is offered through Web Rest Services. Metadata are available in the most common data format

Type of data	Data provider	How to access	Type of access
Seismic waveform	*INGV*	*Link to Network Italian Seismic Network Web Service through the Gateway Portal and EPOS Data Portal*	*Public*
Seismic events	*INGV*	*Link to Network Italian Seismic Network Web Service.* *A dedicated catalogue on Mt. Etna is provided through the Gateway Portal and EPOS Data Portal*	*Public*
GPS data	*INGV*	*Not available at the moment.* *A migration into a GLASS server is under development in the framework of the Horizon Europe Geo-INQUIRE project.*	*Public*
GPS data survey (1994- 2013)	*INGV*	*provided through the Gateway Portal*	*Public*
GPS coordinates / displacement vectors	*INGV*	*Not available at the moment.* *A migration into a GLASS server is mandatory to be compliant with EPOS*	*Limited to registered users*
Hydrophone / OBS waveform	*INGV*	*Not available at the moment*	*Limited to registered users*

Thermal cameras	*INGV*	*Not available at the moment*	*Limited to registered users*
Geochemical Bulk Rock Data	*INGV*	*provided through the Gateway Portal and EPOS Data Portal*	*Public*
Geohazard maps	*INGV*	*Under development. Will be provided through the Gateway Portal and EPOS Data Portal*	*Public*
Wrapped Differential Interferograms	*INGV*	*Provided through the Gateway Portal and EPOS Data Portal*	*Public*
Tiltmeter data	*INGV*	*Under testing. Will be provided through the Gateway Portal and EPOS Data Portal*	*Public*
Mean LOS Velocity	*INGV*	*Provided through the Gateway Portal*	*Public*

In-situ data issues

The in-situ data are provided by INGV. Since also the platform made during the MED-SUV project also expired, the team is working to create the new e-infrastructure described in chapter 3. Part of these data, described in the previous report, have been moved to the new platform, at the beginning in the form of data repository, now as web services compliant with EPOS requirements.
An example of this evolution is the provision of the following services: *Mean Los Velocity* (accessible only through the VOLC-TCS Gateway portal*)*; *Wrapped Differential Inteferograms.* Moreover, two other services are almost ready: the *Tiltmeter data* service is under testing while the *Geohazard Maps* service is under development.

5. Satellite data

Table 2. The satellite data types available for the Mt. Etna Supersite

Type of data	Data provider	Type of access	How to access
ERS-1/ERS-2	ESA	Registered public	(*)
ENVISAT	ESA	Registered public	(*)
Sentinel	ESA	Registered public	(*)
TerraSAR-X	DLR	GSNL scientists	(*)
COSMO-SkyMed	ASI	GSNL scientists	(*)
PLEIADES	CNRS	GSNL scientists	(*)
Landsat 8	USGS	Registered public	(*)
AVHRR	NOAA	Registered public	(*)
MODIS	NASA	Open	(*)
(*) https://vo-tcs.ct.ingv.it/gateway/EtnaSupersite/dataAccess_satellite.php			

Satellite data issues

During the reporting period, the main efforts have concerned the consolidation of the e-infrastructure to manage the data (both EO and in situ); about this activity details are in Section 3. It is continuing the issue encountered in acquiring Radarsat-2 data, owing the difficulties to finalize the update of the agreement with CSA.
The main variation during the biennial period, was the update of the Pleiades quota (13 June 2023), in order to cover up to 4,000 sq. km per year.

Mt. Etna Supersite Data portal described at the section 3, also provided a page to access to satellite data: https://vo-tcs.ct.ingv.it/gateway/EtnaSupersite/dataAccess_satellite.php.

6. Research results

After a short summary of the Mt. Etna volcanic activity, we report below recent research results based on the use of Mt. Etna Supersite data.
Additionally, here are also briefly reported results of researches carried out in the framework of national and international projects that explicitly declared their interest to scientifically support the Etna Supersites; these ancillary projects are both national (ATTEMPT and SAFARI) and international (IMPROVE, DT-GEO).

6.1. Summary of the Volcanic Activity.

During the biennial reporting period, Mt. Etna's volcanic activity consisted mostly in moderate to strong explosive summit eruptions and emission of lava flows from sub-terminal fissures (Figure 1).

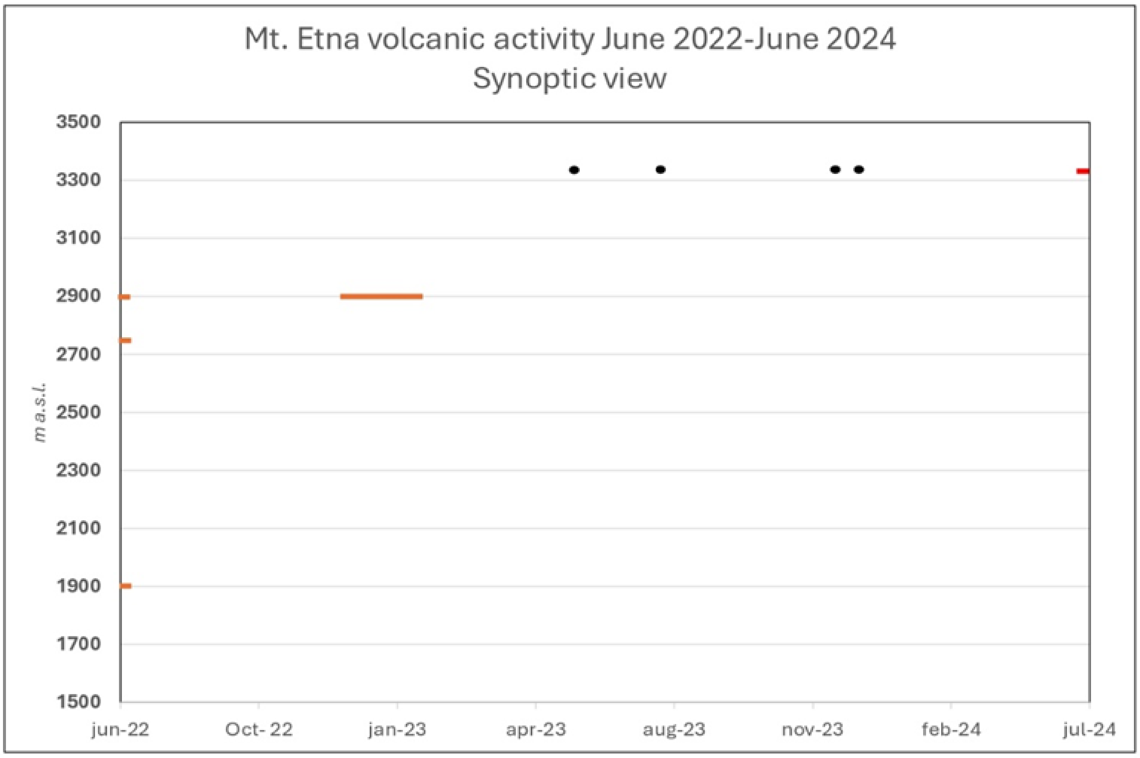

Figure 1. Summary of the volcanic activity at Mt. Etna, from June 2022 to June 2024. Black dots shows the paroxysmal episodes at the SEC; orange lines shows the lava flows in the Valle del Bove area and the red line indicates the activity of the Voragine crater.

The first two weeks of June 2022 were characterized by the emission of lava flows from a fracture system extending in a NW-SE direction along the northern flank of the Valle del Bove (Figure 2). Two distinct lava fields originated from two different segments of the fracture field. In particular, some vents located at the north-eastern base of the South-East Crater (SEC), at an altitude of approximately 2900-2750 m, fed a lava flow whose fronts stopped at

2100 m a.s.l. within the Valle del Bove. Another lava flow was emitted from the same fractures system by some vents opened between 1980 and 1900 m a.s.l. inside the Valle del Bove close to the northern flank. This lava effusion lasted for a few days, producing a lava flow that only expanded for a few hundred meters. Once the effusive activity from both segments of the fracture field ceased (16 June 2022), no eruptive activity was recorded until the end of November 2022 when an effusive vent opened at 2900 m at the north-eastern base of the SEC. The lava flow produced by this vent was fed until early February 2023 when it gradually ceased. This activity generated an intricate lava field characterized by the superimposition of lava flows in the area of the Valle del Leone and on the western flank of the Valle del Bove between 2900 and 2000 m producing a total volume of 6.3 million m^3 (Figure 3) (INGV – Bollettino Settimanale Etna 07/02/2023).

Figure 2. lava flows in Valle del Bove on June 2022. Wite arrows indicate the vents: (1) vent active from 29 May to 13 June 2022 (2850-2730 a.s.l.); (2) vent active on 7-8 June 2022 (1980 a.sl.l.);)3) vent active from 11 to 16 June 2022 (1850 a.s.l.)

