GNGTS 2024

SEISMICITY, VOLCANOES, DATA AND MODELS

Session 1.2

Volcanoes and geothermal fields

Convenors of the session:
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- Geophysical imaging
- Geochemical features
- Petrological data and analysis
- Field observations
- Remote sensing observation
- Geodetic data
- Hyperspectral imaging
- Volcanic unrest
- Effusive/explosive activity
- Models and inversion techniques
- Monitoring
- Hazard

Volcanoes and geothermal fields are the best-known natural expression of the Earth's internal heat, which is mainly caused by the radioactive decay of isotopes in the mantle and the crust. The volcanic activity has played a fundamental role in the Earth's atmosphere and life development and represents the most important source of geothermal energy. Most of our current knowledge about volcanoes and geothermal fields comes from geological, petrological, geochemical and geophysical data and observations mainly collected in the last decades. All these data, along with extensive analysis and modelling, have provided useful information about the structure and geometry of magma storage in the crust and transfer of magmas and geothermal fluids in volcanic or geothermal areas.

Contributes including both observational and theoretical studies as well as summarizing the state-of-the-art and new research directions are also welcome. Moreover, contributes focusing on the ongoing crisis at the Phlegraean Fields are of relevant interest.

An AI-based emulator to enhance SPH lava flows simulations

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Lava flows are complex fluids, exhibiting non-Newtonian rheology with temperature-dependent viscosity and phase transition, capable of overcoming barriers and forming channels and tunnels (Cordonnier et al., 2016). While lava flows are generally not hazardous to nearby populations due to their slow velocities, their passage through towns can cause complete destruction. Therefore, reliable predictions of the areas likely to be inundated by lava flows are of obvious interest to hazard managers during a volcanic eruption (Del Negro et al., 2020). The main factors that govern lava-flow length include the discharge rate of lava at its vent, the lava composition, eruption temperature, cooling rate and the ground topography over which the lava flows. As a result, numerical simulations that consider the key factors influencing the extent of lava flow propagation are crucial for forecasting effusive scenarios (Del Negro et al., 2016). Due to the complex physics of volcanic phenomena and the unique characteristics of lava, mathematical models can assist in simulating the evolution of lava, providing accurate predictions of the spatio-temporal dynamics of the fluid. These kinds of simulations constitute a challenge for Computational Fluid Dynamics (CFD) (Anderson and Wendt, 1992).

Smoothed Particle Hydrodynamics (SPH) (Monaghan, 2005) is a potent CFD method particularly suited for simulating lava flows (Zago et al., 2017, 2018). It is a Lagrangian mesh-free numerical method based on a discrete approximation of the Navier-Stokes equations. It is a particle-based method, where the fluid is discretized using particles, and it has the capability to handle specific fluid details, such as viscous and thermal effects. In addition, it is parallelizable and executable on Graphics Processing Units (GPU), thereby accelerating simulations. However, SPH simulations still require extended run times and substantial computational resources, typically taking weeks to obtain a few minutes of simulation. This poses challenges for achieving real-time applications, especially in the context of volcanic hazard monitoring. While speed-ups of the simulations can be achieved by simplifying the model or increasing computational resources, a simplified version of the model may not capture the complex physical dynamics present in real world applications.

These limitations can be addressed by introducing the use of Artificial Intelligence (AI) (Goodfellow et al. 2016, Bonaccorso, 2017) to reduce the required computation. The combination of CFD and AI allows for the enhancement of fluid modeling performance and the extension of functionalities (Bortnik and Camporeale, 2021). AI algorithms can be trained on SPH simulated data to rapidly learn the behavior of the CFD reference model. Models of this nature are referred to as emulators

(Kasim et al., 2021). Specifically, an emulator is a model where AI algorithms complement the equation-based mathematical representation of physics. The emulator learns from CFD simulations how to reproduce the CFD reference model, enabling the solution of fluid dynamics problems in shorter times (Zago et al., 2023, Amato, 2023). While Eulerian methods have been extensively integrated with AI, providing high-fidelity and reliable results (*e.g.,* DENSE for weather prediction (Kasim et al., 2021)); the combination of AI and Lagrangian methods remains less consolidated.

Here, we introduce an AI-based emulator designed for a SPH model. This emulator, based on an Artificial Neural Network (ANN), is trained using SPH simulations of complex fluids, including viscous and thermal components, such as lava. It successfully replicates the underlying physical laws and accurately predicts their spatio-temporal behavior. To ensure the trustworthiness of the emulator results, it is crucial to validate its prediction ability and assess its generalization capability beyond the conditions encountered during the training phase. To achieve this, we conducted validation using benchmark tests representative of lava flows, characterized by high viscosity and temperature-dependent viscosities. We also tested the emulator's capacity to reproduce problems and settings with varying levels of complexity. The emulator results were then compared with the corresponding SPH simulations, demonstrating the model's good performance and highlighting its reliability and generalizability.

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Imaging the North-South deformation through the application of potential theory to InSAR measurements

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Synthetic Aperture Radar Interferometry (InSAR) is a well-established technique for monitoring and modeling the ground deformation field in volcanic areas and geothermal fields. Specifically, when SAR images are acquired along both the ascending and descending satellites orbits, the retrieval of the East-West (E-W) and vertical components of the related three-dimensional (3D) ground deformation field is conceivable; the North-South (N-S) one is usually not available and different techniques have been proposed to solve this task. However, the resolutions and accuracies of these retrieved measurements are not always satisfactory.

Here, we show a new approach for the retrieval of the N-S component and the reconstruction of the 3D ground deformation field in volcanic frameworks. The proposed methodology is based on the theory of the potential functions and the integral transforms of potential fields. We test our workflow on synthetic deformation datasets computed according to the commonly used analytic volcanic deformation sources (i.e., Mogi's, Okada's and Yang's models). The results show that the proposed technique allows the retrieval of the N-S deformation with negligible errors with respect to the expected one.

We then consider this approach to reconstruct the 3D ground deformation field that occurred at Sierra Negra volcano (Galapagos Islands, Ecuador) during the 2017 – 2018.5 unrest, which has led to the eruption. The comparison with GNSS data shows that we are able to image the pre-eruptive N-S deformation for this volcano with a mean error of about 5%, which is a surprising result for this kind of application.

The next step of this study is the modeling of the volcanic deformation sources through the use of the retrieved 3D ground deformation field and showing the impact in the framework of the ambiguity solving.

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STUDY OF ETNA LAVA FLOW DYNAMICS USING SAR AND OPTICAL SATELLITE DATA AND APPLICABILITY OF THE APPROACH IN OTHER VOLCANIC SETTINGS

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Introduction

The study of lava flows, among the most relevant products of volcanic activity, is definitely a topic for further study, being one of the main causes of displacement of volcanic edifices and therefore a relevant phenomenon to be considered for the proper study of the hazard associated with volcanic activity.

In this work, aiming at the characterization of the dynamics of the Mt. Etna volcano (Southern Italy) lava flows emplaced during the last decade (Figure 1 – left panel), we adopted a multidisciplinary approach comprising the processing of optical and radar satellite data through different remote sensing techniques. Long stacks of Synthetic Aperture Radar (SAR) data, acquired during Sentinel-1 (S1) satellite mission, were processed with the Small Baseline Subset (SBAS) SAR Interferometry (InSAR) technique to study the ground displacements evolution before (January 2016 – December 2018) and after (January 2019 – July 2021) the 24 December 2018 eruption. The validation of the InSAR results was performed by comparing the displacement time series (DTS) with GNSS measurements at some continuous stations located on the Mt. Etna edifice (Figure 1 – left panel). Then, Sentinel-2 (S2) optical data allowed us to identify the lava flows boundaries emplaced during December 2018 and May 2019 paroxysms. The subtraction of Digital Elevation Models (DEMs), generated through the application of the stereo radargrammetry technique to high-resolution COSMO-SkyMed (CSK) data, permitted to estimate the topographic changes caused by the lava emplaced during the aforementioned events. Results allowed the establishment of the influence that the physical mechanisms have on the observed motion, suggesting that thermal contraction of the lava body, viscous compaction of the substrate, and downslope sliding induce significant volcanic ground displacements, acting in different time periods and topographic conditions.

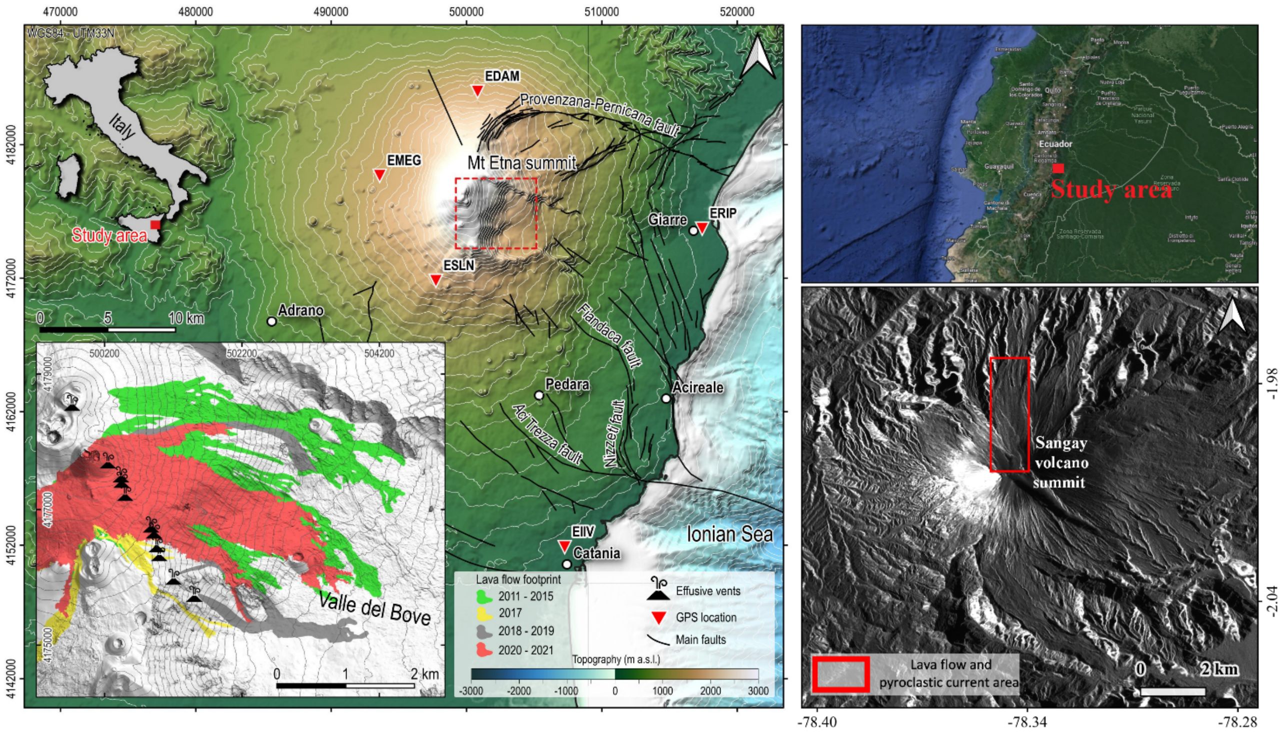

Figure 1 – The left panel shows the Etna volcano study area overview (from Beccaro et al., 2023). Black segments indicate the main tectonic structures, while the red triangles indicate the location of the selected GNSS stations used for InSAR results validation purposes. The dashed red rectangle delineates the study area zoomed in the inset panel where past (2011-2017) and recent (2018-2021) lava flow footprints are shown (data for the pre-2015 period are available from the Etna Observatory geoportal at http://geodb.ct.ingv.it/geoportale/; data for the 2017 and 2020-2021 period are available from Ganci et al. (2023) and De Beni et al. (2021)). The upper right panel shows the Sangay volcano study area location inside Ecuador country (from Google Maps), instead the lower right panel shows a Sentinel-1 amplitude image of the Sangay volcano with the area affected by the pyroclastic current and the lava flow emplaced at the end of 2021 (Hidalgo et al., 2022) and investigated in this work.

The applicability of the approach used for studying the dynamics of Etna lava flows was tested on an additional active andesitic stratovolcano, namely Sangay, located in Ecuador (Figure 1 – right panel). We applied the SBAS InSAR method to retrieve the ground displacements on the Sangay volcano from June 2021 to August 2023. Unfortunately, in this case, the lack of adequate (i.e., with low cloud cover) Sentinel-2 optical data and suitable (i.e., with sufficiently different angles of incidence) Cosmo-SkyMed data did not allow for delineating the boundaries of emplaced lava flow and generating DEMs to evaluate the lava body height. Therefore, aiming to correlate peculiar behaviors evidenced by the InSAR DTS with volcanic phenomena emitted during the investigated time period, i.e., lava flows and pyroclastic currents, we used a polarimetric change detection technique that exploits SAR data set collected before and after the event. Preliminary results made it possible to correlate the peculiar subsidence trend visible on the northern flank of the volcano with the pyroclastic current emitted on November 28, 2021.

Overview of the methods

Satellite Mission	Case Study	Methods	Time Interval	Products	Aim
Sentinel-1	Etna volcano	Small Baseline Subset InSAR approach	Before [Jan 2016 – Dec 2018] and after [Jan 2019 – Jul 2021] the 2018 eruption	Ground displacement maps & displacement time series	Displacements assessment on the entire volcano & displacements evolution study at the lava flows area
	Sangay volcano		Jun 2021 – Aug 2023		
		Polarimetric change detection approach	Before [Nov 2021] and after [Dec 2021] the eruption	Change detection map	Detection of lava flow and pyroclastic current phenomena
Cosmo-SkyMed	Etna volcano	Stereo radargrammetry technique	Before [Jun 2016] and after [Jul 2019] the 2018 eruption	Digital Elevation Models (DEM)	DEM difference analysis for estimating the topographic changes caused by the lava emplacement
Sentinel-2	Etna volcano	Visual inspection & reflectance analysis	December 2018 & May 2019	Lava flow boundaries vector files	Extension retrieval of the lava flows fields

Results

Figure 2 shows the main results obtained for the Etna case study. Displacement maps before the 24 December 2018 eruption (T1 period: January 2016 - December 2018) show general inflation reaching 7 cm/yr at summit areas. Eastward and westward movements are recorded along the eastern and western flanks, respectively. Instead, after the December event (T2 period: January 2019 - July 2021) we observe that the summit inflation decreases the spatial extent and localized patches of subsidence occur inside the Valle del Bove depression. Also, we note a seaward acceleration of the eastern flank confined to the main tectonic features. The Etna summit blow-up exposes in detail the Valle del Bove area which accommodated the lava flows studied here in detail through the DTS analysis and the resultant ground displacement vector computation. This latter at the 2018 - 2019 lava flow area shows a contractional behavior typical of the cooling of young lava flows, suggesting that the thermal lava contraction is the main deformation cause. Instead, the comparable amplitude of subsidence and eastward motion for the overlapping portion of 2011 - 2015 and August 2020 - July 2021 lava flows, suggests that the combined effect of old lavas load and recent lavas thermal cooling should be taken into account. Finally, DTS in the T1 period highlight clear uplift and eastward trends related to volcanic inflation, except for older lava flow where the global uplift is masked by subsidence related to the existing lava flows load on the substrate. DTS executed for the T2 period exhibit subsidence and eastward trends that accelerate after the emplacement of new lava flows. These trends contrast only with the cyclic vertical oscillations recorded outside lava fields, reflecting Etna's breathing process.

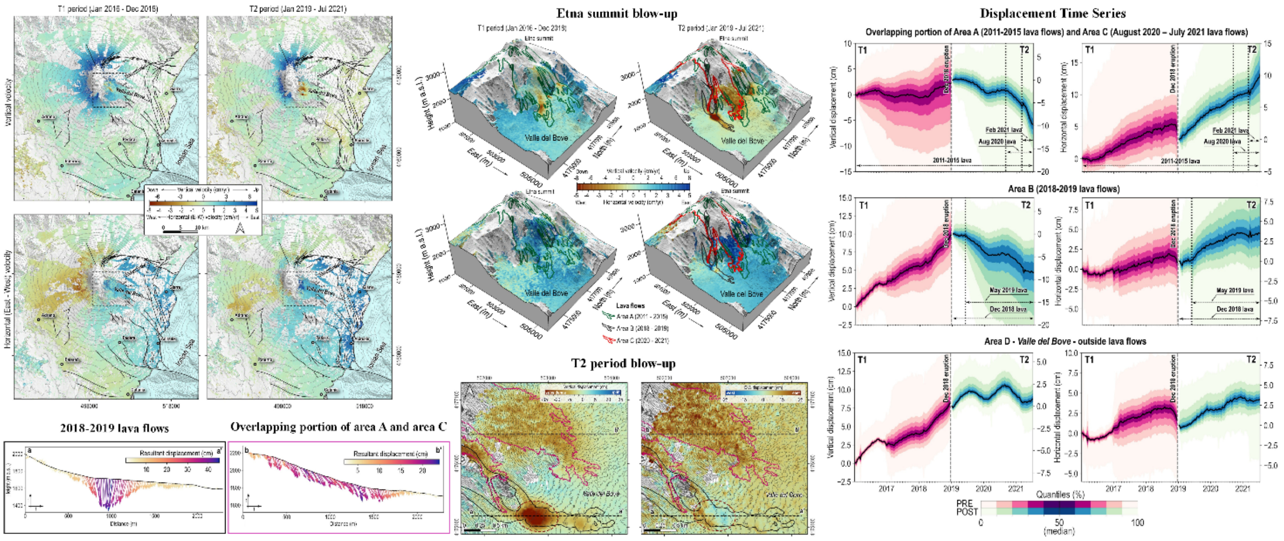

Figure 2 – Main outcomes for the Etna volcano area. From left to right: ground displacement maps, resultant ground displacement vectors for the indicated areas within the figure, and displacement time series.

Figure 3 shows the preliminary results of the Sangay volcano case study. Displacement maps show mainly westward and eastward directed movements of the western and eastern slopes, respectively. In addition, on the western flank of the volcano, clear inflation can be seen, which contrasts with the subsidence recorded on the northern and southeastern flanks. The time series performed along the N flank of the volcano, at the point indicated by the black triangle in the vertical displacement map visible in Figure 3, shows a clear subsidence since early December 2021. Using radar signal intensity variation analysis, it was possible to verify that the behavior can be associated with the cooling of the pyroclastic flow generated on November 28, 2021.

