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Catania, 7 - 9 luglio 2026

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107





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# 7ª Conferenza A. Rittmann

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Cover Effusive activity at the south-western base of the South-East Crater of Mt. Etna taken on August 28, 2025 (photo G. Costa)

*In copertina Attività effusiva alla base sud-occidentale del Cratere di Sud-Est del Mt. Etna, ripresa il 29 Agosto 2025 (foto G. Costa)*

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Keywords  Volcanic systems; Geothermal systems; Volcanic risk assessment; Volcanic plumbing systems; Volcano monitoring; Volcano hazard; Modelling of volcanic processes; Eruption dynamics

# S01 - MULTI-HAZARD AND RISK IN VOLCANIC SETTINGS: PAST EFFORTS, RECENT CRISES, AND THE ROAD FROM ASSESSMENT TO RISK MANAGEMENT S01. MULTI-HAZARD AND RISK IN VOLCANIC SETTINGS: PAST EFFORTS, RECENT CRISES, AND THE ROAD FROM ASSESSMENT TO RISK MANAGEMENT

Conveners:

Annalisa Cappello, Antonio Colombi, Laura Sandri, Eugenio Privitera

# The European Civil Protection exercises as a tool for assessing volcanic risk management. The 2025 volcanic MODEX exercise in Tenerife

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On September 2025, a volcanic emergency exercise was held on the island of Tenerife as part of the European Civil Protection Mechanism's MODEX exercises.
MODEX exercises (MOdule EXErcises) are large-scale simulations funded by the European Commission and are a cornerstone of the Union Civil Protection Mechanism. Their primary purpose is to improve the preparedness of European civil protection modules, ensuring a rapid, coordinated, and efficient response to natural or technological disasters within and outside the EU.
The objectives of MODEX are based on four key pillars: i) interoperability of rescue teams from different European countries in international contexts, ii) standardisation of operational procedures (SOPs) to international requirements, iii) verification of module capabilities for their classification within the European Civil Protection Pool, and iv) sharing of experiences to create an on-site practical learning opportunity for all participants.
The island of Tenerife, the largest of the eight Canary Islands, hosts the highest volcano in Europe, Pico del Teide, which has historically produced spectacular eruptions that have caused extensive damages. With the island's growing urbanisation and thriving tourist industry, a possible volcanic eruption could devastate its infrastructure, triggering cascading events, such as forest fires, lahars, debris flows and consequent economic disruption.
In view of these potential challenges, the Cabildo of Tenerife (governor of the Island) requested that the European Union Civil Protection Mechanism (UCPM) undertake an Advisory mission to highlight possible areas of improvement and enhance its preparedness and capacity to respond to volcanic crises and related impacts.
The exercise, the first MODEX ever organised for volcanic risk, was based on an advisory mission to evaluate Tenerife's preparedness plans for crisis communications, evacuation planning, and emergency sheltering. The exercise also included an assessment of current policies, operational capabilities, available resources, and interagency coordination mechanisms to identify gaps and areas for improvement, and to provide actionable recommendations.
Three Union Civil Protection Teams (EUCPT) exercised simultaneously within the same scenario, but each focused on one of the three highlighted goals, operating independently. Each EUCPT was composed of eight experts with well-codified profiles and functions, among which were experts in the field of volcanic risk and the management of volcanic emergencies.
The Cabildo of Tenerife, in collaboration with the Government of the Canary Islands, will seek to use the results of the three exercise reports to strengthen prevention efforts for a possible volcanic unrest or eruptive phase, focusing on improving resilience, strengthening cooperation between Member States, and implementing effective risk mitigation strategies.

# A long-term probabilistic gas hazard analysis at Vulcano Island (Aeolian Archipelago, Italy)

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Vulcano Island (Italy) experiences recurrent degassing events, during which elevated emissions of volcanic gases, particularly $CO_2$ and $SO_2$, can represent a considerable risk to both the local population and the environment. In this work, we present the first quantitative probabilistic assessment of volcanic gas dispersion hazards for the island, considering three degassing scenarios: i) background activity based on the last 20 years of gas monitoring, ii) unrest linked to the enhanced degassing episodes observed in 2021-2022, and iii) a potential escalation of gas emissions during an exceptionally intense degassing crisis. The study relies on a comprehensive dataset of gas flux measurements collected by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) over the past few decades. Atmospheric variability is accounted for using the ERA5 climate reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) spanning the last 30 years, combined with wind data from a local meteorological station. Hazard and persistence maps are generated through the Python-based VIGIL workflow (v.1.4), which integrates both passive and gravity-driven dispersion models (DISGAS v.2.6.0, TWODEE-2 v.2.6.0). Our findings at a 5% exceedance probability indicate that $SO_2$ dispersion from fumarolic degassing at the crater represents a substantial hazard during the unrest scenario ($SO_2$ > 50 ppm at 2 m above ground in the La Fossa crater, gradually decreasing to 0.05 ppm along the flanks), and even higher under the potentially worsening scenario. Although $CO_2$ dispersion affects much of the inhabited areas, outdoor concentrations generally remain below hazardous levels ($CO_2$ > 5000 ppm occurs only in the crater region at 2 m above ground). Additionally, gas concentration measurements collected at four monitoring sites in the Vulcano Porto area during 2022 were used to constrain the local fumarolic $CO_2$ flux and to estimate the contribution of previously unmeasured emissions. Considering the island's recurring degassing crises and intense seasonal tourism, our study highlights the value of long-term probabilistic hazard assessment to guide effective risk mitigation strategies.

# A lightweight modular MultiGAS platform for adaptable gas monitoring across volcanic and wildfire environments

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Volcanic regions frequently host multiple interacting hazards, including volcanic gas emissions, secondary atmospheric impacts and wildfire activity that complicate hazard monitoring and interpretation of gas measurements. These environments require flexible monitoring strategies capable of measuring gas species associated with magmatic, hydrothermal and combustion processes. In volcanic regions, gas hazard monitoring is commonly used to track gas behavior and changes in volcanic activity. However, overlapping gas sources from combustion, geothermal emissions, and magmatic degassing can complicate the interpretation of measured gas ratios and plume composition. Additionally, many gas monitoring instruments are designed for specific hazard types, limiting their adaptability during complex or evolving hazard scenarios.

This study presents the development of a lightweight and flexible MultiGAS platform designed to support adaptable gas monitoring across combustion and volcanic environments. The instrument architecture was modeled after volcanic MultiGAS systems but adapted to characterize wildfire emissions while retaining the flexibility to integrate alternative gas sensors for diverse contexts. The platform is a compact four-channel data logging system capable of integrating nondispersive infrared and electrochemical sensors. In its wildfire configuration, the instrument measures $CO_2$, CO, and $H_2O$ to characterize combustion phase processes and plume composition. However, the modular design allows sensors to be exchanged depending on monitoring objectives. Alternative configurations can incorporate volcanic gas species such as $SO_2$ or $H_2S$ alongside $CO_2$ and $H_2O$, enabling the same platform to support measurements relevant to both combustion emissions and volcanic degassing.

The system was designed with portability and rapid deployment in mind. Its compact and lightweight configuration allows operation during handheld surveys, fixed monitoring stations, or deployment on small drones. This expands the range of environments that can be sampled, particularly in hazardous or remote terrain where traditional monitoring instruments may be difficult to deploy.

Preliminary field testing demonstrates the instrument's ability to capture high-resolution gas concentration time series in combustion plumes while maintaining compatibility with alternative sensor configurations relevant to volcanic gas monitoring. The platform therefore provides a flexible framework for gas observations in environments where wildfire activity and volcanic degassing may occur simultaneously or sequentially.

Adaptable monitoring tools that can accommodate multiple gas species and deployment strategies may help improve observational coverage in complex environments where multiple hazards interact.

# Advancing lava flow hazard modelling with optimized statistical and deterministic simulation workflows

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Predicting the potential paths of lava flows during ongoing eruptions is essential for volcanic hazard assessment. Two-dimensional (2D) numerical models are widely used for this purpose because they provide a good compromise between computational efficiency and the ability to simulate lava flow emplacement. These models can incorporate input parameters derived from remote sensing and field observations, such as the time-averaged discharge rate (TADR), vent location, and the extent of the active lava field.
However, uncertainties in these parameters, together with simplifications associated with the model approach, make it difficult to identify the optimal conditions that best reproduce observed lava flows. In addition, simple 2D approaches often struggle to simulate complex lava fields generated by multiple overlapping flow units and variable eruptive dynamics, including the opening of new vents and/or ephemeral vents and fluctuations in effusion rate. Addressing such processes through multistep simulations involving multiple vents increases the dimensionality of the parameter space and the associated computational cost.
To efficiently explore the parameter space and identify best-fit solutions, this study tests two optimization approaches: the Metropolis-Hastings algorithm, part of the Markov Chain Monte Carlo (MCMC) family, and the Nelder-Mead method, a direct search technique that minimizes a nonlinear objective function. The former allows a comprehensive exploration of the parameter space and provides probability distributions of the parameters, whereas the latter aims to identify a single optimal solution with significantly lower computational cost, although it may be sensitive to local minima. These approaches are applied to the 27 February - 01 March 2017 eruption and 13 May - 16 June 2022 effusive eruptions at Mt. Etna (Italy) to evaluate their performance in reproducing observed lava flows and supporting rapid hazard assessment.

# Transitioning from Multi-Hazard Assessment to Integrated Risk at Mt. Etna

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Mount Etna presents a complex multi-hazard environment, where effusive and explosive eruptions are frequently accompanied by intense volcano-tectonic seismicity. For the densely populated and highly urbanized areas on its flanks, these simultaneous and sequential hazards (specifically lava flows, tephra fallout, and earthquakes) can produce cumulative impacts, making comprehensive risk assessment critical for civil protection actions and land-use planning. Here we present the results of the INGV project PANACEA (Probabilistic Assessment of volcano-related multi-hazard and multi-risk at Mount Etna), which has developed an integrated framework that addresses the transition from multi-hazard to risk assessment.

The multi-hazard assessment is performed using a "target-based" approach to harmoniously integrate the probabilistic single-hazard assessments. This approach starts by defining a target objective (i.e. a situation of tangible concern) and, for each specific hazard, a critical intensity threshold that, if exceeded, implies the occurrence of the target objective. Probabilistic Hazard Assessment for the different single hazards over harmonized temporal and spatial grids quantifies the probability to exceed the critical thresholds, thus quantifying the probability of the target objective to occur. With this approach, we provide an objective, data-driven multi-hazard metric for the target objective. This multi-hazard information can be translated into comprehensive multi-risk estimates by identifying and characterizing exposed and vulnerable elements (demography, residential buildings and critical lifelines) across six highly exposed municipalities on Etna's south-east flank. We thus developed probabilistic damage scenarios by coupling the hazard intensities with specific vulnerability models and fragility curves. We performed both unconditional risk analyses related to a specific time exposure and conditional risk analyses related to an event with a certain time exposure and probability of excess. In this latter case, it was possible to quantify building damage (the target objective) through a multi-risk assessment due to tephra and earthquake hazard factors calculated with a probability of excess of 5% and 10% and an exposure time of 5, 10, and 30 years.

By linking robust multi-hazard modeling with granular vulnerability and risk assessment, this methodology effectively bridges the gap between scientific assessment and operational risk management. The tools presented enable civil protection authorities and decision-makers to explore multi-risk scenarios, plan interventions, and strengthen preparedness and response capacities for future multi-hazard eruptive crises.

# Reconstruction and probability hazard mapping of deposit-derived pyroclastic density currents at Stromboli

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Deposit-derived pyroclastic density currents (dd-PDCs) are generated by the gravitational instability of hot, unstable volcaniclastic deposits. In the case of Stromboli volcano, their generation is associated with paroxysmal explosions, a transient and impulsive explosive activity more energetic than the volcano's ordinary activity and lower-scale events. Although typically confined within the topographic depression of Sciara del Fuoco, historical events in 1930 and 1944 demonstrated that these flows can pose a significant risk to inhabited areas and hikers.
The first part of the research was dedicated to the quantitative reconstruction of the September 11, 1930 event by integrating new field observations, historical records, and numerical modeling of the flow. Recent erosive floods allowed us to analyze previously unrecognized dd-PDC deposits in the San Bartolo valley, in addition to those already identified in the Vallonazzo basin, which are two of the main basins that directly threat the village of Stromboli. The new data, together with observations coming from historical accounts, were used to constrain maximum flow thicknesses along the two valleys. A shallow-water dense granular flow model coupled with an inversion algorithm were then adopted to simulate the propagation of the flow along the valleys and to reconstruct probabilistically the phenomenon. Simulation results show that, consistently with field evidence, the Vallonazzo flow was able to reach the sea and form a delta, whereas the San Bartolo dd-PDC stopped not distant from the local church. The inversion algorithm indicated remobilized volumes in the range 3-6 $*10^4$ $m^3$. Such volumes represent just a limited fraction of the material erupted during a paroxysm, underscoring the significant hazard associated with this phenomenon. However, we estimated that just an average of about 12% of the flow total volume entered the sea in front of Vallonazzo, therefore representing an unlikely source of the tsunami observed during the 1930 event.
Based on the reconstruction of the 1930 event, the second part of the research allowed to obtain first estimates of invasion probability over future decades in case of events similar to those of last century. The analysis of topographic basins allowed the identification of 6 main drainage basins with impact potential. Among these, San Bartolo, Scalo dei Balordi, and Ginostra "A" show the highest conditional invasion probabilities with values up to 28% at 50 m a.s.l. Moreover, using a new temporal model that links the frequency of paroxysmal explosions to dd-PDC occurrence, a mean probability of at least one flow occurrence outside Sciara del Fuoco of about 9 and 49% over the next 10 and 50 years, respectively, was estimated. When combined with spatial estimates, mean invasion probabilities of up to 4% in inhabited areas of the three more exposed basins over the next decade were computed, which increased sevenfold over 50 years. Results highlight the significant risk, although largely uncertain due to the limited historical record, associated with dd- PDCs at Stromboli and illustrate a novel approach to map such hazard at similar volcanic systems.

S01 - Oral Presentation

# PEOS: an open Earth Observation e-infrastructure supporting multi-hazard monitoring and risk management in volcanic settings

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Volcanic crises are characterized by the interaction of multiple hazards such as lava flows, pyroclastic density currents, ash fallout, volcanic clouds, lahars and volcano-tectonic earthquakes. These phenomena may occur simultaneously or in rapid succession, generating cascading impacts on exposed populations, infrastructures and critical services. In densely populated volcanic regions, the capability to rapidly detect evolving hazards, integrate heterogeneous observations and translate scientific information into actionable products is therefore essential for effective risk assessment and crisis management. Earth Observation data play an increasingly important role in this context by providing synoptic, repeatable and multi-parameter measurements that complement ground-based monitoring networks and support operational decision-making during volcanic unrest and eruptive crises.

Within the framework of the PNRR MEET project (Monitoring Earth's Evolution and Tectonics), Work Package 9 addresses these challenges through the development of PEOS, the Platform for Earth Observation from Space. PEOS is developed within the Earth Space Observation Center (COS) of the Istituto Nazionale di Geofisica e Vulcanologia, which coordinates the institute's activities in satellite observations, remote sensing applications and space technologies for geophysical monitoring. The platform provides an integrated technological environment designed to support the ingestion, processing, management and dissemination of satellite-derived Earth Observation data and value-added products relevant to natural hazard monitoring and disaster risk management.

PEOS is conceived as an open, modular and expandable e-infrastructure capable of hosting heterogeneous processing modules and integrating different categories of satellite-derived datasets within a shared technological framework. The platform supports automated data ingestion, execution of scientific processing chains and publication of standardized outputs through interoperable services. Within volcanic environments, the platform integrates algorithms and products for the detection and quantification of volcanic thermal anomalies, satellite-based observations of ash clouds and plume height, and deformation analyses derived from SAR interferometry and GNSS measurements. Additional datasets include digital surface models derived from high-resolution optical imagery as well as ground-based observations used for calibration and validation of satellite-derived products.

By integrating these heterogeneous observations within a unified environment, PEOS contributes to improving the capability to monitor volcanic activity and to rapidly detect evolving hazard conditions. Satellite-derived products generated by the platform can support the identification of eruptive phenomena, the characterization of volcanic plumes and the monitoring of ground deformation associated with magma migration. These observations provide critical information for hazard assessment and contribute to the definition of dynamic scenarios that are relevant for civil protection authorities and operational monitoring centers during periods of unrest and eruptive crises.

Beyond the generation of specific products, PEOS aims to transform Earth Observation

processing outputs into interoperable digital resources that can be efficiently accessed and reused by both the scientific community and operational stakeholders involved in risk management. The platform promotes the harmonization of heterogeneous workflows through standardized input and output formats, shared metadata descriptions and interoperable service interfaces that enable automated dissemination through dedicated gateways and data portals. This approach facilitates the integration of internally generated products with externally produced datasets, provided they comply with the technological and interoperability standards adopted by the platform.

By enabling the systematic integration of satellite observations into operational monitoring workflows, PEOS contributes to strengthening the link between hazard observation, hazard assessment and risk management in volcanic settings. The platform provides a technological framework capable of supporting the timely dissemination of observational products relevant for crisis response and preparedness, improving the capacity to translate evolving volcanic hazards into actionable information for decision-makers and civil protection authorities. In this perspective, PEOS represents a step toward more integrated and interoperable infrastructures able to support multi-hazard monitoring, risk assessment and emergency management in volcanic regions.

# Shared efforts to link multi-hazard dynamics and social perception in Stromboli (Italy): The NEAM-COMMITMENT project

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Not all attractive islands are the same. Despite its stunning seascape, Stromboli (Aeolian Islands, Italy) is not renowned for its beaches (the coast is mostly rocky cliffs), nor for its terrain (flat areas are very limited). Despite being very crowded during its long tourist season, it is not a classic vacation spot (volcanic rumble can be as constant as the wind), nor is it easy to reach (only smaller ships can moor), and rough seas often dictate the schedule of transportation (in any season). Dominated by the active volcanic edifice, its topography is in a transient equilibrium, with critical mass instabilities, deep channelling, and large landslides (mostly affecting uninhabited areas). Furthermore, among the tourists who visit the island, there is a paradox: some come specifically for its natural beauty, while others arrive unaware that it is an active volcano.
Yet, Stromboli is a unique spot, notably depicted in the 1950 film Stromboli, directed by Roberto Rossellini and starring Ingrid Bergman. Tiny (12,6 km$^2$) and tall (926 m a.s.l.), the steep volcanic island unmistakably bears any solid-earth activity. Major geological evidence is found on the north-western flank, where three debated medieval tsunamis have been attributed to large-scale collapses of the Sciara del Fuoco or its precursor structures; other events in the early 20$^{th}$ century were due to volcanic activity. More recently, landslides along the Sciara del Fuoco triggered the 2002 tsunami, and minor waves resulted from pyroclastic flows (e.g., 2022), reflecting the ongoing instability driven by continuous Strombolian eruptions and lava flows.
Stromboli has been the object of in-depth geological, geophysical, geochemical, and geodetic research for decades, due to its steady volcanic activity and paroxysmal stages that, during the early 20$^{th}$ century, even prompted most of the population to flee the island. These historical events form the core of a persistent social memory and a 'sense of place' that continues to shape current risk perception and community resilience. Among the local population, a deeply ingrained belief has emerged that the volcano is essentially benign: it may rumble, yet it is not regarded as a true threat. Changing this perception is one of the most formidable challenges to implementing an effective risk mitigation strategy.
Seismic shaking and major landslides can potentially trigger tsunamis capable of damaging the

island's coasts. Volcanic hazards, flooding, mud flows, and fire pose additional threats due to a combination of climatic and topographic factors. These combined hazards, along with the peculiar location of Stromboli, have led to a very dense, diverse effort across institutions for 24/7 volcanic, geochemical, seismic, and tsunami monitoring. As mentioned, the human factor introduces further complexities in how the population perceives this combined, multi-risk pattern and in how it reacts or adapts to the countermeasures enacted. The challenge of identifying key figures, for instance, is exacerbated by the coexistence of diverse cultural worldviews. Previous qualitative studies on the island highlight a tension between a strong individualistic orientation and egalitarian solidarity, which significantly influences the acceptance of institutional risk-mitigation measures.

Stromboli is, thus, a vivid demonstration of how tiny geographies can hold a surprisingly vast array of hazards, some of them concomitant or cascading. These affect a local population (ranging from year-round residents to many visitors, either daily or for longer stays) exposed to a complex set of risks and effects, hailing from the land, the sea, in the near- and the far-field, sometimes in contrasting patterns and distribution, calling for choices and adaptation efforts. Therefore, NEAM-COMMITMENT, an EU-funded (DG ECHO) project for the 2025-27 time span focussing on the update of protective measures and strategies to shield local communities from the manifestations of tsunami hazard, selected Stromboli as one of the key target areas to: a) implement joint modelling of multi-hazards in complex coastal settings, and b) extract key lessons on how local communities respond to tsunami countermeasures through a human-centric qualitative approach, to transform local 'lived experiences' into scientific evidence for civil protection strategies.

We report on the joint, elaborate efforts to bring this modelling, planning, and communication activity to a unique environment - both natural and risk landscapes - inhabited by a population that, although tiny, is as storied and diverse as that of larger communities. How such deployments work thus also depends on collective undertakings at the intersection of applied science and society. Beyond information delivery, the project aims to foster the emotional normalisation of risk by bridging monitoring with local knowledge, reducing fatalism, and providing scalable lessons for complex societal contexts.

# Probabilistic hazard maps of lahar inundation in case of a reference-size eruption at Campi Flegrei

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Following a volcanic eruption, the formation of lahars, flows composed of volcanic debris and water with a mud-like consistency, can occur. These flows typically channel through valleys and settle at the base of slopes, representing a very hazardous volcanic phenomenon due to their high mobility, energy, and destructive potential.
The Campi Flegrei caldera (Italy) can be vulnerable to lahar-related hazards since the slopes of the inner craters, as well as nearby valleys, are mantled with tephra deposits originating from past explosive eruptions. These deposits are highly susceptible to remobilization, especially during periods of intense or prolonged rainfall. The area is also densely urbanized with significant human activity that, in some places, has profoundly altered the surface features of the terrain.
Following the methodological approaches proposed in previous studies [de' Michieli Vitturi et al., 2024; Sandri et al., 2024], in this contribution we aim to carry out a probabilistic hazard assessment of lahar inundation within and around the Yellow Zone area. Consistently with the Emergency Plan, we considered the remobilization of tephra deposits from a medium-sized eruption at the Campi Flegrei (Astroni type), which generates a lahar from at least one of the 11 catchments considered.
To model the lahar flows, including erosion and deposition effects, we used the latest version of the IMEX_SfloW2D-v2 code, orchestrated by a workflow running an ensemble of simulations to provide probabilistic hazard maps.
Field data, where available, were used to constrain the range of parameters values to be explored (e.g. bulk grain size distribution, sediment porosity, density). Suitable probability density functions were set to describe the relevant initial parameters, such as the range of slopes where the initial flow detaches and its initial solid fraction. Results from an ensemble of tephra fallout simulations, previously performed with Fall3D [Folch et al., 2020], were used to quantify the available tephra on the ground to be remobilised. Further constraints on the available water, derived from the analysis of the rainfall record in the Campanian area, fully defined the initial volume of the remobilised flow.
Thanks to the availability of computational resources provided by the Supercomputing ICSC (Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing, through the Istituto Nazionale di Geofisica e Vulcanologia and University of Bari) and by CINECA (on Leonardo supercomputer), and to the performance of the most recent model version, we could explore and quantify the effects of the uncertainty on the vent position and on the initial flow conditions on the hazard. To this end, ensembles of model simulations were performed from each of the 11 catchments considered by sampling coherent sets of values for the input model parameters, and performing a large ensemble of simulations (ca. 3100 for each catchment, for a total of 34100 simulations).

The post-processing of the simulation outputs led to the production of (i) probabilistic hazard curves and maps for the maximum flow thickness reached on a grid of points covering the investigated area, and (ii) probabilistic hazard surfaces for the simultaneous overcoming of pairs of flow thickness and dynamic pressure on the same grid. This is an ongoing study whose results may offer valuable support for civil protection planning and risk mitigation efforts.

# Towards a complete and quantitative description of the volcanic hazard at Campi Flegrei caldera with implications for the emergency planning

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Hazard and risk management in densely populated volcanic areas requires the development of quantitative assessments. The Campi Flegrei caldera represents one of the highest-risk volcanic areas on the planet, due to its population density, and is currently in a phase of unrest characterized by ground deformations, seismicity, and gas emissions. Hazard assessment at Campi Flegrei is intrinsically complex, due to the difficulty in interpreting pre-eruptive patterns, and furthermore the caldera shows a great variability in vent locations and eruption sizes, not presenting a simple pattern that can be easily extrapolated to future activity. Here we develop a hazard model based on a Bayesian Event Tree (BET) that integrates eruption forecasting, scenario forecasting and impact forecasting by means of conditional probability rules. In particular: i) the model gives sense of heuristic pre-eruptive information through an entropy-based method and incorporates model heterogeneity through experts' elicitation; ii) takes into account vent and size variability through continuous probability distributions, overcoming the limitations of scenario-based approaches; iii) evaluates the impact of individual hazard phenomena by integrating different computational models. By propagating uncertainties across the BET nodes this approach allows for a transparent and consistent assessment of all possible outcomes in near real time, thus providing a tool that significantly facilitates risk management and decision-making in the Phlegraean area.