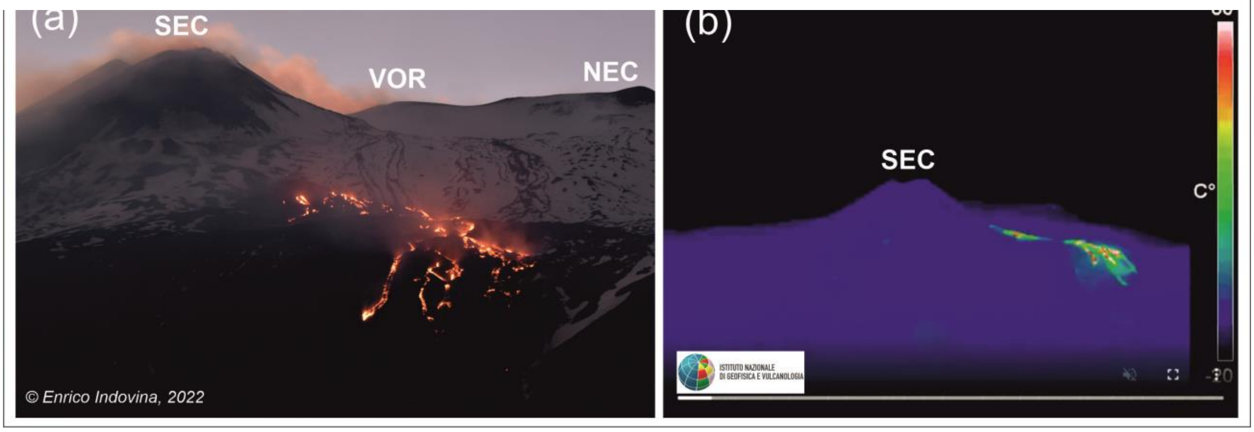

Figure 3. Lava flows in the upper part of the Valle del Bove (November 2022 – February 2023). South East Crater (SEC), Voragine Crater (VOR), North-East Crater (NEC): (a) picture taken from Serracosso area; (b) thermal camera from Monte Cagliato INGV station.

Between June 2022-February 2023, the activity of the four summit craters was dominated by degassing mainly at the Southeast Crater (SEC) and Bocca Nuova (BN), sometimes accompanied by minor episodes of intracraterial strombolian activity with sporadic ash emissions from the SEC. From May to December 2023, four paroxysmal episodes occurred at the SEC (Figure 4) (21 May, 13-14 August, 12 November and 1 December). Each of these episodes was characterized by a sudden unrest of strombolian activity at SEC, often anticipated or accompanied by emission of short lava flows from the crater, that in a few hours (at maximum one day) evolves in sustained lava fountain lasting for 2-3 hours and then stopping abruptly. During the most intense phases of these activities, the volcanic plume reached heights of 4 to 8 km, causing fallout of pyroclastic material along the downwind slopes, also affecting villages. After these events, the volcano showed no signs of eruptive activity until June 2024. Since 13 June, indeed, the Voragine crater (VOR) gradually reactivated; last activity dated of VOR back of to March 2021. The activity, initially characterized only by weak spattering, intensified throughout the month of June, leading to the build-up of a cone inside the crater and the emission of lava flows that flowed into the neighboring BN.

Figure 4. SEC lava fountain of 1st December 2023: (a) picture taken from Schiena dell'Asino area; (b) thermal camera from Montagnola INGV Station.

6.2. *Ground Deformations*

The results of scientific researches aimed at studying the ground deformations were carried out in the framework of institutional activities of INGV and European projects.

Sentinel 1 data has been routinely processed in the framework of institutional activities of INGV to monitor the ground deformation related to the volcanic and tectonic activity observed at Mt. Etna from 2022 to 2024.

In the long term, Mt. Etna was affected by a general dilatation coupled with an eastward movement of the eastern flank (Figure 5).

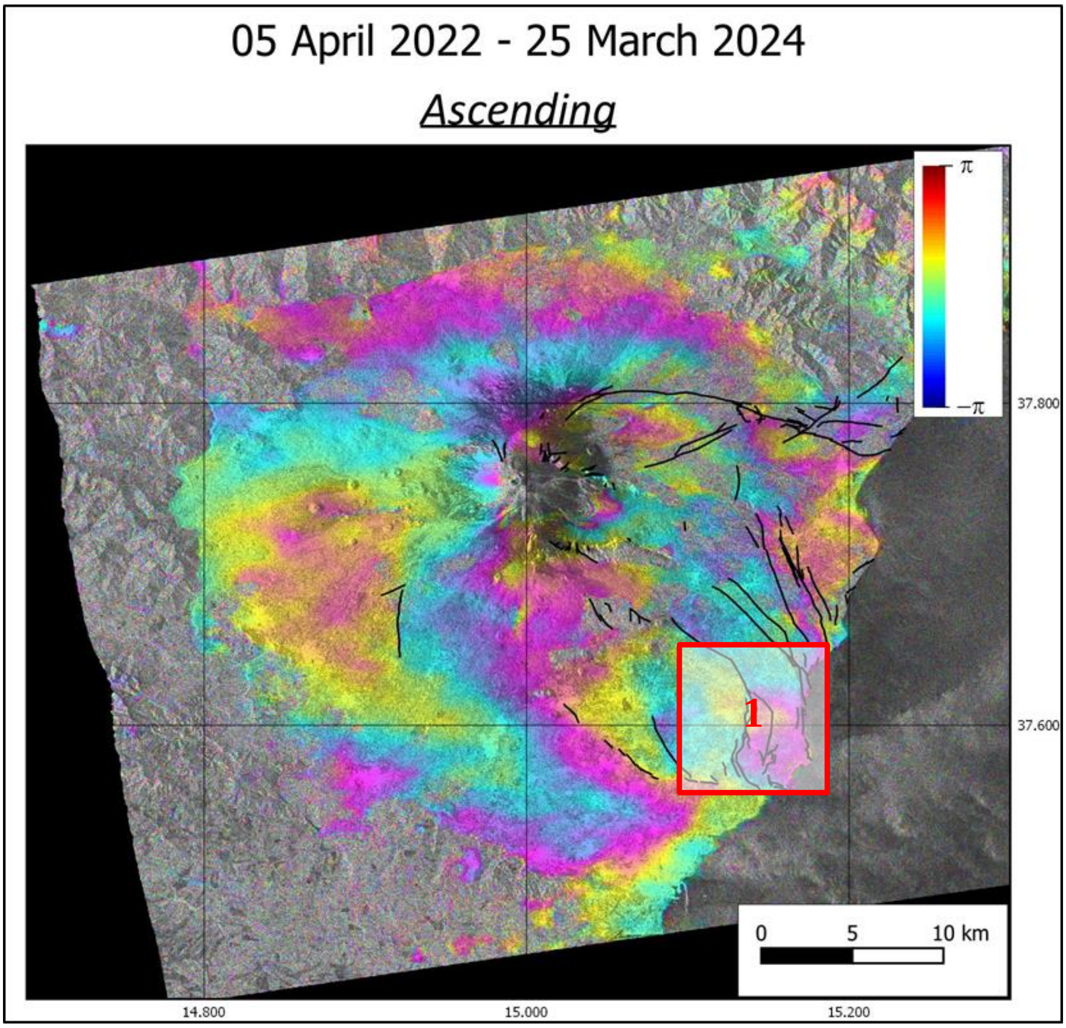

Figure 5. Sentinel 1 A ascending phase interferogram relative to December April 23th 2022 –March 31th 2024. The volcanic edifice is affected by a diffuse dilatation coupled with an eastward movement of the South-eastern flank deflation of about 2 fringes. The box (1) defines the area analysed in Figure 6.

The detail of the short time interferograms (Figure 6) in the area of the Acicatena Fault, highlights the ground deformation occurred between 12-24 April 2023, along a portion of the fault extending approximately 2 km northwest of the homonymous town, with a subsidence of approximately 3 cm (moving away from the sensor) of the eastern bloc (hangingwall) was recorded, as highlighted by the A-A' profile. This deformation gradually attenuates towards the east, reaching zero at approximately 1 km distance from the fault.