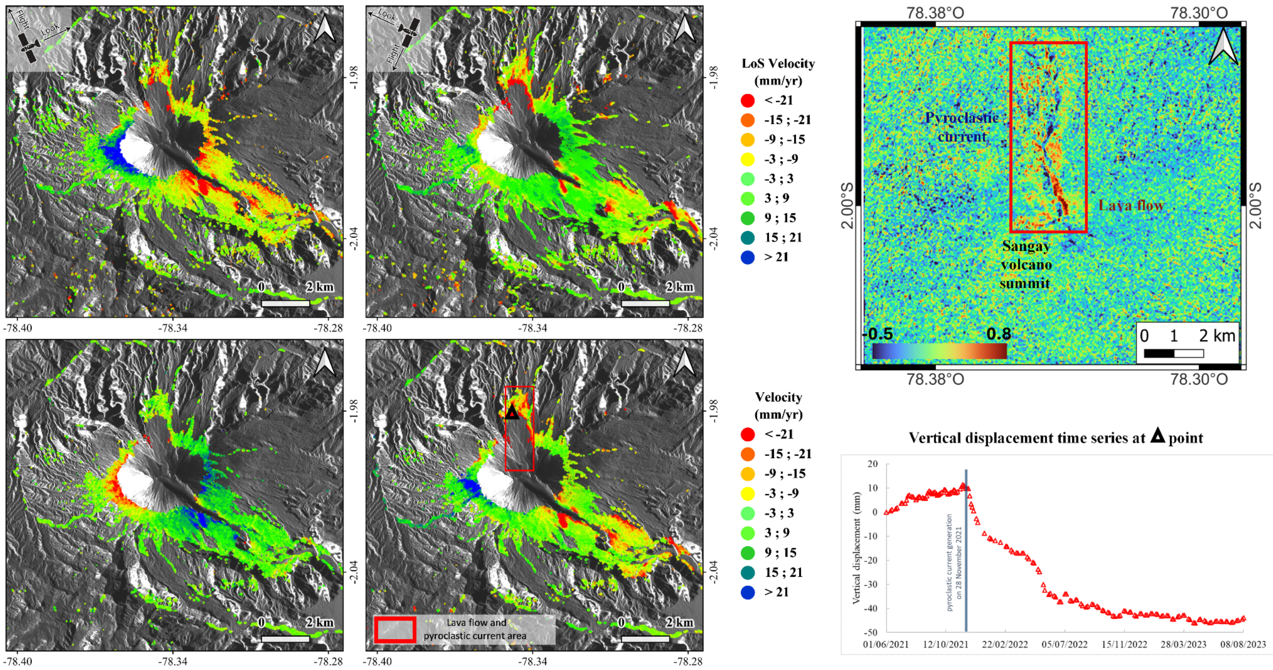

Figure 3 – Left panel: Ascending (upper left), descending (upper right), E-W (lower left) and vertical (lower right) ground displacement maps over Sangay volcano. In the upper right panel is visible the change detection map performed with S1 data acquired on 22 November and 4 December 2021, instead in the lower right panel the vertical displacement time series plotted at the black triangle can be appreciated.

Concluding remarks

Regarding Etna volcano, through InSAR methods we found out the presence of several subsidence areas that overlap with lava flow footprints identified by S2 and literature data. Horizontal displacements at lava flows are directed downslope on areas with high slope angles but directed upslope on areas characterized by low slope angles and larger lava thickness. Results also allowed us to establish the influence that the physical mechanisms have on the observed motion, suggesting that the main factors causing ground displacements are thermal contraction of the lava body and viscous compaction of the underlying substrate, the latter predominant for older lava flows. We tried to apply the same approach in the study of lava flows on Sangay volcano but, different climatic conditions and the inadequacy of some satellite datasets did not allow complete replicability. However, we were able to correlate the dynamics highlighted by the InSAR DTS analysis with the emplacement of a pyroclastic current in the N flank of Sangay at the end of November 2021 by using a polarimetric change detection approach that allows emphasizing changes due to the volcanic eruption.

As future developments, we plan to analyze in detail the displacement patterns measured by InSAR methods to relate them to other volcanic phenomena (e.g., inflation, lava flows, pyroclastic currents) by exploiting polarimetric change detection radar approach and also numerical modeling methods.

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ACU – Sviluppo di una rete prototipale per lo studio delle emissioni acustiche associate ai micro-processi dislocativi

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The main objective of the project ACU is to develop a prototypical network of infrasound sensors, for use on a national scale, dedicated to the monitoring of acoustic waves propagating in the atmosphere in the same frequency range as seismic waves. The range of applications to be covered by this new facility range from volcanic monitoring, detection of anthropogenic events and earthquake rumbles, as well as monitoring of other natural phenomena, like avalanches, landslides or rock falls.

Coupling of acoustic waves into the ground has been first noted on active volcanoes around the world, like e.g., Mt. S. Helens (Kieffer, 1981), Pavlov volcano (Mc Nutt, 1986; Garces et al., 2000); the identification of air-waves even in seismograms from moderate explosion-quakes and volcanic tremor was first reported by (Braun & Ripepe, 1993, Kedar et al., 1996; Ripepe et al., 1996; Hagerty et al., 2000).

The project is divided in the following steps:

- Development of an acoustic wave generator for calibration of the available sensors.
- Comparison and calibration of commercial infrasound sensors.
- Cost-benefit analysis
- Installation of an infrasonic array equipped with high-quality infrasound sensors for the detection and directional analysis of the recorded acoustic waves.
- Preparation of a portable infrasound network, to be deployed in the epicentral area in case of significant seismic events.
- Development and/or individuation of a low-cost sensor for a future widespread equipment of seismic and volcano-seismic networks by infrasound sensors.
- Test measurements in the ultrasonic range (> 20 kHz) inside the National Gran Sasso Laboratory (acoustic emission).

The INGV-laboratory has developed an electro-mechanical device based on a subwoofer, which can be used both as a sensor and as a source for calibration. In a passive "sensor"-mode the pressure acting on the membrane regulates the current inside the subwoofer's voice-coil, while in an active "calibration"-mode a waveform generator steers the oscillation of the subwoofer's membrane, whose amplitude is then controlled by a LVDT-interface. The pressure variations are then channelized through a hose directly to the sensor input pressure interface. As the desired frequency range is the same as for seismic stations, infrasound signals are recorded by commercial seismic digitizers, as e.g., Nanometrics CENTAUR, Cube or GAIA.

The presentation gives an update of the work in progress and will outline future perspectives.

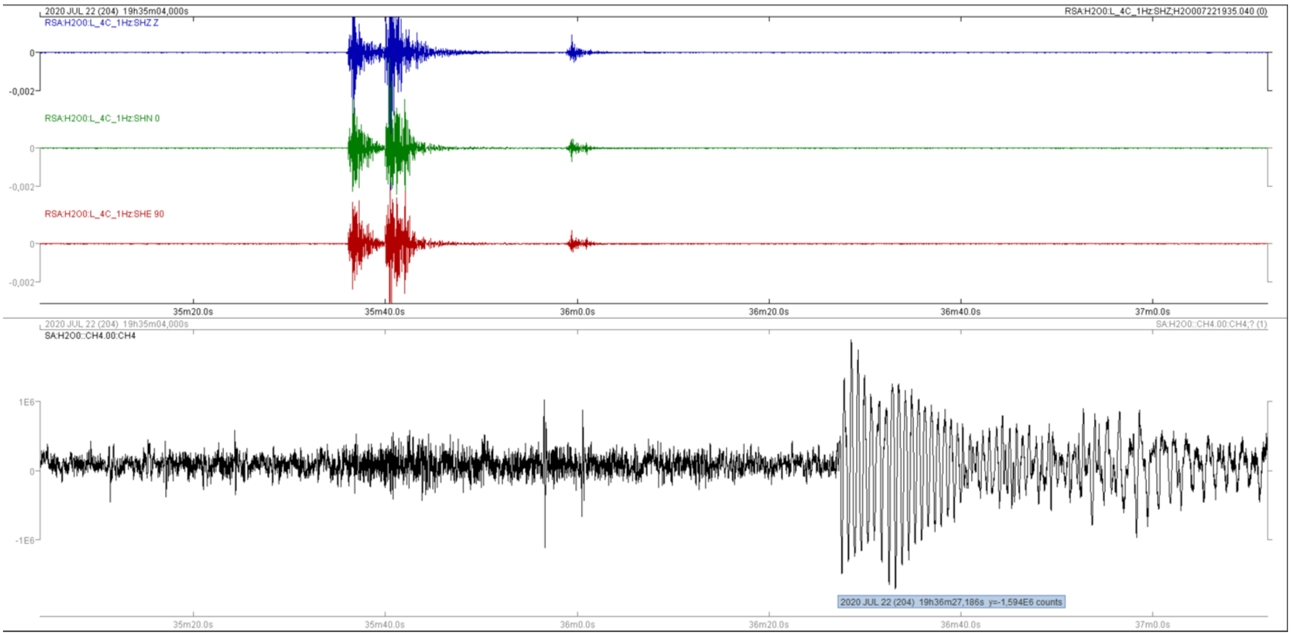

Fig. 1 – Example of an earthquake and rumble located on 22/07/2020 at 19:36 in the area of Montecassino (FR). Note the occurrence of three small seismic events (coloured traces) prior to the infrasound signal (black).

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HVSR analysis to investigate a possible correlation to a gas shallow reservoir in a mud volcanic field: the case of Nirano (MO)

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Multiple studies highlight the evidence of a trough within the low-frequency range in HVSRs measurements performed over a gas field and attribute it to the presence of a hydrocarbon reservoir (Lambert et al., 2007; Saenger et al., 2007; Panzera et al., 2016; Antunes et al., 2022). To explain the natural emission of low-frequency signals Saenger et al. (2007) and Lambert et al. (2007) consider hydrocarbon-reservoir related microtremor, assuming that the reservoir itself acts as a (secondary) source of low-frequency seismic waves by a resonant amplification effect. Furthermore, Panzera et al. (2016) observe that the minimum is identified by an "inverse eye-shaped" feature in the Fourier spectra, related to an amplitude increase in the vertical component of motion due to a velocity inversion. This study focuses on the investigation of the spectral anomaly described above at Nirano mud volcano field, conducted through the analysis of the results obtained by seismic arrays and three directional velocimetric stations (HVSR) deployed in the site. After a cluster analysis carried out on HVSRs have been identified 3 groups of measurements, one of which include HVSRs located in the caldera-like basin area, marked by a minimum in the seismic spectrum at 0.53 Hz. The joint inversion procedure based on Genetic Algorithms of the HVSR curves and the Rayleigh waves dispersion curve shows that the minimum is well reproduced even without a velocity inversion. This proves that it is not uniquely correlated to the mechanisms proposed above and that, therefore, it may be linked to a stratigraphic effect that unites all the measurements concentrated in the group under examination or to the surface wave model used.

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Seismic monitoring of gas emissions at mud volcanoes: the case of Nirano (northern Italy)

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The Salse di Nirano site is a Natural Reserve in Italy distinguished by the presence of mud volcanic phenomena that have manifested in the formation of four main volcanic vents situated within its central part close to pools filled by low viscosity mud. The mud volcanoes of Nirano are relatively small, reaching a maximum of three meters height and exhibit minimal volcanic activity with weak, persistent surface degassing.

Seismic monitoring was conducted at the Nirano Mud Volcanoes during two distinct field campaigns in April 2021 and July 2023, with the aim of exploring the subsurface structure and the dynamics of the volcano. The seismic survey campaigns involved deploying small 'L-shape' seismic arrays composed of vertical geophones and three-directional sensors. Both active and passive seismic acquisition methods were also employed to characterize the first subsoil, focusing on shear wave velocity profiles.

During the recordings, a peculiar seismic pattern emerged, characterized by sequences of short impulsive events (0.1-0.2s) occurring at regular and irregular time intervals. These transient events, commonly referred to as 'drumbeats' by various authors (*Iverson et al., 2006*; *Lupi et al., 2016*), exhibit a spectral structure dominated by frequencies ranging between 10 and 30 Hz and by the presence of subsequent sharp peaks, for which a realistic explanation has been provided in this study.

A rapid automatic location procedure was deployed to identify seismic sources corresponding to these impulsive events, assuming a straight ray path from source to receiver. Approximately 5000 sources were identified over the 7-hour recording period (seven asynchronous arrays recording for one hour each) within a search area of few hundred meters. Most of the sources have been localized at shallow depths (<10m) with a minor contribution of deeper events (within few tens of meters from the surface).

The propagation velocities derived from the location procedure, coupled with the results of the conducted polarization analysis, suggest shear waves are responsible for most of the energy transmitted by these seismic signals.

Considering these findings, an interpretative source model for the recorded seismic pattern was attempted. This model proposes a stick-slip mechanism as the origin of the impulsive signals, due to the interaction between exsolved gas bubbles, mud plugs, and the vent walls.

Upon establishing a source model and proposing a dynamic relation between gas emission and seismic signals, an effort was made to provide an indirect estimate of the surface gas outflow. The outcomes of this analysis are in line with direct measurements of the average gas outflow (CO^2 and CH^4) conducted in the investigated area by other Authors (*Sciarra et al., 2019*).

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Unveiling hidden volcano dynamics with Artificial Intelligence (AI) and Earth Observation (EO)

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Volcano hazard monitoring is essential for understanding the behavior of rapidly changing volcanoes and, consequently, for better forecasting volcanic hazards and related impacts. From this perspective, several satellite sensors are now available, providing thermal infrared data at various spatial resolutions and revisit times. Additionally, future satellite missions are being planned to maintain a near-constant "eye" on thermal volcanic activity across the planet. This huge volume of data necessitates the development of Artificial Intelligence (AI) tools to automatically extract relevant information on the volcano's state in a short time. Recently, we demonstrated the potential of a cascading pipeline for classifying high-temperature volcanic features and quantifying the spatial extension of thermal anomalies in high-resolution satellite data (Sentinel-2 MultiSpectral Instrument, S2-MSI). The ability to combine two separate machine learning models —a scene classifier and a pixel-based segmentation model (Corradino et al., 2022) —into a "top-down" cascading architecture makes this method highly effective, achieving an accuracy of 95%. These findings illustrate how the cascading technique can be used to fully characterize any accessible satellite image in almost real-time, offering valuable assistance in the mapping, monitoring, and characterization of volcanic thermal features. The model's high level of accuracy enables us to detect thermal signals that are often challenging to pick up with current detectors. Indeed, the thermal increase produced by intracrater activity during unrest phases provides valuable data for understanding volcanic phenomena, allowing the development of more accurate predictive models and a better understanding of the internal dynamics of volcanoes. While these thermal detections have already served as possible precursory signals for specific volcanoes, a comprehensive field investigation of such changes has not been conducted yet.

In this study, we aim to examine the thermal changes captured by satellite data on Etna and Stromboli, two of the most active and monitored volcanoes in the Mediterranean region. The objective is to identify and assess significant changes in thermal anomalies during periods of unrest, utilizing the outcomes generated by the cascading model.

Over the last two decades, the eruptive activity of Etna has been characterized by persistent degassing and a frequent intertwining of explosive and effusive eruptions from its four summit craters. Identifying the active craters and quantifying intra-crater budget emissions in terms of the areal coverage of thermal anomalies can unveil interesting scenarios associated with the volcano’s dynamics. Using Google Earth Engine (GEE), we outlined each crater region and computed the contribution of each crater to the overall detected thermal anomalies; a circular area around each crater is considered, namely South-East (SE), North-East (NE), Bocca Nuova (BN) and Voragine (VOR). A period of intense eruptive activity began on December 14, 2020, with the first of 66 paroxysms producing several lava flows (Amato et. al., 2022), with the maximum area quantified being 1,800,000 m2 on 18 December. It is noteworthy that all the craters show consistent increases in the areal coverage of thermal anomalies before the first paroxysm (see Fig. 1), with NE and SE (see Fig. 2a-b) starting in June 2020. Lately, since June 2022, the most active crater has been BN. One of the most recent paroxysm events occurred on November 12, 2023, and was preceded by a net increase in thermal anomalies since October 16, 2023, when SE crater became active.

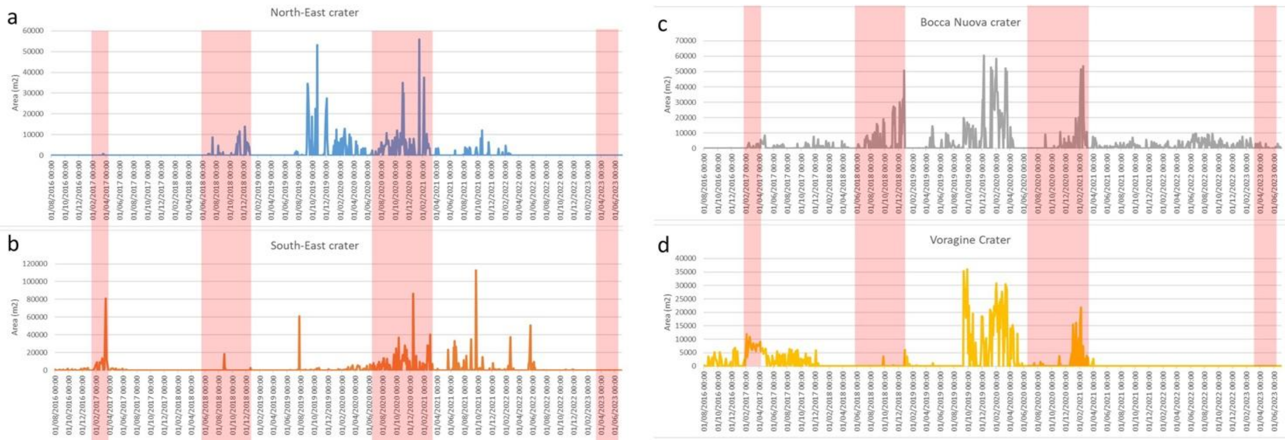

Fig. 1

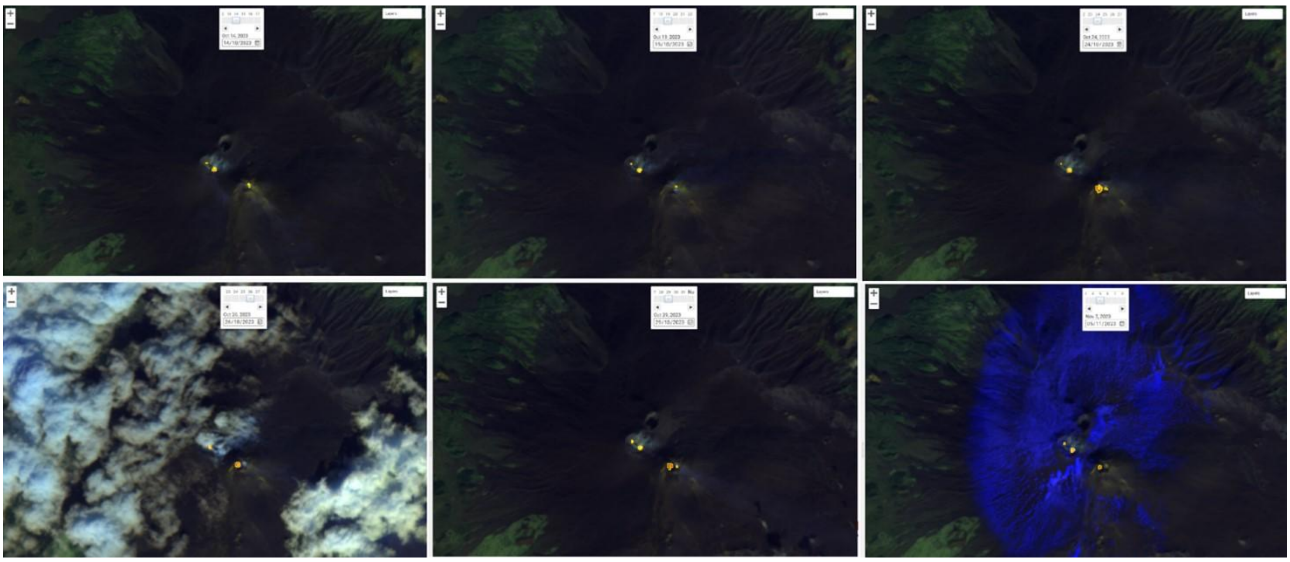

Fig. 2

Stromboli is characterized by persistent explosive activity that can sometimes escalate into more intense events, producing major explosions or paroxysmal events (Calvari et al., 2022, Giudicepietro et al., 2022). These events may lead to lava flows, as seen in October 2023 when a new eruptive activity commenced (Fig. 3). This activity was preceded by a steep increase in the areal coverage of the thermal emissions starting from September 9, 2023, probably due to shallow magma dynamics. The first emplaced lava flow was identified by the cascading algorithm on October 4, 2023, estimating a hot area of about 55,000 m2.