# AI-Based Risk Communication and Conscious Tourism Development in Volcanic Areas. The Case of Mr Plinio, the AI assistant of Vesuvius National Park

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Volcanic areas are environments of exceptional scientific, ecological and cultural value, characterized by multiple layers of risk that require effective communication strategies for residents and visitors alike. In this context, the challenge is not only to protect and enhance fragile territories, but also to promote forms of tourism that are informed, responsible and compatible with environmental safety. This contribution presents the case of Mr. Plinio, the artificial intelligence (AI) virtual assistant developed by the Vesuvius National Park, as an innovative tool for supporting risk communication and fostering conscious tourism in an active volcanic area.

In 2024, the Vesuvius National Park launched an important process of digital innovation, becoming the first Italian national park to adopt an AI-based chatbot as part of its management and communication strategy. This initiative is framed within the Park's commitment to the European Charter for Sustainable Tourism (ECST/CETS) promoted by EUROPARC, and reflects a broader vision aimed at integrating sustainability, visitor services and digital transition in protected area governance. Within this framework, Mr. Plinio was conceived as a digital interface capable of connecting environmental protection, public accessibility and territorial safety.

The relevance of this tool is particularly significant in a context such as Vesuvius, where tourism takes place in a living volcanic landscape marked by both its attractiveness and its vulnerability. Visitors are often drawn by the symbolic and natural importance of the volcano, while not always being fully aware of the specific conditions that characterize access to and use of the area. In addition to the long-term volcanic risk connected to the active nature of Vesuvius, the Park is also exposed to more immediate and recurrent hazards, such as wildfires, temporary trail closures, weather-related restrictions and safety regulations linked to protected area management. In such a setting, communication cannot be limited to generic institutional messaging: it must be timely, understandable, accessible, multilingual, and oriented toward concrete behavioural guidance.

Mr. Plinio responds to this need by offering real-time information on trails, access conditions, visiting rules, points of interest and practical aspects of the visitor experience, while also functioning as a support tool for environmental safety communication. Through the chatbot, users can receive immediate indications on appropriate behaviour in potentially critical situations, access basic guidance related to emergencies, and obtain updated information that may influence how, when and under what conditions to visit the Park. In this sense, the assistant helps translate institutional and scientific information into a more user-friendly and interactive format, reducing informational asymmetries between park management and visitors.

From a risk communication perspective, the value of Mr. Plinio lies in its ability to accompany the visitor before and during the visit, shifting communication from a static and one-directional model to a more dynamic and dialogic one. Rather than addressing risk only in exceptional circumstances, the chatbot contributes to embedding safety awareness into the ordinary tourism experience. It can therefore support a preventive approach, encouraging visitors to understand that a volcanic protected area is not only a destination to be consumed, but also a sensitive environment that

requires attention, respect and adaptive behaviour. This is particularly important in areas where the perception of scenic beauty may overshadow awareness of natural hazards.

More broadly, the case of Mr. Plinio suggests how AI-based tools may contribute to rethinking tourism management in volcanic and high-risk natural environments. By combining visitor assistance, interpretation, accessibility and safety-oriented communication, such systems can strengthen institutional capacity to guide visitor behaviour and improve the overall quality of the tourism experience. At the same time, they may help protected area authorities to promote a model of tourism that is more conscious of environmental limits, more attentive to risk and more aligned with the principles of sustainability.

The poster discusses Mr. Plinio as an emerging practice at the intersection of science communication, digital innovation and protected area management. The Vesuvius National Park case highlights the potential of artificial intelligence not as a substitute for scientific and institutional responsibility, rather as a complementary tool for making risk communication more immediate, widespread and accessible in everyday visitor interactions. In this perspective, AI can play a strategic role in supporting tourism models that are smarter and safer, raising awareness on the risks related to volcanic territories.

# Improved size distribution for improved volcanic hazard assessment

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The size of volcanic eruptions represents a fundamental parameter for hazard assessment, as the type, extent, and intensity of associated phenomena are strongly dependent on it. Many approaches divide volcanic eruption sizes into discrete classes, but while this approach can be a good first-order approximation, it can result in an oversimplification of the hazard assessment. Considering the erupted volume as a proxy for the size of the eruptions, to overcome such discretization, erupted volumes are often modeled with a power-law distribution. However, the distribution of the measured/inferred erupted volume of past eruptions often appears markedly different from a power-law. Here, we show how the uncertainty on the size of past eruptions can affect the shape of the distribution by modeling the magnitude (log-transformation of the volume) with an Exponentially Modified Gaussian distribution (EMG) that takes volume error into account. We apply this method to two large high-risk calderas, Campi Flegrei (Italy) and Taupo (New Zealand), but it can be potentially applied to any volcano. We find that the EMG distribution provides a good statistical fit to both volcanoes' eruptive records, supporting the use of a power-law distribution for forecasting the volume of the next eruption. The use of a continuous distribution of eruptive size allows for a more accurate implementation of computational models of eruptive phenomena, thus significantly improving multi-hazard/risk assessment.

# Web and Social Media Communication During the 2025-2026 Mt. Etna Eruption

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This study presents a case analysis of the Mt. Etna eruptive activity between December 2025 and January 2026, focusing on the web and social media communication strategies adopted by INGVvulcani working group and their impact on the public. The event was characterized by intense Strombolian activity, paroxysmal episodes, and lava flows in the Valle del Bove, accompanied by increased shallow seismicity.
Institutional communication was developed through an integrated system including official bulletins, in-depth articles on the INGVvulcani blog, and timely updates across social media platforms (Facebook, Instagram, Bluesky, and YouTube), using clear language and multimedia content.
Data analysis highlights a strong communication impact: the blog recorded approximately 38,000 views and 30,000 users during the analyzed period, while social media platforms reached hundreds of thousands of views and generated significant engagement. The audience was predominantly local (Sicily), with content mainly accessed via mobile devices.
Sentiment analysis indicates predominantly positive reactions, often linked to the visual appeal of the eruption, alongside peaks of negative sentiment associated with fear and access restrictions. The results underline how timeliness, clarity, and the use of visual content are key elements for effective volcanic risk communication, contributing to strengthening INGV's role as a trusted and authoritative source.

# A space-based volcano observatory: toward an integrated multi-platform and multi-spectral infrastructure for near-real-time monitoring of Italian volcanoes

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New-generation Earth observation satellites operated by international space agencies are equipped with state-of-the-art multispectral and thermal infrared sensors that, considered collectively, constitute a powerful and continuously expanding orbital infrastructure for the detection, characterisation, and surveillance of volcanic activity. Low-Earth Orbit (LEO) and Geostationary (GEO) platforms span a broad and complementary observational parameter space in terms of spatial, spectral, and temporal resolution, offering synergistic perspectives on volcanic behaviour that no single platform can replicate alone.

Through the fusion of multi-source satellite datasets, it becomes possible to characterise volcanic activity across different scales and timescales, while resolving subtle or transient departures from background thermal and spectral states that would remain undetected by any individual sensor.

The rapid advancement of Artificial Intelligence (AI) analytical techniques, increasingly tailored to satellite-derived geophysical datasets, opens new avenues for extracting subtle or hidden signals embedded within complex multi-source observational records. Interpreted within a volcanological framework by domain experts, these signals can be translated into physically grounded constraints on volcanic processes, bridging surface thermal manifestations with shallow to deep-seated magmatic and hydrothermal dynamics.

Here we outline the potential of this growing orbital constellation for the systematic Near-Real-Time (NRT) monitoring of Italian volcanic systems, offering a pathway toward more comprehensive, continuous, and process-oriented space-based monitoring strategies, with direct implications for volcanic hazard assessment and risk reduction at a national scale.

# Lava Flow Hazard and Impact on Natural Habitats: The Mount Etna Case Study

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Volcanic eruptions are among the most powerful natural forces shaping terrestrial ecosystems, influencing the structure, composition, and distribution of plant communities. Currently, impacts on habitats (Hs) are determined by the type of eruption, the chemical properties of the erupted volcanic products (tephra and lava flows), and the proximity to the eruption site. Mt. Etna is the highest active volcano in Europe (3,403 m a.s.l.) and is characterized by nearly continuous eruptive activity from summit craters and fairly frequent lava flows from lateral fissures. The richness of Etna's vascular flora corresponds to approximately one-third of the Sicilian flora, while the endemic component represents over one-fifth of Sicilian endemism. High-mountain Hs occurring in the cryo- and oro-Mediterranean bioclimatic belts of Mt. Etna are examples of vegetation that are often erased following eruptive events. However, Hs located at lower altitudes are also constantly threatened by lava flows, especially in the case of flank eruptions, and future eruptive events are potentially impactful on vegetation.
In this study, we perform a statistical analysis aimed at estimating the potential destructiveness of phytocoenoses from future volcanic events by combining information derived from hazard maps of lava flow inundation and the distribution of Hs on Mt. Etna. Our study aims at identifying the most vulnerable Hs that have the highest probability of being damaged or completely erased by a future eruptive event. Finally, our research provides more quantitative and reliable data on habitats of community interest listed in the Annex I of the Habitat Directive (92/43/CEE) that are continuously influenced by the volcanic activity of Mt. Etna.

# Secondary Volcanic Hazards by using Optical Satellite Data: The Case of Stromboli Volcano

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The extraordinary volcanic activity of Stromboli Island (Aeolian Archipelago, Italy), consisting of explosions of high energy and magnitude known as paroxysms, can trigger wildfires when the projectiles ejected during such activity reach and hit the vegetated areas of the island. The wildfire spreading causes disruption in natural and cultivated areas. Consequently, the loss of vegetation, combined with the thick and unconsolidated tephra deposits, drastically reduce slope stability and enhance surface runoff, favoring the formation of lahars in cases of intense and prolonged rainfall. This work considers 3rd of July 2019 paroxysm, the induced wildfire, the vegetation loss, the accumulation of incoherent material and the remobilization of the loose deposits. Moreover, the wildfire that occurred on the 22nd of May 2022 has been considered as further case study. The secondary hazards have been identified and mapped by using S-2, Landsat-8, ASI-Prisma and Pleiades data. In particular, the wildfire has been detected by using ASI-Prisma data and the related burnt area was mapped through spectral indexes applied to S-2 and Landsat-8 data. In addition, the surface changes that occurred on volcano flanks and generated by secondary hazards have been analyzed through the 3D models of Stromboli pre and post-events obtained by processing Pleiades 1A - 1B data in Tri stereo acquisition mode. The results obtained in this study will also show the impact on the tourist pathways on the Island.

# Validating gas-particle flow dynamics in computational volcanology: From fluidized particle beds to three-dimensional eruption scenarios

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Understanding explosive eruptions and assessing the hazards they pose has long been a challenge in volcanology. Direct field observations are often incomplete, and many explosive events occur with little or no forewarning. Laboratory experiments cannot fully reproduce natural conditions, where initial and boundary conditions are uncertain, and processes operate across a wide range of spatial and temporal scales. These nonlinear, multidimensional, multiphase flow interactions make complex the physical mechanisms controlling eruptive dynamics.
Among these processes, gas-particle flows have a key role in controlling the dynamics of pyroclastic mixture and explosive eruptions. Fluidization within dense granular volcanic flows can strongly influence mobility and runout, making it an important process to capture in multiphase numerical models. Fluidization behavior depends not only on the gas phase but also on particle properties, particularly on grain-size distribution. Differences between monodisperse and binary particle mixtures affect bed expansion, fluidization dynamics, and mixing and segregation rates. To represent these effects realistically in volcanic simulations, the influence of particle sizes must first be validated in controlled environments.
Accurate numerical modeling of gas-particle systems therefore requires physics-based multiphase formulations tested against laboratory benchmarks. Fluidized beds provide ideal validation cases because they isolate relevant gas-particle interactions within measurable experimental conditions. In this work, fluidized-bed simulations are performed using OpenPDAC, an open-source, high-performance computing (HPC) framework built on OpenFOAM. The numerical formulation is based on the Kinetic Theory of Granular Flow (KTGF), which describes dilute and concentrated gas-solid mixtures and allows investigation of fluidization dynamics in controlled numerical experiments.
The model is validated against fluidized bed laboratory experiments from Goldschmidt et al., 2003. These experiments provide well-constrained benchmarks for fluidization behavior, including vertical bed expansion, segregation, and particle mobilization. The simulations allow controlled variation of key physical parameters, enabling the evaluation of the model's ability to capture particle-gas dynamics in both monodisperse and binary systems and to reproduce quantitatively the results of the laboratory experiments.
In addition to the activity aimed at the validation of the model, the framework is extended to volcanic-scale simulations. Three-dimensional simulations of phreatic eruption scenarios have been initiated for vents at Solfatara and Pisciarelli within Campi Flegrei, a densely populated active caldera. An additional case study is underway for Kuchinoerabujima, where recent activity highlights the importance of understanding phreatic explosion dynamics. These simulations explore the development and propagation of particle-laden flows, including ash dispersal and as well as ballistic trajectories across natural topography.
Results from the three-dimensional simulations show that concentrated basal regions can develop within propagating flows. In these regions, particle interactions become increasingly significant, having an influence on overall flow dynamics. Such behavior highlights the importance of multiphase granular modeling approaches capable of capturing particle-particle interactions in dense regimes.

This work combines laboratory validation and volcanic application within an open-source HPC framework. By incorporating grain-size effects and fluidization physics into multiphase simulations based on kinetic theory, the approach provides a pathway toward increasingly realistic three-dimensional models of explosive eruptions. These models offer new opportunities to investigate eruption dynamics and support physics-based hazard assessments for active volcanic systems.

# Natural emergencies: psychosocial vulnerabilities, resilience, and emergency social work

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Natural emergencies cannot be limited to geophysical phenomena alone; rather, they require the integration of psychosocial perspectives in order to fully understand human dynamics ante, during, and post-disaster. Therefore, it is necessary to consider the presence of a coordinating figure, such as the sociologist, who must take into account social vulnerabilities, community networks, and resilience trajectories in order to promote integrated interventions capable of strengthening territorial cohesion, mitigating inequalities exacerbated by disasters, and integrating tools for psychosocial monitoring and the participatory reconstruction of affected communities.
This work aims to develop a sociologically coherent conceptual framework, starting from the distinction between hazard (the objective natural event) and risk (the interaction between hazard and social vulnerabilities), in order to analyze the psychosocial management of emergencies, the role of the sociologist, and the role of emergency social work within highly resilient contexts.
The paper emphasizes the need for emergency strategies that operate synergistically with the sociological analysis of structural inequalities (e.g., territorial socio-economic inequalities). It also suggests the need of psychosocial interventions to redefine the conditions of well-being and community functionality. Disasters, in fact, emerge from the systemic vulnerabilities of a society, influencing both catastrophic outcomes and processes of relational reconstruction.
Individual and collective vulnerability - rooted in structural, relational and cultural factors - determines the impact of disasters and the capacity for resilience. Within this theoretical framework, an emergency social service could play a central role as an operational interface with other actors within a delicate scenario. It should be capable of addressing the vulnerabilities intensified by the event, rebuilding social networks, and mediating with institutions in order to respond to emerging community needs.
The paper intertwines the empirical results of psychosocial studies with the sociology of disasters (e.g., paradigms of social vulnerability and adaptive resilience), proposing a multidisciplinary model based on vulnerability assessment, psychological support, the strengthening of local networks, and the development of an operational platform for social workers.

# S02 - VOLATILES IN MOTION: GEOCHEMICAL INSIGHTS INTO MAGMA DEGASSING, VOLATILE TRANSFER, AND SURFACE GAS EMISSIONS

Conveners:

Andrea Ricci, Pierangelo Romano

# A decade of $SO_2$ flux and thermal observations at Mount Etna: Insights into magma supply, storage and eruptive activity

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Volcanic gases represent a primary expression of magmatic activity and provide key insights into the state of a volcanic system. Among volcanic gases, sulphur dioxide ($SO_2$) is widely recognized as a key tracer of shallow degassing dynamics and magma transport within the upper portion of plumbing systems, becoming a valuable tracer of transitions from quiescence to eruptive phases. Here we present an integrated analysis of nearly a decade (2015-2024) of $SO_2$ flux observations at Mount Etna obtained from a permanent ground-based UV Camera system, combined with satellite-derived thermal fluxes. This long-term dataset allows us to explore the relationship between degassing behaviour and thermal output across different eruptive states.

Using satellite thermal radiance, we identify the Etna's major eruptive phases, which account for more than 90% of the total thermal energy released during the study period. Comparison with the $SO_2$ flux time series reveals a characteristic escalation pattern associated with these phases: mean fluxes increase from ~1957 t/d during inter-eruptive periods to ~2500 t/d in the pre- and post-eruptive intervals, peaking at ~3800 t/d during eruptive activity. This $SO_2$ escalation is successfully detected from the employed UV Camera system in 61%, 72% and 72% of the studied pre-, syn-, and post-eruptive periods respectively, with increasing success for larger eruptions.

By converting $SO_2$ emissions and thermal radiance into magma supply and discharge rates, we further quantify the long-term imbalance between magma input and output at Mont Etna. Our results indicate that, over the investigated decade, only ~28% of the magma supplied to the shallow plumbing system was ultimately erupted, while the remaining ~72% accumulated as excess magma within the volcanic edifice. This imbalance reflects distinct stages of accumulation and withdrawal, consistent with GNSS (Global Navigation Satellite System) observations from a continuous geodetic network.

Overall, our results demonstrate that the combined analysis of ground-based gas measurements and satellite thermal observations provides a powerful framework for investigating magma transport processes and eruptive dynamics at open-vent volcanoes.

# An integrated framework for quantifying gas emissions and heat flux in hydrothermal systems: Insights from Le Biancane geothermal area (Larderello field, Italy)

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The Larderello-Travale geothermal field in the northern Apennines (Italy) represents the oldest exploited geothermal system in the world and is characterized by a large vapor-dominated fractured reservoir producing superheated steam. Our study focuses on the Le Biancane area (~80,000 m2), located in the southern sector of the field, where the impermeable caprock is absent and the shallowest portion of the geothermal reservoir is exposed.
An integrated field and analytical approach was applied, including soil temperature and soil $CO_2$ flux measurements, soil thermal gradient measurements, fumarole sampling with complete chemical analyses, and the collection of soil cores for laboratory characterization. Soil temperature and diffuse $CO_2$ flux surveys were conducted at 345 locations, allowing the production of maps that highlight localized zones of intense degassing and heat release, with $CO_2$ fluxes exceeding 500 $g \cdot m^2 \cdot d^{-1}$ and soil temperatures above 60 °C. These anomalies are spatially associated with NNE-SSW and NE-SW trending fractures and faults, which likely act as preferential pathways for the ascent of deep geothermal fluids. The in-situ investigations also included measurements of the soil thermal gradient at 41 locations and the collection and complete chemical analysis of seven local fumaroles. The field activities were supplemented by laboratory measurements of soil properties on three soil cores drilled to ~50 cm depth (thermal conductivity, porosity, water and air content, bulk and solid-phase densities).
Convective heat transport linked to high-enthalpy vapor was estimated using the $H_2O/CO_2$ molar ratio measured in local fumaroles together with the total $CO_2$ output (~10 t day-1) used as a degassing tracer. By integrating surface measurements with geochemical constraints and subsurface processes such as vapor condensation and $CO_2$ release, the study provides a coherent evaluation of the energy transfer occurring between the geothermal reservoir and the ground surface. Finally, the energy balance at the soil-atmosphere interface was evaluated through surface temperature measurements and by accounting for thermal infrared radiation, solar absorption, and convective heat loss. The results are consistent with the subsurface heat flux estimates.
Although the study does not aim to develop a predictive geothermal model, it introduces a methodological framework for quantifying heat and mass transfer across well-defined domains above and below the ground surface and for identifying the main processes controlling fluid and heat transfer. The integration of surface observations (soil temperature, diffuse $CO_2$ flux, thermal gradients, soil properties) with deeper hydrothermal processes (vapor ascent from the geothermal reservoir, fluid migration along fractures and faults, vapor condensation at shallow levels) enables the construction of a consistent representation of the system's energy budget while explicitly acknowledging uncertainties related to the spatial and temporal variability of the measured parameters.
The proposed approach may be applicable beyond the Le Biancane geothermal area to other hydrothermal and volcanic systems with comparable dynamics.

S02 - Oral Presentation

# Volcanic Sulfur Dioxide estimates through Machine Learning using MSG-SEVIRI and Sentinel-5P TROPOMI

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Sulfur dioxide ($SO_2$) represents the third most abundant volcanic gas released by magma degassing in the shallow crust. Its monitoring provides information on magma ascent rates, conduit dynamics, and eruption style and intensity, thereby supporting volcano monitoring and hazard assessment. The TROPOMI instrument onboard Sentinel-5 Precursor, launched in 2017, is the most recent sensor delivering daily measurements of atmospheric $SO_2$ column densities at an unprecedented spatial resolution of 5.5 km x 3.5 km at nadir.
The aim of the present study is to improve the current $SO_2$ detection capabilities by combining TROPOMI products with data from the MSG-SEVIRI radiometer, which offers higher spatial resolution (about 3 km x 3 km at nadir) and revisit times of 15 minutes, or 5 minutes in Rapid Scan mode.
To enhance $SO_2$ retrieval capabilities, a data-driven AI model was implemented to estimate $SO_2$ vertical column densities at SEVIRI spatial and temporal resolution, using TROPOMI observations as reference. A multilayer perceptron was designed and trained based on the $SO_2$ Vertical Column Density measured by TROPOMI. The model was optimized by minimizing the Mean Squared Error, with an early-stopping strategy applied to prevent overfitting.
This approach allows SEVIRI data to inherit the sensitivity of TROPOMI while preserving its native high-frequency coverage. The method substantially increases measurement density and improves spatial detail, enabling more refined and continuous monitoring of volcanic degassing.
Mount Etna (Italy), with its open-vent persistent degassing activity sustaining $SO_2$ fluxes of 500 to more than 5000 t/day, was taken as a study case. Results were quantitatively validated against measurements from ground-based monitoring networks and satellite data from literature, finding an optimal agreement with the latter and managing to capture the $SO_2$ plume where ground-based instruments fail.
Model performance was evaluated on the held-out test set using several statistical indicators, including the coefficient of determination ($R^2$), the mean squared error (MSE), the root mean squared error (RMSE), and the mean absolute error (MAE). The model achieved an R2 of 0.845 on test data, indicating that approximately 84% of the variance in the observed SO2 VCD is captured by the model predictions. The MSE was estimated at 0.000002 $mol^2\ m^{-4}$, corresponding to an RMSE of 0.0014 $mol\ m^{-2}$, while the MAE was 0.0016 $mol\ m^{-2}$. Overall, these low error magnitudes demonstrate the model's capability to reproduce the observed $SO_2$ VCD with high accuracy.
This integrated technique offers a promising tool for rapid and robust volcanic hazard assessment, introducing improvements to current retrieval methods, and enhancing early warning capabilities for aviation safety, as well as studies of climate impacts from volcanic emissions.

# Magmas from the crust-mantle transition zone driving the 2023-2024 Sundhnúksgígar eruptions, Iceland

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Magma plumbing systems connect storage zones at different depths, yet at mid-ocean ridges most eruptions are supplied from mid-crustal reservoirs where differentiation and degassing can obscure signals from deeper domains. The trans-crustal interaction of magma storage reservoirs can be examined on the Reykjanes Peninsula, where eruptive activity began at Fagradalsfjall in 2021-2023, tapping magmas from the crust-mantle transition zone, and migrated in late 2023 to the Sundhnúksgígar system, which is supplied from a ~5 km-deep mid-crustal magma domain. In this latter system, the deeper magma storage region feeding Sundhnúksgígar remains poorly constrained, as magmas are processed in the mid-crustal domain prior to eruption. Here, we analyze major, trace, and volatile compositions ($H_2O$, $CO_2$) of olivine-hosted melt inclusions (MIs) from the December 2023 to March-May 2024 Sundhnúksgígar eruptions and compare them with MIs from the 2021 and 2023 Fagradalsfjall eruptions. Olivine cores are bimodal, defining low-Fo ($Fo_{78-81}$) and high-Fo ($Fo_{85-88}$) populations. Low-Fo olivines host relatively evolved MIs (7.4-8.0 wt% MgO) with trace element ratios similar to Sundhnúksgígar erupted products and lower $CO_2$ contents (100-700 ppm). High-Fo olivines contain more primitive MIs (8.0-10.5 wt% MgO) with lower La/Yb and higher $CO_2$ (250-2600 ppm), closely resembling Fagradalsfjall MIs. $H_2O$ (0.5-0.9 wt%) negatively correlates with Fo, consistent with fractional crystallization. Our data suggest two magmatic environments beneath Sundhnúksgígar: a mid-crustal reservoir recorded by low-Fo olivines (minimum saturation pressures ~1.1 kbar, ~4 km depth) and a hotter, deeper crystal mush system recorded by high-Fo olivines (minimum saturation pressures of ~4.5 kbar, ~15 km depth), consistent with storage in the crust-mantle transition zone similar to Fagradalsfjall. Although erupted products at Sundhnúksgígar require distinct end-member compositions respect to Fagradalsfjall, the close similarity of high-Fo-hosted melt inclusions in both systems suggests reactivation of a common crystal mush in the crust-mantle transition zone.