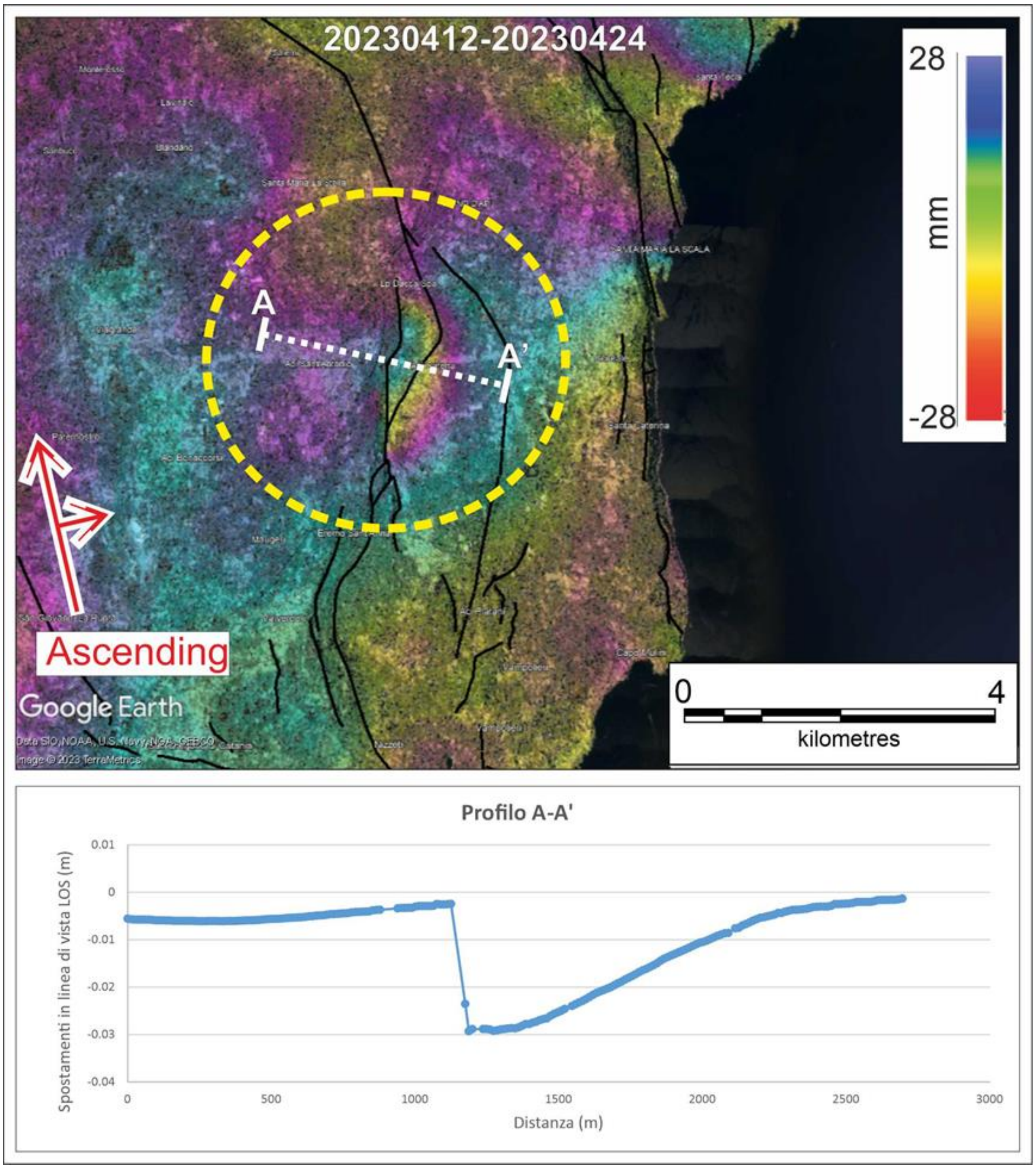

Figure 6. 12-24 April 2023 Sentinel 1A ascending interferogram. The ground deformation is located along the Acicatena Fault (yellow dashed circle), and denotes a movement away to the sensor of about 3 cm.

In the framework of the INGV Volcano Department IMPACT project, a research focused on the Trecastagni Fault (TF) by integrating satellite, ground-based and seismicity, has carried out (Alparone et al. 2022). The analyses were focused on the spatial/evolution of the deformation occurring along the Trecastagni Fault, and in particular the deformation associated with the seismic event occurred during the first decade of 2019 February (see Table 3).

Table 3. Earthquakes occurred in February 2019 along the Trecastagni Fault, with main hypocentral location parameters (from Alparone et al., 2022).

Number Event	DD/MO/YR	Origin Time	Latitude	Longitude	Depth (km)	Ml	No	GAP (°)	RMS (s)	ERH (km)	ERZ (km)	D (km)
1	06/02/2019	23:38:04.91	37.591	15.085	0.49	2.5	29	103	0.30	0.30	0.50	3.9
2	09/02/2019	06:02:19.05	37.576	15.094	2.63	2.9	24	88	0.25	0.20	0.20	2.2
3	10/02/2019	04:00:17.00	37.599	15.073	1.28	2.4	18	140	0.16	0.40	0.90	5.3

During the first period, from 27 January to 8 February, a ground deformation of about 1 cm was visible along the Trecastagni Fault, localized very close to the ML 2.5 seismic event on 6 February; furthermore, a wider deformation was evident along the S. Gregorio-Acitrezza fault (white arrows in Figure 7), occurring in this short period. In the second 6-day period (from 8 to 14 February), the interferograms detected ground deformation localized northwards along the fault, with respect to the previous period, in accordance with the hypocentral location of the ML 2.4 event on 10 February, but no deformation was associable to the ML 2.9 seismic event. In Figure 4, the cumulative (18 days) ground deformation image by the DInSAR data is reported. The results highlighted that the TF is characterized by a continuous aseismic dynamic that sometimes shows transient accelerations and seismic stick-slip behavior with low-energy shallow hypocentres. This dual behavior can be found on different patches of the fault but also in the same segment in different periods.

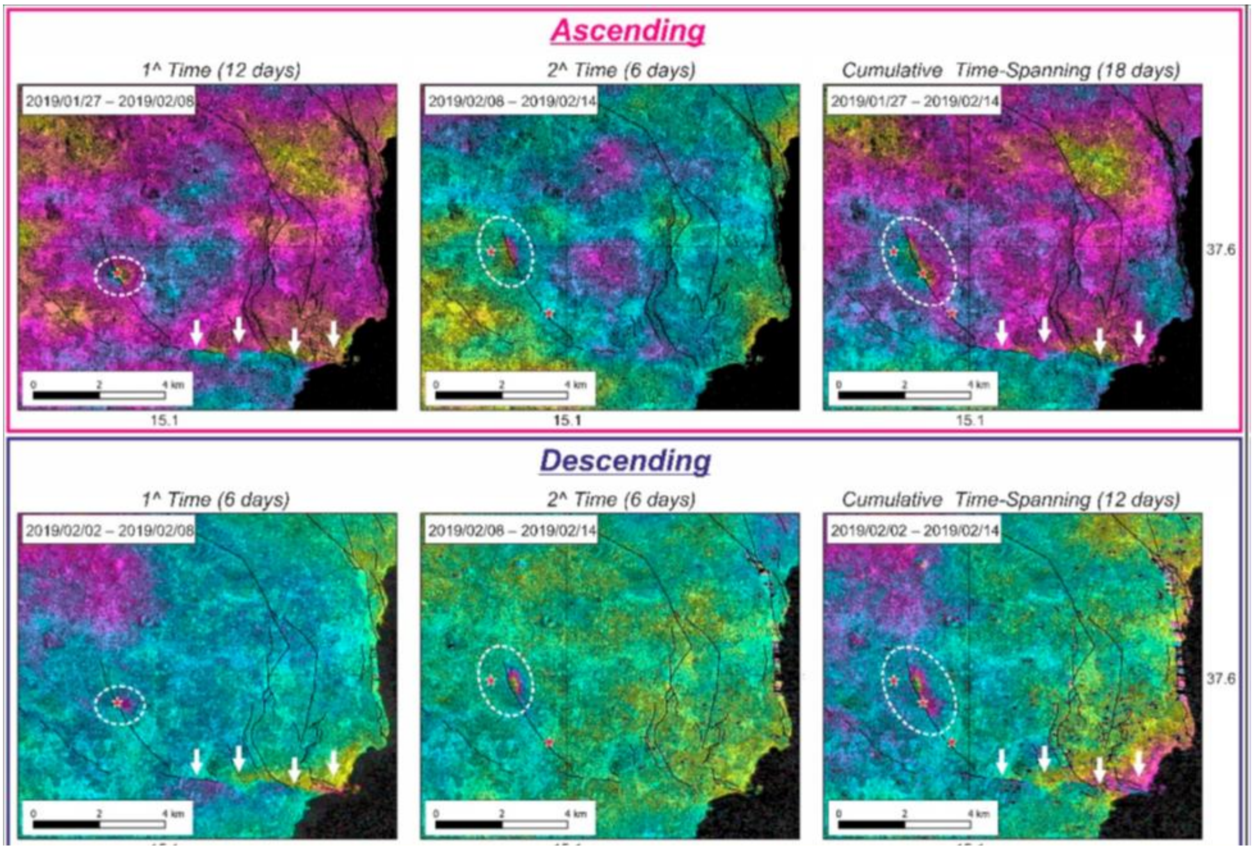

Figure 7 Ascending/descending interferogram from 27 January to 8 February 2019 (1^ time) from 8 to 14 February (2^ time) and the cumulative 27 January–14 February 2019. White arrows indicate the fault lines bounding the ground deformation features observed. For each time, the epicentrals of the seismic events are reported with red stars. The white dash circle represents the interest area. (Alparone et al. 2022).