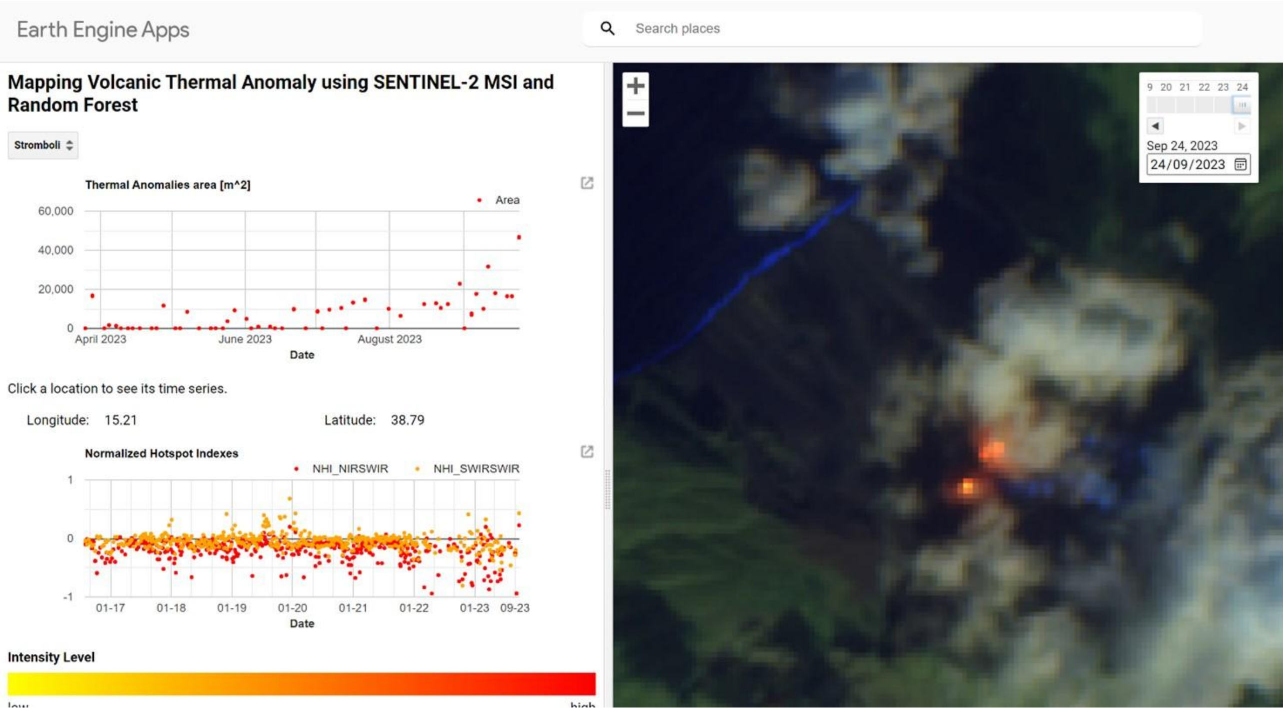

Fig. 3

In conclusion, identifying hidden growth trends within thermal data can be challenging, especially when it comes to identifying small, ever-increasing abnormalities that could be indicative of an imminent eruption. Therefore, the analysis of satellite thermal data, employing accurate AI detection techniques, is crucial for detecting significant thermal changes leading up to volcanic eruptive phenomena.

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Dike-arrest vs dike-propagation: new insights from the Younger Stampar eruption (13th Century), SW Iceland

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Unravelling the parameters that control dike arrest and dike propagation in the shallow crust, and subsequently the associated dike-induced deformation at the surface, is of paramount importance in volcanology. This is because dikes can select among many different paths towards the surface and either stall in the crust or, alternatively, feed volcanic eruptions.

In this work, we study two vertical dikes exposed in the sea-cliffs of the Reykjanes Peninsula (SW Iceland). Both dikes are associated with the Younger Stampar eruption (1210-1240 CE) and were emplaced in the same crustal segment, which includes lava flows and tuff layers. Although one of them fed a lava flow at the surface, the other dike, located at a distance of 30 m from the feeder, became arrested only 5 m below the surface of the active rift zone without inducing any brittle deformation. Hence, this outcrop represents an ideal case study to investigate the factors that favor dike arrest versus dike propagation, as well as the conditions that affect dike-induced brittle deformation.

We collected detailed structural data on the dikes and identified the stratigraphic sequence of the outcrop. We mapped the nearby crater rows of the Stampar eruptions and reconstructed a high-resolution 3D model through drone images and Structure from Motion (SfM) techniques. These data became inputs for 2D Finite Element Method (FEM) numerical models, using the COMSOL Multiphysics® software (v5.6), to explain mechanically the dike arrest and why there is no brittle deformation at the surface induced by the arrested dike. We tested the role of dike overpressure (P_o = 2-4 MPa), the stiffness (Young's modulus) of the layers, and the presence of an extensional or a compressional tectonic stress field.

Our structural data show that the strike of the Younger Stampar crater row is consistent with the strike of nearby historic and prehistoric eruptive fissures, as well as the orientation of the volcanic systems of the Reykjanes Peninsula. Our numerical models indicate that dike-induced compressive stress (caused by the earlier feeder dike), together with the contrasting stiffness of the layers, can explain the arrest of the later dike and the lack of brittle deformation at the surface. Specifically, the presence of a stiff lava flow on top of a soft tuff concentrated the feeder dike-induced compressive stress in the lava flow, favoring dike arrest at the tuff-lava contact. These results have implications for hazard studies in other volcanic areas, particularly as regards dike arrest at shallow depths, in Iceland and worldwide.

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PROMUD Project – multidisciplinary monitoring of Mud Volcanoes

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Mud or sedimentary volcanoes are geological structures built by the ejection of overpressured multiphase pore fluids, mainly composed of cold gases (principally methane), liquid hydrocarbons and high salinity waters, that episodically drag sediments and rock clast at surface. The fluids ascend along lithological or structural discontinuities, such as faults and fractures, or across permeable rocks. The cyclically alternation of eruptive activity and dormancy determines seepage features, i.e. mud cones, gryphons, pools and salsa lakes. Beyond their importance in the monitoring of global warming being the second natural methane source (Mazzini et al., 2021; Etiope et al., 2019), mud volcanoes (MVs) can be a serious source for Geohazard. Sometimes MVs generate paroxysmal events, during which gas blasts and sudden expulsion, fallout and flooding of large amounts of mud can damage facilities and severely hurt persons in their proximity. During the paroxysm occurred at the Maccalube di Aragona (Sicily) in 2014 two children died. However, a monitoring protocols for MV surveillance have never been implemented.

MV monitoring to identify the triggering processes of paroxysms so far carried out is mainly based on the interplay with large earthquakes or hydrocarbon exploration drillings. Anyway a unanimous conclusion has not been reached yet. Other factors, such as the influence of regional tectonic stress, hydrological cycle or periodic inflation-deflation cycles at the crustal scale, as those driven by Earth tides, have been poorly investigated, as well as the MV buried structure. PROMUD project (https://progetti.ingv.it/it/promud) aims to fill these knowledge gaps through a multidisciplinary approach, whose ultimate goal is to intercept reliable precursors and to individuate activity state indicators of the evolution towards a paroxysm.

The Project

PROMUD (“definition of a multidisciplinary monitoring PROtocol for MUD volcanoes”) is a 3-years (2023-2025) INGV project integrating geophysical (seismic, magnetic, geoelectric, environmental radioactivity), geodetic (GNSS and tilt), bio-geochemical (characterization of emitted fluids and vegetation analysis), topographic and geomorphological data, acquired by both permanent networks and spot field surveys.

The research is being carried out by 5 Working Packages (WPs), with their own specific objectives, that interplay and integrate with each other (Fig. 1).

WP1 - *Seismology, Tectonics, Tilt, hydrology and vegetation analysis*, deals with: the analysis of the background seismic noise wavefield and its role in the identification and monitoring of degassing sources and conduits; the response of the MV system to regional earthquakes; the possible link with the regional tectonic structures; the tiltmetric observations and their role in monitoring the MV activity; the hydrological regime and its influence on MV activity; evaluation of river network evolution as a consequence of MV activity; the vegetation pattern definition as a marker of MV evolution in space and time and radio nuclides emissions by soil.

WP2 - *Remote Sensing and Topography*, performs remote sensing for terrain and surface modelling aimed to identify morphological variations by compare multi-temporal models, searching for deformation patterns related to changes in styles, amplitude and rates of MV activity. The WP integrates data from surface variations by levelling and GNSS to estimate volume changes. The group intends to produce first images of a paroxysm, to identify inflation/deflation cycles as proxies of MV activity state. Moreover, the WP is carrying out a research of historical documents and testimonies, to assist the understanding of phenomena.

WP3 - *Geochemistry, Stratigraphy and Rock Magnetism*, foresees to characterize the fluid source by measuring the changes in flux/composition of emitted fluids as a proxy of MV activity state, to produce continuous visible video imagery of MV activity. Micropaleontological and stratigraphic study for depth determination of the mud source and investigations on active microbiological communities thriving within the erupted mud and around the seepage sites are in progress. Finally, the WP is performing a study of the magnetic properties of the mud collected in proximity of pools and cones and of the rocks outcropping nearby and recording the changes over time in the concentration, mineralogy and coercivity of the magnetic minerals.

WP4 – *Geophysics*, is carrying out several resistivity and magnetic anomaly surveys, for the definition of the subsoil configuration geometry by detecting eventual magnetic and electrical conductivity properties of the MV system.

WP5 - *Scientific Outreach*, manages the Website of the project, produces multimedia material (pictures and videos) and is in charge of the risk education activities in primary and secondary schools.

Study areas

We selected two main study sites, the Salse di Nirano (Northern Apennines, Fig. 2B) and the Maccalube di Aragona (Sicily, Fig. 2C). Both the areas are Nature Reserves: Comune di Fiorano Modenese and Ente Parchi dell'Emilia Centrale of Emilia Romagna Region and Legambiente, on behalf of the Sicilian Regional Government, respectively.

Final remarks

Many visitors closely approaching the active mud vents inside the two Natural Reserves and, therefore, to define a monitoring protocol for the mitigation of the risk related to possible paroxystic events, is imperative. For these reasons, the main stakeholders are the organizations that manage the two Reserves, which both are already providing their logistic support to this project and represent the end users of its outcomes.

In summary, PROMUD project has a two-fold challenge, that is to retrieve a model of the spatial and temporal evolution of MV systems from the multidisciplinary observations and the attempt of unravelling the transition from the background state to the paroxysm generation.

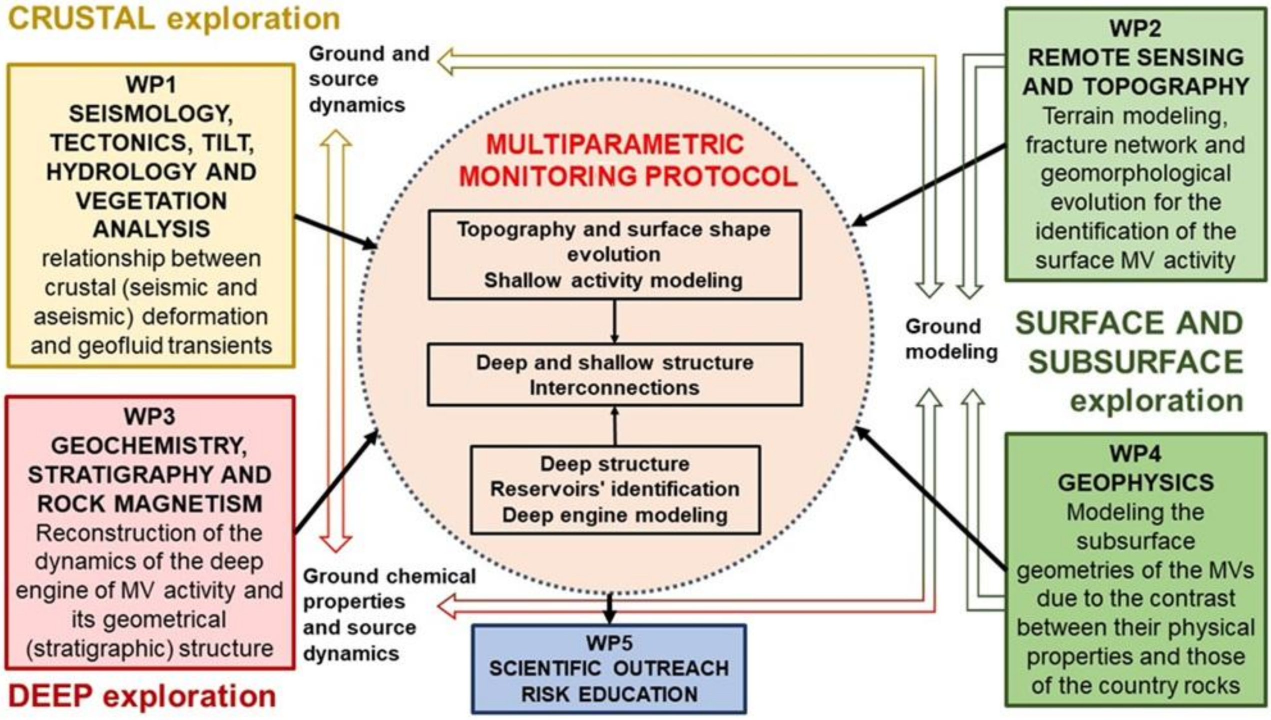

Fig. 1 – PROMUD conceptual scheme to illustrate how the project intends to achieve a significant improvement in the comprehensive knowledge of MVs deep engine and the interconnections with its activity at surface, and to define a correct and efficient multidisciplinary environmental monitoring directed to preserve human life and ecosystem by using this knowledge.

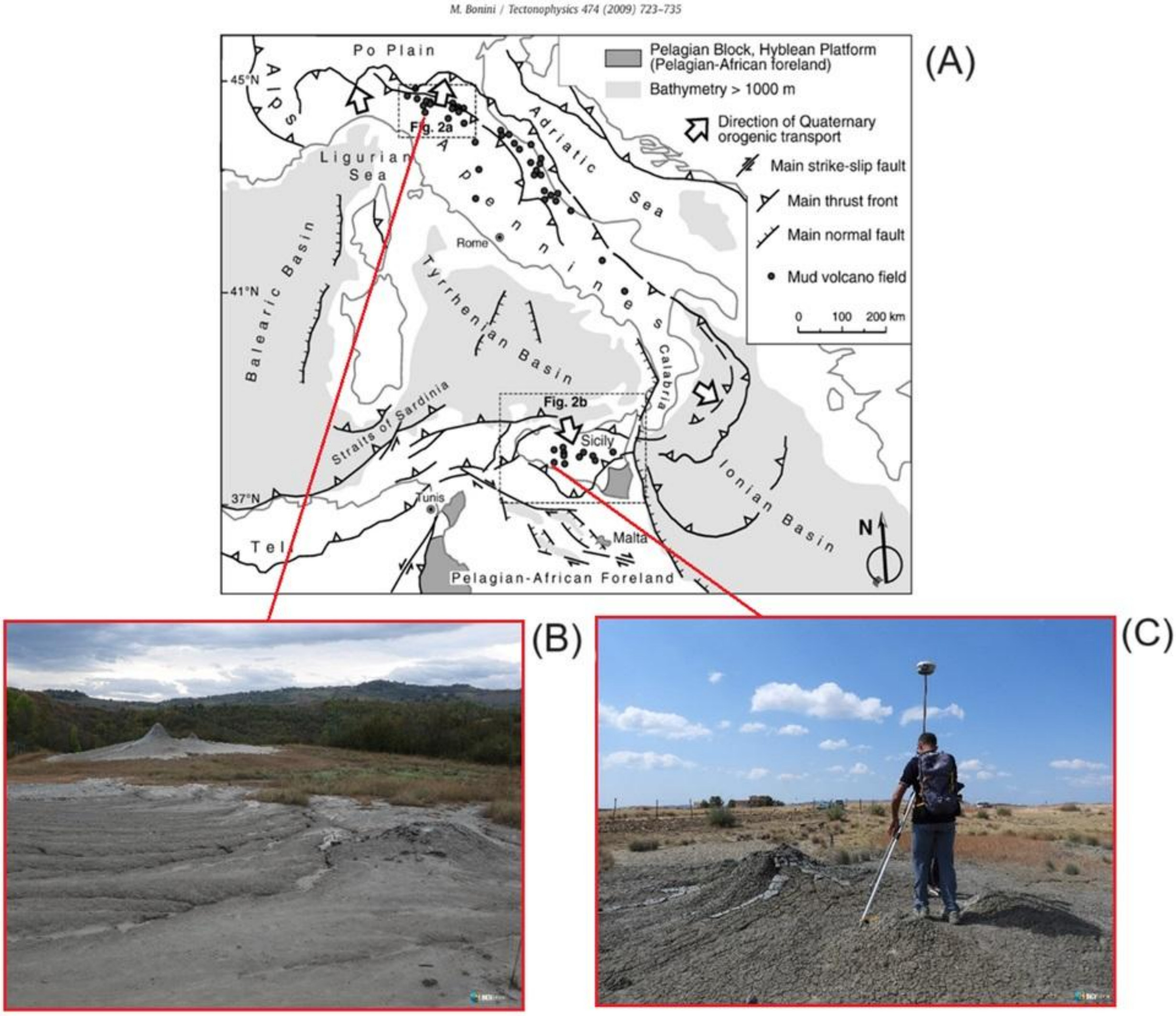

Fig. 2 – (A) Location of Mud volcanoes on the Italian territory (after Bonini, 2009). (B) Salse di Nirano (MO) and (C) Maccalube d'Aragona (AG) sites. Both the pictures were taken by the project staff (WP5 – Scientific outreach).