# Impact of volcanic emissions on atmospheric deposition: the cycle of mercury and other volatile elements at Mount Etna and Vulcano island (Sicily, Italy)

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Characterizing the chemistry of atmospheric deposition provides important information on the volcanic emissions. This study aims to characterize bulk atmospheric depositions on Mt. Etna and Vulcano Island, two different active volcanic systems. The former is an open-conduit volcano characterized by continuous passive degassing from the summit craters, frequently interrupted by explosive/paroxistic activity; the latter is a closed-conduit volcano since the last eruption occurred in 1888-1890, and nowadays characterized by intense hydrothermal activity which manifests as an extensive fumarolic field on the northeastern rim of “La Fossa” crater. Here we report on the atmospheric deposition of major, minor and trace volatile elements, including mercury (Hg), a hazardous element that poses potential risks to human health and ecosystems. Bulk deposition samples were collected on Mt. Etna from April 2024 to March 2025, using a network of five bulk collectors placed at different altitudes and distances from the summit craters, and on Vulcano Island from December 2025 to April 2026, at four sampling sites, two of which were located inside the “La Fossa” crater. For each site, two different bulk collectors were installed: one for major and trace elements, and a second borosilicate sampler, specially designed for Hg collection. The pH values of rainwater ranged from 4.1 to 7.5 at Mt. Etna and from 1.8 to 7.0 at Vulcano. We observed an inverse correlation with distance from the craters, highlighting the effect of the dissolution of acid gases in rainwater. In both volcanoes, the clear imprint of gas-rain interaction was observed both in the major constituents ($F^-$, $Cl^-$, $SO4^{2-}$) and in many trace elements (e.g. Al, As, Cd, Cu, Fe, Se, Te and Tl) which were particularly enriched in the most acidic samples. In particular, enrichments have been observed in the rainwater on Mt. Etna due to the interaction between ash and rain during paroxysmal explosive events. Mercury, which is the most volatile metal, showed high variability in rainwater concentrations, with a minimum value of 1.6 ng $L^{-1}$ to a maximum value of 173 ng $L^{-1}$ at Mt. Etna, and from 10.8 ng $L^{-1}$ to 40 ng $L^{-1}$ at Vulcano Island. Low mercury concentrations confirm the low water solubility of this element in its gaseous form (Hg0), which accounted for approximately 98% of the different species; its most reactive and soluble form, $Hg^{2+}$, accounted for less than 1% of emissions and was probably stabilized in rainwater in the form of chloride ($HgCl_2$). These unpublished results also confirm what previous authors have stated: volcanoes are a major source of gaseous elemental mercury in the atmosphere, and only a small part of it is deposited close to the volcano. However, further studies are needed to discriminate geogenic (volcanoes, marine re-evaporation, forest fires) and anthropogenic sources of mercury.

# Partitioning of mercury between picritic melts, silicate minerals and Fe-Ni (-S) metals under high pressure and temperature conditions

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Magmas generated by partial melting of mantle rocks are the primary carriers of volatile elements (e.g., $CO_2$, $H_2O$, $SO_2$) and trace elements (e.g., REE, Hg, Co) to the Earth's surface. Among these, mercury (Hg) is a key geochemical marker for volcanic events at a global scale [Percival et al. 2018] Despite the predicted low Hg abundance in the Bulk Silicate Earth (~10 ppb) [McDonough and Sun, 1995], isotopic signatures in the sedimentary record provide clear evidence of its predominantly deep (magmatic) origin [Grasby et al. 2019]. However, the deep Hg cycle remains poorly understood, as no experimental work has yet constrained the mechanisms of Hg mobilization and speciation during mantle melting. Currently, the hypothesis that sulphide minerals are the primary Hg host at depth [Canil et al., 2015] relies solely on limited geochemical data from meteorites and peridotite xenoliths, highlighting a significant need for experimental validation.
In this study, Hg solubility in synthetic picritic melts was examined at 3-6 GPa, 1300-1550 °C, and oxygen fugacity buffered near the graphite-$CO_2$ redox equilibrium, using six-anvils cubic presses at the Center for High Pressure Science & Technology Advanced Research (HPSTAR), Beijing [Wu et al. 2024; Xu et al. 2025]. The starting material consisted of a synthetic glass prepared by mixing high-purity reagents by proper amounts and then, heated at 1500 °C for 1 h before quench. The homogeneous glass was powdered and mixed with ~5 wt.% natural HgS (Almaden, Spain). Graphite capsules were used as containers filled with the starting material, compressed to the target P and the temperature monitored with a C-type thermocouple. In addition, Hg solubility in Fe-Ni-S alloy was investigated at 6 GPa and 700-1400 °C using a rotating multi-anvil apparatus with a Walker-type module available at the Department of Earth Sciences, Sapienza University of Rome. The quenched runs were embedded in epoxy resin, polished and analysed by scanning electron microscopy and electron microprobe.
Experimental results show Hg concentrations up to ~1700 ppm in picritic melts likely controlled by the amount of dissolved sulphur. The Hg partitioning into the FeNiS alloy increases significantly with rising temperature up to 3-5 wt%. These experimental constraints, compared with the limited data available for natural volcanic rocks, allow to better quantify the deep Hg cycle and its mobilization processes. In particular, when a batch melting model is applied to our data, we show that 20% of picritic melt fraction can mobilize up to 5% of the primordial Hg stored in the deep Earth, making such melts an efficient carrier from the interior to the atmosphere.

# Distribution and concentrations of magmatic mercury from the earliest submarine activity of Mt. Etna: the case of Aci Castello pillow lavas

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Volcanic systems release a variety of volatiles (e.g., $CO_2$, $SO_2$, $H_2O$) during magma ascent and degassing, along with potentially toxic trace metals such as mercury (Hg). Due to its high volatility, Hg is emitted from mantle-derived melts in widely variable amounts, reaching up to 340 t·yr-1 [Yin et al. 2024]. In the atmosphere, Hg occurs mainly as gaseous elemental Hg (GEM), which has a long residence time (~1-2 years) [Bagnato et al. 2007] and can be transported globally, eventually accumulating in sediments. Over the last decades, Hg has emerged as a valuable geochemical tracer in sedimentary rocks for large-scale magmatic events, such as Large Igneous Provinces (LIPs) [Grasby et al. 2019]. However, available data provide limited constraints on primary Hg distribution and concentrations in mantle-derived melts. Even less is known about the effect of magmatic fractionation and crystallization on Hg partitioning. Available data on volcanic rocks are relative to MORB and indicate Hg concentrations of 1.4 ± 0.6 ng/g [Yin et al. 2024].
In this study, we investigated the Hg concentration of the earliest submarine volcanic products of Mt. Etna outcropped at Aci Castello (south-east flank of the volcano). These ~500 kyr-old tholeiitic pillow lavas represent the initial stages of Etna volcanism and were emplaced at water depths of ~800-400 m onto unconsolidated Lower Pleistocene marine clays [Corsaro and Cristofolini, 2000]. Their submarine emplacement provides a unique opportunity to evaluate Hg contents in magmas that were minimally affected by shallow magmatic differentiation and conduit-related processes.
A total of 40 samples were collected from 13 pillow lavas consisting of tholeiitic basalts with low porphyricity index (6-10%), with olivine and subordinate plagioclase phenocrysts set in a groundmass with intersertal texture made of plagioclase and pyroxene [Corsaro and Mazzoleni, 2002]. Sampling was carried out across individual pillow lavas, from the massive core to the glassy rim, including the clay-rich inter-pillow material.
Accurate analyses of Hg were performed using a Milestone Direct Mercury Analyzer (DMA-80) Tricell available at the Earth Sciences Department of Sapienza University of Rome, employing thermal decomposition at 750 °C, amalgamation, and atomic absorption spectrophotometry.
Preliminary results indicate Hg concentrations of ~1-2 ng/g in both the massive cores and the glassy rims of the pillow lavas; while intermediate portions of the pillows show lower Hg concentrations, generally <1 ng/g. In contrast, the clay-rich inter-pillow material displays higher Hg contents and this explain the observed Hg variability measured within each pillow. These preliminary data, supported by recent experimental models [Boulliung et al., 2025] confirm the high volatility of Hg in basaltic magmas and allow a first estimate of Hg outflux compared with present-day volcanic Hg emissions.

S02 - Oral Presentation

# Diffuse emission of $CO_2$ and geochemical survey from El Hoyon Volcano, El Salvador

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Located along the Central American Volcanic Front (CAVF), El Salvador is characterized by widespread volcanic activity and significant associated hazards. In fact, the local magmatic activity has created areas of shallow thermal anomalies and diffuse gas emissions, which have been exploited to support the expansion of tourism in the country. Despite of this, several volcanic systems remain poorly studied and are not included in global databases (Global Volcanism Program), highlighting the need for comprehensive surveillance programs to better understand the dynamics driving these phenomena. Considering the development of these touristic activities and the need for detailed research on surveillance programs and to understand the behaviour of the thermal anomalies and gaseous emissions, El Hoyon volcano, for example, is a site of particular interest due to its easy accessibility and the lack of systematic geochemical and degassing investigations. For this reason, in this work we present the results of the first systematic campaigns performed between 2022-2024 of soil $CO_2$ degassing mapping, gas sampling, and MultiGAS prospecting at El Hoyon volcano. The combination of the soil diffuse $CO_2$ fluxes measured during the four campaigns showed values between 0.012 $g \cdot m^{-2} \cdot d^{-1}$ and 723 $g \cdot m^{-2} \cdot d^{-1}$. The distribution of $CO_2$ fluxes was modelled as a combination of three log-normal populations: (i) Population A was characterized by a low average $CO_2$ flux value (0.298 $g \cdot m^{-2} \cdot d^{-1}$), (ii) population B showed a mean value of 8.8 $g \cdot m^{-2} \cdot d^{-1}$, while (iii) population C exhibited an average $CO_2$ flux of 195 $g \cdot m^{-2} \cdot d^{-1}$, attributable to a deep input due to the volcanic system as confirmed by isotopic composition of carbon sampled in the fumarolic field ($\delta^{13}C_{-CO2}$ values varied from -7.4 to -1.2). The amount of diffuse $CO_2$ released from the soil by El Hoyon volcano was estimated, with an average total output of 6.2 $t \cdot d^{-1}$ for an area of 0.2 $km^2$. Consistently, $CO_2$ was the dominant component in the composition of the gases as shown by geochemical data. In fact, the MultiGAS prospect, performed inside the El Hoyon crater, showed that $CO_2$ varied from 400 up to 1042 ppm, while sulphur (which is mainly found as $H_2S$) reached values up to 24 ppm ($CO_2/H_2S$ ratios about 29); $SO_2$ was extremely low with values less than 0.5 ppm confirming the hydrothermal signature of the system. Moreover, the soil temperature ranged from 21°C to 100°C at 10 cm depth, and from 22°C to 147°C at 40 cm depth. The ratio of helium and neon (R/RA from 2.45 to 7.11 and $^4He/^{20}Ne$ from 0.6 to 17.2) indicated a clear magmatic contribution to the deep end-member. Overall, these results reveal a previously unrecognized magmatic contribution to El Hoyon's degassing system, underscoring the urgency of integrating this volcano into regional surveillance programs and global volcanic databases, and emphasizing the importance of expanding such investigations to other understudied volcanic areas in El Salvador.

# Gas manifestations at Pantelleria island (Italy): Extensive mapping through usual field methods and Unmanned Aircraft Systems and geochemical characterization of the emitted gases

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Pantelleria island is a quiescent volcanic system between Sicily and Tunisia. It hosts some low and high enthalpy geothermal systems whose surface manifestations are thermal springs, fumarolic areas and steaming grounds.
In the framework of the INGV project Pianeta Dinamico (PANTAREI), an extensive mapping of all gas manifestations of the island known by the authors has been undertaken. During the project, many other have been located thanks to the indications from colleagues involved in the geological mapping of the island and from information given by the inhabitants.
Due to the fact that a large part of the island is very difficult to access, we took also advantage from reconnaissance flights with UAS carrying thermal IR cameras to locate thermal anomalies and with multispectral cameras to discover areas in which the vegetation is affected by geogenic degassing. Most of the UAS surveys were made on the flanks of Mt. Grande where large areas with stunted or absent vegetation strongly contrasting with the nearby areas covered by rich vegetation. Such areas are very difficult to reach on foot because of the intricate vegetation. The survey showed many thermal anomalies evidencing an active degassing of geothermal fluids in these areas. Where possible we reached the sites to collect gas samples and make direct temperature measurements.
About 50 different gas manifestations have been identified. All manifestations have been located through a handheld GPS receiver and their coordinates uploaded in a GIS project. Temperature measurements were taken at 50 cm depth. Gas samples were taken inserting a tube at 50 cm depth, while bubbling gases collected through an inverted funnel and all samples were analysed at INGV-Pa for their chemical and isotope composition.
The collected gas samples can be included into three main groups. The first group comprises gases bubbling in thermal waters (35-60 °C) along the shores of the lake and on the sea coast at Gadir and are composed by almost pure $CO_2$. The second comprises fumaroles and steaming grounds with temperatures between 70 °C and water boiling temperature and the chemical composition is $CO_2$-dominated with abundant $H_2$ and $CH_4$. The third group shows temperatures mostly below 60°C and the chemical composition is air-dominated with $CO_2$ mostly lower than 10 %, absence of $H_2$ and lower $CH_4$ concentrations.
The first group is characterised by strong interaction with the shallow cold and/or low enthalpy hydrothermal aquifers. The second group can be interpreted as fed by the deep high enthalpy geothermal system through the main deep tectonic or volcano-tectonic structures. The He isotope composition of these gases, which shows the highest R/Ra values of the entire Mediterranean region, testifies for a deep mantle fluids contribution. The third group is mainly found in the area of the NW flank of Mt. Grande and its manifestations are fed only by a perched low enthalpy hydrothermal aquifer probably heated mostly by heat conduction with only small contribution from deep derived hydrothermal fluids.

# Long-term gas measurements and satellite imagery give insight into recent activity changes at El Chichón Volcano

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El Chichón is Mexico's most consistently explosive volcano. It also hosts a large and complex volcano-hydrothermal system, with numerous hot springs of very diverse compositions and outlet temperatures, diffuse and fumarolic gas emissions, and a crater lake, which is known for its rapid variations in volume and composition. Over the last 5 years, important changes have been noted in several aspects of its hydrothermal activity, including a spectacular, unprecedented increase of the Crater Lake volume, color change from its usual deep green to grayish turquoise, and native sulfur spherules occasionally floating at its surface. These observations fostered preoccupation because they remind the characteristics of lakes exhibiting a higher activity and a direct injection of magmatic gases.
In this work, we document these changes quantitatively using a new dataset of multiple satellite imagery (LANDSAT, ASTER, SPOT and Sentinel-2), which spans the whole lake history since the year of its formation, and present systematic MultiGas measurements of the distribution of gas composition across the bottom of the crater of El Chichón, and its variation through time. Then, by combining these two novel detests, we propose a model of how the sulfur was formed in the lake. Even if there is currently no evidence of direct magmatic gas injection in the lake, these changes are probably the sign of a further increase in the volcano activity.

# Eruptive style as a key control on volcanic ash leachates chemistry at Stromboli volcano (2019-2024)

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During volcanic eruptions, the deposition of magmatic volatiles as water-soluble salts (ash-leachates) on ash surfaces provides a crucial window into plume chemistry and eruptive intensity. We present a comprehensive 5-year dataset (2019-2024) based on the geochemical analysis of ash-leachates from 112 fresh ash samples collected at Stromboli volcano. This study encompasses a wide spectrum of volcanic phenomena, including ordinary activity, major explosions, paroxysms, littoral blasts and pyroclastic currents, offering an unprecedented view of the volcano's dynamics. Our results demonstrate that the geochemical signature, concentration and mineralogy of these soluble salts are primarily governed by the synergy between eruptive style, fragmentation dynamics and magmatic degassing. This interaction is further modulated by the intrinsic chemical heterogeneity of the tephra and the specific physicochemical conditions within the volcanic environment. Across the dataset, sulfate is the dominant anion (avg. $SO_4$: 8064 μg/g), followed by chloride (avg. Cl: 2113.5 μg/g) and fluoride (avg. F: 81.4 μg/g), while sodium and calcium are the most prevalent cations. A systematic enrichment trend effectively distinguishes different eruptive styles: ordinary activity maintains baseline levels (avg. $SO_4$: 2926 μg/g), whereas major explosions and paroxysms yield significantly enriched leachates (avg. $SO_4$ up to 16481 μg/g). This geochemical shift is driven by the higher eruptive energy and enhanced fragmentation of high-energy events, which drastically increase the specific ash surface area while simultaneously providing a greater volume of emitted volatiles for scavenging. During the 2022-2023 effusive phases, a distinct enrichment emerged in leachates from pyroclastic currents triggered by lava-front collapses (avg. $SO_4$: 9468 μg/g) compared to purely effusive episodes (avg. $SO_4$: 4209 μg/g). The thermal insulation provided by these dense ash flows prevents immediate cooling, sustaining an internal thermal window that facilitates prolonged gas-ash interaction and volatile uptake. The highest salt loads across the entire dataset were documented during the July 2024 littoral events, where a direct comparison between ash-leachates from littoral samples collected before and after the July 11 paroxysm reveals a marked geochemical decoupling. In the post-paroxysm samples, sulfate concentrations reached a peak of 20929 μg/g, while Cl and F levels declined sharply. In these cases, the influx of marine chlorine shifts the chemical signature toward low S/Cl ratios, whereas the negligible fluorine content in seawater artificially inflates S/F values. This underscores how hydromagmatic interaction acts as a chemical filter, where steam-driven scrubbing selectively masks the primary magmatic signal. By correlating leachates chemistry with direct gas plume measurements through S/Cl vs. S/F molar scatterplots, we identify distinct volatile signatures. High S/Cl (up to 10) and S/F (exceeding 40) ratios in paroxysms and effusive episodes with associated pyroclastic flows, fingerprint the arrival of gas-rich magma batches from depth. In contrast, baseline ratios (S/Cl below 10) during ordinary activity reflect steady-state degassing from the shallow, more degassed magma. However, discrete magmatic flushing episodes were identified even during ordinary activity, where S/Cl values reached 44, signaling deep-seated sulfur enrichment independent of major explosive events. Finally, SEM-EDS mineralogical

validation and stoichiometric scatterplots reveal coupled Na-Cl and Ca-S-O peaks, providing an unequivocal link between bulk leachates chemistry and ash surface assemblages like halite and anhydrite. The stability of these halogen-sulfur patterns since 2019 mirrors previous ash-leachates studies conducted between 2007 and 2009, indicating a consistent volatile source over the last decades. This consistency suggests that ash-leachates chemistry can serve, at least to some extent, as a reliable proxy for tracking eruptive transitions and assessing the environmental impact of ash dispersal.

# $H_2O$-$CO_2$ solubility in Pomici di Base trachyte (Somma Vesuvius): new experimental constraints

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The solubility of $H_2O$ and $CO_2$ in silicate melts is fundamental for understanding magmatic degassing, fluid-phase saturation, bubble nucleation, and, consequently, the dynamics and style of explosive eruptions. Although the solubility of $H_2O$ and $CO_2$ has been investigated in various magmatic systems, experimental constraints for evolved trachytic compositions representative of Somma-Vesuvius are still limited. This gap hinders a robust assessment of volatile behavior and the evaluation of whether currently available solubility models are applicable to the evolved magmas of the Vesuvius system.

In this study, we present new experimental $H_2O$-$CO_2$ solubility data for a trachytic melt representative of the Plinian Pomici di Base eruption. The experiments were conducted in an Internally Heated Pressure Vessel (IHPV) at 1200 deg C and pressures between 50 and 300 MPa, at an intrinsic oxygen fugacity of $NNO^{+3}$. In each experiment, capsules containing $H_2O$-$CO_2$ fluids with different compositions (XH2O = 0-1) were used to explore conditions ranging from $CO_2$-rich to $H_2O$-rich. $H_2O$ and $CO_2$ contents in the experimental glasses were determined by FTIR and checked by thermogravimetry for $H_2O$ and by carbon-sulfur analysis for $CO_2$.

The results show a systematic increase in $H_2O$ solubility with pressure, from 3.99 +/- 0.06 wt% at 100 MPa to 8.21 +/- 0.14 wt% at 300 MPa under $H_2O$-rich conditions. $CO_2$ solubility also increases with pressure, from 500 +/- 200 ppm at 100 MPa to 1320 +/- 80 ppm at 300 MPa under the most $CO_2$-rich conditions. FTIR spectra also suggest the presence of carbonate species and, in some samples, a possible molecular $CO_2$ component; however, this requires further quantitative verification.

Overall, these data provide new experimental constraints for a trachytic composition directly relevant to Somma-Vesuvius and broaden the available framework for interpreting volatile solubility in evolved alkaline magmas.

# Depth, temperature and oxygen fugacity for the origin of mantle fluids: a preliminary revaluation

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Mantle fluids, tied to different geodynamic settings, play a pivotal role in numerous processes in the mantle, driving mineral stability [Holdaway and Goodge,1990], partial melting [Dasgupta and Hirschmann, 2010], metasomatism [Putnis and Austrheim, 2010], and deep seismicity [Malusà et al., 2022]. Despite their importance, the origin and evolution of these fluids - often represented by the simplified C-O-H-S chemical system - remain poorly constrained with an unsolved mismatch between the thermodynamic prediction of their composition and observations in nature, likely due to decompression, cooling, varying redox conditions, and fluid/mineral interaction. Over the last decade, experimental studies supported by thermodynamic modelling [Zhang and Duan, 2009] have pointed out the role played by the mantle redox state in affecting the chemical composition of fluids such as those trapped in rock-forming minerals of peridotite xenoliths in both oceanic and continental settings.
For instance, $CO_2$-rich fluids are known to form by reactions between minerals like (1) dolomite + orthopyroxene = clinopyroxene + olivine + $CO_2$ or like (2) orthopyroxene + magnesite = olivine + $CO_2$ in the case of carbonated lherzolites and harzburgites, respectively. Similarly, $H_2O$ and $SO_2$-rich fluids from the decomposition of hydrous (e.g. phlogopite and amphibole) and S-bearing minerals (e.g. sulfide and sulfate). However, the effect that the oxygen fugacity (fo2) buffered by the coexisting silicate minerals for the formation of oxidised fluids remains unconstrained.
A preliminary study consisting of building a dedicated P-T-X-$f_{O2}$ database results in entrapment P-T conditions of $H_2O$- and $CO_2$- rich fluids of ~0.7 - 2 GPa at ~1000-1200 °C with $f_{O2}$ above 0.5 log units (with respect to the fayalite-magnetite-quartz - FMQ, buffer chosen as reference) according to thermodynamic calculations [Zhang and Duan, 2009]. However, fluids trapped in peridotitic minerals have shown evidence of graphite and methane [Marras et al., 2024 and references therein], which would require $f_{O2}$ significantly more reduced than what predicted.
Experiments conducted using the multi anvil press and piston cylinder with starting materials representative of (1) and (2) show that, at graphite saturation, $CO_2$ can form at P of 2.5-2.8 GPa and T between 1100 and 1265 °C, i.e., at notable lower $f_{O2}$ between -0.8 and -1.2 log units to the FMQ than thermodynamically calculated [Stagno and Frost, 2010]. Additional experiments are in progress that will bridge the gap between experimental data, thermodynamic models, and observations in nature.