The 2020-2023 SAOCOM-1A/1B SAR data, acquired in ascending geometry, was processed with the GAMMA-IPTA package using conventional SBAS A-DInSAR technique.
The SAOCOM (Satélite Argentino de Observación COn radar de Microondas) is part of the Italian-Argentine System of Satellites for Emergency Management (SIASGE, Sistema Ítalo-Argentino de Satélites para la Gestión de Emergencias), created by the National Commission of Space Activities (CONAE, Comisión Nacional de Actividades Espaciales) and the Italian space agency (ASI, Agenzia Spaziale Italiana) to contribute to emergency management and economic development. The SAOCOM acquire in L band, have an 8 days temporal resolution, and its constellation is formed by 2 identical full polarimetric satellites, 180° apart from each other.

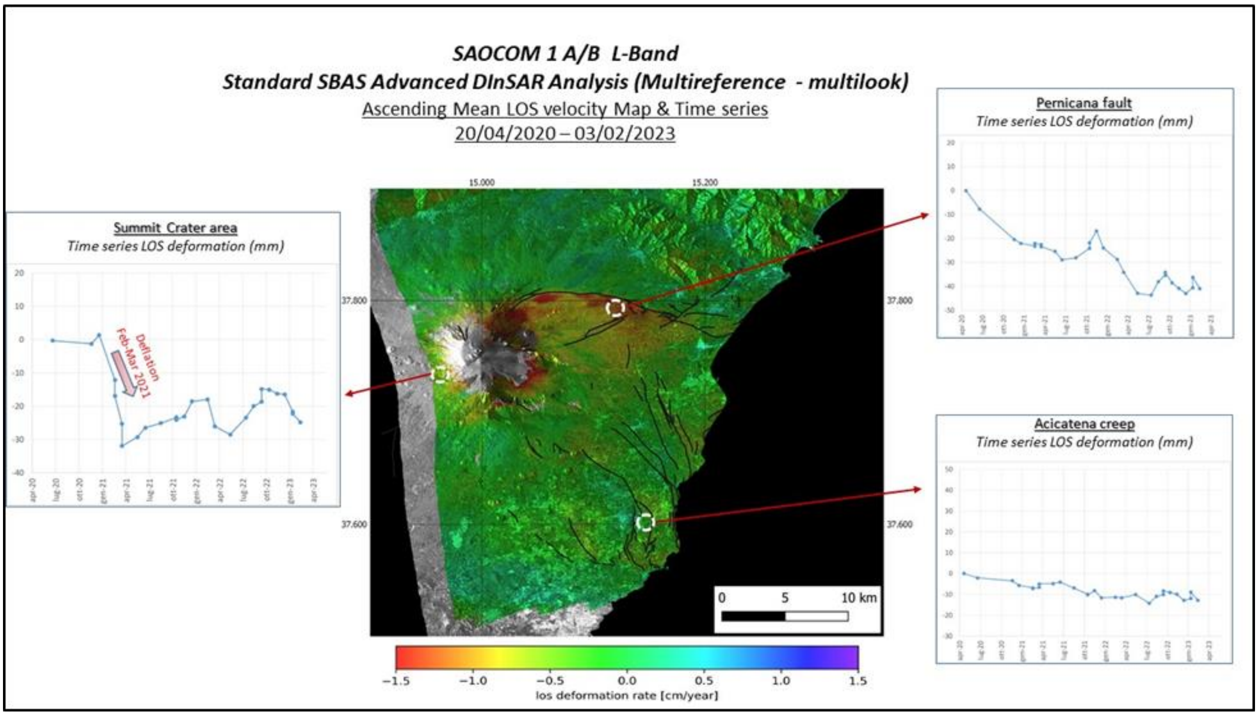

Figure 8. 1SAOCOM 1 A/B IPTA Advanced DInSAR Analysis. Ascending Mean LOS velocity Map & Time series relevant to 2020/0401/20-2023/02/03 time span. Details of the time evolution of the 2021 deflation is reported in the left plot. The East flank shows the deformation related to the persistent flank motion

The obtained mean LOS (Line of Sight) velocity map and the relative Time Series are reported in Figure 8 and show that a deflation phase accompanied the start of the 2021 paroxysms of Mt. Etna, with about 3 cm in moving away from the satellite. Furthermore, the time series relative to South-eastern flank (along the Pernicana Fault and Acicatena Fault) are shown

Important results on the ground deformation studies of Mt. Etna have been obtained in the framework of the IMPROVE MCSE ITN project. In this framework the Early Stage Researcher (ESR) based at the INGV in Catania has as objective to implement a conceptual model of the volcano, by studying the recent volcanic activity and in particular the 2020-2022 period, which was characterized by about sixty lava fountains episodes. The scientific focus is to investigate the phenomena in the range of frequencies between the seismic and quasi-static deformations through the analysis of ground deformation data (SAR, GNSS and tilt) and the integration of these results with seismic data. The preliminary results were presented at international conferences (IUGG 2023, EGU 2023 and 2024).

ATTEMPT was a project funded in the frame of the INGV "Pianeta Dinamico - Working Earth" coordinated project (https://progetti.ingv.it/it/pianeta-dinamico), which ended in March 2024. ATTEMPT was aimed at realizing a demonstrator of an integrated system capable of collecting multi-parametric space borne data to monitor different natural hazards over Mediterranean. Mt. Etna Supersite was the test site for the volcanic hazard. WP3's objective is to evaluate the volcanic unrest by integrating warning indices obtained from SAR and Infrared (IR) sensors. In this framework it has been carried out the analysis of the acceleration which occur on the eastern flank of Mount Etna. It is assumed as the keystone to understand the volcano tectonic dynamics that, apart from the tectonic and volcanic processes. In particular, the ground deformation (GNSS and InSAR) that occurred between 2016 and 2019 on the south-eastern flank of Mount Etna have been analyzed. The preliminary results were presented at international conferences (IUGG 2023, EGU 2023 and 2024).

6.3. Morphological changes

Since 2021, Pleiades images have been acquired in tristereo configuration with continuity. At INGV Catania Section - Osservatorio Etneo, a semi-automatic procedure was developed in order to obtain updated digital surface models (DSMs) from very high spatial resolution satellite images acquired in stereo, tri-stereo or multiview configuration (Ganci et al., 2018). Moreover, a fusion algorithm was developed (Ganci et al., 2023) to update digital topographic data from multi-source satellite imagery, exploiting the complementary characteristics of multi-source satellite-derived DSMs. The main objective is to minimize blunders and artifacts due to occlusions (e.g., the presence of clouds, snow or ash plumes) in the source images, resulting in improved accuracy and quality versus those that are not merged.
The fusion algorithm is based on six steps that are:
(1) Regridding and coregistration of the different DSMs - which includes mandatory preliminary processing operations and consists in resizing all DSMs in the same overlapping domain and exporting them in the same grid for the co-registration;
(2) Domain decompositions of the DSMs into patches - where all the DSMs are divided into regular sub-regions or patches. A minimum and a maximum size for the patch is established and different decompositions are accomplished for all the DSMs according to patch sizes;
(3) Patches decomposition - For each patch configuration, and for each square path, two different sub-regions are determined using a morphological filtering based on the slope;
(4) Selection of the best sub-patch - For each patch size the best sub-patch among all the available decomposed DSMs is selected by taking the minimum standard deviation of the Laplacian operator;
(5) Preliminary DSMs production - For each patch size, a preliminary DSM is produced mosaicing the best sub-patch;

(6) Production of the final DSM - Steps 4 and 5 are repeated for all the patch sizes considered, in this way a number of preliminary DSMs equal to the number of patch sizes is retrieved. The final merged DSM is obtained as the pixel-per-pixel median values of all the preliminary merged DSMs (Figure 9).

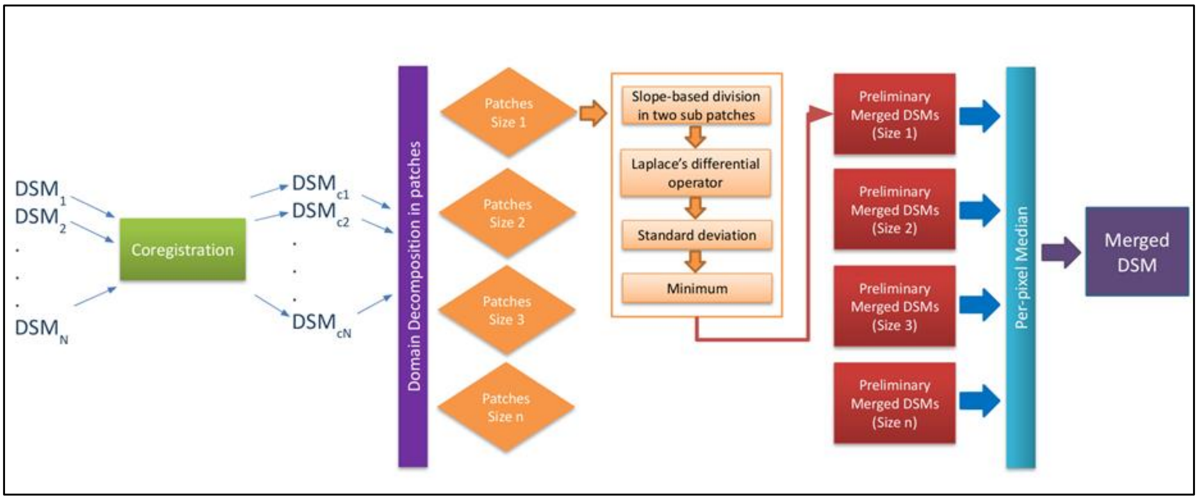

Figure 9. Scheme of the algorithm developed for Digital Surface Models (DSM) fusion