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Statistical analysis of the seismicity of the last 30 years at Mt. Somma-Vesuvius

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The last eruption of Mt. Somma-Vesuvius occurred in 1944, and since then has been quiescent showing only fumarole activity and moderate seismicity. The Md=3.6 event recorded on 09/10/1999 is the strongest record in the last 30 years.

Here we present an updated statistical analysis of the seismicity by analysing the three main seismic catalogues constantly filled in by INGV – Osservatorio Vesuviano:

- The catalogue of detected events at station OVO which starts in 1972 and counts 11783 earthquakes with duration magnitudes ranging from -1.5 to 3.6.
- The catalogue of detected events at station BKE which starts in 1998 and counts 20196 events.
- The catalogue of located events which starts in 1998 and counts 8558 events. Magnitudes of events in this and BKE catalogues range from -2.5 to 3.6.

The completeness magnitude computed for the OVO catalogue is Mc=1.9 and the b-value ranges between 1.0 and 2.5. The higher values correspond to the period 1980-1985, successively the b-value decreased to about 1.0 until the early 2000's. More recently, the b-value for the OVO catalogue slowly but steadily increased again to about 2.0 (~2014-2016), decreasing to 1.8 at present time. The annual occurrence rate is currently much lower than before 2000 (with a maximum of almost 700 events/year in 1999 when the Md=3.6 was recorded) and is generally lower than 100 events/year.

The analysis of the BKE catalogue gives an overall completeness magnitude of Mc=0.5 and a b-value in the range 0.8-1.2 in recent years. The annual seismicity rate, which reached values of 2000 events/year during 1999, decreased to less than 500 events/year in 2004. In successive years, seismicity grew up to about 750 and 1000 events/year in the period 2007-2010 and 2018-2022, respectively. However, the Gutenberg-Richter distribution shows a knee around Md=2.1. Our analysis, in agreement with previous results (D'Auria et al., 2013), suggests that at least two populations of earthquakes coexist in the BKE catalogue. This characteristic is mainly visible in the data before 2015, whereas it does not show up in more recent records. The two populations were analysed separately and gave values close to b=1 and b=1.7.

The main characteristic of the catalogue of located events is a significant variation in completeness magnitude with time, with completeness magnitude abruptly lowering during 2015 from about

Mc=1.5 to Mc=0.5-0.2. Our analysis shows how this dramatic change is produced by the improvement of the seismic network monitoring the volcano and by the increased sensitivity of the network. The annual rate of located events, in the order of hundreds per year in 1999/2000, dropped down to less than 100 events/year during the period 2001-2014. Since 2015, almost 1000 events/year have been recorded and located.

The GR analysis shows similar result with respect to the BKE catalogue, suggesting the presence of at least two populations of earthquakes also in the catalogue of located events. The first population is associated with earthquakes located within the cone of the volcano, above the sea level, whereas earthquakes belonging to the second class are located at greater depths well below the edifice.

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Trans-dimensional Mt. Etna P-wave anisotropic imaging

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Trans-dimensional inference identifies a class of methods for inverse problems where the number of free parameters is not fixed. In seismic imaging these methods are applied to let the data, and any prior information, decide the complexity of the models and how the inferred fields partition the inversion domains. Monte Carlo trans-dimensional inference is performed implementing the reversible-jump Markov chain Monte Carlo (rjMcMC) algorithm; the nature of Monte Carlo exploration allows the algorithm to be completely non-linear, to explore multiple possibilities among models with different dimensions and meshes and to extensively investigate the under-determined nature of the tomographic problems, showing quantitative evidence for the limitations in the data-sets used. Implementations of this method overcome the main limitations of traditional linearized solvers: the arbitrariness in the selection of the regularization parameters, the linearized iterative approach and in general the collapse of the information behind the solution into a unique inferred model.

We present applications of the rjMcMC algorithm to anisotropic seismic imaging of Mt. Etna with P-waves. Mt. Etna is one of the most active and monitored volcanoes in the world, typically investigated under the assumption of isotropic seismic speeds. However, since body waves manifest strong sensitivity to seismic anisotropy, we parametrize a multi-fields inversion to account for the directional dependence in the seismic velocities. Anisotropy increases the ill-condition of the tomographic problem and the consequences of the under-determination become more relevant. When multiple seismic fields are investigated, such as seismic speeds and anisotropy, the data-sets used may not be able to independently resolve them, resulting in non-independent estimates and corresponding trade-offs. Monte Carlo exploration allows for the evaluation of the robustness of seismic anomalies and anisotropic patterns, as well as the trade-offs between isotropic and anisotropic perturbations, key features for the interpretation of tomographic models in volcanic environments. The approach is completely non-linear, free of any explicit regularization and it keeps the computational time feasible, even for large data-sets.

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The state of art of the temperature monitoring network on La Fossa cone (Aeolian Islands, Italy)

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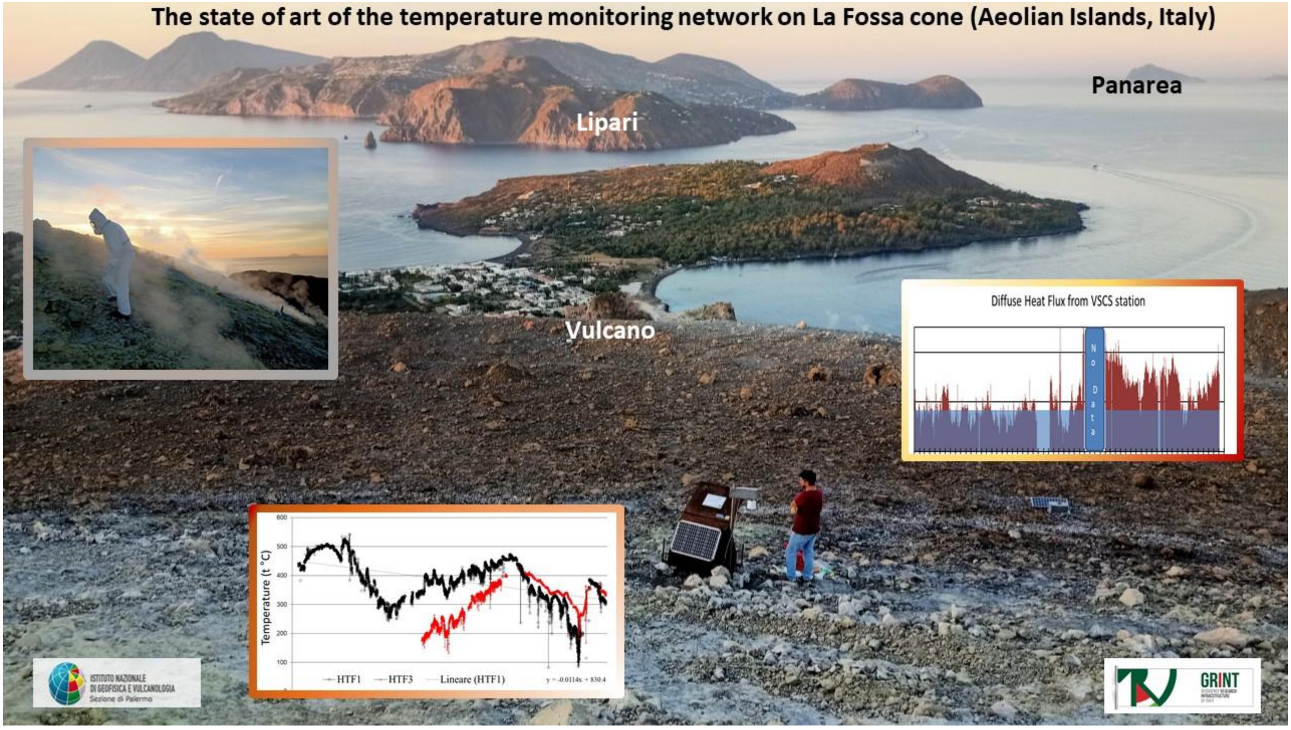

We present the long-term monitoring data, hourly recorded in the high temperature fumaroles (HTF) on the summit of La Fossa Cone, a close conduit volcano on the Island of Vulcano, and describe the actual implementation of the monitoring network. Its last eruption dates back to 1890. The thermal monitoring of the fumaroles output was included in the framework of geochemical monitoring activity in 1984 (Inguaggiato et al., 2018), the longest and uniform time series of data started in 1990 (fig 1) and is still uninterrupted. During 33 years the HTF temperature has been showing a general decreasing trend, some cyclic modulations (with the major periodical variation of about 20 years), with superimposed peaking variations (Diliberto, 2013). The peaking variations are correlated to unrest periods. The maximum temperatures recorded by the monitoring network ranged from 250 to 540 °C (Diliberto 2017). In 2023, this network has been implemented, and the number of monitored fumaroles increased to six high temperature vents (Fig. 2, HTF 1-6). Moreover, beside the HTF we started monitoring the temperature of the ground in two diffuse degassing zones (Fig. 2, T gradient). The new HTF sites are located within two radial fractures elongated in the outer flank of the northern slope, with the outlet temperature reaching 320 °C, at the time of installation (December 2023). In the zones of diffuse degassing we have choosen two monitoring sites in a ground section of pyroclastic breccia (Fig. 2, T gradient), where we buried four sensors, at different depths. These diffuse degassing zones (DDZ) generally show at the surface a mild thermal anomaly because the ground is heated by the massive condensation of steam at shallow depth (a few meters below the line of sensors). At the time of installation of the monitoring profile (VSCS in …, G-Termis in November 2023, Fig. 2) the ground was permeable and dry, with temperature increasing at depth. In the DDZ, in the absence of water and steam, heat transfer is essentially diffusive and the convective component is negligible. In this dry condition, the temperature gradient is a proxy of the surface heat flux, being the only variable directly related to it. Moreover, the extrapolation of temperature gradient to the boiling temperature suggests a reference level for the minimum depth where the rising steam condenses within the ground. So, the continuous monitoring of the temperature gradient allows to track the local changes in heat flux and the vertical movements of the steam front in the summit area, at distance from the HTF zone. The G-Termis station is located about 190 m (linear distance) to the east of HTF zone, whereas the VSCS station is located about 210 m to the west of HTF zone (Fig. 2).

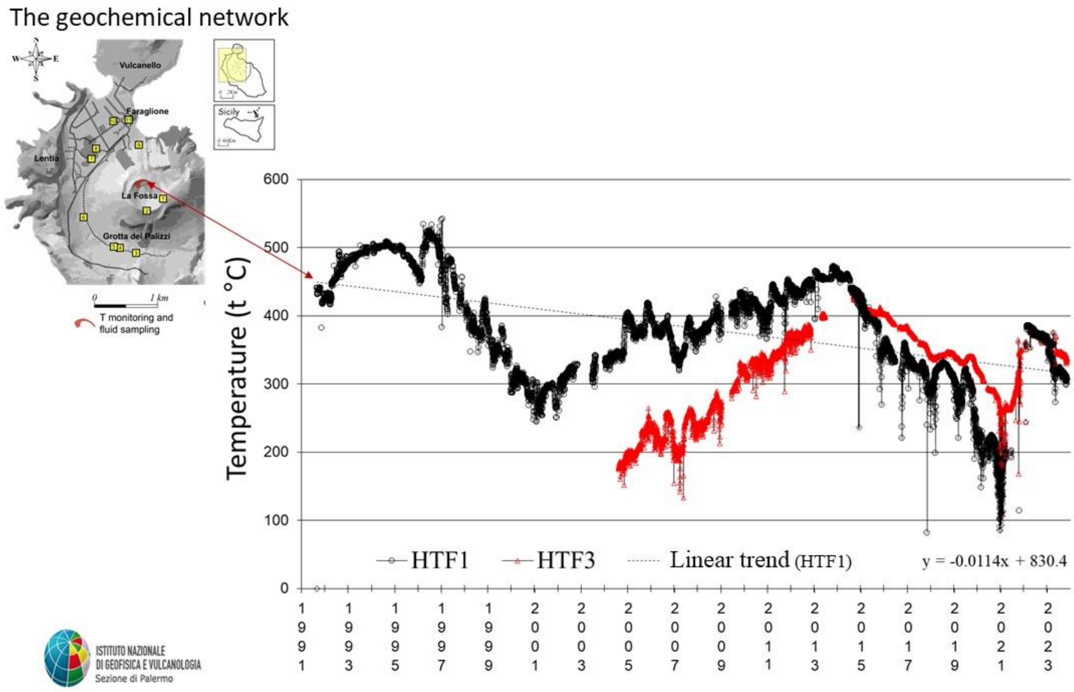

Fig. 1 – The longest time series of fumarole temperature recorded at La Fossa crater. The map showing the geochemical network is on the left corner.

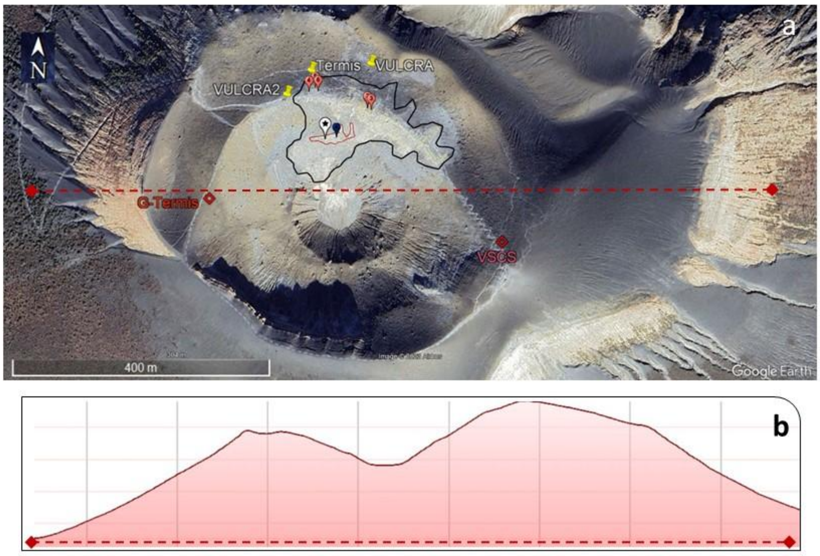

Fig. 2 – a) Google Image of summit area of la Fossa cone showing the temperature network for thermal monitoring of the active cone. The red line traces the profile reported in b. - b) E-W topographic profile of the summit area.

As an example of the information obtained by monitoring the temperature gradient in the diffuse degassing zone we show in Figure 3 the updated time series of heat flux, as it was registered at the VSCS station. The elaboration of the data set of temperatures revealed an increase of the thermal anomaly during the summer 2021, reaching the maximum intensity in September 2021 (Inguaggiato et al., 2022) due to the raising upward of a massive convective front below the VSCS station. The ground temperatures at VSCS station showed the highest peak with the maximum increasing rate registered from 17 September to October. To date even if the diffuse heat flux values from VSCS station, along with the other geochemical parameters are lowered from 2022, they have not yet returned to background values before the unrest of 2021. All the data recorded from the temperature monitoring network on La Fossa cone have been considered as ground control references for local application of thermal remote sensing (see for example Pailot et al., 2023; Silvestri et al. 2019). The updated time series are included in the periodical reports to the Italian Department of Civil Protection for volcanic surveillance.

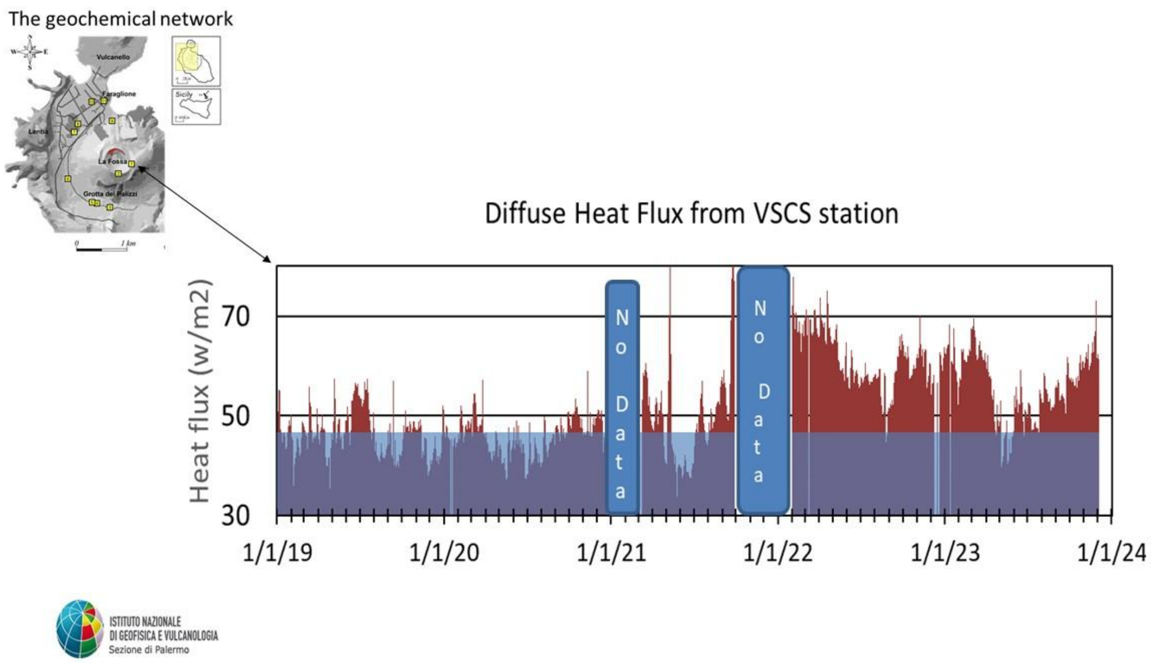

Fig. 3 – Heat flux variations evaluated from the time series of temperature gradients in a diffuse degassing zone. The blue shaded area shows the upper limit of background variations (47 w/m2); this value results from a statistic approach on the thermal records registered in the same site during a low degassing period. The map showing the geochemical network is on the left corner.