# Radon time series in the Etna area: integrated analysis with meteorological, seismic, and volcanic data (2022-2025)

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This study analyzes the role of radon gas ($^{222}Rn$) as a tracer of geodynamic processes and a possible precursory indicator of volcanic activity on Mount Etna.
This work focuses on the time series of radon recorded at the Santa Venerina site, located on the eastern slope of the volcano, over a period between 7 November 2022 and 12 July 2025. The study area is characterized by a complex volcano-tectonic structure, marked by the nearby presence of the “Timpe Fault System” and Santa Venerina Fault that facilitate the rise of gases from the subsoil through areas of high permeability.
The methodology involved the integration of soil radon data, collected both continuously and through discrete measurement campaigns, with environmental parameters (air temperature, barometric pressure, humidity, rainfall, wind speed), seismic data (volcanic tremor amplitude and seismic strain), and observations of eruptive activity. To isolate the radon signal linked to endogenous causes, the time series were filtered by meteorological and seasonal influences through the application of mathematical filters and multiple linear regression models.
Anomaly thresholds of the filtered radon signal and of the volcanic tremor amplitude were defined using robust statistical tools such as normal probability plots.
The results highlighted a significant correlation between radon anomalies and magmatic dynamic using a probabilistic approach. In particular, radon anomalies preceded major paroxysmal events and phases of Strombolian activity, confirming the potential of radon as a short- and medium-term geochemical precursor. Furthermore, Spearman's cross-correlation analysis, validated using Monte Carlo significance tests, indicates that the radon activity in Santa Venerina site and the volcanic tremor amplitude is not statistically significant, suggesting that the fluctuations of the two signals are, at present, independent or linked to random factors. No significant correlation was found between radon and seismic strain.
Integrated monitoring of soil radon and seismological parameters is therefore confirmed as a fundamental tool for understanding magma and fluid ascent mechanisms. This approach will be very useful to improve volcanic surveillance systems.

# 3D geothermal modeling of the Lacco Ameno fault system (Ischia, Italy)

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Although fault geometry is often approximated using 2D models, understanding fluid circulation in porous media requires a 3D perspective to properly evaluate non-uniform flow dynamics and the heterogeneous distribution of related seismogenic structures. Our research focuses on the fault systems of Ischia Island, specifically the Lacco Ameno system, which is characterized by deep-seated volcanic gas emissions (primarily $CO_2$ and $H_2O$). We modeled the flux of these magmatic fluids using the 3D geothermal simulator TOUGH2, which is capable of handling non-isothermal, multicomponent (water and carbon dioxide), and multiphase (gas and liquid) fluid flows within porous and fractured media. By using surface flux measurements and assigning distinct permeability values to the fault and the surrounding host rock, we applied a 3D Voronoi tessellation to estimate the energy released by the deep source (enthalpy of $H_2O$ and $CO_2$ injected at depth). Furthermore, we assessed the pressure and temperature distributions along the fault zone, which may correlate with the non-uniform spatial distribution of local earthquakes.

# Application of activated carbon traps to quantify mercury emissions in volcanic and hydrothermal environments

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Mercury (Hg) is classified by the World Health Organization as one of the top ten chemicals of major public health concern due to its high toxicity and propensity for bioaccumulation. While anthropogenic emissions have been extensively studied, natural contributions such as volcanic degassing remain poorly constrained. Volcanic activity is a significant natural source of Hg, contributing approximately 340 Mg $yr^{-1}$ [Bagnato et al. 2007; Yin et al. 2024], primarily in the form of gaseous elemental mercury (Hg0, GEM). The Hg undergoes long-range global transport, necessitating a more precise quantification of these natural inputs. Several studies have been carried out to understand the volcanic Hg budget using techniques such as Au traps and Lumex RA-915 mercury analyzer [Edwards et al. 2020 and reference therein].
This study aims to test activated carbon traps across different geological settings to quantify the concentration of the Hg outflux. Sampling has been conducted at Vulcano Island, Campi Flegrei, Paternò and Montecchie. After sampling, all activated carbon traps have been analysed using a Milestone Direct Mercury Analyzer (DMA-80) Tricell available at the Earth Sciences Department of Sapienza University of Rome. The sampling procedure has consisted of exposing the traps under controlled flow rate varying from 0.5 to 5 L $min^{-1}$ and for different duration from 6 to 120 min. Traps have been located both in the vicinity of and above fumaroles. Furthermore, soil gas measurements have been carried out using a pump and syringe system for gas extraction.
Preliminary results obtained from the different geological contexts show Hg quantities ranging from 0.23 ng at Montecchie up to 272 ng in the soil gases of Pisciarelli (Campi Flegrei) as a function of exposure time and flux. Similar values are also recorded in Paternò with 0.24 ng of Hg both at 6 and 12 minutes.
Our data will be discussed in terms of establishing a protocol for the use of activated carbon traps in different geological environments and to be able to contribute to the volcanic and hydrothermal Hg monitoring.

# Insights into mercury degassing at Mt. Etna: From interstitial soil concentrations to gaseous elemental mercury (GEM) emissions using the accumulation chamber method

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Mercury releases into the atmosphere originate from both anthropogenic and natural sources, with volcanic emissions considered a significant component of the natural ones. It is well known that active volcanoes are significant sources of mercury, primarily from open-vent craters, but also from fumarolic fields. However, peripheral degassing and diffuse degassing from the soil remain poorly understood, partly due to the lack of a standard measurement protocol. This research focuses on the geochemical study of mercury at Mt. Etna, an open-conduit volcano where permanently passive degassing from the summit craters is often punctuated by explosive and paroxysmal activity. The levels of gaseous elemental mercury (GEM) were measured in real-time using the Lumex RA-915M portable mercury vapor analyzer, an atomic absorption spectrometer that utilizes the Zeeman effect and high-frequency modulation of light polarization (ZAAS-HFMLP). It operates at a flow rate of 10 L $min^{-1}$ with a wide range of data acquisition frequency (minimum time intervals of 1 second) and low detection limits. During the monitoring campaign, the instrument operated in a data logger mode, with zero correction applied every 5 minutes to reset the baseline. In several field campaigns, GEM concentrations were measured in the atmosphere at different sites of Mt. Etna, in diffuse degassing areas and in the interstitial soil gases. The determination of GEM in interstitial soil gases was performed by connecting a rigid Teflon tube embedded in the ground at a depth of approximately 50 cm, and the soil gases were collected with a 100 mL syringe and injected into the inlet port of the instrument. In case of free gases (fumaroles and bubbling pools), GEM was collected using an inverted funnel placed inside the degassing pools and connected to a three-way valve. The next step of this research was to determine GEM emissions from diffusely degassing areas using the LUMEX RA-915M in combination with a static closed chamber (SCC), the latter assembled at the INGV of Palermo, alongside $CO_2$ measurements were performed at the same investigated sites. One of the aims is to compare the different sampling methodologies employed to estimate GEM levels in interstitial soil gases and diffuse degassing areas. The GEM emissions surveys were conducted near low-temperature fumaroles (CRT01, BOT), where previous GEM concentration in interstitial soil gases ranged from 146 to 9615 ng $m^{-3}$ at the CRT01 site (Soil Temperature: 29 - 59 °C; $CO_2$ fluxes: 16 - 2340 $g \cdot m^{-2} \cdot d^{-1}$) and from 114 to 3109 ng $m^{-3}$ at the BOT site (Soil Temperature: 12 - 90 °C; $CO_2$ fluxes: 30 - 3990 $g \cdot m^{-2} \cdot d^{-1}$). These preliminary results are part of a broader study aimed at characterizing the mercury cycle in a volcanic context through the quantification of mercury in different natural systems, including atmospheric deposition, soil content and emissions from the peripheral degassing areas of Mt. Etna.

# Visibility Graph analysis for the characterization of soil $CO_2$ emissions from an active volcano

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The study of volcanic gases is a fundamental tool for the investigation of magmatic processes; in particular, the comprehension of the complex dynamics of degassing is critical for the volcano monitoring and the assessing of volcanic hazards. In this study, we apply Visibility Graph Analysis (VGA) to a decadal, high-resolution time series of daily soil $CO_2$ flux recorded by a standardized monitoring network at Mt. Etna volcano (Italy).
By converting time series into complex networks, we demonstrate that the connectivity degree distributions follow a power-law described by the exponent "gamma", which reveals a self-similar behaviour of gas emissions. We observed that the long-term gamma exponent represents an upper-limit reference which is interpreted as a site-specific measure of flux efficiency. Then, we introduce the gamma-deviation, namely the variation of the scaling exponent from its long-term site-specific baseline, as a novel proxy for degassing efficiency. Temporal and spatial variations of the gamma exponent can be ascribed to factors such as fluctuations in the sources or changes in the efficiency of fluids transport pathways. Our results identify a transition from a period of discordance across the monitoring sites (pre-2016) to a phase of network-wide concordance (after 2016). The striking correlation between topological gamma-deviations and the established normalized network signal validates the methodology, suggesting that VGA is able to capture the same underlying magmatic drivers.
This study establishes VGA as a robust and reliable tool for medium- and long-term monitoring, potentially capable of identifying the occurrence of large-scale magmatic processes and refining the characterization of fluid transport dynamics in active volcanic systems.

# Carbon-based geochemical proxies reveal hidden magmatic $SO_2$ input in hydrothermal systems

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In closed-conduit volcanoes, hydrothermal aquifers act as intermediate buffers between the magmatic plumbing system and the surface, effectively retaining a substantial fraction of magmatic volatiles. These aquifers can significantly modulate volcanic degassing and obscure early warning signals of unrest, for example, by delaying the detection of $SO_2$, HCl, and HF at the surface. Although, early degassing of such volatiles may not be directly detectable, it can induce strongly oxidizing conditions within hydrothermal systems. Redox-sensitive parameters, like hydrocarbons, may therefore serve as indirect tracers of magmatic $SO_2$ input. Here we show that variations in magmatic flux significantly affect the chemical speciation and isotopic composition of organic carbon compounds in hydrothermal gases lacking direct magmatic gas signatures. We use Vulcano bay as a natural analogue for a hydrothermal system strongly influenced by magmatic degassing and we characterize its compositional fingerprints. Gases from Vulcano bay exhibit among the highest reported $\delta^{13}C$ and $\delta^{2}H$ values of $CH_4$, elevated alkene/alkane, i/n-butane, and $CH_4$/ ($C_2H_6$+$C_3H_8$) ratios, together with benzene enrichments. Methane isotope systematics are consistent with carbon and hydrogen isotope fractionation via sulfate-mediated $CH_4$ oxidation, i.e., thermochemical sulfate reduction (TSR), at high temperatures. Methane oxidation is expected to become more pronounced under increasingly oxidizing conditions, as these promote sulfate formation and enhance TSR process. High alkene/alkane ratios and elevated benzene contents provide independent evidence for more oxidizing subsurface conditions beneath Vulcano bay. These conditions are plausibly linked to a significant input of magmatic $SO_2$, consistent with the proximity to the main magmatic gas transport zone of Vulcano (La Fossa crater), where a $SO_2$-rich fumarolic plume is observed. Comparison with other hydrothermal systems, a global compilation of volcanic and hydrothermal datasets, and equilibrium modeling further demonstrates that the presence of $SO_2$ in surface emissions correlates with elevated alkene/alkane ratios, supporting a direct link between magmatic sulfur input and hydrocarbon geochemistry. We finally propose a suite of hydrocarbon-based parameters and diagnostic plots that could be applied in volcanic surveillance for tracing the arrival of sulfur-rich magmatic gases, without requiring direct surface detection of $SO_2$.

# The February-April 2021 sequence of lava fountain paroxysms on Mt Etna: source mechanism deciphered from ground based and satellite survey of volcanic gas emissions

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Between 16 February and 1 April 2021, the Southeast Crater (SEC) of Mt Etna produced a spectacular sequence of 17 lava fountain paroxysms, separated by 2.5 days on average, which generated 10 km or higher eruptive columns and heavy tephra fallout over populated surroundings. We examine the magmatic processes responsible for these events based on pre- and syn-eruptive data for the mass flux and chemistry of Etna gas emissions, surveyed both from the ground (scanning DOAS, OP-FTIR spectroscopy) and from space (TROPOMI, SEVIRI), and comparing with the seismic tremor. Bulk plume $SO_2$ emission rates determined from the ground and from space are consistent with one another. We show that after several months of background summit activity, sustained since June 2020 by open-system degassing of ~$29{\cdot}10^6$ $m^3$ (DRE) of magma through the central volcano conduits, an influx of deeply derived primitive magma led to a pressure build-up phase from early December 2020 to 13 February 2021, marked by a rapid increase in the $SO_2$ flux and tremor (the former interpreted to represent an ~ 3 times higher magma degassing rate) and decreasing $SO_2$/HCl plume ratio. The fountain paroxysms were characterized by sharp increases in tremor amplitude, intense $SO_2$ release, and higher volcanic gas $SO_2$/HCl ratios. The magnitude of $SO_2$ emission rate correlates with the proportion of primitive magma in co-erupted products during the first half of the sequence. The estimated total gas discharge, compared to the co-erupted tephra mass, suggests a large excess gas release for most events, which is proportional to the length of the repose interval. Combining these observations with models of S and Cl degassing from Etna trachybasalt, we infer that the February-April 2021 lava fountai n series resulted from the recurrent accumulation of $H_2O$-$CO_2$-rich bubble foams at ~ 2-3 km depth beneath SEC, whose periodic collapse promoted fast magma ascent and fragmentation associated with essentially syn-eruptive degassing of S and Cl. Our study thus provides further insight into the complexity of magmatic processes determining lava fountain paroxysms at Mt Etna and, possibly, other basaltic volcanoes.

# Effect of water on $CO_2$ diffusion in basaltic melts: experimental insights

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Although $H_2O$ is the dominant volatile species in magmas and the primary driving force behind volcanic eruptions, the less soluble $CO_2$ begins to exsolve at depths where $H_2O$ remains dissolved in the melt. This early exsolution triggers bubble nucleation at depth, while the subsequent bubble growth rate—ultimately controlling eruption explosivity—is limited by volatile transport in the melt. However, experimental studies have largely focused on $H_2O$ transport in melts, while $CO_2$ diffusion remains poorly constrained for key magma compositions. In basaltic systems, for example, prior work has focused on anhydrous melts, neglecting the significant influence of $H_2O$ on $CO_2$ diffusion [Watson et al., 1982].

In this study, we systematically investigated $CO_2$ diffusion in a K-rich basalt from Stromboli (PST-9; [Di Carlo et al., 2006]) under dry and hydrous conditions. Diffusion couple experiments were conducted at 300 MPa and temperatures ranging from 1150 to 1315 °C using a rapid-quench internally heated pressure vessel. Symmetrical $CO_2$ concentration-distance profiles were measured by FTIR microspectroscopy on doubly polished glass sections and fitted with error functions to determine diffusion coefficients ($D_{CO2}$).

Our results exhibit clear Arrhenius behavior, with $D_{CO2}$ increasing exponentially with temperature. Under anhydrous conditions, these values are consistent with previous results for Fe-free basalts [Watson et al., 1982]. Dissolved $H_2O$ exerts a dominant control on $CO_2$ transport, increasing $D_{CO2}$ by approximately one order of magnitude with the addition of ~4 wt% $H_2O$ (e.g., from log $D_{CO2}$ = -11.26 to -10.45 $m^2/s$ at 1250 °C) while simultaneously lowering the activation energy. When compared to diffusion trends in highly polymerized silica-rich melts, we observe remarkably similar behavior across this extreme compositional range at high temperatures. These results suggest that $CO_2$ transport is primarily controlled by temperature and hydration state rather than melt structure. The systematic dataset of $CO_2$ diffusion coefficients obtained in this study provides new quantitative constraints on volatile transport, enabling more accurate modeling of $CO_2$ degassing and its impact on eruption dynamics in hydrous basaltic magmas.

# Thermal response analysis of soil heated by CO2 emissions detected by a TIR camera estimates the most abundant vent emission flux in Lake Mefite

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Monitoring natural $CO_2$ emissions from geothermal areas and volcanic soils is critical for the investigation of emission systems and environmental and safety applications. Direct measurement of gas temperature at the vent is often impractical due to accessibility or hazard constraints. Remote thermal imaging offers a non-contact alternative, but the measured temperature is not the gas temperature itself; rather, it is the temperature of the soil surface heated or cooled by the gas flux. The soil acts as a thermal buffer, with its own heat capacity and thermal resistance, introducing a time lag and filtering rapid fluctuations. Understanding the dynamic relationship between the source's $CO_2$ flux and temperature and the measured soil surface temperature is essential for interpreting thermal images and extracting quantitative information about the source. Thus, a time series of soil surface temperatures, sampled at high frequency using a thermal camera located 60 metres from a $CO_2$ emission vent in Lake Mefite, has been analysed. This work is part of the FURTHER project, which recently examined the role of fluids during the preparatory phase of earthquakes in southern Italy, revealing non-steady behaviour of the Mefite emissions.
In this case, $CO_2$ is slightly warmer than the surrounding soil, causing localised heating. The soil responds as a first-order thermal system with a time constant of 18.5 minutes and an error of 1.2 minutes, consistent with a thermally active layer depth of 2-5 cm. Change-point detection reveals three significant transitions in the thermal regime, the most prominent at t = 155 minutes, with a temperature variation of +1.5°C and p less than 0.05, interpreted as an increase in $CO_2$ flux or source temperature. An ARMA (1,0) model captures the system dynamics with an AR coefficient of 0.95, corresponding to a time constant of 19.5 minutes. The power spectrum shows that energy is concentrated at low frequencies (periods longer than 30 minutes), which confirms that soil thermal inertia acts as a low-pass filter. A physical model that uses the heat balance of the top layer of soil is calibrated, giving heat transfer coefficients of 15-25 $W/m^2K$ and an equivalent $CO_2$ heat flux of 20-40 $W/m^2$. The results demonstrate that remote thermal imaging can effectively monitor sub-surface thermal anomalies, with the soil layer acting as a natural low-pass filter that attenuates rapid fluctuations while preserving information on longer-term changes in the source.

# S03 - TRACKING MAGMA ASCENT FROM RESERVOIRS TO SURFACE: BRIDGING EXPERIMENTS, MODELLING AND OBSERVATIONS TO INVESTIGATE PRE- AND SYN-ERUPTIVE PROCESSES

Conveners:

Barbara Bonechi, Emily C. Bamber, Elisa Biagioli, Giuseppe La Spina

# Protracted magma fragmentation during mafic explosive eruptions

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Magma fragmentation generates pyroclasts and drives explosive volcanic eruptions. Mounting evidence suggests that fragmentation is not a single event but a multistep process occurring in variable and currently poorly defined conditions. We present features of pyroclasts that shed new light on the variety of conditions under which mafic magmas fragment during explosive activity of different styles. We describe and quantify microtextures related to magma fragmentation in pyroclasts from recent eruptions of Etna and Stromboli (Italy) and Cumbre Vieja (Spain) volcanoes by integrating Scanning Electron Microscopy, X-ray microtomography, and image analysis. Pyroclast contours range from smooth to ragged but also with intermediate features, indicating fragmentation before, after, and right at the viscous to brittle transition. The presence of pyroclasts re-incorporated into magma, and then re-fragmented records multiple break-up and fusing events. Broken crystals within intact glass reveal the passage of brittle cracks through magma and the subsequent viscous healing of the melt. Both crack healing and clast fusing leave behind identifiable sutures. During the Cumbre Vieja eruption, the abundance of these microtextures changed with changing eruption style. Sutures abundance peaks in lava fountain deposits, suggesting deep and hot fragmentation favoring frequent re-welding of cracks and pyroclasts. Broken crystals and incorporated pyroclasts are more frequent in less vigorous jetting activity, dominated by shallower, cooler fragmentation closer to quenching temperature. We propose that mafic magma fragments through multiple fracturing and healing events that protract across a range of temperatures and environments and reflect in the abundance of specific pyroclast microtextures.

# Pre- and syn-eruptive conditions of the 1631 eruption of Mt. Vesuvius: Implications for eruptive style transitions

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Volcanoes produce a wide range of eruptive activity, from effusive lava emission to highly explosive eruptions. Constraining the relationship between eruptive behaviour, pre-eruptive magmatic reservoir conditions and syn-eruptive conduit processes remains one of the principal challenges in volcanology. While transitions in eruptive style have been investigated for basaltic and silicic systems, K-rich magmas remain comparatively understudied.
Here, we investigate the 1631 eruption of tephri-phonolitic to phono-tephritic magmas at Mt. Vesuvius, a complex event which began with sub-Plinian activity and culminated in a Vulcanian phase. We integrate multidisciplinary approaches to investigate magma storage conditions, ascent processes, and eruptive dynamics. These approaches include analitycal techniques as 2D back-scattered electron (BSE) image analysis and 3D X-ray micro-computed tomography (μCT) for textural characterization, as well as electron probe microanalysis (EPMA) and secondary ion mass spectrometry (SIMS) to determine the chemistry and volatile contents of minerals, glass, and melt inclusions. Additionally, we conduct high-pressure and high-temperature quenching experiments to reproduce shallower magma reservoir conditions and magma ascent during the sub-Plinian and Vulcanian eruption. We combined the experiments with thermodynamic reconstructions, using Rhyolite-MELTS and geothermometric calculations.
Our results indicate that tephri-phonolitic and phono-tephritic magmas ascended rapidly from 16 km to 4 km, corresponding to pressures of ~400 MPa to ~100 MPa. The tephri-phonolitic magma is associated with the high-intensity sub-Plinian phase, whereas the phono-tephritic magma corresponds to a decrease in eruptive intensity and transition to Vulcanian behaviour. 2D and 3D textural data show that phenocryst abundance remains approximately constant across eruptive units, while microlite abundance varies significantly. Sub-Plinian tephra is characterized by lower total crystallinity and high vesicularity, whereas the last erupted Vulcanian products are nearly fully crystallized at the microscale and poorly vesiculated. The Vulcanian magma is more crystallized in microlites and more extensively degassed, suggesting transient stagnation within the shallow conduit, promoting conduit overpressure and episodic explosive activity. These findings suggest that transitions from sub-Plinian to Vulcanian behaviour in K-rich systems can be driven by changes in outgassing efficiency and microlite crystallization. Rapid ascent favours low crystallinity and sustained explosive discharge, whereas conduit stagnation enhances crystallization, increases magma viscosity, and promotes overpressure-driven Vulcanian eruptions.

# Tracing magma emplacement with surface and subsurface imaging

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We demonstrate how surface analyses can be used to identify actively emplacing magma bodies at middle/shallow crustal levels along with their long-term evolution. We invert the river network to extract spatially explicit maps of rock-uplift rates from topographic data, representing a parallel significant advantage over previous methods in imaging blind magma intrusions. Based on the plethora of geological and geophysical data, we select the Larderello-Travale-Magmatic-System (LTMS) in the Northern-Apennines (Italy), where a low shear-wave velocity anomaly (SW) from ambient-noise-tomography (ANT) reveals a large subsurface partial melt body (5000 $km^3$). The combination of our pattern of rock-uplift rates with SW-ANT allows us to document a correlation in space and wavelength between subsurface magmatic processes and surface topographic responses. We estimate a cumulative uplift of about 300 meters over 1.2 Ma, corresponding to an accommodation space volume of ca 400 $km^3$. On these bases, we therefore propose a long-term evolutionary model for magma emplacement beneath the LTMS, describing the topographic-magmatic features and attempting to quantify magma injection rates.
This study also documents how river network inversion models can serve early-stage exploration of geothermal green-fields fed by crustal magmatic intrusions, thus representing a non-invasive, environmentally sustainable and extremely low-cost tool.

# Multidisciplinary constraints on magma dynamics fueling the 2022-23 volcanic activity at Mt. Etna

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Petrological data, volcanic tremor and $SO_2$ emission rates have been integrated to investigate the activity of Mt. Etna in the period between March 2022 and August 2023. Over this period, two relatively long effusive phases occurred at the South-East Crater, the first in May - June 2022 and the second in the period November 2022 - February 2023. A few months later, the same crater also produced lava fountains on May 21 and August 13, 2023. We have analyzed the chemical record of olivine crystals from products erupted during the effusive and explosive phases to identify episodes of magmatic intrusion and remobilization preceding the eruptions and derive their timescales through Fe-Mg diffusion. We found strong temporal correspondence between the petrological evidence of mafic magma pulses at various crustal depths and the geophysical and geochemical signals of volcanic unrests associated to magma/gas migration through the upper conduits. In this context, volcanic tremor and $SO_2$ flux intensified in early May 2022 following the ascent of fresh, gas-rich magma towards the shallowest portion of the plumbing system, at depth lower than 2 km below the summit area, feeding the early effusive activity at the South-East Crater during May - June 2022. The onset of effusive activity in November 2022 was preceded by new magma pulses from deeper reservoirs, which gradually remobilized the residual melt previously emplaced in the upper-intermediate plumbing system. Compared to the effusive phase, the 2023 fountaining activity was fed by more mafic magmas. The shift from dominant effusive to highly explosive behavior follows the activation of deep magmatic environments located at depth higher than 9 km below the summit area. Crystals indicate a major phase of deep mafic replenishment during April - May 2023, shortly before the fountaining episode of May 21. This occurred in conjunction with significant volcanic tremor amplitude and $SO_2$ flux increase, as a result of the rapid migration of magma releasing large amounts of volatiles upon decompression. By integrating multiple datasets, we were able to accurately decrypt recurrent magmatic conditions and processes that drove changes in volcanic activity and led to different eruptive styles.