We tested the algorithm on Etna volcano by using three DSMs of July 2021 derived from two tri stereo Pleiades acquisitions of 13 and 25 July 2021 (acquired in the framework of the Etna Supersite) and a stereo WorldView-1 acquisition of 27 July 2021.
The fused DSM has a horizontal resolution of 1 meter and spans an area of ~12 × 8 km, which covers the summit craters and a portion of the south-east flank of the volcano, including the upper part of the Valle del Bove. The lowest elevation is 1080 m a.s.l., while the highest point of 3347 m is reached on the north rim of the SEC suggesting a height increase of 60 m in about 6 years. Quality enhancement of the fused DSM is visible to the naked eye, with major improvements in the north-west portion of the summit area where meteorological clouds affect the WorldView-1 image (Figure 10).

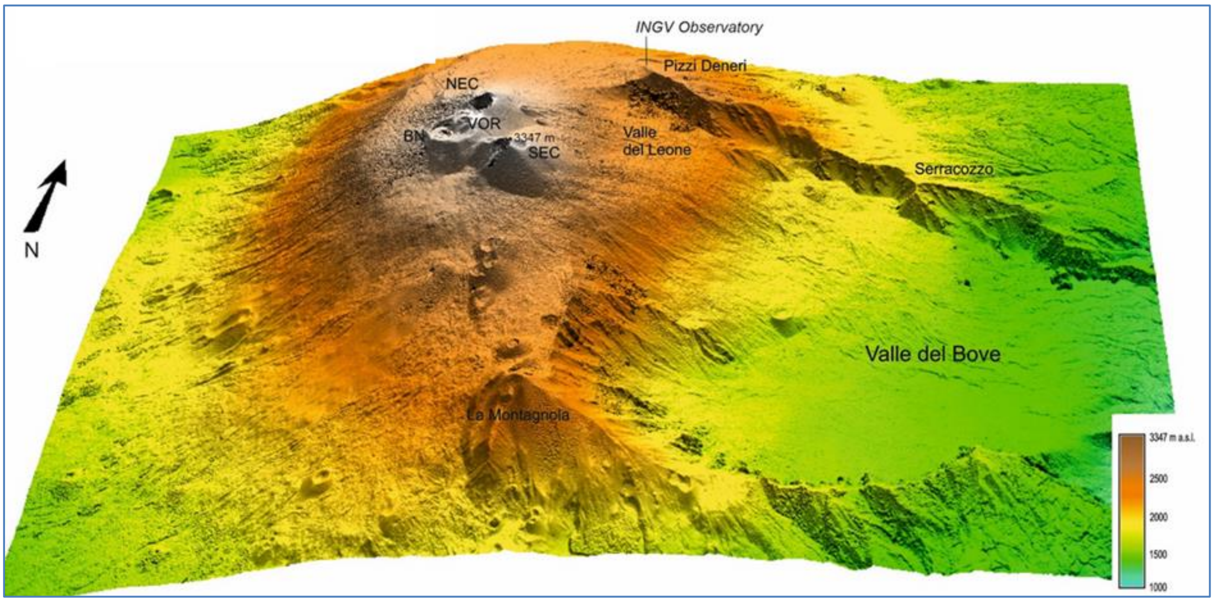

Figure 10. Digital Surface Model (DSM) of Etna volcano obtained by fusing three satellite-derived DSMs updated to July 2021.

As for 2023, we processed the Pleiades triplet acquired on 11 July and produced an updated topography at 1-meter spatial resolution (Figure 11a). These primary products were processed by using the MicMac open source library (http://micmac.ensg.eu, Rupnik et al.,2017). The DSM was coregistered with the previously available DSM from June 2022 and the difference was computed in order to evaluate the emplaced lava flow field and the growth of the South-East cone (SEC) (Figure 11b). In particular, the volcanic deposit observed can be divided into three distinct areas named: LF1, LF2 and P1. LF1 and LF2 represent the lava flows emplaced during November 27, 2022-February 6, 2023 and the paroxysmal event of May 21, 2023, with maximum thicknesses of 30 and 15 meters, respectively; P1 highlights the area affected by the accumulation of pyroclasts emitted during the paroxysmal episode of May 21, 2023, with a maximum thickness of 25 meters.

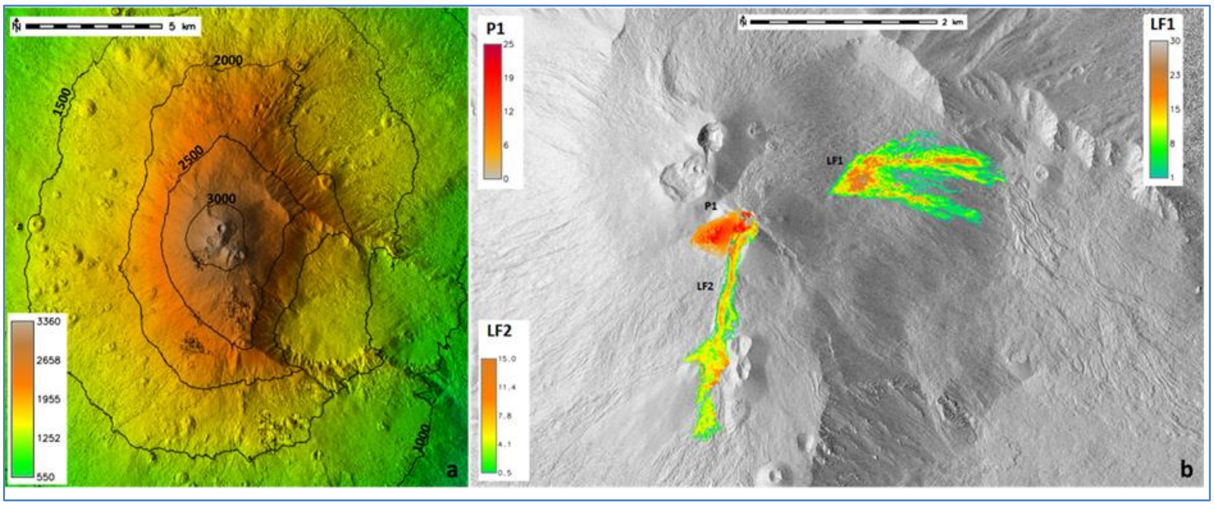

Figure 11 a) DSM of Etna obtained from the Pléiades triplet acquired on 11 July 2023. b) Deposits thickness obtained from DSM difference from June 2022 to July 2023.

6.4. Satellite-data driven lava flow modeling

Lava flows represent the most common hazard in basaltic volcanoes. A correct hazard assessment is an essential component in reducing the economic losses due to lava flow inundation. In case of real-time application during an ongoing eruption, numerical modelling of lava flow is a potential tool to estimate the likely paths that lava flows may follow and the kinetics of emplacement. However, complex lava fields are challenging to reproduce due to the high number of variables that affect the emplacement of the lava field (e.g. opening of multiple vents, formation of lava-tube with ephemeral-vents, variations in effusion rates). In the framework of the SAFARI and DT-GEO projects, complex lava fields were simulated by using an optimization algorithm to constrain the conditions which minimize the discrepancy between the actual flow field, observed from satellite imagery, and the modelled lava flows. Optimization algorithms are evaluated to reduce the number of simulations to be run (which represents the most computationally intensive part), to explore the variability induced by the uncertainties affecting the input parameters used to model lava flows, and to choose the best parameters that provide the optimal fit with the observed lava flow field. In particular, an approach based on Markov Chain Monte Carlo was developed to perform sequential simulations by sampling these parameters randomly at each iteration (Figure 12).