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The magma chamber before the 79 CE Plinian eruption of Vesuvius

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The 79 CE eruption of Vesuvius is the first documented Plinian eruption, also famous for the archaeological ruins of Pompeii and Herculaneum. Although much is known regarding the eruption dynamics and magma reservoir, little is known about the reservoir shape and growth, and related ground deformation. Numerical modelling by Finite Element Method was carried out, aimed at simulating the reservoir growth and ground deformation with respect to the reservoir shape (prolate, spherical, oblate) and magma overpressure. The modelling was tuned with volcanological, petrological and paleoenvironmental ground deformation constraints. Results indicate that the highest magma overpressure is achieved considering a prolate reservoir, making it as the most likely shape that led to eruption. Similar deformations but lower overpressures are obtained considering spherical and oblate reservoirs. These results demonstrate that ground deformation may not be indicative of eruption probability, style/size, and this has direct implications on surveillance at active explosive volcanoes.

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Mapping of volcanic deposits through the use of satellite techniques: the case of 2021 Mt. Etna eruptions

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During explosive eruptions tephra fallout represents one of the main volcanic hazards and can be extremely dangerous for air traffic, infrastructures, and human health. Here we present a new technique aimed at identifying the urban areas covered by tephra after an explosive event based on the processing of PlanetScope satellite imagery. These recent multispectral data are acquired from a constellation of over 180 microsatellites and exhibits a relatively high spatial resolution (~ 3 m pixel size) covering once a day each point in the Earth surface.

Our technique is based on the introduction of a new index that we call 'Tephra Fallout Index (TFI)' computed from the mean reflectance values of the near infrared (NIR) band analyzing pre- and post-eruptive data in paved areas adjacent to the summit craters of Etna and more distal paved areas, to have an overall view of the distribution of the tephra deposit.

We use the Google Earth Engine computing platform and define a dynamic threshold for the TFI of different eruptive events to distinguish the areas affected by the tephra fallout.

We demonstrate our technique by applying it to the eruptive events that occurred in 2021 at Mt. Etna (Italy), which mainly involved the eastern and south-eastern flanks of the volcano, sometimes two or three times within a day, making field surveys difficult. Whenever possible, we compare our results with field data and find an optimal match.

The use of satellite imagery acquired from microsatellite constellations, such as PlanetScope, providing an optimal compromise between spatial and temporal resolution, may prove fundamental for identifying tephra deposits during eruptive episodes, such as those occurred in 2021 at Mount Etna volcano. In particular, our method provides a near real time result, making it ideal also for the mapping of other hazardous events worldwide.

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Monitoring of the radon emission from the surface soil in the Maccalube natural reserve

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The reserve of Maccalube di Aragona (Ag) in Sicily (Italy) is unfortunately known because of the death of two children in 2014 due to a sudden explosion of a mud volcano. Indeed, that reserve covers a large area made of mud volcanoes which emit different gases with high percentage of methane, followed by liquid hydrocarbons and high salinity waters [1-3]. Such overpressure fluids migrate towards the surface across discontinuities in subsoil often creating mud cones. The activity is generally of small intensity but, suddenly, as occurred in that tragic day of 2014, it could evolve in a paroxistic phase producing flooding which, in turn, causes damages and even injuries. For these reasons, mud volcanoes constitute a geohazard problem and, thus, are currently studied.

In the framework of the PROMUD Project (https://progetti.ingv.it/it/promud), in order to characterize the part of the reserve that is not under law restriction, in terms of environmental radioactivity, we performed measurements of radon in soil gas. Moreover, radon can be used as a naturally occurring tracer for environmental processes [4]. By means of grab-sampling or continuous monitoring of radon concentration, it is possible to assess several types of dynamic phenomena in the environmental matrices (air, water, etc). The preliminary survey was carried out at the end of November 2023 by using a radon and thoron detector (RAD7 Durridge) coupled with a soil probe for subsoil measurements and an accumulation chamber for surface emission [5]. The measurement points are in Fig. 1. Not negligible values of radon activity concentration at surface, of the order of thousands of Bq/m^3 in concomitance with the emitting active centers were detected, as well as values under the limit of detection (LD) elsewhere. Such high concentration at the only active centers could suggest that radon likely uses gases, i.e. methane, as carrier to way out from soil whereas no escape is possible due to the presence of a compact clay layer.

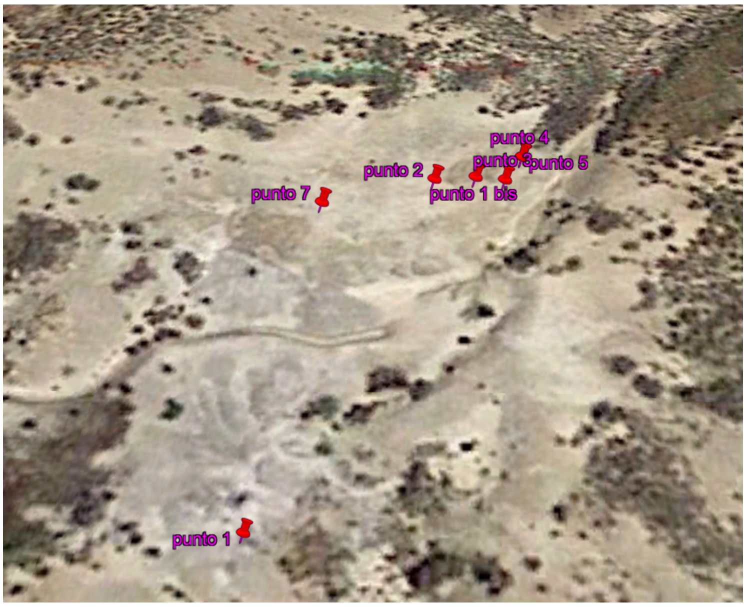

Fig. 1 – Measurement points at Maccalube reserve.

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How multiple observations tracked the onset and evolution of the 2021-2023 unrest at Vulcano Island (Southern Italy), and unveiled the processes behind it

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In September 2021, the La Fossa volcano entered a new phase of unrest. The monitoring system recorded a sudden variation in seismicity, ground deformation, fumarole temperatures, and soil and plume degassing. These variations were ascribed to the fast vaporisation and expansion of the central hydrothermal system (Federico et al., 2023), strongly impacted by the input of heat and chemicals from the magmatic source. By the onset of the unrest, fumarole chemistry showed clear-cut variations, related to the dominant contribution of the magmatic gas over the hydrothermal one. The CO_2 content and the He isotopes of the magmatic gas revealed the appearance of a more primitive magma during the climax of the unrest. The increased contribution of magmatic gases was already evident since 2018, so the 2021 unrest could have been the outcome of a long-lasting preparatory phase. The anomalous outflow of magmatic gases gradually extended northwest of La Fossa cone and involved the thermal area of Baia di Levante, where several low-temperature (100°C) fumaroles emit a vapour coming from a local hydrothermal aquifer. The gas composition had been typical of hydrothermal systems, with equilibrium temperatures close to 200°C but, by the onset of the crisis, it was gradually modified by the magmatic gas. In May 2022, a sudden and likely explosive release of gas occurred in the Baia di Levante, which was testified by the whitening of the seawater in the bay, and by the appearance of typical pockmark structures on the seafloor. At that moment, the gas composition of the monitored fumarole on the beach closely approached that of crater fumaroles. This episode drove the attention of the scientific community to this area, for several months affected by a significant input of magmatic vapour, because of the risk related to the huge CO_2 emission and the eventual overpressurization of the local hydrothermal aquifer. The magmatic contribution is persistently high in the fumaroles of La Fossa crater by the time of this communication, whereas it is declining in the Baia di Levante. The gas output in the crater area, and at the base of the cone is declining as well.

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Automated detection, characterization, and localization of Very Long-Period seismic events specifically designed for volcanic monitoring applications on Stromboli Island.

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Real-time applications in seismology have become essential for actively monitoring and surveilling volcanoes. They serve as valuable tools for promptly identifying volcanic unrest. In open-vent active volcanoes, the detection of Very Long Period (VLP) seismicity, typically associated with mild and persistent explosive activity, holds paramount significance in volcano monitoring. Variations in the occurrence rate and magnitude of VLP seismicity may indicate an impending phase of unrest. This study introduces a novel method for the automatic real-time detection and characterization of VLP seismicity at the Stromboli active volcano in Italy.

The detection algorithm relies on Three-Component Amplitude (TCA), derived from waveform polarization and spectral analysis of continuous recordings. It furnishes crucial information such as the time of detection, azimuth, incidence, amplitude, and frequency of the identified VLP. The automatically detected amplitude is then presented as peak-to-peak and root mean square amplitude, facilitating the automated amplitude localization of VLP.

The VLP detections and characterizations obtained through our automatic detection algorithm are compared with those derived from manual and automatic inspections of the seismic record, as well as with VLP time histories from existing published datasets. The comparison reveals that the VLP detection time series generated by the automatic algorithm effectively mirrors fluctuations in VLP activity, as manually identified by operators over an approximately 20-year period. This validation allows for the integration of the automatic algorithm into the real-time processing framework employed at Stromboli for volcano surveillance.

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Nonlinear convective motion of the asthenosphere and the lithosphere melting. A model for the birth of a volcano

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The processes of heat transfer occurring between the Earth's asthenosphere and lithosphere are responsible for partial melting of rocks, leading to the magma generation and its migration and segregation in the crust and, possibly, to volcanoes generation at the surface. Convection is the dominant mechanism regulating the heat transfer from the asthenosphere to the lithosphere, although many aspects of the whole process are not yet clear. Therefore, the knowledge of the physical processes leading to the melting of the lithospheric rocks has important consequences in understanding the interior Earth dynamics, the surface volcanic dynamics, and its related hazards. Rock melting occurs when the temperature gradient meets the rock solidus. Here, we propose a nonlinear convective 1D analytical model (representing an approximation of more 3D complex models). The steady state solution of our equation is in good agreement with the estimated geotherms of the asthenosphere. A perturbative approach leads to a heat swelling at the boundary between asthenosphere and lithosphere able to determine its melting and the birth of a volcano. A generalization of the analytical model admits only numerical solution and put some constraint to the model.

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An innovative system for the worldwide monitoring of volcanic thermal anomalies through Sentinel-2 and Landsat 8/9 data integration

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The NHI (Normalized Hotspot Indices) algorithm was developed to map high-temperature volcanic features through the analysis of near infrared (NIR) and shortwave infrared (SWIR) data, at mid-high spatial resolution (up to 20 m), from the Operational Land Imager (OLI) and the Multispectral Instrument (MSI), respectively aboard the Landsat-8/9 and Sentinel-2A/B satellites. The algorithm was then implemented within the Google Earth Engine (GEE) platform, which offers an extended dataset of geospatial data together with high computational resources. The developed GEE App enables the analysis of volcanic thermal anomalies at global scale, in terms of hotspot number, total SWIR radiance and hotspot area, without requiring any authentication from the users. The *NHI tool/system* then provides automated notifications about recent (over the past 48 hours) volcanic thermal activity globally, exploiting the increased temporal coverage of the combined Sentinel-2 and Landsat 8/9 observations. In this work, we present the NHI tool, and some recent results achieved by investigating eruptions occurred at different volcanoes (e.g., Mauna Loa, Kilauea, Ambrym, Etna). These results, providing accurate information about location, intensity, and spatial extent of hot targets (e.g., lava flows/lakes), which may be further enriched by quantitative characterization (e.g., in terms of volcanic radiative power), demonstrate the relevance of the developed GEE-App in the operational monitoring of active volcanoes, as a complement to the information provided by satellite systems offering higher temporal/lower spatial resolution products.

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Thermo-poro-viscoelastic deformation sources

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1. Introduction. Thermo-poro-elastic (TPE) deformation sources allow to explain seismicity and deformation induced by pore-pressure (*p*) and temperature (*T*) changes in geothermal and volcanic environments. In the last years, TPE inclusions have been applied to model the displacement and the stress field in the caldera of Campi Flegrei (Italy), where pore-pressure and temperature changes are assumed to derive from the exsolution of fluids from a deep magmatic chamber. In the literature both analytical and numerical models of TPE inclusions with different geometries exist (Belardinelli et al., 2019, Mantiloni et al., 2020, Belardinelli et al., 2022, Nespoli et al., 2021 and 2022). While previous works were focused on TPE induced static deformation patterns, in the present work we show how to model the transient effects on displacement, strain and stress. Such transient effects can be modeled by extending the TPE models to the Thermo-Poro-ViscoElastic (TPVE) ones.

2. Method. The inclusion method allows us to model the static mechanical effects of pore-pressure and temperature changes occurring inside a closed volume (i.e. an inclusion) embedded in an elastic medium (Eshelby, 1957). To model transient mechanical effects one can include the effects of viscoelasticity. A viscoelastic behavior should be expected in high temperature and fluid saturated rocks, due to thermally activated and pressure-solution creep. The analytical thermo-poro-viscoelastic (TPVE) solutions for a disc-shaped inclusion embedded in a uniform viscoelastic medium can be obtained through the correspondence principle (Fung 1965, Nespoli et al., 2023a) assuming that the medium is a homogeneous Maxwell half space.

3. Discussion and Conclusions. The TPVE analytical solutions indicate that including the viscoelastic behavior inclusion can explain a decrease in seismicity rate accompanied by an increase of surface uplift, as was observed in the late stage of the 1982-84 unrest phase at Campi Flegrei. This behavior is in contrast with what is expected according to the elastic response, in which the seismicity increases during the uplift and decreases during the subsidence. Our approach allows us to extend the relevance of hot and pressurized inclusion models to the interpretation of transient mechanical effects, which can be observed in several areas of the World.

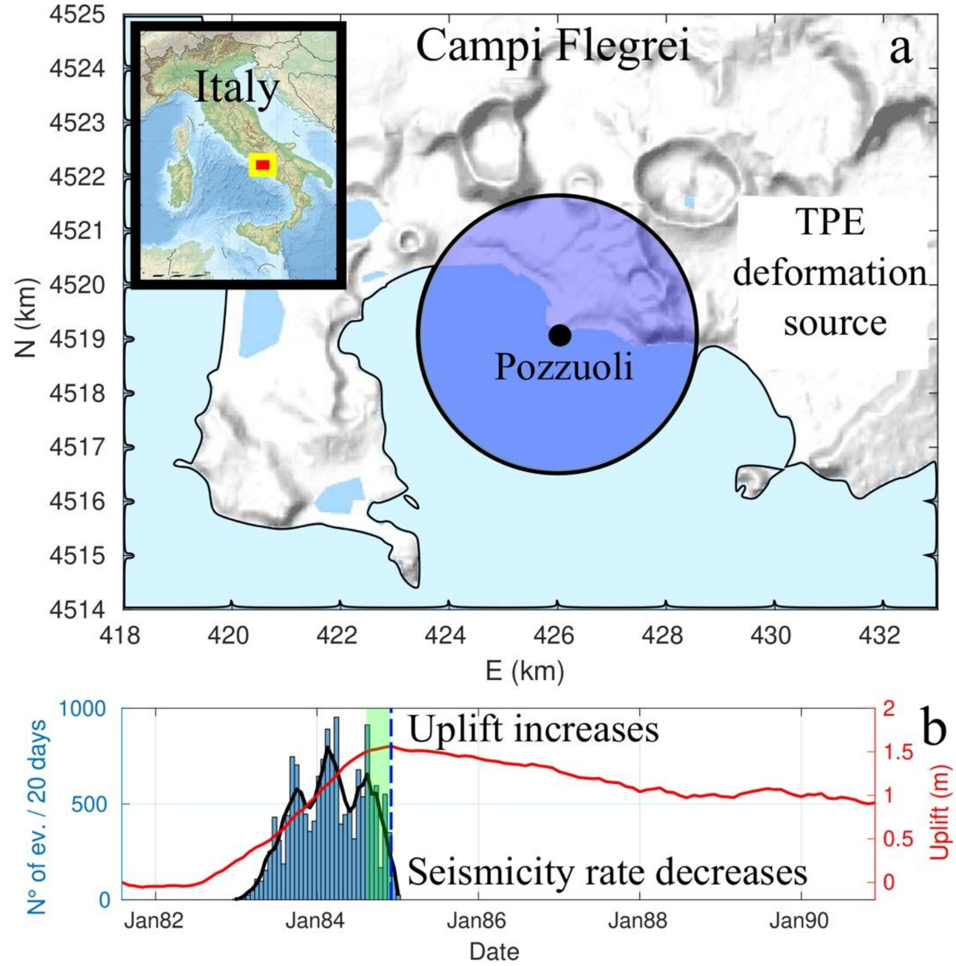

Figure 1. (a) Caldera of Campi Flegrei (Italy). The blue circle represents the projection of the TPE inclusion as inferred from the inversion of geodetic data measured during the period June 1980–1983 (Nespoli et al.2021). (b) Uplift (red curve) as a function of time, measured in the location of maximum measured uplift (Pozzuoli harbor) from 1980 to 1990. Histograms represent the number of events in time windows of 20 d. The black curve shows the number of events computed with a moving average.

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Magnetic Anomaly Survey of the Martignano Lake maar center, Sabatini Volcanic District, Central Italy.

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Introduction

A magnetic anomaly survey was conducted at the Martignano Lake volcanic center, which was formed during the final phases of the evolutionary history of the Sabatini Volcanic District (SVD) and persisted until 70 ka when the last documented SVD eruption took place at the Martignano maar (Marra et al., 2019).

The SVD became active 0.8 Ma and was characterized by explosive eruptions causing the deposition of pyroclastic flows and falls, surges and localized lava flows (Cioni et al., 1993). This volcanic activity developed during Pleistocene times due to the post-orogenic extensional tectonics that led to the Tyrrhenian Sea opening (Malinverno & Ryan, 1986). The SVD extends over an area of 1800 km^2 and is characterized by the lack of a central volcanic edifice as the activity was distributed over a large area. The SVD hydromagmatic centers mostly consist of tuff rings and subordinate tuff cones with maar-type craters located in the central area of the SVD, to the N and E of present-day Lake Bracciano (Sottili et al., 2012). The erupted tephra volumes from either monogenetic or polygenetic SVD maars ranged 0.004–0.07 km^3 during individual maar-forming eruptions.

The structure of Martignano lake was created by a sequence of hydromagmatic eruptions forming a composite maar type crater (Sottili et al. 2012).

The maar structure is a common volcanic morphology that occurs when magma interacts with groundwater, leading to multiple underground explosions and the formation of a crater that cuts into the pre-eruptive surface. Maar volcanoes subsurface structure is a cone-shaped geometry (diatreme) generated by mass deficiencies in the root zone, where the eruptive explosions occur; the diatreme and the maar crater are mainly due to explosions, collapse, and subsidence mechanism (Lorenz, 2003). Where no exposure of the diatreme exists, the application of geophysical modeling techniques can provide a method to model the geometry of a maar-diatreme, its feeder dikes, and any intrusions (Skacelova, 2010, Blaikie et al., 2014, Mrlina, 2009). Potential field methods have proven valuable in providing information about volcanic structures and subvolcanic bodies, presenting a valid approach to probe through a volcanic pile (Nicolosi et al., 2014, 2016). Short wavelength magnetic anomalies have been observed inside maars craters, often associated with high gravimetric signature and interpreted as dikes that intruded the diatreme in the center of the main crater (Blaikie et al., 2014).