# Olivine zoning and diffusion chronometry track the reawakening of the Voragine crater at Etna during the summer 2024

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In the period July-August 2024, Mt. Etna volcano produced a new sequence of six paroxysmal eruptions at the Voragine crater. This study combines whole-rock and glass major-element analyses with a detailed investigation of crystals found in erupted products in order to constrain the plumbing system dynamics preceding and accompanying the eruptive sequence. The petrological approach is primarily based on the zoning of olivine crystals, specifically the core-to-rim compositional variations of the forsterite content. Petrological evidence indicates a progressive replacement of magma in the shallow portions of the feeding system extending from 1 to 5 km below the summit during the Strombolian activity that preceded the paroxysmal sequence. This is supported also by the variation of glass compositions through time that became progressively more mafic from June 16 to the onset of paroxysmal eruptions on July 4. Olivine compositions and thermodynamic modeling further suggest that the main magma source feeding the eruptions was located at depths of 3-9 km beneath the summit. From this level, magma ascended rapidly to the surface, as indicated by the abundant non-zoned crystals and by the L.O.I. values of the bulk rock higher than those of the past activities. Timing of transfer between the magmatic environments activated during the period has been constrained by applying the Fe-Mg diffusion chronometry to zoned olivine crystals. Diffusion models indicate timescales of approximately 3-4 months (i.e., April-May 2024) for mafic recharge from depths of ~9-11 km toward storage zones located at 6-9 km of depth, followed by further migration into the intermediate-shallow feeding system 1-3 weeks prior to the onset of Strombolian activity on June 14. Overall, our results reveal some differences in the dynamics of Etna's plumbing system compared to those related to the activity at Voragine on 2015-16 and at the Southeast Crater on 2020-22. In contrast to the earlier episodes, which emphasized rapid deep-to-surface magma transfer, the 2024 dynamics suggest that magma is now more prone to reside at intermediate levels without major magma accumulation in the uppermost reservoirs.

# Dynamics of fumarole emissions during the eruptive activity of Mount Etna, 2019-2021

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The study focused on the results of geochemical monitoring of fumarole gases using a permanent station located on the North-East Rift of Mt. Etna (altitude of about 2,500m a.s.l.). This site was specifically selected due to the presence of stable emission of steam and other fumarole gases from a vent that opened during the 2002 flank eruption. The gases show distinct chemical and isotopic signatures. The dominant non-condensable gas species is carbon dioxide ($CO_2$), followed by methane ($CH_4$); the isotopic ratios both of carbon of $CO_2$ and of He are indicative of a magmatic source, while $CH_4$ carbon isotopic ratios point to its thermogenic origin.
The monitoring was carried out during the summer months of each year from 2019 to 2021, with sampling step of 5 minutes. Negative peaks in $CO_2$ concentration were observed in many occasions and they were found to be precursory signals of summit eruptions. Actually, in almost every instance a sharp decrease in $CO_2$ concentrations was followed by increased volcanic activity—either Strombolian or paroxysmal—at the summit craters 24-48 hours later.
Our interpretation of the observed changes proposes a complex mechanism of fluid-dynamic events in which gas-rich magma migrates rapidly from a deep reservoir (1-6 km b.s.l.) to a shallow one (1-2 km a.s.l.). This sudden, high-velocity movement of magma and the associated sharp release of a gas phase would induce a marked pressure drop within the volume of rocks surrounding the volcanic conduits. Similar to the Venturi effect, the rapid variation in gas flow within the volcano's central conduits would drag gases away from the peripheral fumarole vents, thereby reversing the normal outward flow gradient. This process would explain the significant $CO_2$ decreases measured at the surface.
It is theorized that the transition from steady degassing to violent lava fountains is the result of the composition of the magmatic column. Strombolian activity usually starts the eruptive cycle by gradually consuming or ejecting the thick, degassed, and cooler magma that normally resides at the top of the magma column. Once the magma cap becomes thin enough, it can no longer suppress the pressure of the underlying, fresh, gas-rich magma. In this instance, the ascending, gas-rich magma disrupts the equilibrium, leading to the rapid expansion of gas bubbles and the subsequent formation of a lava fountain.

# The role of crystal-bubble interactions, outgassing and magma composition in the ascent dynamics of alkaline magmas: Implications for eruptions at Vesuvius

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Intermediate to evolved alkaline magmas (phono-tephritic, tephri-phonolitic, and phonolitic) display a broad spectrum of eruptive behaviours and have generated some of the most catastrophic eruptions recorded in human history, including the AD 79 Plinian eruption of Mount Vesuvius. Nevertheless, eruptive dynamics are governed by complex, non-linear processes occurring within volcanic conduits during magma ascent, which calls for an integrated approach to evaluate their role in controlling explosivity. In this study, synchrotron radiation X-ray computed microtomography (SR microCT) is combined with a one-dimensional steady-state conduit model to examine how crystal-bubble interactions, pre-eruptive conditions, outgassing processes, and magma composition influence eruptive style in alkaline volcanic systems, using Vesuvius as a case study.

Pyroclasts from the AD 79 Plinian and 1944 lava-fountaining eruptions were analysed using SR microCT. The results show that heterogeneous bubble nucleation may be further promoted by leucite crystals, contributing to the high bubble number densities (higher than $10^4$ $mm^{-3}$) observed in Plinian products. Despite a high degree of bubble connectivity, low throat-to-pore size ratios (i.e., the ratio between the radii of the throats and their connected vesicles) and increased tortuosity limit gas-melt separation during rapid magma ascent, thereby favouring fragmentation. Numerical simulations indicate that tephri-phonolitic and phonolitic magmas are susceptible to fragmentation under a wide range of conditions, leading to highly explosive eruptions. Only relatively high temperatures (higher than 1050 °C) and low bubble number densities ($10^2$-$10^3$ $mm^{-3}$) favour effusive behaviour such as lava flows and lava fountaining. In contrast, phono-tephritic magmas can produce highly explosive eruptions at significantly lower temperatures (lower than 950 °C). Temperature exerts a primary control on magma viscosity, which affects ascent rate and outgassing efficiency and, consequently, influences conduit dynamics and eruptive behaviour.

Overall, our results indicate that in alkaline volcanic systems the range of conditions favourable to highly explosive eruptions broadens as magma composition evolves and viscosity increases. These findings improve our understanding of eruption mechanisms and provide important constraints for volcanic hazard assessment and emergency planning in alkaline volcanic settings.

S03 - Oral Presentation

# Rise of bubble-like cavity in saturated granular media: a new mechanism for subsurface fluid ascent and explosive release

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Liquid-fluidization pipes are widely observed in geophysical contexts, including volcanic systems and subsea fluid release, where they are associated with rapid and violent fluid-particle discharge and represent significant geohazards. However, their structural and dynamical properties remain poorly constrained, particularly with respect to grain-size distribution.
From a fundamental physics perspective, fluid injection at the base of a saturated granular medium has been extensively studied in fluidized beds, yet it continues to reveal unexpected and poorly understood behaviours.
With the aim of investigating fundamental processes of subsurface fluid migration relevant to volcanic systems, we performed laboratory experiments injecting water into a water-saturated granular layer of controlled porosity in a Hele-Shaw cell. In our experiments we systematically varied grain-size distribution and injection conditions. Our observations reveal a puzzling regime. Under specific conditions, such a critical high h_c and flux Q , fluidization leads to the formation of a detached fluid cavity that separates from the injection point and rises through the sediment. To our knowledge, this "bubble-like" behaviour has not been previously reported. The cavity exhibits a stable upward propagation while remaining fully embedded within the sediment, suggesting a dynamic balance between erosion at the top and deposition at the base. This unexpected stability raises fundamental questions regarding the mechanisms that prevent collapse and allow sustained ascent.
We propose that this behaviour provides a new framework for understanding transient fluid storage and sudden release in shallow subsurface environments. In volcanic settings, it may represent a simplified analogue for fluid accumulation and rapid pressure release processes involved in phreatic and phreatomagmatic activity.
Our results highlight the critical role of small-scale fluid-granular interactions in controlling large-scale eruptive behaviour, emphasizing that laboratory analogue experiments provide a fundamental and important framework for understanding the physical mechanisms driving geophysical and geological processes at larger scales.

# Rheological constraints on mantle derived volatile bearing magmas from high pressure and temperature experiments: advances and limitations

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Erupted lavas and peridotite mantle rocks often show evidence of interaction with fluids, the chemical composition of which has been often referred to as volatile-bearing melts leading to unusual enrichments in Na and Ti [Coltorti et al. 2004-Lithos; Perinelli et al. 2008-JGSL; Scribano et al. 2009-MinPetr]. The chemical composition of near-solidus melts is expected to vary dramatically as result of pressure, temperature and mantle redox state, covering a broad spectrum of compositions from pure carbonatitic to dacitic [Stagno 2019-JGSL]. Variations in composition along with decompression and cooling are expected to cause significant changes in the rheological properties of these magmas (e.g. density, viscosity and melt structure) with important implications for their mobility, residence time, kinetics of fluid-rock interaction and ascent rate.
This contribution provides updates on experimental studies aimed at determining the rheology of (volatile-bearing) melts with variable $SiO_2$ content from carbonatitic to carbonate-silicate to $CO_2$ and $H_2O$-bearing ultrabasic and basaltic melts. Focus is given to viscosity measurements conducted at pressures between 0.3 - 8 GPa and temperatures of 1000-1600 °C with the falling-sphere method using using the Paris-Edinburgh press combined with the in-situ synchrotron radiation at both 16BM-B and 13 ID-C beamlines at the Advanced Photon Source of Argonne National Lab (USA). In these experiments, the falling velocity of a metallic sphere (either rhenium or platinum) through the synthetic melt is measured by ultrafast X-ray radiography using a high-speed camera with a 250-1000 fps recording rate. The viscosity is, then, calculated using the Stokes equation including the correction factors for the effect of the wall and the end effect. Further, the atomic arrangement of the liquid is investigated at high pressures and temperature using either multi-angle energy or monochromatic X-ray diffraction technique [Stagno et al. 2018 ChemGeo; Bonechi et al. 2022-ScRep; Stopponi et al. 2024, 2025-ChemGeo].
Results show viscosities from 0.02 Pa s for carbonate-silicate melts that increase up to two orders of magnitude in the case of ultrabasic and basaltic melts explained by the progressive formation and connection of silicate tetrahedra as the abundance of network formers such as $Si^{4+}$, $Al^{3+}$ in the melt increases. Ti-rich carbonated melts, more representative of metasomatic fluids, are also characterized by low-viscosity ($10^{-1}$ Pa s).
The available viscosity data allows the calculation of the hydrostatic melt mobility, proportional to the gravity-driven melt transportation, which is estimated to vary from ~60 to 0.2 g $cm^{-3}$·$Pa^{-1}$ $s^{-1}$ within the compositional range of interest. Calculations of the ascent rate through mantle lithologies as a function of melt fraction, grain size, chemical composition and source depth are also presented. For instance, the high mobility of Ti-rich melts combined with their small volume fractions results to long residence time necessary to promote chemical reactions with the surrounding rocks.
Despite the amount of data that allows modelling the ascent rate of primary magmas, to date, a major challenge is represented by the missing link between the viscosity of mantle-derived melts with that of more evolved crustal magmas due to processes like assimilation, crystal fractionation and degassing that can alter the initial role played dominantly by the composition.

S03 - Oral Presentation

# New insight into the plumbing system dynamics of the present-days activity of Stromboli from a clinopyroxene-only geothermobarometer

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Understanding the plumbing system of active volcanoes, with the prediction of crustal magma storage conditions (pressure and temperature), is fundamental to volcanic hazard assessment. Pyroxenes are among the most common minerals of mafic volcanic rocks and their compositional variations record important information on the anatomy of volcano feeding systems. In this study we have investigated the clinopyroxene composition of scoriae and pumices erupted by the present-days activity of Stromboli in the last 110 years, as well as in the paroxysmal eruption of 1456 CE.

This basaltic activity is characterised by persistent mild explosive (normal Strombolian) eruptions, periodically interrupted by lava flows and more energetic explosions (major eruptions and paroxysms). A degassed and highly porphyritic magma (hp magma), with a shallow level origin, is erupted by the normal activity and lava flows, whereas a volatile-rich magma of deeper origin and with low phenocryst content (lp magma) is also erupted as pumices by major eruptions and paroxysms. During ascent, the lp magmas pass through a cumulate crystal-mush zone and transport antecrysts/antemelts into the shallower reservoir.

Our clinopyroxene dataset, complemented by an exhaustive literature dataset, includes all the eruption types, from normal Strombolian to paroxysmal eruptions, for a total of 1595 high-quality analyses of 328 clinopyroxenes from 120 samples. The overall clinopyroxene dataset includes diopsides (Mg-number higher than 80, the equilibrium crystals with the lp magma) and augites (Mg-number lower than 80, the equilibrium crystals with the hp magma) and shows interesting compositional variations linked to the different types of activity, such as two distinct trends in the Mg-number versus $Al_2O_3$ diagram.

A recent Feedforward Neural Network geothermobarometer [Chicchi et al. 2023 - EPSL 620, 118352] was applied to the clinopyroxene dataset, including the different zones of the crystals (core, intermediate, rim) to obtain robust pressure and temperature predictions. Diopside yields a major peak in pressure between 2.5 and 3.5 kbar, with a tail to lower pressure, down to 1.0-1.5 kbar and a minor tail to higher pressures (3.5-5.5 kbar). In contrast, augite yields an almost gaussian distribution with a peak at pressure of 1.0-1.5 kbar, and nearly symmetrical P tails. To the best of our knowledge, this is the very first time that a single-crystal (clinopyroxene) machine learning algorithm is able to distinguish the two major transcrustal storage zones of the present-days plumbing system of Stromboli. The observed tails also indicate a continuum crystallization from about 5 kbar to 0.5 kbar, revealing however some different behaviours depending on the eruption styles. In terms of temperature, diopside has an almost gaussian distribution of crystallization temperature between 1050 and 1100 °C, with tails up to 1150 and 1025 °C. Augite has an asymmetric distribution of crystallization temperature, with a peak at 1075-1100 °C and a significant tail to lower temperature, down to 950 °C. The overlapping temperature range of diopside and augite is in agreement with the different volatile contents of the respective lp and hp magma of crystallization.

The application of this geothermobarometer to the different crystal zones has also allowed to

detail the pressure and processes of lp magmas interaction with the antecrysts during their ascent, recognising deep crystal-mush sources. Moreover, the P-T relationships, associated to the higher $Al_2O_3$ content of clinopyroxenes from paroxysms, suggest different ascent modes of lp magmas between major eruptions and paroxysms.

# Conduit dynamics during the 726 CE Santorini submarine explosive eruption revealed by 3D pumice textures

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The 726 CE eruption represents the most recent historically documented explosive event of Santorini volcano. Contemporary accounts describe boiling seawater, dense steam production, and ejection of hot volcanic material, forming a pumice raft that drifted over 400 km across the Aegean Sea. Yet, only sparse on-land deposits are preserved on the Kameni islands within the Santorini caldera, leading to long-standing uncertainty on the eruption's magnitude. The tephrostratigraphic record suggests that major explosive events at Santorini typically follow tens-of-thousands-of-years-long edifice-building cycles, the latest culminating in the 1630 BCE Late Bronze Age ("Minoan") caldera-forming eruption. Consequently, current hazard scenarios predominantly favour future effusive or mildly explosive activity from the Kameni islands, with limited impact on the main island of Santorini.
Recent sediment cores collected within the caldera floor during IODP Expedition 398, however, revealed a massive pumice deposit chronologically linked to the 726 CE eruption. This finding prompted a substantial reassessment of the erupted volume, indicating that the eruption reached VEI 5 intensity and challenging existing hazard scenarios, as recurrence intervals for highly explosive eruptions may be shorter than previously expected (e.g., potentially only a few thousand years).
To constrain eruptive dynamics, we performed quantitative textural analyses of pumice using integrated 2D (SEM) and 3D (3DXuCT) imaging techniques. This approach enables statistically robust characterisation of vesicularity, permeability, and crystallinity, revealing microstructural signatures diagnostic of conduit processes during magma ascent. Preliminary observations identify distinct ash particle populations, varying in colour (white to dark) and vesicle morphology (subspherical to elongated), variably distributed across the deposit cores. Within them, variations in vesicularity (40-80%), number density (1-8·$10^4$ $mm^{-3}$), aspect ratio, and size distributions suggest fluctuating ascent conditions across the conduit. These parameters provide a basis for constraining ascent rates, as well as bubble (and crystal) nucleation and growth processes, offering new insight into the mechanics of the 726 CE submarine eruption. These results contribute to a reassessment of volcanic hazard at Santorini, particularly in submarine environments where water-column pressure modulates eruptive behaviour.

# 3D visualisation of nanolite aggregation in basaltic magmas using X-ray ptychography

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Nanoscale crystals, or nanolites, are becoming increasingly recognised in the products of volcanic eruptions and laboratory experiments, across a range of magma compositions and explosivity. Despite their low particle content in magmas, nanolites can have a considerable impact on magma viscosity through the physical impact of the nanoparticle suspension, their influence on the chemistry and structure of the residual melt and by facilitating heterogeneous bubble nucleation. Due to their high surface area, nanolites are also susceptible to aggregation, increasing their impact. However, despite the potential influence of nanoscale particle interactions on magma viscosity, the morphology and spatial distribution of nanolites has not yet been investigated using a 3D approach.

We present an innovative, 3D nanometre-scale visualisation of nanolites in basaltic scoriae, obtained using X-ray ptychography. We find that titanomagnetite nanolites aggregate, forming elongate, irregular structures in 3D. Nanolite crystallisation also leads to the depletion of Fe and Ti in the surrounding melt, forming differentiated boundary layers with higher viscosity. The syn-eruptive crystallisation of nanolites and their interaction is estimated to have increased magma viscosity by 2-3 orders of magnitude, increasing the potential of magma fragmentation during ascent. Our results provide insight into the nanoscale structure of volcanic products and also the driving mechanisms of highly explosive Plinian eruptions at basaltic systems.

# Pre- to post-eruptive crystallization of trachybasaltic melts and related timescales: clues from the 1651-1654 CE lavas of Mount Etna (Sicily, Italy)

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The cooling dynamics and rheological properties of basaltic lavas play a first-order control on their ability to flow on the surface, produce extended lava fields and/or generate lava tunnels, and ultimately halt. Therefore, the modelling of crystallization dynamics and volatiles (mostly $H_2O$) degassing of magmas and lavas is of paramount importance for understanding the behaviour of long-lasting effusive eruptions with high emission rate, which pose a major hazard for human infrastructures and settlements [Troll et al., 2024, Geology Today]. In this work, the pre- to post- eruptive crystallization dynamics of trachybasaltic melts was investigated on lavas emplaced during the 1651-1654 CE eruption on the western flank of Mount Etna volcano (Sicily, Italy). This event represents one of the most important of the 17th century due to its prolonged duration, the extension of the lava field, and its reach into inhabited areas on the volcano flank, causing the damaging of farmhouses and cultivated areas, as well as the partial invasion of the town of Bronte [Branca and Abate, 2019, JVGR]. The lava field is made of the superposition of numerous lava flow units having thickness up to 5 m and displaying characteristic “pahoehoe” surface morphology, nowadays exposed and accessible along fractured pressure ridges. To reconstruct the crystallization history of the 1651-1654 CE lavas and quantify the extent of crystallization at pre- and post-eruptive conditions, a multi-technique approach combining 2D and 3D (Synchrotron Radiation computed microtomography) textural, chemical (X-Ray Fluorescence), spectroscopic (Fourier-Transform InfraRed spectroscopy) and mineralogical (X-Ray Diffraction and Electron Probe Microanalysis) analyses was performed on different layers of a single unit flow, from its inner to its outer (pahoehoe crust) portion. Results indicate that all portions of the flow have porphyritic texture, with large euhedral to subhedral phenocrysts of plagioclase and clinopyroxene and smaller phenocrysts of olivine and Ti-Fe oxides immersed in a groundmass varying from microcrystalline in the inner portion to glassy in the crust of the flow. The inner portions of the lava flow are more massive and contain less bubbles (5-8 area%), with glass present only as interstitial phase between the groundmass microlites, while the outer portions are more glassy and bubble rich. Mineral chemistry and thermobarometric modelling show that olivine and clinopyroxene cores cluster at Mg# between 70 and 77, and record crystallization temperature of 1070±30°C, at pressure ranging from 6.3 down to 3.1±1.7 kbar. The Mg-richer antecrysts bearing witness of deeper and hotter crystallization conditions are not present. Plagioclase crystallization started in a water rich ($H_2O$ = 4 wt%) and continued during/after its exsolution threshold at pressure lower than 2.5 kbar. Degassing continued to the surface during lava emplacement, as testified by the numerous bubbles and by a residual $H_2O$ content of 0.07-0.14 wt% measured in the glassy crust of the flow. Along with degassing, crystallization continued during lava emplacement, with a rapid cooling of the pahoehoe glassy

crust testified by the presence of a chemical boundary layer around plagioclase microlites. Using the model of [Lucassen et al., 2009, CMP], the subaerial growth rate of plagioclase microlites was estimated to be in the order of 0.2-4.5 µm/s, which translates to fast timescales (minutes) to ultimate cooling of the flow. These results advance our understanding of lava behaviour during emplacement and pose the basis for future improvement in predictions of mafic lava paths, leading to better petrological monitoring and response during volcanic crises similar to the 1651-1654 CE eruption.

# Role of superheating and clinopyroxene nucleation delay in mafic magmas: implications for ascent dynamics and eruptive style

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Superheating plays a critical role in controlling crystal nucleation in mafic magmas, yet its impact on eruption dynamics remains debated. In natural magmatic systems, superheated magma may arise directly from the mantle and enter in subliquidus conditions within the crust, or from decompression of water undersaturated magmas during ascent, which effectively increases the temperature relative to the liquidus without requiring external heat input. We investigate the role of superheating on clinopyroxene nucleation in tephritic magmas from the 2021 Tajogaite eruption (La Palma, Spain) through in situ 4D (space + time) synchrotron X-ray microtomography and ex situ experiments. Non-superheated melts ($\Delta T_{sh}$ = 0 °C) crystallise within 20 min, producing numerous small crystals (~200 um), whereas superheated melts ($\Delta T_{sh}$ ~90 °C) exhibit nucleation delays up to 8 hours and form fewer, larger crystals (~400 um). Differential scanning calorimetry confirms that increasing superheating systematically delays crystallisation onset and peak temperatures, reflecting structural homogenisation and dissolution of pre-existing nuclei. Crystal growth rates are inversely correlated with superheating, with in situ experiments showing faster growth ($1{\cdot}10^{-6}$-$5{\cdot}10^{-7}$ cm $s^{-1}$) than ex situ (~$2{\cdot}10^{-7}$ cm $s^{-1}$). Incorporating these nucleation delays into a 1D conduit model, we performed numerical magma ascent simulations demonstrating that prolonged delays maintain low crystal content (~20 vol.%) during rapid ascent, producing high mixture velocities and mass eruption rates (~$4{\cdot}10^{4}$ kg $s^{-1}$) consistent with lava fountaining. Shorter delays (~20 min) allow syn-eruptive crystallisation (~40 vol.% total crystals), slowing ascent and favouring effusive eruption (~$2{\cdot}10^{3}$ kg $s^{-1}$). These findings show that pre-eruptive superheating fundamentally controls nucleation and growth, thereby modulating magma viscosity, ascent velocity, and eruptive style. Comparison between thermodynamical modelling and thermal evolution paths of ascending magma representative of strong disequilibrium and near-equilibrium crystallisation, further indicates that superliquidus conditions are promoted under high $H_2O$ content and reduced redox states, defining distinct superheating regimes. Overall, our results elucidate a mechanistic link between superheating, nucleation delay, and eruptive behaviour in mafic magmas, with implications for experimental protocols, numerical models, and volcanic hazard assessment.

S03 - Oral Presentation

# Bullet eruptions and crustal assimilation in fast-ascending magmas (Logudoro Volcanic Field, Italy)

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Tectonically-controlled volcanic fields are predominantly characterised by monogenetic activity following "bullet eruptions" dynamics, in which small volumes of magma rapidly ascend from the mantle, preventing, therefore, differentiation processes. In this study, we assess whether this model can be also applied to the Logudoro Volcanic Field. In particular, we aimed to investigate the processes responsible for the differentiation paths suggested in the literature. Detailed petrographic analyses were performed on 17 samples (lavas and scoriae) representative of the different bulk compositions and eruptive centres of the volcanic field.

All analysed samples are petrographically classified as olivine basalts, with a homogeneous magmatic assemblage dominated by plagioclase, olivine, and clinopyroxene. Phenocrysts usually relatively small (less than 400 µm in size), exhibiting rapid growth features such as elongated habits and skeletal textures. Xenoliths/xenocrysts are abundant and are comprised of quartz grains from the crystalline basement, magmatic quartz crystals from Oligo-Miocene intrusions, Oligo-Miocene trachytes and rhyolites tuff rocks, heteradcumulates (Ol + Di + Cr-Spl) likely derived from unerupted Plio-Quaternary magma batches, and lherzolite peridotite xenoliths from the lithospheric mantle.