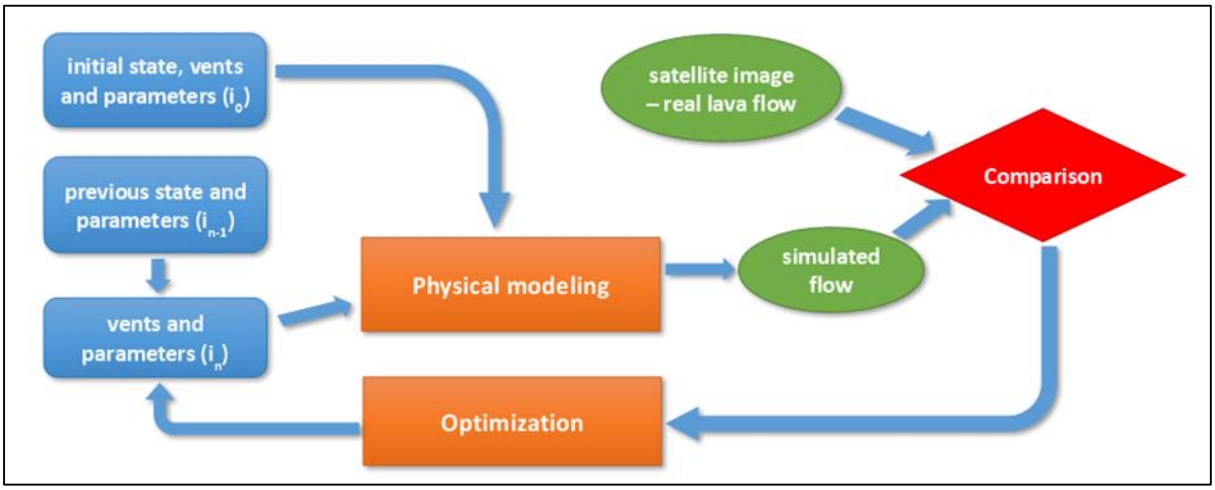

Figure 12. Workflow of the algorithm used for complex lava flow simulations

We derive the effusion rate (TADR) from low spatial resolution satellite imagery (e.g. MODIS, SLSTR, SEVIRI) and use higher spatial resolution imagery, such as MSI Sentinel 2, OLI & TIRS Landsat 8/9 or Planetscope, to retrieve detailed information on the lava flow field (spatial resolution from 3.9 to 30 m) in terms of extension of the active portion of the flow and presence and position of active vents.
We also take into account the main source of uncertainties for the lava flow simulations, that are: (1) Locations (i.e. latitude and longitude) and number of both main and ephemeral vents; (2) TADRs value, derived from the conversion of the thermal power estimated by satellites and used as input for modelling lava flows; (3) Distribution of TADR to the active vents (due to the low spatial resolution of satellite images, the contribution of each vent cannot be isolated); (4) Water content of the lava flows, which controls their viscosity.

This algorithm was applied as a case study to the 27 February - 1 march 2017 eruption at Mt Etna (Figure 13).

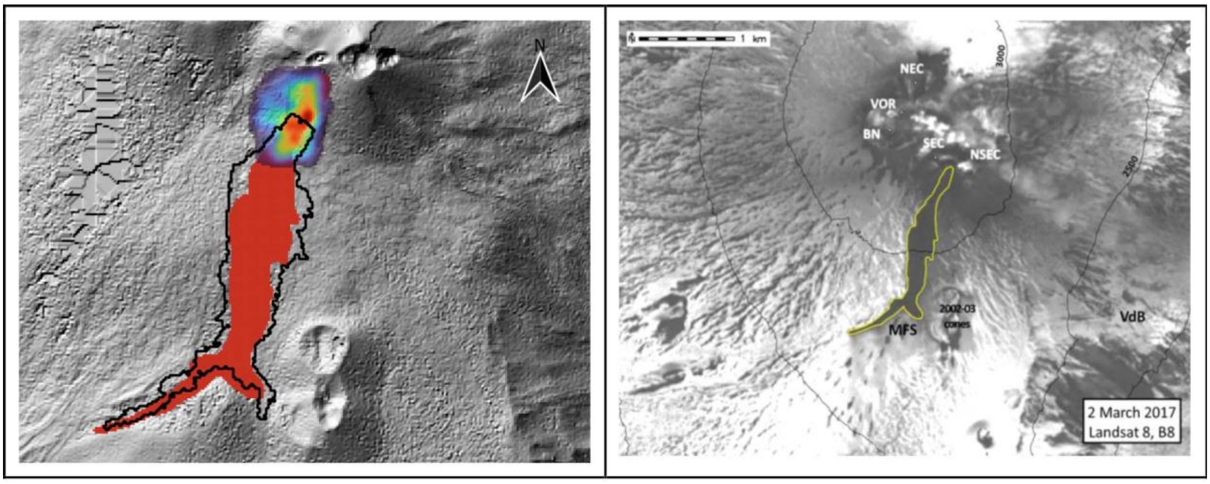

Figure 13. a) Heatmap density associated to the positions of the accepted samples and confrontation between the observed lava flow (in red) and the best fit modelled lava flow (black line) defined by the Metropolis algorithm by using as likelihood function. b) Landsat 8 image (band 8 - panchromatic) of 2 March 2017.

The Metropolis algorithm successfully reproduced the observed lava flow by defining the best-fit values that maximized the likelihood function. The method provided posterior distributions of the investigated parameters, ensuring that the samples were collected from the most likely regions of the parameters space and also allowing the presence of local optima to be observed.

6.6. Publications

Peer reviewed journal articles
Alparone, S.; Bonforte, A.; Gambino, S.; Grassi, S.; Guglielmino, F.; Latino, F.; Morreale, G.; Patti, G.; Privitera, L.; Obrizzo, F.; et al. (2022). Characterization of an Active Fault through a Multiparametric Investigation: The Trecastagni Fault and Its Relationship with the Dynamics of Mt. Etna Volcano (Sicily, Italy). Remote Sens., 14, 4760. ***https://doi.org/10.3390/rs14194760***
Ganci, G. et al., (2023). Data Fusion for Satellite-Derived Earth Surface: The 2021 Topographic Map of Etna Volcano. Remote Sens. 2023, 15, 198. ***https://doi.org/10.3390/rs15010198***
Ganci, G.; Bilotta, G.; Zuccarello, F.; Calvari, S.; Cappello, A. A Multi-Sensor Satellite Approach to Characterize the Volcanic Deposits Emitted during Etna's Lava Fountaining: The 2020–2022 Study Case. Remote Sens. 2023, 15, 916. ***https://doi.org/10.3390/rs15040916***
Conference presentations/proceedings
Carnemolla, F., Bonforte, A., Brighenti, F., Briole, P., De Guidi, G., Guglielmino, F., and Puglisi, G. (2023): GNSS and InSAR study of the ground deformation of the eastern flank of Mount Etna from 2016 to 2019, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-17466, ***https://doi.org/10.5194/egusphere-egu23-17466***
Puglisi, G., Bonforte, A., Buongiorno, M. F., Cacciola, L., Guglielmino, F., Ganci, G., Musacchio, M., Scollo, S., Reitano, D., Silvestri, M., and Spampinato, L. (2023): Integration between space- and ground-based observations in areas prone to volcanic hazard: the experience of Mt. Etna Supersite, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-12310, ***https://doi.org/10.5194/egusphere-egu23-12310***
Vásquez Castillo, A., Guglielmino, F., and Puglisi, G. (2023): On the 2021 Volcanic Paroxysmal Activity of Mount Etna: a Ground Deformation Analysis Using InSAR, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-10489, ***https://doi.org/10.5194/egusphere-egu23-10489***

*Vásquez Castillo, A., Guglielmino, F., Cannavò, F., Bonforte, A., and Puglisi, G. (2024): Etna's paroxysmal activity in 2021: A deflation episode revealed by joint DInSAR and GNSS ground deformation analysis, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-11682, **https://doi.org/10.5194/egusphere-egu24-11682**.*

6.7. Research products

A part from the papers and presentations listed above, it has been recently updated the data set of the INGV-OE Remote Sensing Lab service to visualise the interferogram products obtained from the Sentinel-1A/1B and SAOCOM data acquired at Mt. Etna (Figure 14). The products consist in the ascending and descending mean LOS (line-of-sight) velocity maps. The SENTINEL data sets have been updated with the velocity maps of ascending orbits 2018-2019 and 2019 2022, and descending orbits 2020-2021; the SAOCOM data sets refer to 2020-2023 period. The service allows to display the time-series of the displacements (positive toward the sensors) and comparison between time series that can be get by clicking the individual maps (Figure 15).