The Martignano lake survey

The magnetic survey of Martignano center represents a novelty, as this type of data has never been acquired for this volcanic center before. The survey was conducted using an inflatable boat designed for lake navigation and equipped with a GEM Systems GSM 19 magnetometer to measure the total magnetic intensity. Additionally, a GPS system for obtaining spatial coordinates of the magnetic measurements is integrated into the magnetometer platform.

The entire surface of the lake, which measures approximately 1890x1400m, was surveyed using profile lines oriented in the N-S direction and spaced 50 meters apart (Fig. 1). A series of Tie-lines E-W oriented were acquired to correctly level the main survey lines. While navigating the lake, echosounder measurements were conducted using a Garmin Striker V7 unit equipped with a transducer operating at 200 kHz. These measurements were gathered to construct a model of the lake's bathymetry and to examine morphological structures originating from volcanic activity. Throughout the measurements, numerous gas bubble emissions in the form of flares (continuous release of gas bubbles,) were observed. These emissions, characterized by high sonic impedance of the bubbles, scatter the echosounder signal, making them distinctly visible (Caudron et al. 2012). They were particularly concentrated in an area labeled FL in Fig. 3. Exploration of the lake bottom focusing on the region of higher density of observed flares was conducted using a submarine ROV (Remotely Operated Vehicle) equipped with a camera and a robotic arm.

Two aeromagnetic profiles, obtained during a previous survey covering the entire SVD, are situated to the west and east of the lake border in a north-south direction (referred to as L1 and L2, as shown in Fig. 2). The average altitude maintained during the aeromagnetic survey was 400 meters above ground level.

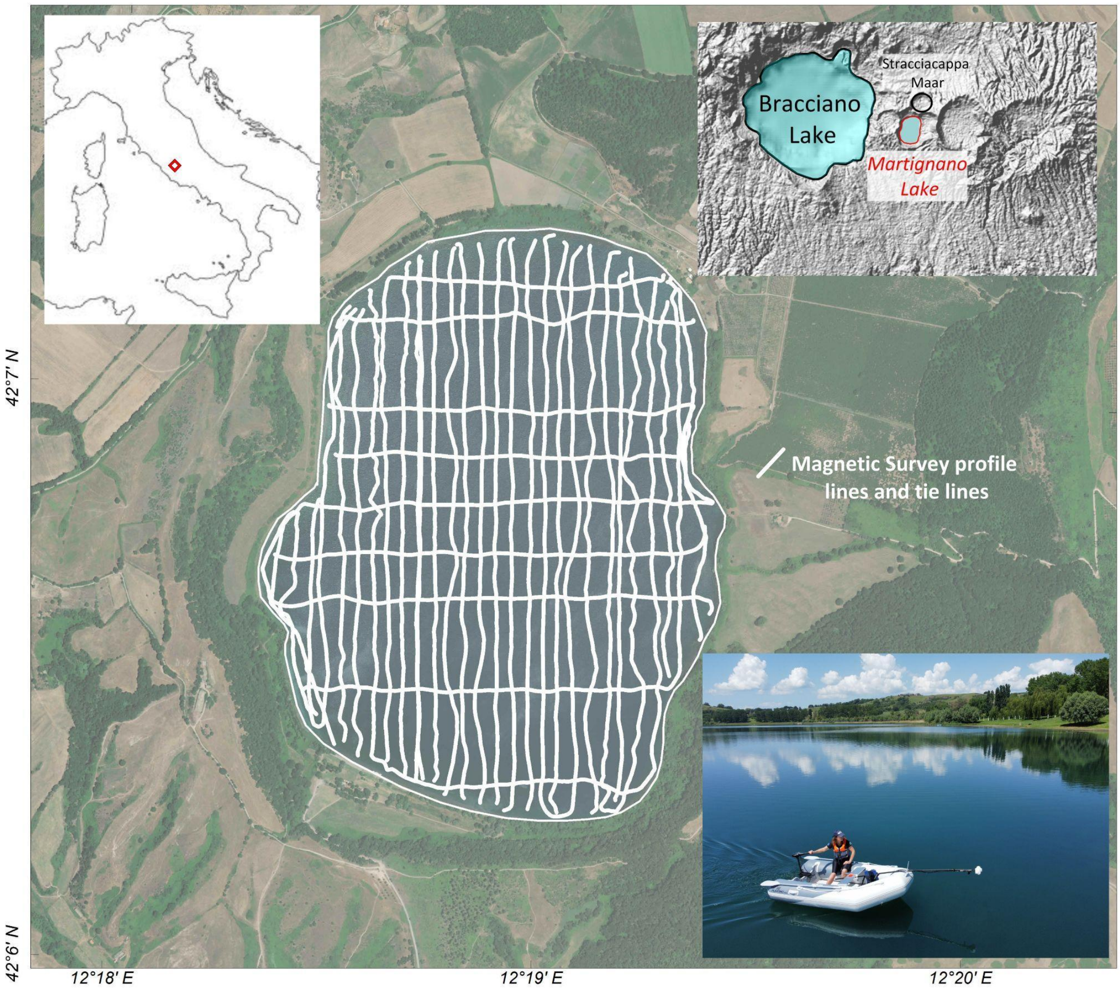

Fig. 1 - Location of the magnetic survey lines and tie lines acquired in Martignano Lake.

Results

The magnetic anomaly map resulting from the survey, shows that the Martignano magnetic anomalies are due to the presence of a negative magnetization contrast with the surrounding volcanic rocks; the primary dipolar structure of the magnetic intensities observed at the southern and northern borders of the lake (negative magnetic intensity lobe at point A and positive one at point B, Fig. 2) is attributed to the contrast in magnetization among the hydromagmatic products originating from the Martignano center, mostly consisting of stratified and cross-stratified tuffs with alternating fine-ash rich and coarse-ash to fine-lapilli rich horizons, the underlying structure of the maar, and the pre-maar composition, predominantly consisting of alternating pyroclastic deposits and lava flows from the SVD's activity. Nicolosi et al. (2019) estimated a bulk magnetization of 3 A/m for SVD products. This magnetization value surpasses the average values recorded from outcrops of the hydromagmatic products found at the Martignano lake by an order of magnitude, resulting in a significantly lower measurement. This contrast can also be considered representative for the diatreme and crater infill products.

The presence of decimetric lava lithics and bombs in the hydromagmatic deposits associated with the Martignano activity and the outcrop of a scoria cone deposit on the lake southern border (Sottili et al., 2012), suggests the presence of a highly magnetized lava plateau that was partly fragmented by the onset of the maar eruptive activity at Martignano. Anomaly D in Fig. 2 can represent the magnetic effect of the scoria cone deposits. The existence of a pre-eruptive 10-meter thick lava plateau is also documented for the nearby Stracciacappa maar crater (Moscatelli et al., 2021) (Fig. 1).

The negative magnetization contrast between Martignano and surrounding SVD products is testify by the two aeromagnetic profiles reported in figure 2, where a intense positive anomaly is observed along profile L1 and L2 at the northern border of the lake, mirroring the positive anomaly B of figure 2 and indicating the presence of higher magnetized material separating Martignano and Straccicappa maars (figure 1); this magnetic anomaly is not compatible with the presence of the low magnetized hydromagmatic products outcropping in the northern rim of the Martignano crater. Magnetic anomaly B in Figure 2 is therefore interpreted as the result of subsurface lava and pyroclastic products from the SVD which previously formed the topography of the pre-maar activity. The geometry of magnetic anomaly B suggests a thinning of the magnetized material and an inclined surface that deepens toward the center of the lake marking the contact surface between maar's diatrema and the pre-maar products;

The negative intensity sub-circular magnetic anomaly observed in the central region of the crater lake (G in Fig. 2) represents the effect of low magnetization material; this zone can be interpreted as the area where the magnetized pre-maar volcanic pile disappears due to the presence of the maar diatrema and infilling products.

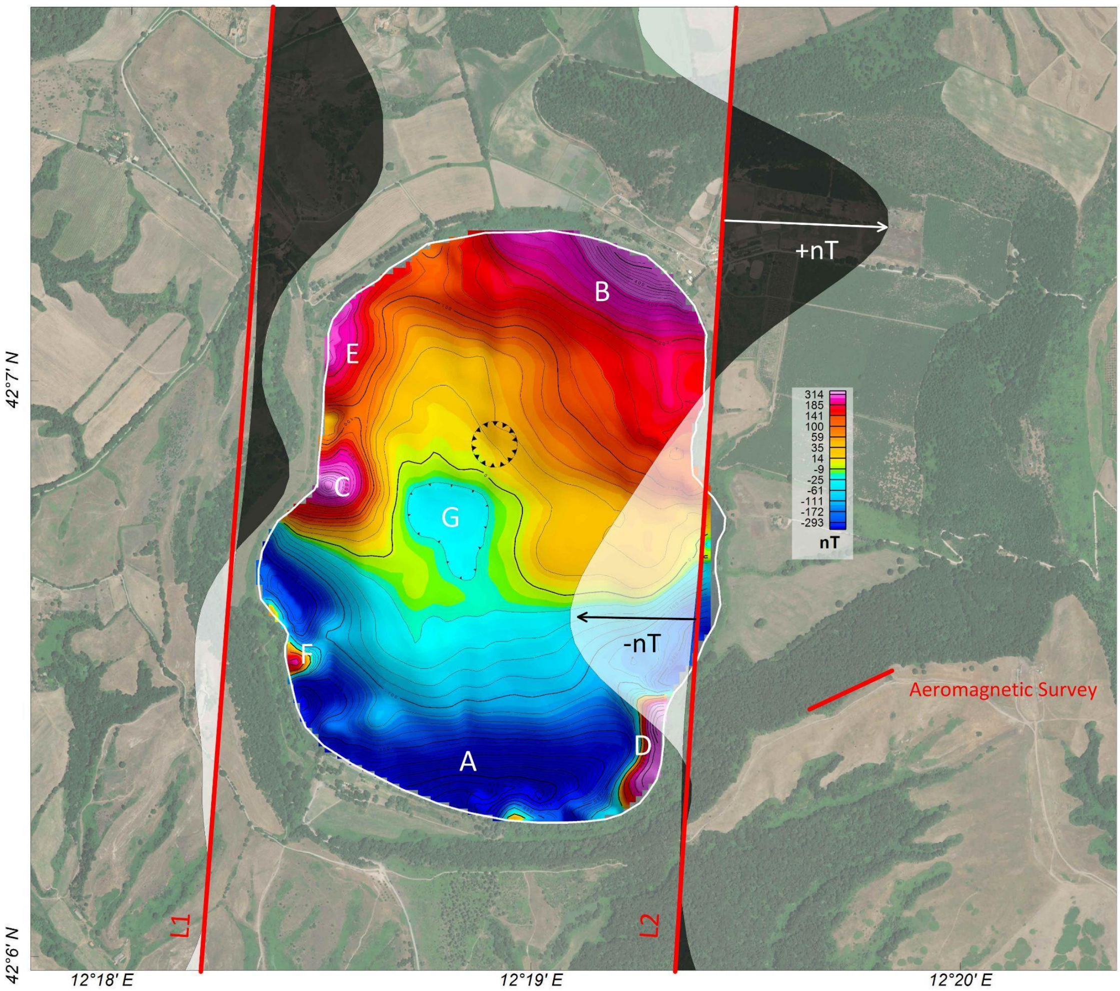

Figure 2 - Magnetic anomaly map of Martignano Lake displayed using a nonlinear intensity color scale and contour lines. Letters denote magnetic anomalies discussed in the main text. Red lines indicate survey lines from the 2008 aeromagnetic survey of the Sabatini Volcanic District (Nicolosi et al., 2019).

During the echosounder survey, numerous gas emission flares were observed across the entire lake bottom surface. A concentrated area with higher flare density was identified (FL, Fig. 3). This area coincides with a local magnetic anomaly minimum oriented in the N-S direction, with its southern boundary corresponding to the magnetic anomaly minimum G depicted in Fig. 2. Gas and fluid circulation might serve as an additional factor contributing to the reduction in magnetization properties of volcanic products. In this particular area, a submarine ROV was deployed to capture images of the emission sources originating from the lakebed. The acquired images depict an extensive field of gas sources emerging from small pockmarks and craters excavated in the mud due to gas efflux.

The lack of significant local magnetic dipolar anomalies within the crater perimeter suggests the absence of intrusions of dikes and lava effusions from the Martignano diatreme system.

The intense dipolar anomalies situated on the western border of the lake (E, F in Fig. 2) are associated with local lava outcrops whereas anomaly C is attributed to the presence of a bathymetric rock spur. This spur can be interpreted as a remnant of the fused crater rims resulting from multiple explosions scattered within the lake perimeter, with non-coincident points of origin (Sottili et al., 2012).

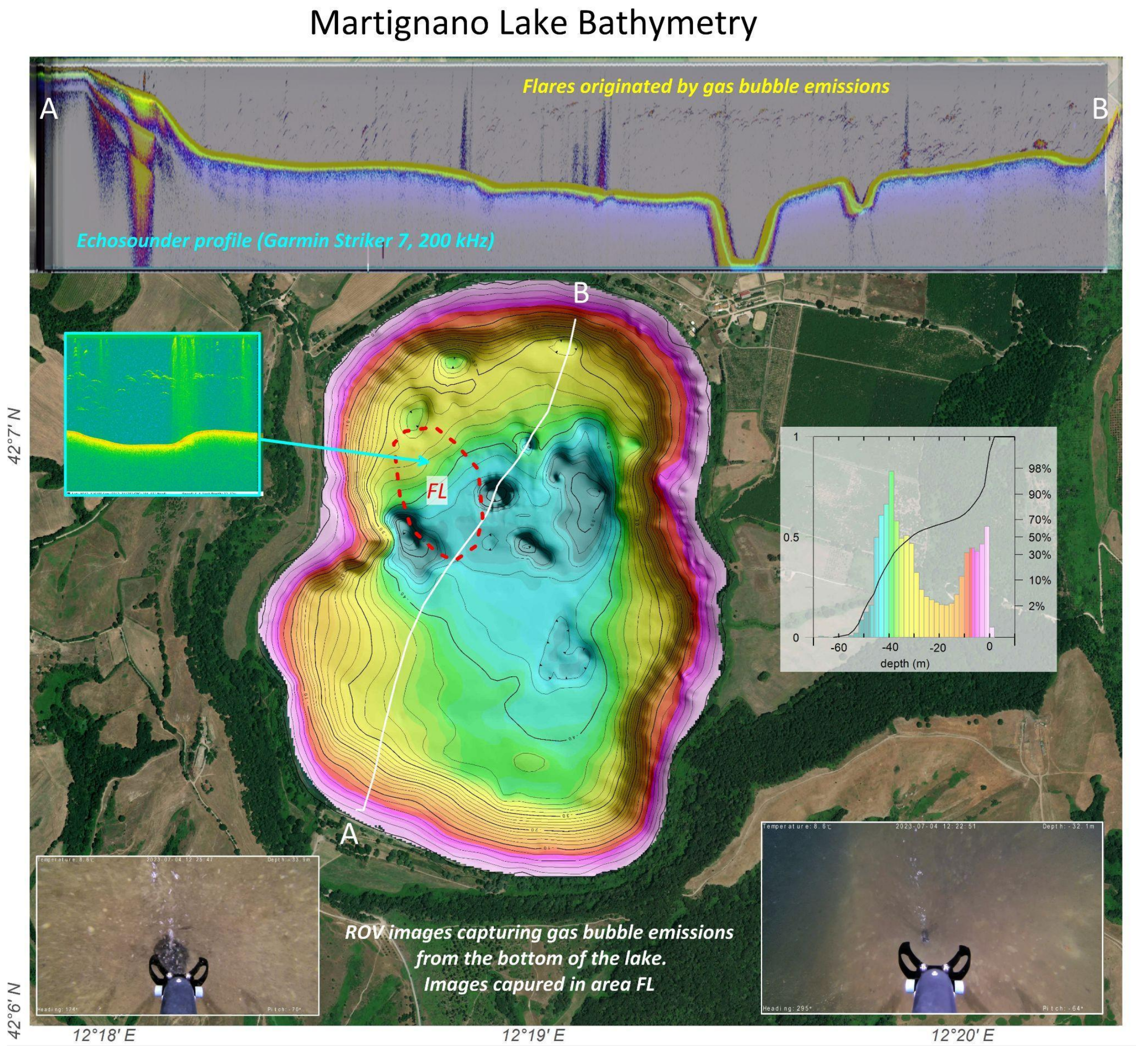

Figure 3: Bathymetry map of Martignano Lake displayed using a nonlinear color scale and contour lines. AB represents an echo-sounder profile line intersecting two craters.

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Twenty years of Campi Flegrei seismic monitoring by Istituto Nazionale di Geofisica e Vulcanologia- Osservatorio Vesuviano: history, performances and future developments

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The Campi Flegrei caldera is one of the highest-risk volcanic areas in the world due to the large number of people living there. In response to this high risk, the Campi Flegrei are one of the most monitored volcanoes in the world and the high level of anthropisation represents a constant challenge to improve the quality of monitoring data.

The INGV-Osservatorio Vesuviano (INGV-OV) is responsible for monitoring and studying the Campi Flegrei volcano and is the authoritative institution for the volcanic surveillance and monitoring.

The INGV-OV has been operating the instrumental seismic network in the Campi Flegrei since the 70s. Since then, this monitoring network has been constantly updated and upgraded in their instrumentation and topology.

At the present more than 30 stations are recording seismic data. All of them are equipped with velocimeters (SP, LP, BB and VBB sensors) and, among them, a subset is equipped with accelerometers. Moreover, by using multi channels digitizers, infrasound channels are also recorded (Figure 1).