Quartz-melt reactions reveal different degrees of dissolution depending on texture. Mono-polycrystal xenoliths (500 µm crystals) develop small, regular reaction coronas, whereas granular xenoliths composed of numerous crystals exhibit larger, irregular coronas. These differences indicate at least two quartz protolith types sampled at different crustal depths, resulting in different melt-xenolith interactions. These petrographic features are consistent with rapid magma ascent and indicate that the observed evolutionary trend is primarily driven by crustal contamination through mingling processes, involving mechanical mixing between basaltic melt and xenoliths/xenocrysts of variable size, down to the submillimetre scale. Data obtained in the study, combined with Logudoro's lava bulk compositions in the literature, in fact, shows that $SiO_2$ content correlates directly with the increase of the ratio of high-$SiO_2$/mafic lithics. On the other hand, if we consider the temporal evolution of the volcanic field, we observe a general decrease in $SiO_2$ content, associated with a decrease in the high-$SiO_2$/mafic lithics ratio. This suggests an "ageing" of the crust caused by gabbroic intrusions during volcanic activity, resulting in a decrease in the ratio between high-silica and mafic xenoliths, reduction in SiO2 content and in the evolution trend observed in literature.

This model provides novel insights into the dynamics of magma ascent and evolution in tectonically-controlled volcanic fields, where mechanical crustal contamination plays a crucial role. Future determination of the erupted volumes, eruption dating and vent-fault relations in the Logudoro volcanic field will further refine the proposed model.

# Pressure-temperature-$H_2O$ controls on the crystallization of tephri-phonolitic magmas: Experimental insights from the Ventotene volcanic system

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Understanding the physico-chemical parameters controlling magma storage and evolution within volcanic plumbing systems is fundamental for interpreting eruptive dynamics. Pressure, temperature and volatile content strongly influence phase equilibria and crystallization sequences in alkaline magmas, yet constraining pre-eruptive storage conditions remains challenging. Experimental petrology provides a powerful tool to investigate these processes and to link mineral assemblages with specific pressure-temperature-$H_2O$ conditions.

Here, we present high-pressure-high-temperature crystallization experiments on a tephri-phonolitic composition (sample MD1), with a mineral assemblage composed of plagioclase, dark mica, amphibole, clinopyroxene, scarce alkali feldspar and oxides, that is representative of the juvenile pyroclasts erupted during the Parata Grande Plinian, caldera-forming eruption of Ventotene volcano (Pontian Islands, Tyrrhenian Sea). Experiments were conducted at 600 and 300 MPa over a range of temperatures (840-1050C) and variable $H_2O$ contents, spanning both undersaturated and oversaturated conditions. A subset of runs at 600 MPa included a supra-liquidus thermal step for a fixed time prior to cooling to the target temperature, in order to avoid the potential occurrence of crystalline nuclei that could act as nucleation sites and thus influence crystallization kinetics. Indeed, runs without this supra-liquidus step preserve olivine resistates, metastable relicts that react with the melt to produce biotite microlite coronas. In contrast, runs with the supra-liquidus step yield olivine-free assemblages. Under $H_2O$-undersaturated conditions, apatite and Fe-Ti oxides represent the earliest crystallizing phases at 1050 C, followed upon cooling by clinopyroxene, biotite, plagioclase and K-feldspar. $H_2O$-oversaturated conditions produced a similar mineral assemblage (clinopyroxene + biotite + plagioclase + apatite + Fe-Ti oxides) but at lower temperature (900C). At 840C, amphibole crystallizes instead of K-feldspar, highlighting the strong control of water activity on phase relations in these evolved alkaline magmas.

At 300 MPa, experiments over the 900-1000 C interval yield a constant phase assemblage of clinopyroxene, biotite and Fe-Ti oxides, with negligible modal variation across the explored temperature range. Experimental glass compositions at 600 MPa define two distinct trends: runs with the supra-liquidus step evolve toward phonolitic compositions, whereas those without it trend toward trachytic compositions. At 300 MPa, glass compositions cluster within the trachyte field regardless of run conditions.

The results contribute to improving our understanding of differentiation processes in alkaline magmatic systems and provide an experimental framework for interpreting mineral assemblages and inferring pre-eruptive storage conditions within the Ventotene volcanic plumbing system.

S03 - Oral Presentation

# Quantifying the effect of vesiculation, crystallization and magma mixing on eruptive behaviour using X-ray microtomography: Insights from the Cuicuiltic eruption, Mexico

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Magma mixing is widely recognized as a major trigger of explosive eruptions, yet the kinetics of vesiculation and crystallization during magma hybridization remain poorly constrained. Understanding how these processes interact is essential for unravelling what drive highly explosive eruptive behaviour. The Cuicuiltic eruption (6.4 ka) of the active Los Humeros caldera, located in the eastern Trans-Mexican Volcanic Belt, provides an exceptional natural case study to investigate these dynamics. This eruption involved shifts in eruptive style associated with the interaction between a trachydacitic (TD) and basaltic trachyandesitic (Bas) magmas, producing a hybrid trachyandesitic (TA) magma. The evolved magmas (TD and TA) correspond to Plinian phases, whereas the mafic magma (Bas) is linked to a Strombolian episode.

We used X-ray microtomography to quantify the physical properties of pyroclasts from each magma composition directly in 3D. The results reveal a strong contrast in the parameters, reflecting distinct vesiculation and crystallization pathways during magma mingling and mixing, and associated changes in eruptive style. The evolved TD and TA magmas exhibit crystal number densities ($10^3$ $mm^{-3}$) and order of magnitude higher than Bas ($10^2$ $mm^{-3}$). Likewise, connectivity (C=0.98) and porosity (P=0.60) in samples from the Plinian units are substantially higher tahn those of Bas (C=0.61; P=0.36). Vesicle number densities also differ markedly among magmas (TD=5.21·$10^3$ $mm^{-3}$; Bas=1.85·$10^3$ $mm^{-3}$; TA=1.47·104 $mm^{-3}$). These characteristics suggest that, despite their high porosity and connectivity, outgassing was inefficient during the Plinian eruptions, limiting gas escape and promoting rapid magma ascent and brittle fragmentation. In contrast, the Bas magma characteristics are more consistent with lava-fountaining behaviour. These findings improve our understanding of how crystal-bubble interactions during magma mingling and mixing affect eruptive style. More broadly, they highlight the value of integrating 3D microanalyses to reconstruct complex eruptive histories and provide essential insights for volcanic hazard assessment in nearby densely populated regions.

# Insights from the TUBES Project: New Approaches to Lava Tube Formation and Preservation

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Volcanic eruptions are potentially catastrophic phenomena with significant impacts on both the environment and society. Effusive eruptions generate extensive lava flow fields capable of traveling considerable distances from the main vent, spreading along volcanic flanks through the development of channels and morphological structures. Their geometry and extent are controlled by several factors, including magma properties (e.g., viscosity and density), topographic conditions (e.g., slope and roughness), effusion rate, and emplacement duration. The formation of lava tubes is one of the key processes controlling the maximum extent of lava flows. The development of a stable crust around flowing lava, driven by cooling, reduces heat exchange with the atmosphere and enhances flow efficiency. This phenomenon is particularly significant in volcanoes producing voluminous lava effusions and characterized by steady effusion rates (e.g., Hawaii and Mount Etna), but it has also been described in explosive volcanoes with low lava production rates (e.g., Mount Vesuvius). Previous studies have largely focused on field-based descriptions of lava tube development, while only a limited number have quantitatively investigated the physical processes involved in their formation, and even fewer have addressed these mechanisms through a multidisciplinary approach. The TUBES project (undersTanding lava tUBe formation and prEservation) aimed to fill this gap by integrating volcanological, petrological, and physical (e.g., rheological) analyses with structural investigations (e.g., guided wave analysis and acoustic emission testing) and numerical modeling. The project focused on the effusive activity of Etna and Vesuvius, with the goal of improving the understanding of the mechanisms governing lava tube formation and evolution. The results contributed to a better characterization of lava flow emplacement processes, providing essential insights for volcanic hazard and risk assessment in highly urbanized areas. Furthermore, lava tubes at Etna and Vesuvius are located within protected park areas and are accessible to tourists; the results of this study have been used to improve the information provided to visitors and the general public, increasing awareness and knowledge. For the first time at Vesuvius, a multidisciplinary approach was applied, combining fieldwork, 3D scanning, 360° photography, explanatory panels, and SWOT analysis, with the aim of creating and providing visitors with an accessible and comprehensive itinerary to explore volcanic activity. As a result, we acquired data to develop a virtual tour of the study area. Virtual tours allow users to explore and learn about a site from their computers or mobile devices, anywhere in the world.

# Exploring subsurface magma dynamics during the Aug-Oct 2015 Piton de la Fournaise eruption via numerical modelling

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Long-lasting effusive eruptions provide valuable opportunities to investigate magma transport from reservoirs to the surface. The 24 August-17 October 2015 eruption of Piton de la Fournaise, Réunion Island, was a long-lasting effusive eruption and one of the largest events observed at the volcano in the last several decades. It began with a short but intense peak of the time-averaged discharge rate (TADR) of 60 $m^3/s$, followed by a gradual decrease. In a second phase of the eruption, TADR increased from less than 10 $m^3/s$ to more than 20 $m^3/s$ before the eruption suddenly stopped. The deformation pattern showed an initial phase of moderate summit deflation, followed by inflation and then renewed deflation until the end of the eruption. While deformation and TADR were initially well correlated, they became anti-correlated after 25 September [1, 2, 3].

The transition from correlated to anti-correlated behaviour between deformation and discharge rate raises questions about the subsurface processes controlling magma transport during the eruption. This work investigates the subsurface conditions that can sustain the observed eruptive behaviour by using a 1D steady-state numerical model for conduit magma ascent [4]. The modelling framework accounts for key processes such as volatile exsolution, crystallisation, and changes in magma rheology during decompression. We explore how parameters such as magma chamber overpressure, conduit geometry, temperature and volatile content influence magma ascent dynamics and discharge rates.

This work contributes to ongoing efforts to link geophysical observations with physical models of magma transport, thereby improving our understanding of magma ascent processes and their role in controlling the temporal evolution of the 2015 eruption and, more broadly, the behaviour of long-lasting effusive eruptions at basaltic shield volcanoes.

# Thirteen years of petrological monitoring at Etna

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This contribution reconstructs the dynamics of the Mount Etna feeding system between 2011 and 2024 through a consistent and integrated petrological and geochemical approach consolidated over the years. During this period, the volcano exhibited a wide range of eruptive styles, including sequences of lava fountains, Strombolian activity, lava flows, sub-terminal and flank eruptions occurring in various sites at the summit. Such a diversity of eruptive behaviors over a relatively short time interval is unusual when compared with the historical record and suggests that actually the plumbing system is highly dynamic. The 2011-2013 paroxysmal sequence at the Southeast crater was sustained by repeated magma injections occurring over timescales of 1-18 months [Giuffrida and Viccaro, 2017]. During the first years of this sequence (2011-2012), the system was supplied by relatively primitive magma rising from depths of ~8-20 km, progressively replacing resident magmas and the crystal cargo still bearing pre-1971 geochemical signatures. Since 2013, the eruptive activity was mainly controlled by magma transfer within shallower levels of the plumbing system (20 km, revealing previously unrecognized deep magmatic environments and emphasizing the role of ascent in controlling the final eruptive dynamics [Cannata et al., 2018]. The following activity, between February and April 2017 again at the Southeast crater, was mainly effusive and sustained by self-feeding replenishment within the plumbing system, establishing a steady-state regime, in which intermediate reservoirs were continuously recharged from depth [Viccaro et al., 2019]. The 2018 flank eruption in the high western wall of the Valle del Bove likely resulted from a temporary disruption of this steady-state, allowing pressure to accumulate at intermediate depths until a dike intrusion triggered the eruption [Borzì et al., 2020]. Between July 2019 and January 2020, the reactivation of the Southeast crater with Strombolian explosions and lava effusions was followed by renewed activity at Voragine, restoring equilibrium between deep recharge and surface discharge after the post-2016 replenishment and the partial drainage associated with the 2018 flank eruption [Giuffrida et al., 2021]. Between December 2020 and February 2022, the Southeast crater produced 62 lava fountaining episodes fed by the most mafic magmas throughout the decade. The sequence developed in two main phases: an initial stage (December 2020-April 2021) characterized by the fast ascent of primitive magma from deep portions of the plumbing system (i.e., 18-20 km of depth), followed by a phase (May 2021-February 2022) dominated by magma transfer chiefly involving the intermediate-shallow reservoirs (~3-8 km) with only a few episodic deep injections [Giuffrida et al., 2023]. During the 2020-2022 sequence ~$108 \cdot 10^6$ $m^3$ of magma were erupted, a volume comparable, although even higher, to that produced during the 2011-2013 sequence but over a shorter time interval. This is an indication that the plumbing system is currently capable of very high discharge rates. New data on the July-August 2024 paroxysmal sequence at Voragine indicate residence times of ~3 months within the intermediate plumbing system, following mafic recharge from deeper levels. The predominance of non-zoned olivine suggests that magma transfer occurred from accumulation zones located ~3-9 km beneath the summit directly to the surface, without significant re-equilibration at shallower levels as observed during the 2011-2013 and 2020-2022 sequences. Our continuous petrological monitoring highlights significant temporal variability in magma ascent dynamics, driven by changes in the deep magma supply

and evolving stress conditions within the volcano edifice. Within this framework, the eruptive sequences at the Voragine crater represent key turning points in the equilibrium of the plumbing system, capable of destabilizing previous configurations and initiating new eruptive cycles.

# Direct observation of vesiculation dynamics in basaltic magmas via in-situ X-ray radiography

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Transitions in eruptive styles at basaltic volcanoes depend on the efficiency of gas-magma decoupling during ascent. Strong gas-melt coupling favours explosive eruptions, while weaker coupling promotes lava flows and fountaining. However, the mechanisms driving transitions between closed- and open-system degassing remain poorly understood due to limited direct observations of bubble dynamics under natural magmatic conditions.
Here, we used a novel high-pressure/high-temperature X-ray Transparent Internally Heated Pressure Vessel apparatus combined with X-ray synchrotron radiography to perform in-situ experiments. These experiments enabled real-time, 2D observation and quantification of bubble growth and coalescence in basaltic magmas during decompression from 100 MPa to surface conditions. For low-viscosity magmas, bubbles coalesced and regained a spherical shape within 3 seconds, indicating that gas and melt remained coupled until the final ascent stage (i.e., the last hundred meters of the conduit), consistent with lava fountaining activity. In higher-viscosity magmas, slower bubble recovery facilitated the formation of connected pathways, leading to gas-melt decoupling. This behaviour was directly observed as bubbles expanded, connected to open pathways, and contracted as gas escaped. This study provides quantitative insights into bubble dynamics in basaltic magmas under pre- and syn-eruptive conditions. The novel apparatus advances our ability to observe degassing in real time, opening new frontiers in understanding magmatic processes. These findings are critical for improving our understanding of the mechanisms driving eruptive styles transitions and enhancing volcanic hazard assessment and risk mitigation strategies.

# Experimental Insights into Clinopyroxene-Melt Interactions and Mush Reactivation

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Current petrological models suggest that magmatic reservoirs spend the majority of their existence in a "crystal-mush" state, characterized by a semi-rigid framework of crystals in close or frictional contact. The transition of these reservoirs from a "locked-up" state to an eruptible, crystal-rich suspension is frequently triggered by the injection of hotter, primitive magmas.
While zoned phenocrysts provide a petrological record of these replenishment events, the specific kinetics of the resulting mineral-melt interactions remain poorly constrained. Experimental studies focusing on crystal-melt reactions are therefore essential to provide insights into these processes and their implications for volcanic systems.
Time-series experiments were conducted at the HP-HT Laboratory of Sapienza University (Rome, Italy) using a piston-cylinder apparatus to replicate sub-volcanic storage conditions. Experimental starting materials included a Campi Flegrei K-basalt and diopsidic clinopyroxenes (cpxL) in chemical disequilibrium with the K-basaltic reacting melt. Two types of experimental configuration were used: melt-single clinopyroxene crystal and melt-clinopyroxene polycrystals. The P-T conditions were maintained at 600 MPa, corresponding to mid-low crustal depths of 20-22 km, to simulate deeper crustal environments, and in the super-liquidus state (1300 °C) relative to K-basalt at the pressure under investigation (Tliquidus ~ 1270 °C). The duration of the runs was between 15 and 90 minutes.
In both experimental setup, at the 15-minute interval, the system is dominated by crystal dissolution, exhibiting rounded cpxL edges and sharp interfaces. Localized glass-filled channels and vugs penetrate cpxL along cleavages and cracks, initiating necking and fragment isolation. By 30-90 minutes, a coupled dissolution-recrystallization phase occurs. This is evidenced by 10-15 µm overgrowth rims on the resorbed cpxL surfaces and the nucleation of a population of euhedral, zoned microcrysts (cpxN). The dissolution of cpxL initially enriches in CaO and MgO the basaltic melt in the zone close to the crystal. However, as recrystallization progresses, the residual glass composition evolves from the original K-basalt to trachybasalt and eventually shoshonite, that shows a marked decrease in the CaO/MgO ratio and enrichment in $Al_2O_3$ and alkali. Consistently, the cpxN overgrowths and microcrysts are chemically distinct from the pristine diopside, showing higher contents in $Al_2O_3$, $TiO_2$, FeO, and $Na_2O$. These findings demonstrate that a modest thermal perturbation of ~30 °C provides sufficient energy to rapidly re-equilibrate mid-to-lower crustal mush zones, such as the clinopyroxene-rich cumulates identified beneath Campi Flegrei [Perinelli et al., 2019; Isaia et al., 2025]. The generation of glass-filled channels and the increase in local melt fraction facilitate reactive infiltration, which promotes porosity-driven mechanical weakening. By lowering the threshold for disaggregation and enhancing permeability, these micro-scale kinetic processes provide a plausible physical mechanism for the progressive weakening of stagnant mush domains, accelerating melt extraction.

# Unconventional ways to derive viscosity of melts prone to crystallization

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Understanding the mechanisms of magma fragmentation and the explosive behavior of volcanoes is one of the key challenges in volcanology and eruption forecasting. Central to this is magma viscosity, which significantly influences fragmentation and the likelihood of explosive eruptions. However, recent evidence suggests that the chemical and temperature dependence of magma viscosity is not yet fully understood, impacting the accuracy of numerical models used for probabilistic eruption predictions. Extending insights from glass-ceramics studies, it has been shown that nanocrystal formation can significantly alter magma viscosity measurements. This contribution shares a multipronged analytical and experimental approach using thermal analysis techniques (standard and flash DSC, TMA), Raman and Brillouin spectroscopies, and transmission electron microscopy. These methods enable the derivation of the glass transition temperature and fragility of glass-forming melts prone to nanocrystallization. Additionally, this contribution will highlight the need for further research, particularly on the dependence of melt viscosity on structurally bonded water. We will discuss how a multidisciplinary effort, including in situ observations, can lead to a comprehensive understanding of nanocrystal formation processes. This effort will highlight their impact not only on magma viscosity and volcanic eruptions but also on fundamental studies of glass-forming melts.

# Petrology as a monitoring tool: insights from the 2021 Mt. Etna eruptive period

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Volcanic eruptions are high-risk phenomena for both human lives and the economy. Volcanoes with basaltic composition (e.g., Mt. Etna, Italy) represent a large proportion of the world active volcanic systems and can significantly impact human activities through highly energetic eruptive phenomena. Volcano monitoring is one of the most effective tools for mitigating the impact of volcanic activity and tracking its evolution through time. Although petrological analysis has proven essential for understanding subsurface magmatic processes and reconstructing the evolution of volcanic systems, its integration with real-time signals/observations acquired during monitoring activity remains limited. The aim of this project is to strengthen the contribution of petrology to volcano monitoring by investigating the relationships between petrological parameters and monitoring signals recorded at the surface, including geophysical and volcanological observations. To address this objective, we investigate textural (vesicle and crystal size distributions) and chemical (glass and mineral compositions) variability in products erupted during the 2021 eruptive period of Mt Etna. This eruptive period, characterized by 55 lava fountaining events, can be divided into two main paroxysmal sequences: Feb-Apr (Sequence 1) and May-Oct 2021 (Sequence 2).

Both sequences gradually peaked in primitive magma composition on Feb 28 and Aug 29, before gradually declining. The activity was extensively monitored and the eruptive products were densely sampled, providing a unique opportunity to investigate the relationships between petrological variability, monitoring signals, and eruptive dynamics. Scoria samples from twelve selected fountaining events along the two sequences (including initial, peak and closing events) have been texturally and chemically analysed. 3D tomography scans were acquired on scoria samples from each eruption (three clasts per eruptive episode) using a µ-CT system to quantify vesicularity and vesicle size distributions. Large 2D backscattered electron panoramas were acquired from thin sections of all samples to investigate textural variability within and between eruptions. Selected groundmass areas were further analysed using electron backscatter diffraction. For each episode, phenocrysts, microlites, and residual glass were characterised for major element composition with an electron microprobe. The resulting multi-parametric petrological dataset, integrated with monitoring data collected during the eruptive period, will allow us to examine correlations between chemical and textural variables and seismic and volcanological signals. This approach provides a first-order basis to identify the magmatic processes driving these relationships and to evaluate which petrological indicators are most effective for monitoring volcanic unrest and eruptive crises.

# Pre- and syn-eruptive conditions of the 2020-2021 paroxysms at Mt. Etna

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Mt. Etna (Italy) exhibits a wide range of volcanic activity, from lava flows to Strombolian activity and more explosive paroxysms. Between 2020 and 2021, more than 50 paroxysmal episodes were recorded at the South-East summit crater, producing a series of lava fountains of varying height, duration and intensity. Volcanic ash from these events disrupted air traffic and infrastructure, caused damage to vegetation, and posed a threat to public health. Understanding the driving mechanisms of intense eruptive activity is, therefore, important for managing the volcanic hazards associated with ash fall.

Here, we present a 3D quantitative textural analysis of volcanic clasts from the December 2020-October 2021 paroxysmal sequence at Etna, obtained using X-ray computed microtomography (micro CT). We provide constraints on the connected pore network geometry in volcanic clasts, such as porosity, connectivity and the tortuosity of connections between pores, to evaluate how these properties influence magma permeability and outgassing during ascent. We combine our X-ray micro CT results with EPMA data and compare clasts from five paroxysmal episodes which occurred between December 2020 and August 2021, to investigate how pre- and syn-eruptive conditions influenced outgassing and eruptive style at Etna during the 2020-2021 paroxysmal sequence.

# Insights into the processes and timescales of magma storage and ascent at Campi Flegrei caldera: From natural samples to experiments

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The Campi Flegrei caldera is an outstanding example of large silicic calderas, offering critical insights into magma storage, transfer dynamics, and eruptive precursors in such systems. Since the last eruption in 1538 CE, the caldera experienced subsidence, interrupted by unrest episodes in 1950-52, 1970-72, 1982-84, and ongoing unrest since 2005. Here we integrated the results from recent 2D/3D microstructural and chemical characterizations of representative natural eruptive products with advanced high-temperature, high-pressure experiments conducted under controlled conditions to comprehensively investigate the magma storage and ascent conditions of this volcanic system. Petrological evidence reveals a long-lived, multi-level magmatic system, with a deep mafic reservoir (~300-400 MPa, 12-16 km depth) and a shallower, zoned, sill-shaped chamber (~150-200 MPa, 6-8 km depth), still detected today by recent geophysical surveys in this area. Small-volume intrusions occasionally reach upper crustal levels, near lithological discontinuities, to rapidly cool or erupt. These shallower intrusions are typically linked to small-scale eruptions, marked by slow magma ascent, open-system degassing and potential stasis at shallower depths, leading to prolonged unrests or failed eruptions. In contrast, large explosive eruptions involve rapid, sustained magma ascent and closed-system degassing, likely associated with fast conduit propagation and brief, deeper precursory signals. In this context, the combination of these petrological results with geochemical data highlights that the recent dynamics started during the 1982-84 unrest, reflects significant magma transfer (~1-3 $km^3$) in the deeper part of the system (greater than 200 MPa), which released hot gases into the overlying hydrothermal system, deforming and fracturing the upper crust.

# Shear-induced crystallization as a trigger for rapid solidification of basalts: Implications for magma dynamics

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The eruptive style of mafic volcanoes is critically influenced by magma rheology, which is in turn modulated by crystallization during cooling and decompression as magma ascends toward the surface. Although the role of undercooling is well established, the influence of deformation on crystallization kinetics in magmas remains poorly constrained. Here, we experimentally investigate the rheological and textural evolution of Mt. Etna trachybasalt under isothermal conditions (1170 °C) using concentric cylinder rheometry at varying shear rates (up to 10 $s^{-1}$). Real-time viscosity monitoring reveals that stirring exerts a fundamental influence in enhancing magma solidification due to crystallization, shortening nucleation times and reducing the duration needed to reach thermomechanical equilibrium. Crystal textures confirm that stirring shifts crystallization from growth-dominated to nucleation-dominated regimes, with nucleation rates increasing by up to two orders of magnitude at the highest shear rate. Complementary electron back-scatter diffraction data indicate a non-linear structural response to deformation. Low-to-intermediate shear rates (0.1-1 $s^{-1}$) induce a certain degree of crystals preferred orientation, while a shear rate of 10 s-1 produces chaotic, isotropic textures due to rapid and spatially dispersed nucleation. These findings outline that deformation actively drives crystallization, capable of dramatically accelerating magma solidification. We discuss how shear-enhanced crystallization is a key mechanism in volcanic systems, facilitating the attainment of rheological thresholds that trigger transitions in eruptive style. These deformation-driven effects offer new constraints for the understanding of basaltic Plinian eruption trigger mechanisms, identifying a threshold above which microlite production and magma strengthening are significantly accelerated during ascent.