Type of product	Product provider	How to access	Type of access
Ground Deformation Time series	*Francesco Gugliemino (INGV)*	http://tsd.ct.ingv.it/tsdws/sar	*public*

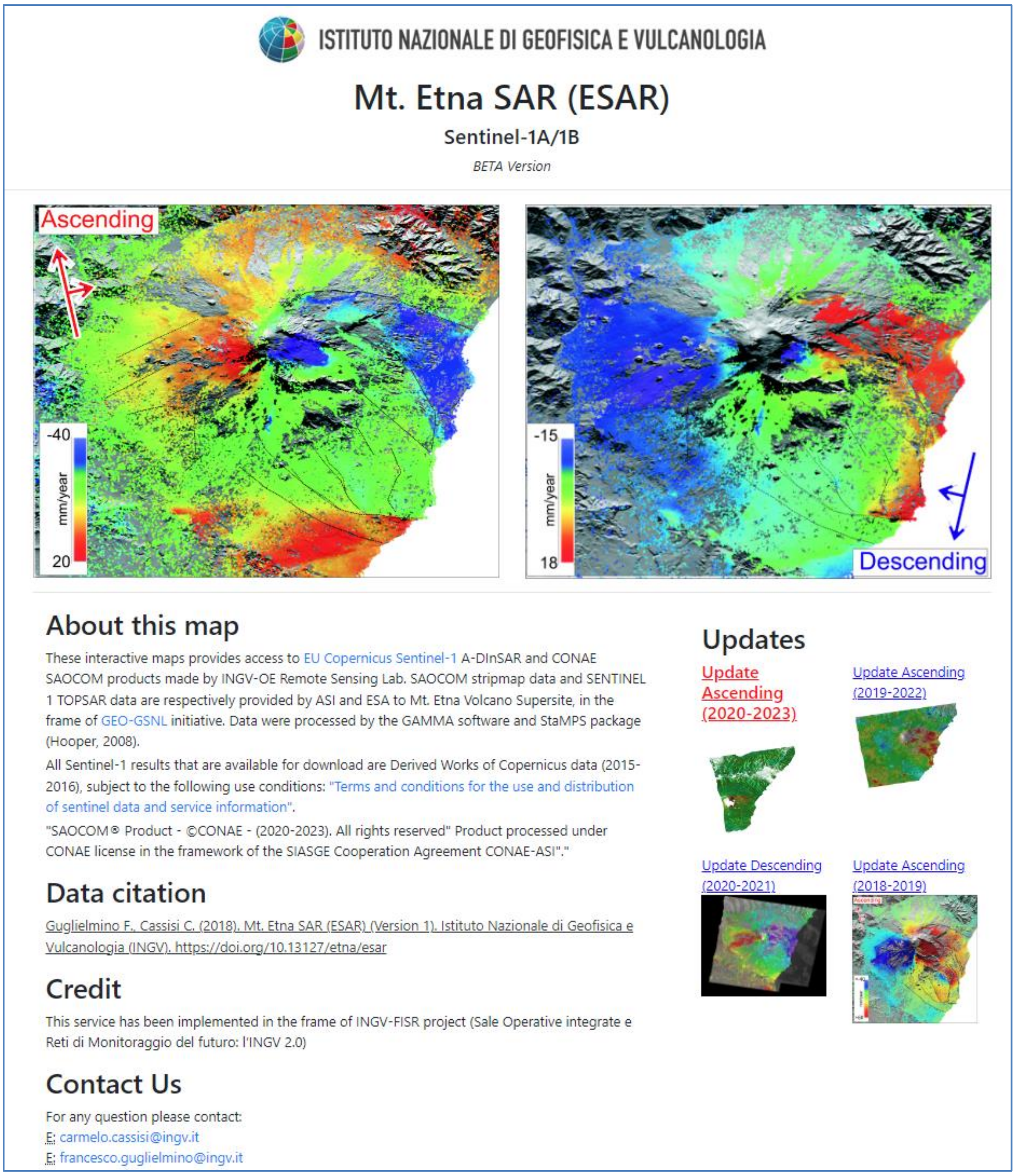

Figure 14. WEB-Gis home page

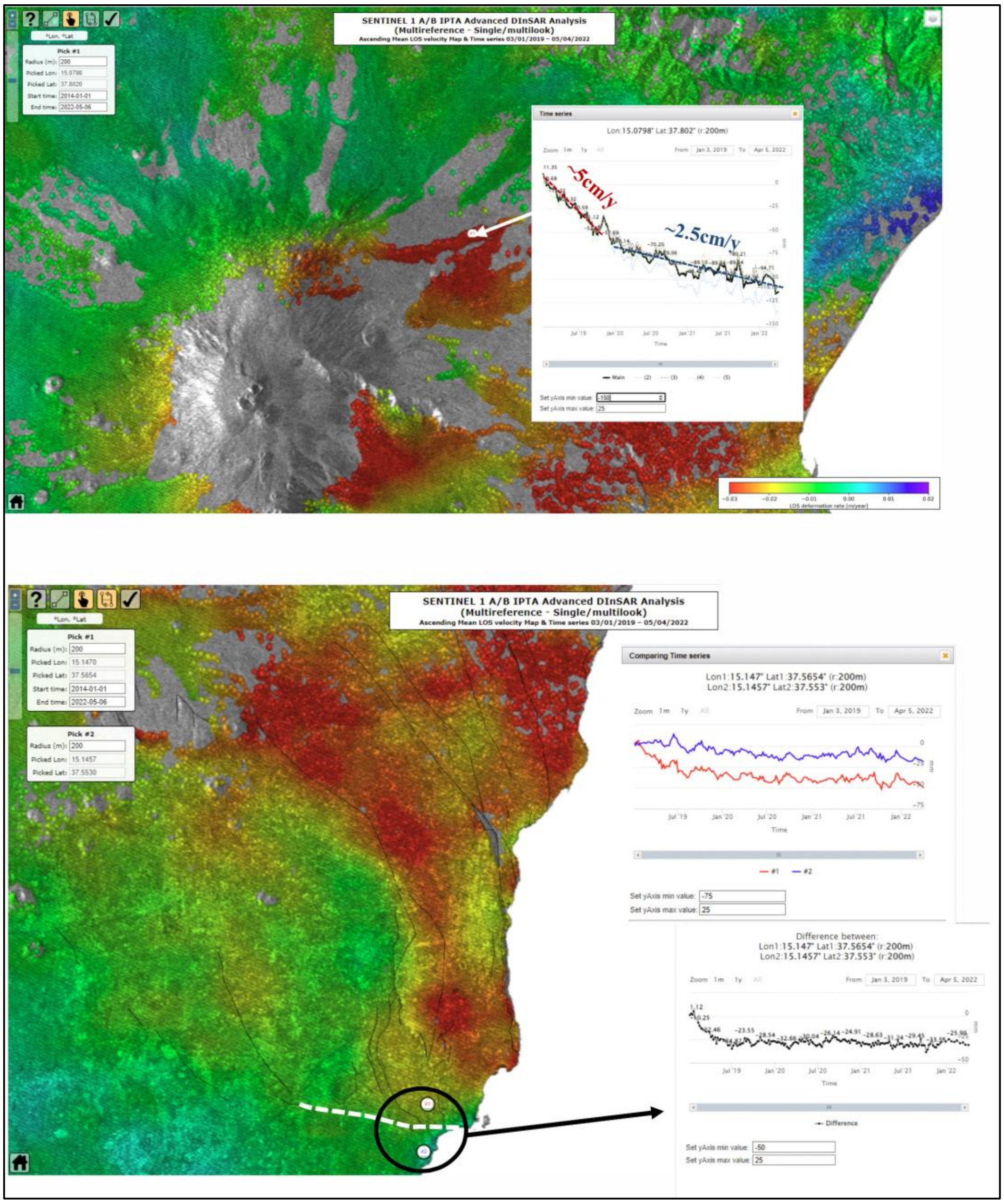

Figure 15. (upper part) Single Time Series Visualization; (lower part) Snapshot of Comparing Time Series tool

7. Dissemination and outreach

During the reporting period, the main dissemination event was the Summer School “Multiparametric Volcano Monitoring: Data Processing, Analysis and Modelling” organized in the frame of the IMPROVE MCSE ITN project (figure 16).
The summer school was attended by 30 students in total, represented by the 15 IMPROVE ESRs plus other 15 external students recruited through an open call, and selected among nearly 40 applications received. The students were invited to arrive in Nicolosi, on the flank of Mount Etna and where the school was going to be held, on the 23rd of July. The site of the school has been the INGV building in Nicolosi, as well as the nearby premises of the conference centre of the Nicolosi municipality. The school has been organized with the intention to provide the students with as much practical as possible training on “multiparametric volcano monitoring and data processing, analysis and modelling” (that being the title of the school). To do so, the students were trained on the use of sophisticated software representing the product of several years of research and technology developments at INGV as well as at partner Universities. The software was provided to the students as open source, so as to represent a powerful tool for their research activities once back home. Frontal lessons were kept to a minimum, and focused on providing the basics to understand the use and relevance of the software provided.
The activities of the school were subdivided into those happening in a lecture room (fig. 17 a, b), and those organized into an exercise room (Figure 17 c, d, e). A mid-school field trip has organized to show some stations of the multiparametric monitoring system of INGV that operate on this volcano and to discuss the main volcanologic features of Mt. Etna (fig.17 f).