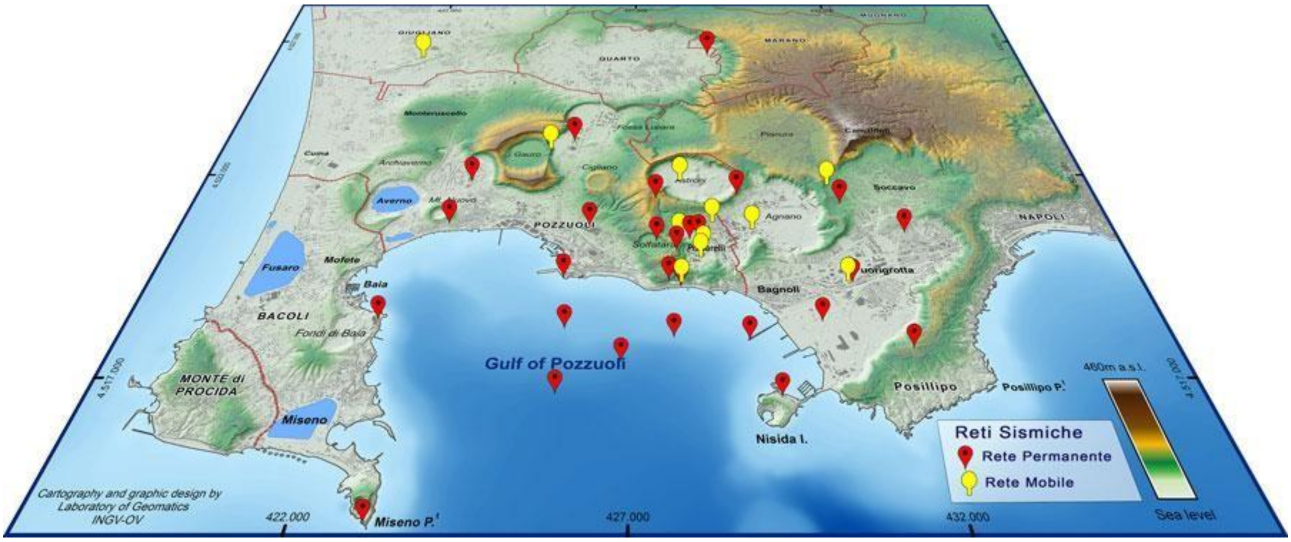

Figure 1 - The present Campi Flegrei seismic network. The map represents the permanent stations (red points) and mobile stations (yellow points). From http://www.ov.ingv.it

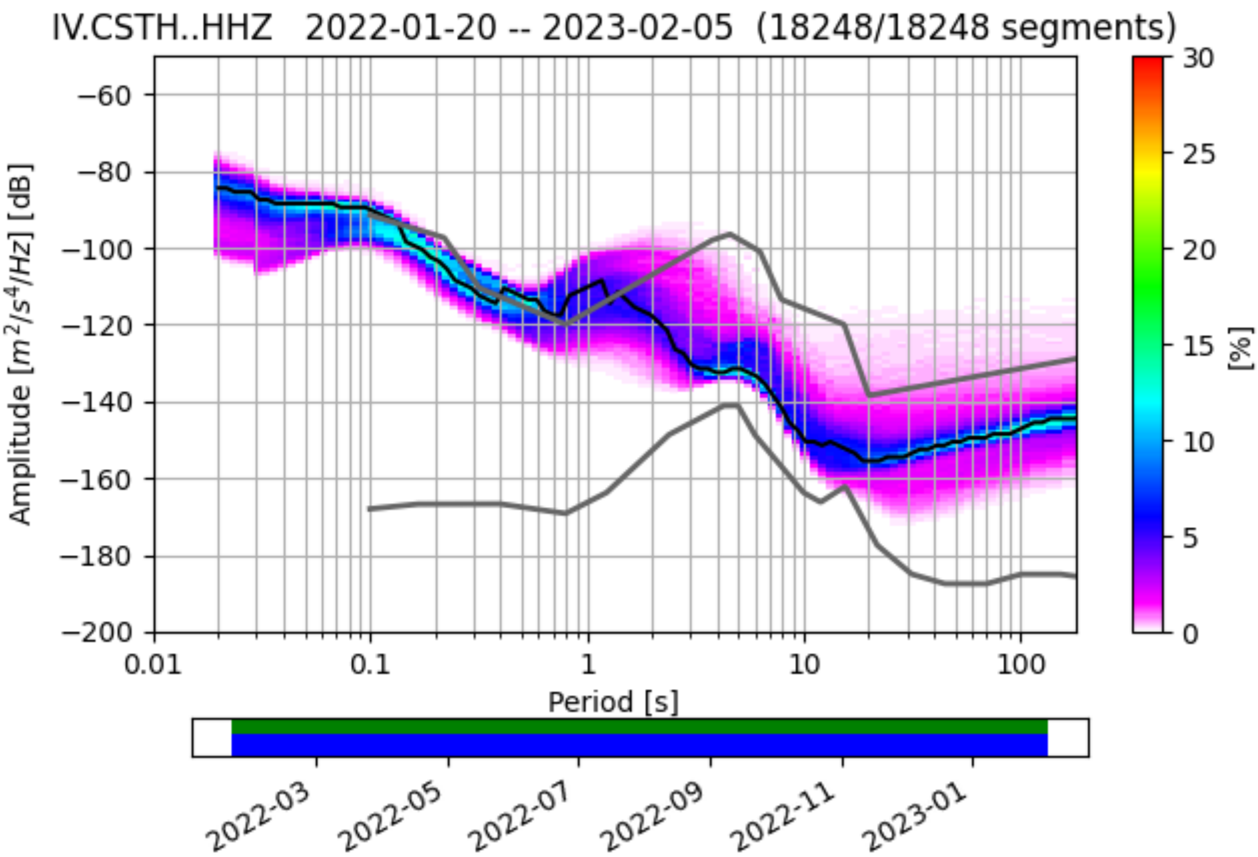

Figure 2 - Power Spectral Probability function of CSTH seismic station, which is the historical reference station for Campi Flegrei area. The plot represents about 14 months of data.

Over the past 20 years, European, Italian and Regione Campania supporting infrastructure projects have been the key factor in improving the equipment, while the implementation of digital communication network developed and managed in-house has led to an improvement in coverage of the area.

To better illustrate the current seismic monitoring network, we will also present the performance in terms of minimum detection magnitude over time and space, and other typical characteristics, such as the noise power spectral density of some key seismic stations (Figure 2).

Here we present this technological evolution aimed at improving the detection capability and at lowering the detection threshold.

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Preliminary characterization of the area of the Salse del Dragone mud volcano (Northern Italy) through surface-wave seismic prospecting

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Mud volcanoes are geological structures due to the surface expulsion of fluids, such as mud, water and hydrocarbons which originate within a sedimentary sequence. In particular, the ascent of these materials is favoured by the presence of fluid-rich over-pressured deep sediments characterized by low density and viscosity respect to the surrounding deposits. The emission activities related to mud volcanoes have significant implications in terms of energy resource exploration, seismicity, atmospheric budget of greenhouse gases (Mazzini and Etiope, 2017) as well as geohazard assessment (e.g., Gattuso et al., 2021).

About 60 subaerial mud volcanoes exist in Italy, mainly located along the outer Apennine belt and Sicily (Martinelli and Judd, 2004). The structure known as "Salse del Dragone" is one of the 18 mud volcanoes located in the Emilia-Romagna region, specifically situated in the Northern Apennine belt about 20 km far from the city of Bologna. Actually, the area affected by clear emitted mud presence is about 1300 m^2 and the emission area (about 200 m^2) is characterized by a flattened positive structure with a plateau-like shape less than 0.5 m high (Martinelli and Judd, 2004). Although the emission activity currently appears to be quite bland, some historical references (Calindri, 1780; Bombicci, 1873) report intense and loud eruptions with huge mud emission: it is precisely this type of lively activity that gave the site its name ("Dragon Salsa"). Moreover, a large active mud debris flow originates from the emission area: actually, it is not clear if these deposits were generated directly from mud volcano flows, if are related to a surface flow of the outcropping formation ("Argille Varicolori"), or are a combination of both. In order to identify the main subsoil features of the area and try to understand the nature of the debris flow deposits, a preliminary seismic survey based on passive and active surface-waves acquisitions was carried out; in particular, several single-station and multiple-station measurements (e.g., Foti et al., 2018) were performed. The first ones were analyzed using the HVSR (Horizontal to Vertical Spectral Ratios) technique, while the latter were devoted to retrieve the Rayleigh wave phase velocity dispersion curves. The joint use of these two analyses made it possible to characterize the subsoil materials in terms of shear-wave velocity values and to identify the main seismic impedance contrasts at depth. The preliminary outcomes show significant differences between the emission area and the zone affected by mud debris flow deposits.

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Geodetic imaging of magma ascent through a bent and twisted dike during the Tajogaite eruption of 2021 (La Palma, Canary Islands)

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On Sept. 19th, 2021, the Tajogaite eruption on the island of La Palma began with short precursors, lasting only eight days. The seismicity started on Sept. 11th with a westward and upward migration of hypocenters. Permanent GNSS stations started recording deformation on Sept. 12th on the island's western side, which reached more than 15 cm just before the eruption. After the eruption onset, the ground deformation increased, reaching a maximum on Sept. 22nd and showing a nearly steady deflation trend in the following months. To better understand the dynamics of the eruption, we exploited a joint dataset of GNSS and Sentinel-1 SBAS time series along both ascending and descending orbits. To obtain the geometry of the causative source of the ground deformation, we combined the result of a preliminary non-linear inversion and the precise location of the seismicity. The resulting geometry of the source is that of a twisted dike bending eastward.

We performed inverse modelling to obtain the spatiotemporal kinematics of the opening function of the dike. The forward modelling has been realised using a 3D finite-element approach considering the island's topography. Our findings reveal a close correspondence between the magmatic intrusion and pre-eruptive seismicity. The ascent of the magma occurred along two branches, and the rheology of a previously identified ductile layer strongly affected the magma propagation process. Finally, we found evidence of an early shallow deformation, which we interpret as the effect of ascending hydrothermal fluids. Our findings highlight the need for advanced modelling to understand pre-eruptive processes in basaltic volcanoes.

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Determining the magmatic or hydrothermal nature of volcano unrest through Bayesian joint inversion of ground displacements and gravity changes.

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Volcanic unrest may be caused by a replenishment of magmatic or hydrothermal reservoirs, or by fluid transport through the elastic brittle crust. In either case, the nature and amount of fluids involved in the unrest determine the hazard associated with any impending eruption. The key questions to be addressed are: what kind of fluid (magma or hydrothermal), and how much of it, is driving the unrest? We show how these questions may be answered, and uncertainties in the expected scenarios may be reduced, through joint inversions of surface displacements or other kinds of ground deformation data (baseline changes, uplift, tilt, strain) and gravity changes.

First, we present a new Bayesian approach to the joint deformation-gravity inversion, involving a rigorous treatment of the covariance between co-located uplift and gravity changes, and a simultaneous estimate of the optimal relative weights of different observation types. We show how this approach may help reduce the uncertainties on the inferred mass of the magmatic fluids and on the deformation source parameters, such as location and volume change of the source underlying the unrest.

Next, we show that the estimated mass and volume change, together with information on the density and compressibility of the fluids potentially involved in the process, can be used to constrain both the volume fraction of exsolved volatiles in the fluid intrusion, and the nature of the fluids. We show example applications to Long Valley Caldera and Mt. Etna.

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Inverse modelling as a powerful tool for estimating gas flow emission rate from stationary hydrothermal vents

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Submarine hydrothermal systems emit into the sea water huge amounts of both elements and energy, in terms of gas emissions, thermal water and solid deposition. The interest of the scientific community in these systems, classified as extreme environments in relation to their features (e.g. high temperature, low Ph) is increasing, especially in the last few years. However, direct measures can be challenging due to the extreme environmental conditions [Heinicke et al. 2009, Longo et al. 2021].

In this framework, passive passive hydroacoustics may represent a sustainable and safe method for both short- and long-term monitoring, since the typical source mechanisms present in the hydrothermal fields radiate sound pressure following different acoustic modes directly related to ascending fluids release (Dziak et al. 2002, Dziak et al. 2012, Li et al. 2021).

Particularly, the research activity presented here has been focused on the estimation of the gas flow emission rate from a stationary-high flux vent (Leifer and Tang 2007) located at ~16 meters depth, inside the hydrothermal field 2 miles East offshore Panarea island (see Fig. 1) in the NE sector of Aeolian arc (Aeolian Island, Italy).

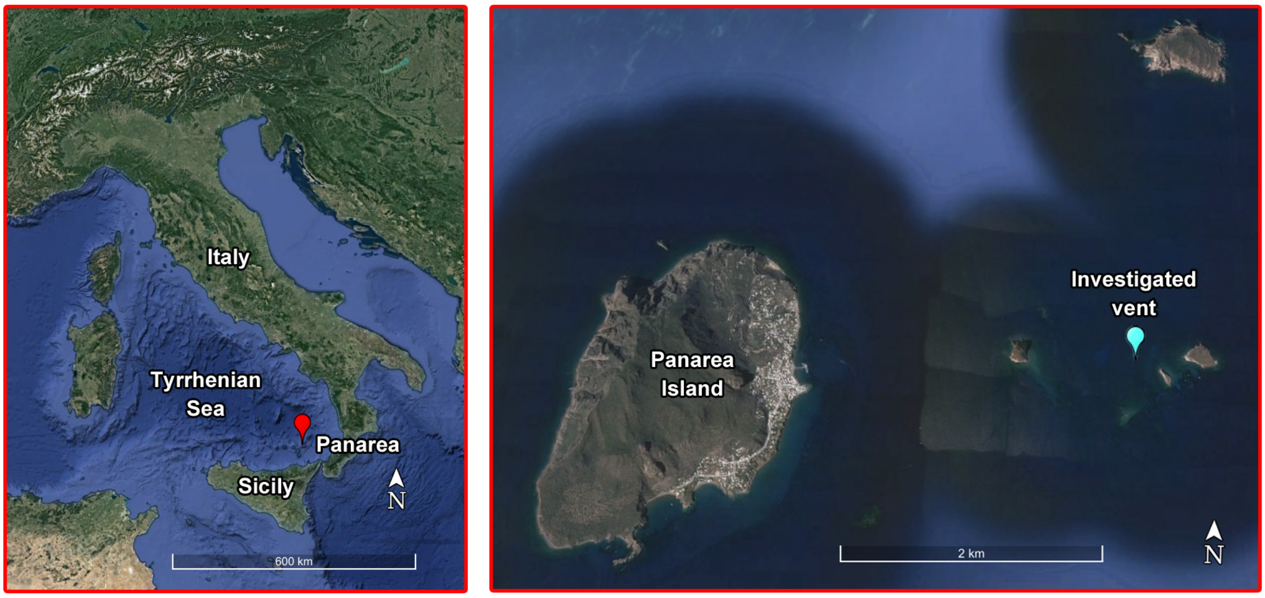

Fig. 1 – Maps showing the position of Panarea Island in Southeastern Tyrrhenian Sea (red marker in left panel) and the position of the investigated vent (cyan marker in right panel).

To carry out the estimation of the gas volume emitted by the hydrothermal vent we implemented a spectral method (Leighton and White 2011, Roche et al. 2022), based on a specially developed inverse modelling algorithm. The adopted approach, founded on the assumption that the acoustic signature of a single bubble event evolves over time as a sinusoid that exponentially decays (Leighton et al. 2011, Walton et al. 2005), is based on the formulation of a forward model for the sound radiated by the bubbles plume, then the path is backward analysed to obtain an estimation of the flow emission rate.

High-resolution audio frames were recorded by using an autonomous smart hydrophone, able to collect and store digitised audio frames in the frequency band [1 - 12.800] Hz.

The hydrophone was deployed in mooring configuration in the proximity of the investigated vent, acquiring data for ~10 hours at the maximum sampling frequency. Hence the collected audio frames were treated with preliminary analyses, aimed to characterise the spectral features of the vent, thus identifying the acoustic signature of the source and the frequency range connected to signals attributable to the bubbling events. The analyses of the Power Spectral Density (PSD) and Pressure Power Spectrum show the presence of different persistent energetic frequency peaks over the environmental background noise which are compatible with the dynamic of the hydrothermal field (see Fig. 2).

Among these, the most energetic ones are likely due to the acoustic signal radiated by a huge, resonant bubble plume, consistently confirmed by the coupling of the estimated radius with direct observations.

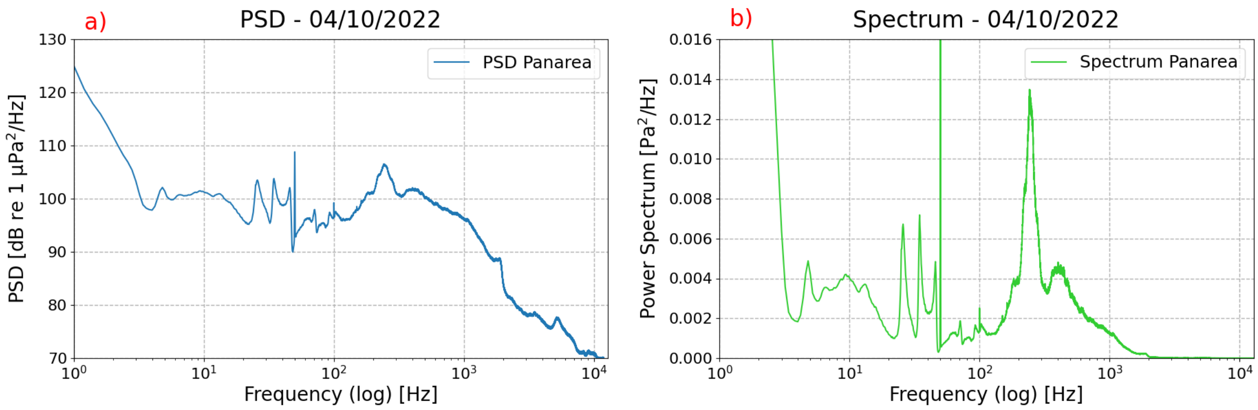

Fig. 2 – Power Spectral Density (PSD) (panel a) and Pressure Power Spectrum (panel b) of 04/10/2022.

The Spectrum analysis allows us to identify the main features of the vent, characterised by bubbles radii of 0.02 m that produce the main energetic peak centered at ~250 Hz, also visible in the Spectrogram along with smaller bubbles that produce less energetic peaks up to 2 kHz. Therefore, in the algorithm, we take into consideration a wide frequency range, spanning from 150 Hz to 2250 Hz, in order to estimate all the gas released by the vent.

The Spectrogram confirms that the energy spans in a wide bandwidth which is compatible with the size of the bubble observed.

In this framework, the inversion algorithm was applied to the dataset, considering the frequency range from 150 to 2250 Hz, as shown in Fig. 3.