# Influence of magma flow on the crystallization kinetics of basalts

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Crystal size, number density, and texture record the solidification history of magmas and can be used to quantify nucleation and growth rates during crystallization. In natural systems, crystallization occurs under dynamic and disequilibrium conditions driven by cooling, convection, and magma flow. Despite this, most experimental studies have investigated crystallization under static conditions.

Here we experimentally assess the influence of flow on the crystallization kinetics of basaltic magmas. Isothermal subliquidus experiments (1170 °C) were conducted on Stromboli basalt using a concentric cylinder apparatus at a constant shear strain rate of 1 $s^{-1}$. Crystallization kinetics were monitored through the temporal evolution of viscosity and subsequently quantified by textural analysis of quenched samples using SEM

Viscosity stabilized after ~2 hours, indicating completion of crystallization. Textural analyses reveal strong spatial heterogeneity within the crucible, with distinct domains characterized by different nucleation and growth regimes. Nucleation rates peak near the spindle, where flow enhances mass transport, and decrease toward the crucible walls where flow velocities are lower. This results in up to an order-of-magnitude reduction in nucleation rates from the inner to the outer regions. Overall, crystal growth and nucleation rates are on the order of $10^{-8}$m $s^{-1}$ and $10^{9}$m-3$s^{-1}$, respectively.

Compared with literature data obtained under static conditions, nucleation rates are enhanced by up to two orders of magnitude, highlighting the strong influence of stirring on crystallization kinetics. A flow model was developed to estimate velocity fields within the crucible and relate them to experimentally derived nucleation and growth rates. Experiments also show flow localization, expressed by preferred crystal orientations.

These results demonstrate that magma flow can significantly accelerate crystallization and generate strong spatial variability in crystal textures. Such processes may play an important role during magma transport, for example during dyke emplacement, where flow-induced crystallization can strongly affect magma rheology and eruptive dynamics.

# The role of magma composition and pre-eruptive conditions during the 2020-2022 paroxysmal activity at Mt. Etna: a numerical investigation

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Mt. Etna is one of the most active basaltic volcanoes on Earth, producing a wide range of eruptive styles, from relatively gentle effusive eruptions to highly hazardous explosive eruptions. During the last three decades, Etna has produced numerous highly explosive paroxysmal events, generating intense lava fountaining and ash clouds that reached several kilometres in height. In particular, between December 2020 and February 2022, a series of more than 60 paroxysms occurred at the South-East Crater, the youngest summit crater of Mt. Etna. Petrological and geochemical analyses of erupted samples collected throughout the entire eruptive period showed a compositional evolution between two end-members: a cooler, evolved, volatile-poor magma and a hotter, primitive and volatile-rich magma.

To investigate the role of magma composition and of pre-eruptive conditions on magma ascent dynamics during paroxysmal activities at basaltic volcanoes, we performed a series of numerical simulations with a conduit model, using the Etna 2020-2022 paroxysmal sequence as a test case scenario. We found that, for the Etnean end-member compositions studied here, the different pre-eruptive conditions of the magma mainly control the eruptive style and not the composition itself. Indeed, we found that, at the right thermodynamic conditions, the Etnean evolved magma can produce lava fountaining, whereas the Etnean primitive magma can generate effusive eruptions. However, starting from the same pre-eruptive conditions, both magmas produce almost the same magma ascent dynamics. Using initial conditions constrained by analytical and field observations, magma ascent dynamics, eruption rates and eruptive styles obtained from the numerical simulations are in agreement with those observed during the 2020-2022 eruptions. In particular, numerical results show that sustained fountaining activities require an inlet temperature (at 4 km from the vent of the conduit) higher than 1090-1100 °C and an inlet crystal content lower than ~20 vol.%. Effusive eruptions consistent with those observed during the 2020-2022 eruptions, instead, require an inlet temperature lower than 1110-1120 °C, a water content lower than ~3 wt.% and an inlet crystal content greater than ~20 vol.%. We also identified the presence of critical thresholds, that, when exceeded, trigger a transition in eruptive style with a sudden increase in mass eruption rate of more than an order of magnitude. These transitional points are independent of the thermodynamic conditions of the magmatic system, but they are controlled by conduit geometry, outgassing efficiency and timescales of crystallisation and magma ascent.

# Sutures in mafic pyroclasts

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Micrometer-scale Fe (iron)-rich filaments are common in mafic pyroclasts, yet their origin remains debated. These filaments have been variably interpreted as sutured fractures in magma, the product of magma mingling, compositional boundary layers detached from plagioclase crystals, or oxide shells stripped from bubbles. Here, we compare new observations from several case studies with previous results, concluding that shared features point to a common origin of filaments in all eruptions. Key shared features of filaments are: 1) Fe, Mg, and Ca enrichment; 2) variable degree of contortion, sharpness, and Fe-oxide microlite content; 3) inclusion of small vesicles and microlite fragments; 4) transition into cracks and broken crystals; 5) connection to sharp concavities of vesicles and pyroclast edges; and 6) separation of regions within pyroclasts with distinct textures. Focused Ion Beam, micron-sized trenches cut perpendicular to the polished section, and X-ray computed microtomography images reveal that the two-dimensional filaments have complex three-dimensional surfaces resulting from magma suturing. These sutures form by fusing molten, Fe-enriched surfaces, whether exposed crack surfaces within pyro-clasts, the surfaces of colliding pyroclasts, or the surfaces of different portions of the same pyro-clast folded over themselves. During fusing, sutures entrap voids and crystal fragments present on the surfaces. After fusing, sutures evolve by diffusion, crystallization, and viscous deformation. Sutures witness the complex thermal and deformation history of pyroclasts during and after magma fragmentation, and act as unique telltales of otherwise invisible processes that affect pyroclast final size, chemical composition, and vesicle and crystal size distributions.

# Multi-level magma storage and recharge dynamics governing the 1928 AD lateral eruption of Mascali (Mount Etna, Italy)

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The 1928 lateral eruption of Mount Etna represents one of the most destructive flank eruptions in recent history, culminating in the destruction of the town of Mascali. The eruption began with explosive activity at the Northeast Crater, followed by the rapid propagation of an eruptive fissure system along the NE rift zone and the emission of multiple lava flows at progressively lower elevations, eventually reaching Mascali. Here, we present an integrated textural, petrological, geochemical, and thermobarometric study of lava samples collected along the 1928 flow field, from proximal to distal sectors, with the aim of reconstructing the architecture of the plumbing system and its evolution during the eruption. Although trachybasaltic magma with subtle variability in whole-rock major-element composition was erupted, olivine, clinopyroxene, and plagioclase textures show complex zoning patterns indicative of open-system processes. Clinopyroxene-only thermobaRtry and hygrometry identifies two main levels of pre-eruptive magma storage: (i) a deep reservoir at 270-330 MPa, where primitive clinopyroxene (Mg# up to 79) formed at 1070-1075 °C from a hydrous trachybasaltic magma (3.3 wt% $H_2O$) and a (ii) shallower reservoir at 130-165 MPa, where evolved clinopyroxene crystallised (Mg# 70-75) at 1055-1070 °C from a slightly more evolved trachybasaltic melt with comparable amount of water (2.8 wt%). Concentric zoning within clinopyroxenes, with resorbed evolved cores and primitive overgrowths yielding similar pressures coherent with the deep reservoir, suggests the coexistence of compositionally distinct melts within the deep reservoir. Olivine records complementary evidence of magma recharge and crystal recycling as more primitive core (up to Fo82), commonly resorbed, crystallised at 1090-1110 °C, whereas homogeneous evolved phenocrysts (Fo70) formed at 1047-1060 °C. Reverse zoning and primitive bands within olivine further indicate repeated mafic recharge events in the shallow reservoir. Plagioclase thermometry and hygrometry provide consistent results, with An-rich cores (An61-88) recording higher temperatures (1055-1063 °C) and $H_2O$ contents of 2.4-3 wt%, consistent with the formation in the deep reservoir after olivine and clinopyroxene. On the other hand, rims and groundmass microlites record lower temperatures (1005-1038 °C) and lower H2O in the melt (0.5-0.9 wt%), reflecting degassing-driven crystallization. The emerging picture is a vertically developed plumbing system in which a deep reservoir is periodically recharged by primitive magma, promoting mixing, crystal dissolution, and crystal recycling, while a shallow reservoir acts as a zone of magma storage, differentiation, and degassing. These results highlight how magma storage in a multi-level ponding zone and recharge processes acted during the onset of hazardous flank eruptions on Etna.

S03 - Poster

# Refining elemental partitioning schemes in primitive to intermediate magmatic systems

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Elemental partitioning between rock-forming minerals and silicate melts provides the fundamental quantitative framework for interpreting magmatic systems. The distribution of trace and minor elements serves as a critical proxy for tracking magma differentiation and as a basis to constrain timescales of magma dynamics. Consequently, robust partitioning data are indispensable for understanding magmatic processes, as well as to assess volcanic hazard. Furthermore, these same elemental fractionations dictate the concentration of critical raw materials into economically viable magmatic ore deposits, linking fundamental petrology directly to mineral resource assessment. Despite the predictive power of established thermodynamic and crystal-chemical frameworks, such as the lattice strain model, their application to complex natural systems highlights the limitations of the current empirical database. To advance predictive petrology, it is imperative to expand the experimental knowledge base across a broader P-T-X parameter space. Specifically, new experimental constraints are required to disentangle the competing effects of temperature, pressure, melt polymerization, and volatile activity on coupled substitution mechanisms in the most common magmatic mineral phases including plagioclase, clinopyroxene and amphibole. However, the fidelity of any new partitioning model is strictly bound by the quality of the underlying microanalytical data and robust methodologies to establish former thermodynamics equilibria in natural systems. Advancing the field necessitates experimentally-calibrated schemes for assessing mineral-melt equilibria, possibly aided by statistical learning tools. By coupling an expanded, rigorously validated experimental database with state-of-the-art microanalytical workflows, the next generation of partitioning models will significantly refine our capacity to model active and quiescent volcanic plumbing systems, and advance our understating of magmatic ore resources.

# Melt composition control on nanocrystallisation and crystallisation dynamics in basaltic melts

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Basaltic eruptions represent the most common volcanic activity on Earth and span a wide range of eruptive styles, from effusive to highly explosive. Although basaltic magmas are typically associated with low explosivity, more explosive sub-Plinian to Plinian eruptions (e.g., Etna 122 BC, Tarawera 1886) are also encountered [Coltelli et al., 1998; Houghton et al., 2004; Rowe et al., 2021], demonstrating their potential hazard. Transitions in eruptive style are commonly attributed to an increase in magma viscosity during shallow ascent, driven by syn-eruptive crystal growth [Arzilli et al., 2019]. Yet, the magnitude of syn-eruptive crystallization varies significantly within the basaltic realm. Of particular interest here is therefore the role of melt composition in controlling crystallisation tendency in basaltic magmas and, thereby, their rheological evolution. To evaluate the role of melt composition, a database of more than 50 basaltic eruptions worldwide spanning effusive to highly explosive styles was compiled. Major oxide variation diagrams and crystal content is explored.
Based on the database inspection, six representative basaltic compositions were selected. The anhydrous melts were investigated using a multipronged approach including viscometry, differential scanning calorimetry (DSC), and Raman spectroscopy.
Our preliminary results demonstrate that melt composition exerts a first-order control on crystallisation tendency in basaltic magmas. We identified compositional controls that are expected to severely influence magma rheology during ascent, with implications for the transition in eruptive behaviour.

# Kinetics of clinopyroxene crystallization in a basaltic melt from Stromboli volcano

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Crystallization is a fundamental process driving magma evolution and the eruptive styles of active volcanoes. Among other factors, the degree of undercooling (DT), defined as the difference between the liquidus temperature and the actual crystallization temperature (Td), is a critical parameter that governs crystallization. Clinopyroxene (Cpx), a common constituent of basaltic magmas, is widely used to reconstruct the architecture of plumbing systems and to decipher magma dynamics.
This study experimentally investigates the effect of different DT/t paths on Cpx crystallization at Stromboli volcano (Italy), an open-conduit basaltic system characterized by persistent activity regulated by the interplay of two magmas: a volatile-rich (low-porphyritic) LP-magma ascending from depth and a shallower, degassed, (high-porphyritic) HP-magma. The starting material is a basaltic glass (PST9) representing the most primitive LP-magma, whose Di-rich sector-zoned Cpx crystals record the ascent conditions in the conduit.
Time-series kinetic experiments (t from 2.5 to 20 h) were conducted in an IHPV at 250 MPa, Td from 1100 to 1140 °C, under a$f_{O2}$ near NNO. Both fluid-absent and fluid-present charges were investigated, with melts being systematically hydrous ($H_2O$ from 2.3 to 3.2 wt percent) and carbonic ($CO_2$ from 1581 to 1717 ppm). The liquidus temperature of PST9, refined from prior experimental phase equilibrium studies, yielded DT from 16 to 68 °C. However, in kinetic experiments, crystals only formed at DT greater than 20 °C, regardless of t and $X_{CO2}$. This demonstrates that DT, preferentially to t or dissolved $CO_2$, controls the undercooling of volatile-bearing basaltic melts, and that the LP-magma can be significantly undercooled. The formation of Di-rich, sector-zoned Cpx macrocrysts at relatively small DT (20 to 40 °C), resembling natural sector-zoned crystals, confirms previous kinetic interpretations for the crystallization of Stromboli LP-magma.

# Experimental constraints on carbonate-silicate melt interaction at 1 GPa in natural ultrabasic systems

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Carbonatitic magmas represent a volumetrically minor but petrologically and economically important component of Earth's magmatic budget. Their origin is mostly related to direct partial melting of carbonate-bearing mantle sources or to extreme differentiation of $CO_2$ rich, $SiO_2$ undersaturated silicate magmas. An alternative process that can lead to enrichment in a carbonate component is limestone to dolostone assimilation by basic and ultrabasic silicate magma at shallow to mid crustal depths. In this study, carbonate and silicate melt interaction has been investigated at 1 GPa in piston cylinder experiments performed on three $SiO_2$ undersaturated natural rocks from the Bohemian Massif: a polzenite (BM1), a monticellite-bearing melilitite/vesecite (BM2), and an olivine basanite (BM3). Each composition was mixed with 10, 30 and 50 mass percentage synthetic $CaCO_3$ and equilibrated at 1200 and 1300 degrees C to evaluate the capacity of these melts to assimilate carbonate and to compare the resulting liquids with those previously obtained at 0.2 GPa [Lustrino, M., Luciani, N., Stagno, V., Narzisi, S., Masotta, M., and Scarlato, P., 2022]. Experimental evidence on the origin of Ca rich carbonated melts formed by interaction between sedimentary limestones and mantle derived ultrabasic magmas. Geology, 50 (4), 476-480.] using the same starting materials. At 1 GPa, increasing $CaCO_3$ (cc) addition systematically drives experimental glasses toward lower $SiO_2$ and higher CaO contents. BM2 produces the most extreme compositions, with BM2 plus 30 percentage cc and BM2 plus 50 percentage cc yielding microcrystalline groundmasses with carbonatitic kimberlitic compositions ($SiO_2$ from 15 to 22 mass percentage and CaO from 33 to 40 mass percentage). Given the high CaO content, clinopyroxene crystallization is favoured, further depleting the residual liquids in silica contents. Interstitial calcite occurs only in experiments characterized by relatively high degrees of crystallization and in residual melts that are CaO rich and $SiO_2$ poor, suggesting the combined role of crystallization pathways and bulk composition in controlling calcite saturation. Moreover, no physical separation between liquid of different composition was observed, suggesting that residual melts (relatively $SiO_2$ poor and CaO and $CO_2$ rich) derived from basic to ultrabasic rocks may remain a single homogeneous phase even at depths comparable to the continental Moho. These preliminary results indicate that strongly $SiO_2$ undersaturated mildly alkaline magmas can record assimilation of sedimentary carbonate rocks at crustal levels, a process that is not incompatible with the presence of carbonate components in upper mantle sources, such as what is claimed to have happened for the volcanic rocks of the Pleistocene Intra Apennine Province (IAP).

# Geomorphological, mineralogical and geochemical characterisation of postglacial lava flows of the Nevado Coropuna volcanic complex (Peru)

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The Nevado Coropuna Volcanic Complex (NCVC) is an active volcano located in the Peruvian Andes; its last (postglacial) activity consists of the emplacement of three silicic lava flows along the West (W, 6-12 ka), North East (NE, 2 ka), and South East (SE, 1-1.5 ka) flanks of the volcanic complex [Úbeda Palenque, 2011; Bromley et al., 2019]. Here we present a geomorphological, mineralogical and geochemical study of these lava flows. We pursued two objectives: 1) to estimate lava flow thickness and volumes through reconstruction of the pre-eruptive topography, and 2) to characterise the lava samples in terms of bulk rock composition, mineralogical phases, and crystals and vesicles content. The measured lengths range between 4.75 km and 5.79 km, with the SE lava flow being the shortest and the W the longest. The maximum thicknesses are 112.65 m for the W lava flow, 69.99 m for the NE, and 70.66 m for the SE. The estimated volumes are 0.232 $km^3$ for the W lava flow, 0.095 $km^3$ for the NE lava flow, and 0.057 $km^3$ for the SE lava flow. The geomorphological analysis also revealed the presence of levées along the margins, and ogives and large lava blocks on the surfaces of all three lava flows. In addition, the NE and SE are overlapping lava flows, each consisting of two distinct flow units, whereas the W lava flow is a simple flow. The lava flows of NCVC are dacites (62.96-64.31 wt.% $SiO_2$) belonging to the high-K calc-alkaline series. They show similar textural features under the polarised microscope with phenocrysts of plagioclase, clinopyroxene, orthopyroxene, amphibole, mica, opaque minerals, and quartz in a fine-grained/glassy groundmass. The study of major, minor, and trace elements showed minimal variations among the lava flows. The volumetric content of each phase was similar; the lavas show high crystal content, mafic minerals and oxides make up 9.18-12.45 vol% of the samples. Only the sample from the SE lava flow shows a lower crystal content (mafic and oxides ~6 vol%) and higher vesicle content (21.9 vol% compared to 3.6-11.45 vol% in other samples) as the sample was collected in the outermost portion of the blocks forming the lava flows surface, where more rapid cooling limited crystallization. In summary, this preliminary study shows that the postglacial lava flows of the NCVC display all the characteristics of silicic lavas related to lava domes, including large thickness, high silica content, high crystal content, and the formation of levées; and together with monitoring and literature data this makes the NCVC an active volcanic centre that poses several hazards (lava flows, ashfalls, and lahars) to the people living in this area.

# Fractal behaviour and discharge rate in lava flows: case studies from Etna volcano

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Changes in the effusion rate of a lava flow reflects in the flow dynamics and, consequently, in the morphology (i.e., geometry of the outline) of the flow. By establishing a relationship between these factors, it would be possible to estimate the effusion rate (or its variations) simply by analyzing the lava flow's boundaries.
The literature suggests that the margins of lava flows exhibit fractal behaviour, reporting examples from a few volcanoes worldwide. This has been used as a classification tool for different types of lava flows. In the present study, the goal is to verify, through fractal analysis, if and how, changes in the effusion rate are reflected in the shape of a lava flow's margins.
As a case study, we report the flow of the eruption that occurred at Etna in 2025. By analyzing the flow using the Fractal Dimension analysis through its developing phases, we found that the estimator D is correlated with the discharge rate retrieved from satellite observations. This approach was tested on historical lava flows and the inferred information about the effusion rate was compared to independent observations, such as magma composition and viscosity estimates. If validated, this method could be useful for estimating the effusion rates of historical lava flows by analysing only the shape of the flow.

# S04 - REVEALING THE DYNAMICS OF MAGMA ASCENT IN OPEN-VENT AND DORMANT VOLCANOES

Conveners:

Flora Giudicepietro, Lucia Pappalardo

# Seismic data analysis for the characterization of landslide and spattering signals at Stromboli volcano (Italy)

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Stromboli volcano, located in the Aeolian Islands (Italy), is characterized by typical Strombolian activity, with hundreds of explosions per day. Recently, its activity has intensified, with phenomena such as paroxysms, crater collapses, PDC formation, and lava overflows, which, in some cases, have significantly impacted the morphological evolution of the Sciara del Fuoco, the northwestern flank of the island.
The study aims to identify the landslide seismic signals most closely associated with eruptive activity in the upper sector of the flank of the Sciara del Fuoco and distinguish them from those related to low-level marine erosion.
For this purpose, Real-time Seismic Amplitude Measurement (RSAM) measurements were performed using frequency bands typical of landslides (10-25 Hz), volcanic activity (1-7 Hz), and marine noise (0.1-0.3 Hz). Seismic data from stations STRA (high-elevation site), STRE (intermediate-elevation site), and STRG (low-elevation site) were analyzed between October 8 and 17, 2022.
The results showed a correlation between the landslide signal (10-25 Hz) and the marine noise signal (0.1-0.3 Hz) recorded at stations STRG and STRE on October 13 and 14, 2022. This evidence was attributed to landslides triggered by adverse weather and sea conditions in the Aeolian Islands.
A polarization analysis was then performed on the signal in the 0.1-0.3 Hz frequency band recorded at station STRA on October 17, 2022, which indicated that the signal in that frequency band was oriented toward the summit craters. This analysis proved to be a further significant support for a comparison with the signals recorded in the lower part of the Sciara del Fuoco by the STRE and STRG stations.

# Volcanic ash erupted from Stromboli volcano during "normal activity" can help in anticipate eruptive style transitions: implications for petrologic monitoring

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Stromboli is an open-conduit volcano that has been persistently active since at least the eighth century AD [Rosi et al., 2013]. Over the past 20 years, several explosive eruptions more energetic than the "normal" mild Strombolian activity (i.e. major explosions and paroxysms) have altered the general perception of risk and increased exposure to the hazards associated with these events: tephra fall, ballistics at low altitude, wildfires, pyroclastic density currents (PDCs), tsunamis, and lahars. These hazards affect the small community of about 500 people and the volcanological guides who permanently reside on the island. In recent years, significant progress has been made in understanding the triggering mechanisms and timescales of major explosions and paroxysms through integrated geophysical [Ripepe et al., 2021], geochemical [Aiuppa et al., 2021], coupled-fluid numerical modelling [Caricchi et al., 2024], and petrological investigations [Landi et al., 2022; Petrone et al., 2022; Pichavant et al., 2022; Voloschina et al., 2023; Lasinga et al., 2025; Masotta et al., 2025; Costa et al., 2026]. Collectively, these studies converge on a general framework in which the rapid ascent of CO2-rich, low-porphyritic (LP) magma from depth (6-11 km) plays a fundamental role in triggering high-energy events.
To investigate whether products erupted during normal Strombolian explosions - typically dominated by a degassed and high-porphyritic (HP) magma - contain evidence of the deep magma processes driving the shift towards major explosions and paroxysms, we conducted a petrological study on tephra erupted at Stromboli in 2023 and 2024. During these years, all three types of explosive activity - normal, major explosions, and a paroxysm - occurred. We focused specifically on volcanic ash and fine lapilli, as their rapid cooling in air makes them representative of the textural and compositional features of the feeding magma. Additionally, compared to larger bombs, small particles better reflect the variability of the eruptive mixture. Samples were collected during eight survey campaigns at the summit of Stromboli volcano, between July and December 2023 and April and August 2024. Ash samples represent cumulative fallout collected in an ash-sampler, a homemade collector installed at approximately 800 m a.s.l., about 500 m east of the North-East (NE) sector of the crater terrace. This location was chosen based on several factors, including proximity to the active vents, appropriate distance from the ballistic trajectories of potentially destructive large bombs erupted during normal activity, ease and safety of access for operators, and alignment with prevailing wind directions. Ash componentry under stereomicroscope and SEM-EDS-based morphological, textural, and geochemical analyses of groundmass glasses and mineral phases were conducted at the Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa (INGV-PI). The results show that in all samples, the ash, and in some cases the lapilli, are characterised by: 1) complex mingling textures between LP and HP magmas; 2) inverse compositional zoning of mafic minerals; 3) presence of LP clasts recycled at high temperatures; and 4) evidences of LP magma interaction with the conduit walls at shallow levels. These petrological signatures indicate that interaction

timescales between the deep LP magma and the shallow HP reservoir are on the order of days to hours. Systematic analysis of products erupted within short time intervals has enabled tracking of a progressive supply of LP magma into the shallow system prior to the transition from normal to high-energy events, which begins up to two months earlier (May 2024) in the case of the 11 July 2024 paroxysm.