Day 1	24 July 2023 – VOLCANO DEFORMATION
8:30 – 8:50	Registration, material collection
8:50 – 9:00	Welcome by the Coordinator (P. Papale) & School Directors (E. Privitera, G. Puglisi)
9:00 – 10:30	Volcano Ground deformations: introduction and measurement techniques • Introduction on volcanic processes and volcano deformation (G. Puglisi) • Tilt (S. Gambino) • Strain (G. Currenti) • GNSS (A. Bonforte) • SAR (F. Guglielmino)
10:30 – 11:00	FAIR data principles and the EPOS hub (J. Michalek)
11:00 – 11:30	Coffee break
11:30 – 13:00	Analitical models for ground deformation (F. Cannavò; F. Guglielmino) • General introduction and exercises
13:00 – 14:00	Lunch
14:00 – 16:30	Numerical models for ground deformation (D. Garg) • General introduction and exercises
16:30 – 17:00	Coffee break
17:00 – 18:00	Slide presentations by the individual exercise groups, showing their results and interpretations for both the analytical & numerical exercises
18:00 – 19:00	First group of ten poster presentations by the students, with evening drinks

Day 2	25 July 2023 – VOLCANO DEGASSING
9:00 – 9:30	Observing degassing in volcanic plumes (G. Salerno)
9:30 – 10:00	The H_2O-CO_2-melt system (P. Papale)
10:00 - 11:00	Exercises on the H_2O-CO_2-melt system (part 1)
11:00 – 11:30	Coffee break
11:30 – 12:30	Exercises on the H_2O-CO_2-melt system (part 2)
12.30 – 13.00	Technological developments in measuring volcanic degassing (L. Coppo)
13:00 – 14:00	Lunch
14.00 – 14.30	The H_2O-CO_2-SO_2-H_2S-melt system (R. Moretti)
14.30 – 16.30	Exercises on the H_2O-CO_2-SO_2-H_2S-melt system
16:30 – 17:00	Coffee break
17:00 – 18:00	Slide presentations by the individual exercise groups, showing their results and interpretations
18:00 – 19:00	Second group of ten poster presentations by the students, with evening drinks
21:30	After dinner movie presentation of the Etna field trip on the following day (Boris Behncke)

Day 3	26 July 2023 – FIELD TRIP ON MOUNT ETNA, SOUTH FLANK
	Lead: B. Behncke
7:30	Leave from Nicolosi on bus, then cable car to 2750 m a.s.l.
9:40	Ascent to the Barbagallo crater, arrival at 10:30
12:00	Cisternazza and Belvedere areas (view on Valle del Bove)
14:00	Cone of the 2001 eruption. Demonstration on the use of drones (T. Ricci & others)
15:00	Multiparametric monitoring station at Monte Frumento Supino
15:30	Start descent from the volcano (on foot)
17:00 / 17:30	Leave on bus, arrival at Nicolosi by 18:00
	NOTE: the program might be modified depending on climate and unrest/eruptive conditions.

Day 4	27 July 2023 – VOLCANO SEISMICITY
9:00 – 9:40	Introduction to the seismicity of active volcanic areas with particular reference to Mount Etna volcano (E. Privitera)
9:40 – 11:00	Volcano-tectonics seismicity: location methods (M. Aliotta) • General introduction and exercises (part 1)
11:00 – 11:30	Coffee break
11:30 – 12:00	Volcano-tectonics seismicity: location methods, exercises (part. 2) (M. Aliotta)
12:00 – 12:30	Analyses of infrasound events and tremor (L. Zuccarello)
12:30 – 13:00	Volcanic tremor amplitude analyses and location methods for volcanic tremor sources (A. Cannata)
13:00 – 14:00	Lunch
14:00 – 16:30	Exercises on: volcanic tremor amplitude analyses and location methods for volcanic tremor sources (A. Cannata) and analyses of infrasound events and tremor (L. Zuccarello)
16:30 – 17:00	Coffee break
17:00 – 18:00	Slide presentations by the individual exercise groups, showing their results and interpretations
18:00 – 19:00	Third group of ten poster presentations by the students, with evening drinks
20:30	Social dinner

Figure 15. The Summer School “Multiparametric Volcano Monitoring: Data Processing, Analysis and Modelling” program.

Figure 17. Snapshots of the IMPROVE Summer School: a) and d): frontal lessons in the lecture room; b), c), d) group exercises; e) students' poster sessions; f) mid-school field trip on Mount Etna.

8. Funding

The analysis of the economic support to the Etna Supersite should be distinguished between the support to the scientific activities and the management.

Considering the absence of specific financial support for scientific researches on the Supersite, the scientific results relevant to the Mt. Etna Supersite, the institutional activities of the INGV and national and international projects contributed to support this initiative.
During the biennial period, the active projects directly linked to the Mt. Etna Supersite were e-SHAPE; IMPROVE; Geo INQUIRE; DT GEO; ATTEMPT, MEET, SAFARI). The scientific impact of these projects in the Supersite activities is summarized in the Section 6.
Furthermore, the Mt. Etna Supersite benefitted from the improvement of the INGV-OE multi-parametric monitoring system funded by the national project implemented by the Italian Ministry of the University and Research in the framework of the European Regional Development Fund (ERDF) (PON Geoscience Research INfrastructure of Italy – GRINT; https://progetti.ingv.it/it/pongrint), which concluded its activities at the end of 2023 and other institutional funds.
The IMPROVE MCSE ITN project (https://www.improve-etn.eu/) started in September 2021. It supports the scientific coordinated projects of five Early Stage Researchers (ESRs) on Mt. Etna and dissemination activities as the Summer School held on Etna in July 2023. This project will give a significant contribution also from the infrastructural point of view, because it is going to implement a database for the project results fully compliant with EPOS.
In the 2022-2024 period two Horizon Europe projects started, which include Mt. Etna Supersite as privileged specific location for their activity: Geo-INQUIRE (https://www.geo-inquire.eu/) and DT-GEO (https://dtgeo.eu/). Both projects will encourage the trans-domain use of the research infrastructure; with regard to this objective, the Mt. Etna Supersite will have the opportunity to confirm its potentiality already exploited in the past years (see the previous biennial reports).
Geo-INQUIRE is aimed at improving the offer of scientific data and foster the advanced use of the research infrastructure. In this framework, Mt. Etna Supersite will benefit from the implementation of updated services (namely, a service to access to GNSS data fully compliant with EPOS, and the contribution to the implementation of the European Catalogue of Volcanoes), new tools to analyse the data and specific training activities.
DT-GEO is aimed at designing and experimenting the concept of "Digital Twins" in different contexts, among which there are the volcanoes; Mt Etna will be the volcano test site of this project. New workflows for assessing the hazard for specific volcanic processes are under development (sub-surface dynamics, lava flows and volcanic plumes).
MEET (https://meet.ingv.it/) is one of the Italian national projects that contribute to the achievement of the Next Generation EU. MEET started in 2023 and it is led by INGV. It aims to renew, implement and in some cases create monitoring nodes to build research infrastructure networks fit for the future, in line with European and international standards. In this framework, Mt. Etna Supersite will benefit from the update of the Open Access facilities at Mt. Etna volcanological observatory at Pizzi Deneri (2800 m a.s.l.).

The management of Mt. Etna Supersite is largely based on the in-kind contribution of the INGV, through the personnel efforts and a little financial support to maintain the MED-SUV portal. During the previous biennial periods we paved the way to structure the management of the Supersite by appointing a specific working group at the Etna Observatory the INGV branch in Catania and benefitting from the support of the technical activity related to the Mt. Etna supersite in the framework of the EPOS Italia Joint Research Unit activity.

9. Societal benefits

The main benefitting no-scientific stakeholders are the national and regional (Sicilian) departments of Civil Protections, which take advantage of the possibility of INGV to use the remote sensing data provided in the framework of the Supersite. Indeed, INGV is an official "Centre of Expertise" (Centro di Competenza) of the national Civil Protection system, which assignment is to scientifically support the National and Regional departments in disaster risk management activities. Such a benefit is proved by several contributions based on satellite data included in the periodic reports to and meetings with the Civil Protections departments provided by INGV.

10. Conclusive remarks and suggestions for improvement

During the 2022-2024 period of activity of the Mt. Etna Supersite, the main scientific achievements referred to the use of the EO data for investigating the dynamic of the volcano. This activity had also an important impact for the society, as these results have been exploited in the framework of surveillance activity for Civil Defence purposes. Furthermore, a few relevant scientific achievements resulted from some national or international projects that foresee Mt. Etna Supersite as a reference site for their activities.

We pursued the objective of the consolidation of the data infrastructure in the framework of the EPOS European infrastructure. The re-structuring of the data portal, still ongoing, is benefitting also from the contribution of the support of national and international projects (EPOS Italia JRU, e-SHAPE; IMPROVE; Geo INQUIRE; DT GEO; ATTEMPT, MEET).

The positive experience gained in promoting the Mt. Etna Supersite in the framework of national and international projects encourage continuing in this direction for the future activity of the Supersite.

Overall, the management of the Supersite is continuing along the strategic guidelines depicted in the previous biennial report, i.e., to strengthen the link with national and international initiatives aimed at implementing the system of the research infrastructures in Europe and worldwide, to attract research projects to use Mt. Etna Supersite data to carry out advanced researches, to expand toward research domains different from that of the study of the volcano internal dynamics and to foster access modalities different from those linked to the virtual access to the data sets.

11. Cited References

Ganci, G. et al., (2018). Mapping Volcanic Deposits of the 2011–2015 Etna Eruptive Events Using Satellite Remote Sensing, Front. Earth Sci., doi: 10.3389/feart.2018.00083

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