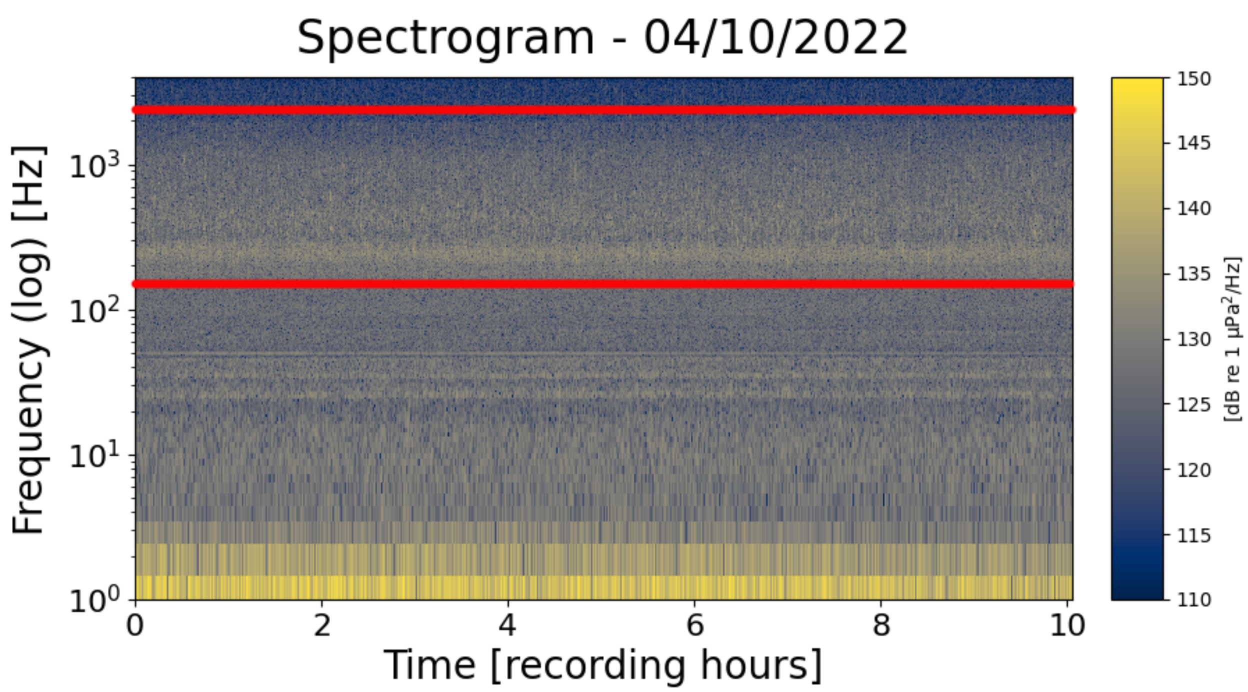

Fig. 3 – Charts showing the Spectrograms recorded on 04/10/2022 on which the inversion range is indicated (red lines).

The flow emission rate estimated through the inversion algorithm, which assumes a mean value of 8.32 liters per minute, is in good agreement with the direct observations. This confirms that passive acoustic methods represent a valid and robust tool for both monitoring and research activity in submarine hydrothermal fields, providing to be also a long-lasting instrument able to detect the fluctuations connected to the variations of such natural systems.

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Dynamic and static strain sensitivity of velocity variations at Ischia Island, southern Italy

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Ischia Island is the westernmost, active volcanic complex of the Campanian plain (Southern Italy, Civetta et al., 1991). A long-term depressurization (Sepe et al., 2007) in the local hydrothermal system is causing deflation and contraction (Galvani et al., 2021) of the surrounding volcanic edifice. In the 2017 a Mw 3.9 very shallow earthquake occurred in Casamicciola, in the northern part of the island, causing landslides and several collapse. Here we present dv/v measurements over 8 years (2016-2023) for variable coda waves time lapse using empirical Green's functions reconstructed by autocorrelation of seismic noise recorded at local velocimeters. We compared velocity variations time series with the temporal evolution of the strain, obtained at the network of GPS stations deployed on the island. We also investigated the coseismic variations of seismic waves velocity occurred during the 2017 earthquake. We found high values in both dynamic and static strain sensitivity of velocity variations with appreciable differences on the island, reflecting the anisotropic pattern of the depressurization. This also testify a significant non-linearity in the elastic properties of the local volcanic rocks, as expected for multi-fractured and heterogeneous materials where large amount of microcracks are commonly present.

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The current unrest of Campi Flegrei caldera: seismicity and ground deformation

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Campi Flegrei is one of the areas with the higher volcanic risk in the world due the active volcanic field and the presence of almost 500.000 people living in the area that could be invaded by pyroclastic flow in case of eruption. Its morphology is dominated by a large caldera collapsed during two caldera-forming eruptions. The caldera includes a continental sector and a submerged part, the Pozzuoli gulf. The caldera floor is punctuated by tens of craters' remains of monogenic volcanic activity origins. The Campi Flegrei area is characterised by intense uplift periods followed by subsidence phases (bradyseism). The area of the maximum uplift is located at Pozzuoli town and it decreases with a radially symmetrical shape. The uplift phases are associated with the unrests and are accompanied by seismicity that is usually shallow and with low-to-moderate magnitude. The Campi Flegrei caldera is currently in an unrest phase started at the end of 2005 when the subsidence phase, started at the end of 1984, was interrupted and the central part of the caldera started to uplift again. This trend persisted up till now with a varying rate. The increments in the velocity of the uplift are often associated with an increment in the earthquake occurrence rate.

In February 2022 the uplift at Pozzuoli exceeded the maximum level reached at the end of the last bradyseseimic crisis (1982-84). Between August and September 2023 an increment in the recorded seismicity in terms of rate and maximum magnitude was recorded. At the end of this period, 21-23 September, the uplift suffered an acceleration: almost 1 cm in 3 days. The rate of the earthquakes per month with MD>=2.0 passed from 5 between January and July 2023 to almost 20 in August and September. On September 27th a MD=4.2 was recorded by the seismic network of the INGV-Osservatorio Vesuviano. This is the highest magnitude earthquake recorded in the area since 1980.

The increment in the seismicity alerted the population and triggered a governative mitigation plan. At the same time the scientific community, already engaged in monitoring, focused even more on understanding and studying the ongoing phenomenology. The researchers and technicians of the INGV-Osservatorio Vesuviano that is in charge of the monitoring of Campi Flegrei supplied all the data and possible interpretations to the authorities and to the decision maker.

A decrease in the rate of the seismicity and in the velocity of the uplift was recorded in October and November 2023. Other seismically anomalous periods like the one recorded in August-September were recorded during the current unrest of Campi Flegrei. But this last one was characterised by a rate of seismicity and magnitudes that made the authorities and population worried and recalled that both the volcanic and seismic risk are to be constantly faced in this area.

We will present the data collected by the monitoring system of the INGV-Osservatorio Vesuviano during this last period of the current unrest focusing mainly on the seismicity and ground deformation.

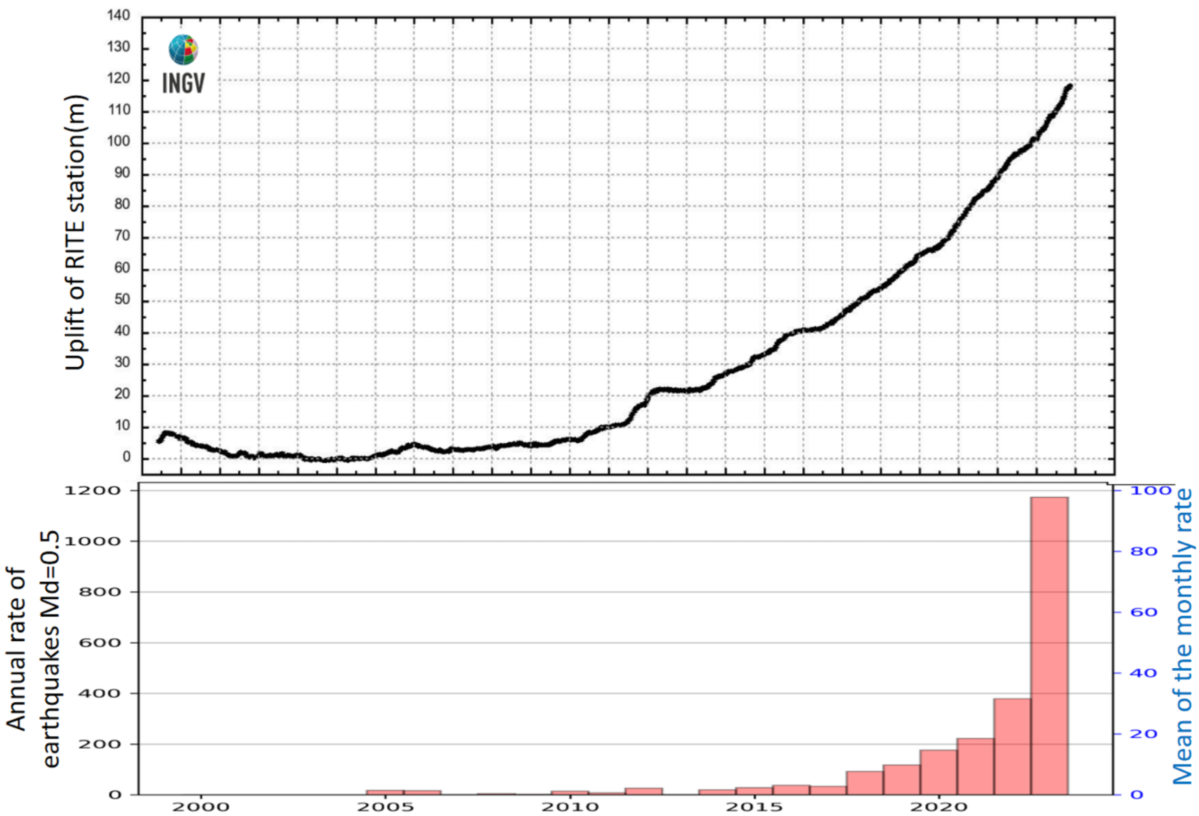

Figura 1 - Vertical displacement recorded at the station RITE (Rione Terra) and histogram of the number of earthquakes per year recorded at Campi Flegrei since 2000.

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b value tomography at Campi Flegrei: enlightening different rheological behaviour in volcanic areas

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The b-value represents the relative proportion of large and small events in the Gutemberg-Riechter relation:

$$\log(N)=a-bM$$

where N is the cumulative number of earthquakes with magnitude larger than M and a and b are constant that characterize the seismic catalogue and, consequently, the area where the catalogue is filled in. The b value is, generally, close to 1 in tectonic areas. Its value increases with the medium heterogeneity and temperature and it decreases with increasing stress.

We used the seismicity recorded in Campi Flegrei since 2005 to perform a tomography of the b value.

This tomography revealed values that ranges between 0.7 and 1.8.

A very good correlation with the structure of the hydro-thermal system at the basis of the bradiseismic phenomenon is evidenced. The lowest values characterize the caldera at depth of 2-4 km. The highest values characterize the shallower structures below Pisciarelli and Solfatara. More precisely we observe the smallest b values where we expect the higher stress concentration and for deepest seismicity. Conversely the highest b values are observed where the presence of a porous medium allows the passage of the volcanic gases. Values of b more close to typical tectonic ones are observed where the presence of faulting structure is documented.

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Multiscale Analysis of Physical Rock Properties at Stromboli Volcano: What controls the frictional properties?

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The physical, mechanical and fracture properties at Stromboli volcano have been integrated at multiple scales to understand whether the interplay between a presumed NE/SW rift zone and the Sciara del Fuoco (SDF) depression has resulted in a zone of weakness able to promote fracturing prone to flank instability (Tibaldi et al., 2004; Alcock et al., 2024). Multiscale fracture quantification by imaging via FracPaQ toolbox both fractures and sample scale fractures has been integrated with rock physics and rock mechanics experiments on cm samples belonging to the Paleostromboli, Vancori, Neostromboli, Pizzo and Present Deposit volcanic cycles that have been taken from within and outside the rift zone. The structural changes to the edifice have been quantitively assessed by mapping at different scale fracture properties such density and orientation within and outside the rift zone allowing to identify the potential damaged zones that could reduce the edifice strength.

Results indicate that basalt textures, microfracture density, porosity, chemical zoning and preferential alignments, despite lithologically dependent, can be related to the NE/SW zone of weakness at the regional scale and to collapsed volumes that have been subject to continuous intrusive activity. Numerical inversion models have been performed to cross correlate fracture density in the basalts at multiple scales.

A link between microfracture density and seismic velocities has been also established via numerical modelling, allowing to interpret in terms of degree of fracturing the results of seismic tomographies at the field scale, providing a novel method to image crack damage evolution within the inner structure of the volcano edifice.

In order to image and constrain the fracturing mechanisms controlling the initiation of rupture in the instable sector of SDF in Stromboli a multiscale approach has been consequently designed by first identifying and analyzing via satellite fractures and then exploring via laboratory experiments how the initiation of rupture and the frictional properties evolve under different loading conditions, pore fluid content and effective pressure. An initial assessment on the potential frictional properties was performed by determining the slip tendency (Ts) from 2-D Imagery and sampling lithological units according to the remote sensing analysis and the location with respect the instable sector of SDF (Fig.1). Triaxial direct-shear tests, via a purpose-built housing rig, equipped with two Piezo-Electric Transducers on 50 x 20 mm rectangular slabs at 5, 10 and 15 MPa both in dry and wet conditions were carried out to explore the coupled evolution of the frictional and seismic properties. Confining pressure and saturation have affected the friction coefficient. Rate and state friction parameters and friction coefficient are controlled by changing sliding velocity (Alcock et al., submitted). Microearthquakes recorded (Acoustic Emissions) and their key attributes, such amplitude, frequency and duration and their evolution confirm the relation to sliding velocity, confinement and porosity. Post mortem SEM analysis has revealed the impact that textural features on the evolution of fracture damage and their control on the frictional properties. These findings have been related to the field scale slip dilation analysis providing quantitative support for the identification of structurally weak zones across the SDF and constraint the mechanical behaviour of the fractured zones prone to instability.

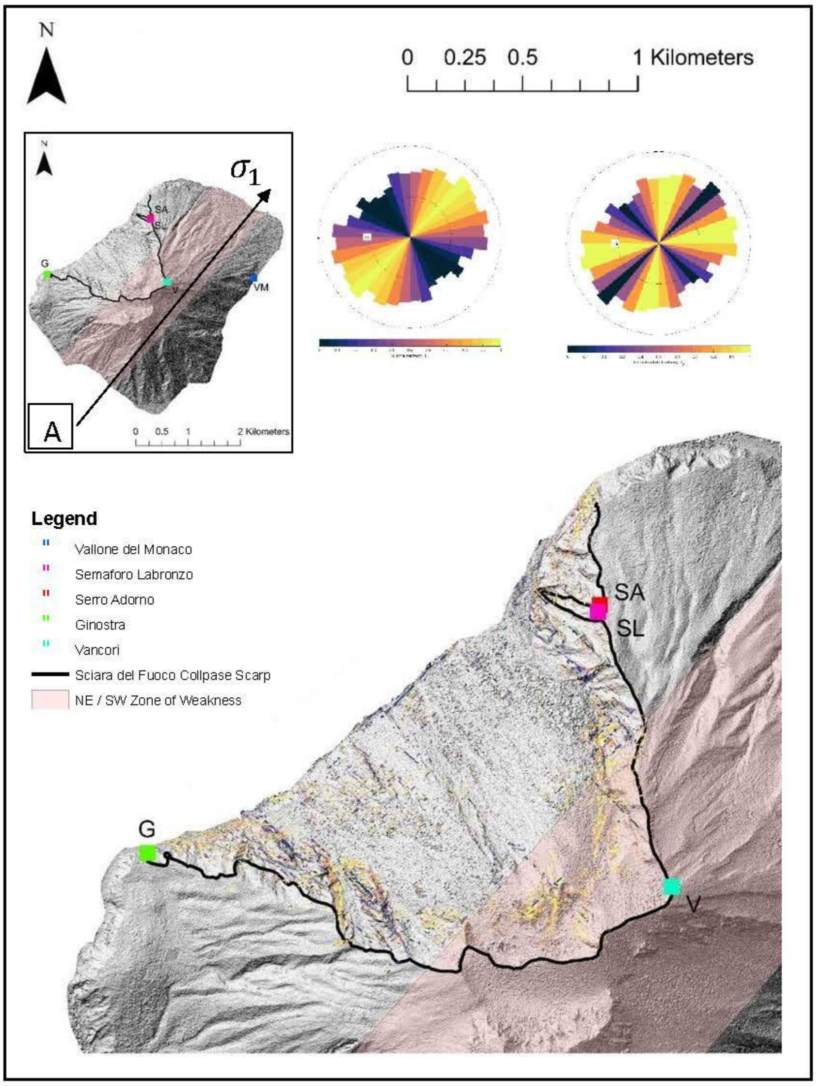

Fig. 1 - Slip tendency fracture map of the Sciara del Fuoco collapse scarp with sample site locations (A) of Vallone del Monaco (VM), Semaforo Labronzo (SL), Serro Adorno (SA), Ginostra (G) and Vancori (V) in relation to the NE/SW direction of σ1 aligned with the zone of weakness across the edifice. Rose diagrams of Td (B) and Ts (C).

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AI-based emulators for data driven CFD model reconstruction

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Computational Fluid Dynamics (CFD) models have become fundamental tools for the study of fluids and the design of their applications. Their use becomes crucial when the fluid exhibits complex behaviors, which can be due to flow conditions or the physical properties of the fluid. Geophysical flows are good examples of these flows. Among these, a fluid with a high intrinsic complexity is Lava, which include non-Newtonian rheology, a behavior strongly dependent on temperature, and the coexistence of the three phases, solid, fluid and gas (Cordonnier et al., 2016). Numerous CFD approaches have been developed to simulate lava flows. The Smoothed Particle Hydrodynamics (SPH) has proven particularly suited for this application, thanks to its Lagrangian and mesh-free formulation (Zago et al., 2017, 2018). However, despite the good level of description that these models can provide, one of the main limitations in practical application to complex fluids comes from the epistemic uncertainty, which is due to the poor observability of these flows for which detailed studies and measurements are hard or impractical.

A solution to this lack of information can come from CFD models themselves, which can be used to get information about the real phenomena. For example, one can create the so-called digital twins of the studied system or perform reverse engineering. This potential becomes even higher if we consider the growing fusion between CFD methods and Artificial intelligence, which have highly increased the potentials of physical modeling (Kasim et al., 2021, Amato 2023, Amato et al, 2023A).

Here we present an illustrative application of a combined CFD-AI model adopted to retrieve information about the viscous model of Lava. The model that we use is an AI based emulator of the SPH method (Zago et al., 2023, Amato et al, 2023B), which is applied to a lava flow simulated with SPH, with a known acceleration field. The emulator can recreate pressure and viscous interaction forces, to reconstruct the SPH model originally adopted to generate the simulation, and to generate new simulations, emulating the behavior of the unknown SPH model. These results provide a concrete step toward the development of physically accurate models involving a minimal knowledge of the real phenomena.

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