We therefore strongly believe that, if integrated into routine volcanic surveillance, these results will provide essential insights for refining the petrological monitoring of Stromboli, thereby enhancing our ability to infer and anticipate transitions in eruptive style.

# Deciphering Volcanic Unrest: Ground and Satellite Insights into Hydrothermal Buffering and Sealing at Vulcano Island (2018-2024)

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In this work, we investigate the evolution of the La Fossa crater and Baia di Levante system at Vulcano Island between 2018 and 2024, focusing on the period following the 2021 unrest. Using a multiparametric dataset of ground and remote observations, we tracked the extent and intensity of volcanic degassing as it migrated from a primary, deeply sourced vent (La Fossa crater) to a peripheral, more hydrothermal zone (Baia di Levante, a bay at the base of the volcano). Our spatiotemporal analysis identified five distinct periods, each characterised by specific physicochemical changes in both areas. We observed a variable delay between the peaking of degassing in the central area and the arrival of gas in the peripheral zone, spanning from 7 months to nearly synchronous timing. Specifically, we suggest that the intense influx of deep fluids in mid-September 2021 transformed the complex network of fractures and shallow geothermal aquifers beneath Baia di Levante, significantly reducing its buffering capacity. This altered state persisted until the end of 2024, when a new deep fluid input observed at La Fossa crater was followed by an increased delay in degassing at Baia di Levante. We explain this variable delay through mechanisms such as fluid drainage and/or hydrothermal sealing of the more peripheral areas. This study underscores the critical importance of continuous monitoring of a volcano's fluid-discharge capacity, particularly to identify areas where reduced degassing could lead to the hazardous accumulation of gas overpressure, as highlighted by the case of the island of Vulcano.

# Investigation on the dynamics of paroxysmal eruptions through a joint analysis of high-precision deformation data and video recordings during 2012-2022 Etna lava fountains

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In this work, we investigate the dynamics and evolution of paroxysmal activity at Mt. Etna volcano by estimating and comparing the ascent rate and the exit velocity of magma during lava fountain episodes in the period 2012-2022. Ascent rates and exit velocities are retrieved from the analysis of the data recorded by the permanent monitoring network installed at Etna and managed by Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE). Magma ascent rate is inferred from high-precision deformation data recorded by borehole strainmeters [Bonaccorso et al., J. Geophys. Res. B: Solid Earth, 2016], while exit velocity is retrieved from the videos recorded by the monitoring cameras.

At Etna, paroxysmal episodes typically manifest as lava fountains [Andronico et al., Earth Sci. Rev., 2021]. These events are gradually growing processes starting from a mild Strombolian activity which progressively increases in intensity and potentially evolves towards a sustained eruption column. Lava fountains are characterized by a high variability in the degree of explosiveness, duration and amount of erupted material (both lava and tephra deposits), reflecting complex magma dynamics. During lava fountains, a deflating magmatic source located at depth feeds the eruption, causing very tiny co-eruptive deformation of the ground. This deflation cannot be captured by traditional geodetic techniques, such as GNSS and InSAR, because of their low resolution and low sampling time, respectively. Conversely, thanks to the high resolution (10-12 m3/m3) and the wide frequency range (0 - 20 Hz), borehole strainmeters are highly suitable to record the ultra-small deformation that occurs during eruptions [Currenti & Bonaccorso, Sci. Rep., 2019]. The derivative in time of the co-eruptive deformation signal (strain rate) is a robust proxy of the ascent rate of magma moving from the source toward the surface [Carleo et al., J. Geophys. Res. B: Solid Earth, 2025].

At the vent, magma is discharged and rapidly ejected in the atmosphere. To date, the exit velocity at which magma is expelled can be indirectly estimated from thermal cameras considering the vertical extension of the incandescent zone at the vent, or measured from the electromagnetic waves transmitted by radar systems and backscattered by lapilli and blocks ejected during the eruption. Here, a PIV (Particle Image Velocimetry) analysis is applied to measure the velocity from visible images. The PIV results, validated over a large dataset of events, provides accurate measurements of the exit velocities consistent with those obtained from other existing methods (thermal cameras and radar systems).

The joint analysis of magma ascent rate, inferred from high-precision deformation measurements, and exit velocity, estimated from video recordings, gives new insights for the characterization of the lava fountains, the involved eruptive process and its dynamics. This information allows precisely tracking the evolution of Etna lava fountains with important implication for support decision-making tasks for volcanic risk assessment.

# Unraveling post-unrest instability phases in long-lived hydrothermal systems: A multiparametric analysis of cyclical reactivation episodes in 2024-2025 at La Fossa Cone (Vulcano, Italy)

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At dormant volcanoes dominated by long-lived hydrothermal activity, both the escalation toward unrest and return to background conditions are non-linear processes. Post-unrest recovery phases are often characterized by transient reversals episodes complicating the definition of a stable baseline. Due to the low intensity of this kind of volcanic activity with respect to those involving magma bodies directly, anomalous patterns can often be hidden by external factors (e.g. meteorological and solar heating effects). For this reason, a multiparametric monitoring is essential to discriminate between background variability and actual changes leading to phases of potential concern. Following the 2021-2022 main unrest at La Fossa Cone (Vulcano Island, Italy) the system showed a general recovery phase punctuated by intermittent periods of instability marked by notable change in the geophysical and geochemical parameters. In this context two main reactivation phases occurred in spring 2024 and summer 2025. This study analyses these episodes integrating geochemical, seismic, and thermal datasets. Both of them have been preceded by an increase in the bulk crater $SO_2$ flux, signaling a renewed injection of magmatic volatiles from the shallow feeding system to the hydrothermal one. The spring 2024 episode represented the first actual reversal of the post-unrest cooling trend. During this phase, a moderate increase in magmatic gas input triggered a distinct rise in ground temperatures within the crater's most permeable sectors, although the spatial extent of the thermal anomaly did not expand considerably. This localized heating was accompanied by a modest but clear increase in background local seismicity. In contrast, the summer 2025 episode displayed a markedly elevated intensity and more extensive spatial distribution. Although short-lived (from late July to late September), it was characterized by a massive release of heat and gases across a significant portion of the crater. This second pulse was defined by a notable increase in $SO_2$ flux and an abrupt escalation in volcano-seismic activity reflecting a strong pressurization of the shallow hydrothermal system. Continuous data acquisition from four permanent ground temperature stations located proximate to the summit and inner crater revealed a significant rise in soil temperature, reaching levels comparable to the 2021-2022. This finding emphasizes the system's considerable capacity for the rapid restoration of critical thermal and structural conditions that could potentially lead to phreatic or phreatomagmatic explosive events. The synchronicity between the $SO_2$ flux increase, the pressurization of fluid-filled fractures, and the sudden surface thermal response in absence of clear meteorological events (rainfall/low pressure system) confirms that both episodes are driven by a dominant endogenous component effectively decoupled from exogenous forcing. The recurrence of these transient episodes demonstrate that La Fossa Cone system has not yet returned to its pre-2021 background state and continuous multiparametric monitoring is crucial to provide a robust baselines to correctly assess volcanic hazard and mitigate the risk in such a touristic volcanic area.

S04 - Oral Presentation

# Decoding the Plumbing System, Pre-Eruptive Conditions and Timescales of the 1906 Mount Vesuvius Eruption: Constraints from Petrological and Geochemical data, and modeling

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Mount Vesuvius is regarded as one of the most famous and dangerous volcanoes in the world. Known worldwide for the 79CE eruption which buried the Roman cities of Herculaneum, Pompeii, Stabiae and Oplontis and for the founding of the first ever Volcano Observatory in the world, founded in 1845 by will of Ferdinand II of Bourbon. Vesuvius activity started at least about 39ka ago, with the formation of Mount Somma edifice. Somma-Vesuvius complex has been the stage of major eruptive activities, which volcanologists divided in cycles that lasted up to 18 March 1944, the day in which began its last eruption. It has been more than eighty years now since Vesuvius last erupted and Volcanology as a whole, has come a long way in understanding and deciphering the volcanic phenomena and their dynamics. Today more than 700,000 people live around the slopes of the volcano and are at risk of being affected by a resumption of its activity so it is compelling for the scientific community to study now, in this repose time, its old activity to be better prepared in the face of its future activity.
The April 1906 eruption of Mt. Vesuvius, belonging to the last eruptive cycle, is a quintessential example of open-conduit paroxysmal activity, analogous to those we observe at Stromboli and Mount Etna, yet it lacks the modern high-resolution in-depth studies afforded to other older, Vesuvian events, that are more popular in the scientific community. Despite its impact, being the largest of the 20$^{th}$ century for Vesuvius, which caused more than 216 deaths, most existing literature surrounding the eruption is decades old. Building upon a comprehensive re-evaluation of historical records (e.g., Matteucci and Mercalli, contemporary to the eruption), preliminary geochemical and textural surveys and literature data, this study aims to provide a modern analytical update to the 1906 plumbing system, timescales and pre- and sin-eruptive dynamics. We integrate chemical, isotopic, and textural data from both historical ash collections stored at the Osservatorio Vesuviano Museum and samples representative of the fall deposits emitted mostly during the apex of the eruption (April 8$^{th}$, 1906), collected at 'Castello di Ottaviano' locality. By combining i) mineral-melt geothermobarometry with ii) mineral chemistry and iii) the study of zoning patterns in Clinopyroxene from the sampled erupted Units we constrained the storage depths and the thermal conditions of the magma body/ies fueling the eruption, and reconstructed the Magmatic Environments (ME) and their relative interactions before and/or during this violent Strombolian (VEI 3) eruption.
The core of this research is the study and characterization of the complex zoning patterns featuring the Clinopyroxene crystals and the use of diffusion chronometry to:

1. allow quantifying the timescales of pre-eruptive processes, including magma recharge, mixing, degassing, and crystallization;
1. estimate the magma ascent rates and the "lead time" between the possible deep-seated recharge and eruptive onset;
1. refine the interpretative model of the plumbing system, moving from a static storage view to a dynamic, multi-stage ascent model for this long-neglected eruption.

By filling this long-standing data gap, this work aims to demonstrate that Vesuvius remains a critical laboratory for understanding the past behavior of a volcano and with, this knowledge, try to put forward hypothesis on its possible future behavior, providing vital constraints for hazard assessment in one of the world's most densely populated volcanic regions.

# Long-term magma output rate at Stromboli volcano from satellite-derived thermal data

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Volcanoes like Stromboli can stay active for millennia, but the amount of magma they release changes over time. Measuring how much magma erupts is important for understanding how volcanoes work and for evaluating volcanic hazards. In this study, we use 25 years of satellite heat measurements, combined with records of volcanic activity, to estimate how much magma Stromboli has erupted and how it moved inside the volcano. Our results show that Stromboli released magma at a higher average rate over the last 25 years than it has over the past century. Most of the magma was erupted during flank eruptions, while smaller but steady amounts were released through short-lived lava overflows and frequent Strombolian explosions at the summit. We also find that, in recent decades, Stromboli has increasingly released magma from shallow parts of its plumbing system, while flank eruptions have contributed less magma overall. This suggests that the volcano's internal pathways have gradually become more open, allowing magma to rise and erupt more continuously. When compared with longer-term records, this behavior appears to be part of broader, century-scale cycles in magma supply within the volcano.

# Modeling surface deformation at Campi Flegrei induced by dike ascent

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Campi Flegrei caldera, located in the densely populated Neapolitan area, represents one of the most hazardous volcanic systems in the world. Its dynamics is characterized by significant ground deformation episodes, known as bradyseism, which have been historically documented and intensively monitored over the last decades. Currently, the caldera exhibits a progressive, large-scale ground deformation characterized by an axisymmetric, bell-shaped vertical displacement pattern. This signal, typically attributed to a centralized pressure source located beneath the town of Pozzuoli, shows a maximum uplift rate in the caldera's center, decaying towards its margins.

However, high-resolution geodetic observations, including GNSS and Satellite Interferometric Synthetic Aperture Radar (InSAR) data, highlight significant local deviations from this idealized geometry. A notable anomaly is observed in the Monte Olibano and Accademia area, where the ground exhibits a lower uplift rate compared to the theoretical values predicted by a purely axisymmetric model. Such localized "deformation deficits" suggest a complex interplay between the primary magmatic/hydrothermal source and local structural discontinuities, such as faults or variations in the elastic properties of the caldera's shallow crust.

In this framework, a critical challenge for volcanic hazard mitigation is the early identification of deformation patterns that signal the transition toward an eruptive phase. Specifically, the detection of patterns associated with a possible ascent of a magmatic dike is of paramount importance. While the central inflation might be driven by long-term hydrothermal pressurization, a rising dike represents a more immediate precursor to a potential eruption.

This study aims to quantify the surface deformation signature associated with dike propagation as a function of its geometric parameters, including length, width, depth, and dip angle. Using analytical forward modeling based on elastic dislocation theory in a homogeneous half-space, we simulated the dike's migration toward the surface. Our results demonstrate that dike intrusion produces a distinctive "double-peak" fingerprint. The simulated signal is characterized by two distinct uplift lobes, whose symmetry and relative magnitude are highly sensitive to the dike's dip angle. As the dike ascends, the intensity of these peaks increases and they migrate toward each other, converging above the dike's tip. A major constraint in monitoring such patterns at Campi Flegrei is the caldera's partially submerged nature. Since a vast area of the potential deformation field lies within the Gulf of Pozzuoli, the detection of the full bi-lobed signal is frequently hampered by the lack of geodetic coverage over the sea. InSAR, while powerful, loses coherence over water, effectively obscuring one of the two characteristic lobes. This observational gap makes the identification of rising dikes significantly more complex, as the diagnostic "twin-peak" signature may appear only as a single, truncated lobe. The findings of this study provide the physical basis for developing automated pattern recognition algorithms capable of operating under these constrained conditions.

# Coseismic displacement in the Campi Flegrei caldera (Italy): the 1 September 2025 earthquake swarm in the Mt. Olibano-Accademia area

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In September 2025, a moderate earthquake occurred in the Campi Flegrei volcanic area near Naples, Italy. Although its magnitude was relatively low (Md 4.0), the event produced an unusual and remarkably well-defined ground deformation. By combining satellite observations, including GNSS and DInSAR measurements, we detected surface displacements of up to approximately four centimeters occurring within a few seconds. This represents the largest and clearest coseismic ground movement ever documented for an earthquake of this magnitude at Campi Flegrei. The spatial pattern of the deformation indicates that a specific sector of the caldera, the Mt. Olibano-Accademia area, is actively involved in the coseismic displacement and the ongoing volcanic unrest. The clarity of the geodetic signal associated with this event also enabled a retrospective analysis of GNSS data recorded in the previous months, leading to the identification of smaller, analogous deformation episodes that had previously gone unnoticed due to their weaker signatures, close to the detection threshold of the measurement method. These results provide new insights into the mechanical response of the shallow crust at Campi Flegrei during unrest. In particular, they highlight the role of localized fracturing and faulting processes and their interaction with the broader deformation field affecting the caldera. Improving our understanding of these processes is essential for interpreting the evolution of the long-term unrest and enhancing monitoring and hazard assessment in this densely populated volcanic region.

# Relationships between the Vesuvius and Campi Flegrei volcanic systems in the 16th-17th centuries as evidenced by artistic and literary sources

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Vesuvius is one of the highest-risk volcanoes worldwide, primarily due to the dense urbanization of its surrounding areas. While its eruptive history is well constrained from 1631 to the present, the preceding period, particularly the 15th and 16th centuries, remains poorly defined. This interval is generally interpreted as a prolonged phase of quiescence, although several historical sources report episodes of volcanic activity. Understanding this time window is crucial for interpreting Vesuvius's eruptive behavior, especially in clarifying the relationship between large explosive eruptions, such as the 1631 event, adopted as the reference scenario in the current national emergency plan, and the more frequent effusive or mixed eruptions that characterize the volcano's persistent activity. Moreover, historical evidence indicates that during the 16th century the activity of Vesuvius coincided with that of the nearby Campi Flegrei caldera, suggesting possible interactions or coupled dynamics between the two volcanic systems. Investigating these potential relationships may contribute to a better understanding of the regional stress field and of the mechanisms governing volcanic activity in closely spaced volcanic districts. Recent studies have undertaken a critical reassessment of historical "accounts" of volcanic activity during the 16th century, integrating new scientific, historical, and art-historical evidence. These analyses have revealed previously unrecognized features of Vesuvius's behavior, highlighting aspects that warrant further investigation. In this context, artistic and literary sources provide a valuable and often underutilized perspective for reconstructing volcanic activity in periods lacking systematic observations.



S04 - Oral Presentation

# A new conceptual model for Stromboli's magma dynamics

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Persistently degassing basaltic volcanoes typically erupt less magma than is degassed, with excess volatile flux maintained by density-driven magma convection. Stromboli volcano, Italy, serves as a natural laboratory to study these processes, notably due to its frequent hazardous paroxysms, with 36 recorded between 1860 and 2020. These paroxysms characteristically erupt low-crystallinity (espite extensive study, the physical mechanisms driving these eruptions remain debated, ranging from foam accumulation at shallow depth to gas-driven ascent from deeper magma storage zones. Here we propose a new model to explain the observed explosive activity on Stromboli, with insights arising from a combination of gas observations, petrology of erupted products and models of magma dynamics.

# Machine Learning-Based Applications on Stromboli Volcano Data for Monitoring Purposes: A Review

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In recent years, Machine Learning (ML)-based methods, particularly Artificial Neural Networks (ANNs), have seen widespread development across all fields, from economics and society to science and technology. The use of these techniques has also increased significantly in the fields of seismology and volcanology for the automatic classification and clustering of geophysical data, as well as for predictive time series analytics.
This study presents a review of Artificial Neural Network (ANN)-based applications at Stromboli volcano. Stromboli, in the Aeolian Islands, is one of the most active volcanoes in the world and this makes it one of the most studied worldwide. Its typical activity, known as Strombolian, consists of individual explosions emitting gas and pyroclastic fragments. Sudden, dangerous phenomena that interrupt ordinary Strombolian activity are generally associated with lava flows, major explosions, or paroxysms, such as those that occurred on July 3 and August 28, 2019.
In the applications presented here, ANNs have been used for event classification and detection, unsupervised clustering, and forecasting purposes, such as recognizing changes in Stromboli's eruptive patterns that preceded paroxysms.
The Artificial Neural Networks (ANNs) primarily used in this work are the supervised Multi-Layer Perceptron (MLP) [Bishop, 1995] and the unsupervised Kohonen Self-Organizing Map (SOM) [Kohonen T., 1997].
The MLP has been applied mainly to classify different types of seismic signals, such as distinguishing among landslides, explosion-quakes, and microtremor signals [Esposito et al., 2006], for the automatic recognition of landslide signals [Esposito et al., 2013a], or for discriminating hybrid events from explosion-quakes [Esposito et al., 2017].
The SOM allowed to cluster the waveforms of Very Long Period (VLP) events associated with explosive activity [Esposito et al., 2008]; to group a particular type of seismic events called "hybrids," which characterized the effusive eruption on February 27, 2007 [Esposito et al., 2011], thereby improving their localization [Longobardi et al., 2012]; to investigate the waveform variation of the explosion-quakes to identify a possible relationship between the temporal changes of these events and the volcano seismic activity [Esposito et al., 2013b]; and to perform an unsupervised analysis of seismic and infrasonic data of Strombolian explosions to provide new insights into eruptive mechanisms [Giudicepietro et al., 2022].
The results obtained demonstrate the validity of the neural techniques used and allow for improved automatic, real-time monitoring of Stromboli and other open-vent volcanoes.

# From micro-scale bubble dynamics to large-scale volcanic processes

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Experimental and natural observations demonstrate that bubble dynamics determine the critical balance between gas containment and release, influencing the stability of the volcanic system and controlling the transition in eruptive style, including the potential switch from effusive to explosive activity. A critical gap persists in current modeling approaches. While large-scale flow models have reached a significant level of maturity, the micro scale physics governing bubble dynamics is inadequately formalized to be effectively integrated into the large scale models. Current bubble dynamics models face two main limitations: (i) the assumption of a monodisperse bubble population, which neglects key processes such as nucleation and coalescence; and (ii) the lack of rigorous experimental validation. Because of these simplifications, when these models are coupled to large-scale flow simulations, microscale processes are strongly simplified, failing to account for the evolution of bubble size distributions, which ultimately control magmatic permeability and degassing efficiency. Recent numerical approaches based on the Population Balance Equation (PBE), such as the MAGMAMOM model [Colucci et al., 2025], attempt to overcome these limitations by solving the temporal evolution of a polydisperse bubble distribution, accounting for bubble growth, nucleation and coalescence; however, experimental validation remains challenging. An alternative validation strategy involves comparison with Direct Numerical Simulations (DNS), which allow fully resolved numerical experiments in which a bubble population is simulated at the microscale, providing fundamental information for defining the constitutive laws to be used in population balance models. In this project, DNS simulations will be performed using the open-source Palabos library (https://gitlab.com/unigespc/palabos), developed and maintained by the research group at the University of Geneva.The DNS simulations will be used for validating, and eventually developing the constitutive equations of the kinetic model that describe growth and coalescence of the bubbles. Finally, the new validated kinetic model will be implemented in the one-dimensional numerical conduit model MAMMA (https://demichie.github.io/MAMMA/). This approach aims to quantify the control exerted by micro scale bubble dynamics on large scale conduit flow processes. In particular, the development of magmatic permeability that promotes degassing and eventually transitions in the eruptive style, from explosive to effusive. Petrographic and textural analyses of natural samples from Etna and Stromboli will also be performed. The MAMMA model will be applied to these two study cases to decipher the role of bubbles in determining the observed eruptive style transitions.

In this regard, this project addresses a fundamental limitation in volcanic eruption modeling by developing a multi-scale kinetic framework that couples micro-scale bubble dynamics with macro-scale conduit- flow processes.

# Unravelling the reactivation of long dormant magmatic reservoirs using petrological and experimental constraints: the case of La Palma 2021 eruption

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After 47 years of quiescence, the reactivation of the long-dormant volcanic system of La Palma (Canary Islands) in September 2021 produced the longest (85 days) and most voluminous (ca. 0.2 km$^3$) historical eruption on the island, resulting in significant societal and economic impacts. Nevertheless, this eruption provided a unique opportunity for the scientific community, as the event was comprehensively monitored using a wide range of geophysical, gas, and petrological techniques, yielding key insights into the processes governing this important eruption.

Analysis of precursory seismicity, deformation, and gas signals suggests enhanced magmatic activity at depths of 15-32 km between September-October 2017 and June-July 2021. However, the seismic swarm that marked the onset of magmatic unrest leading to the eruption began on 11 September 2021 at shallower depths (10-12 km) than the earlier signals and progressively migrated upward until reaching the surface at Cabeza de Vaca on 19 September. Syn-eruptive seismicity recorded from the onset of the eruption until approximately 1-5 October indicates that the amphibole-bearing tephrites emitted during this period were mainly sourced from a crustal reservoir located at ca10-12 km depth. Only after this date was deeper seismicity (25 km) detected again, suggesting the reactivation of a deep mantle reservoir and the subsequent migration of magma toward the shallower reservoir. Mixing between these deep-sourced melts and those stored in the crustal reservoir resulted in significant changes in mineralogy (e.g., disappearance of amphibole and increased proportions of olivine and clinopyroxene) and a progressive increase in magma maficity. Whole-rock compositions reached a plateau of ca. 8.5 MgO by mid-October and remained broadly constant until the end of the eruption on 15 December.

To date, numerous studies have applied a wide range of petrological approaches—including mineral geothermobarometry, fluid barometry, and olivine diffusion chronometry-to the 2021 La Palma products in order to reconstruct the pre- and syn-eruptive evolution of the magmatic plumbing system. Based on these methods, the most widely accepted model proposes: (1) hot (approx.1150 °C) and deep mantle storage conditions for all magmas, consistent with the seismicity observed until June-July 2021; and (2) a process of deep magma injection from 25 km to 10 km depth accompanied by the recycling of pre-existing amphibole-bearing syenitic/gabbroic crustal bodies a short time (8-10 days) prior to the eruption.

However, the short-term evolution of precursory and syn-eruptive seismicity, together with petrological observations from the earliest erupted products, calls into question the relevance of this model. In particular, early magmas ascended and were emitted from a reservoir located at ~10 km depth without evidence of contemporaneous mantle-level seismic activity. Furthermore,

the presence of euhedral and compositionally homogeneous amphibole in the early tephrites indicates temperatures lower than 1050 °C, according to available phase-equilibrium studies on basanite-phonotephrite magmas. In addition, the occurrence of low-Mg# amphiboles together with clinopyroxene crystals displaying low-Mg cores containing phonolitic melt inclusions and showing multi-step reverse zoning toward more primitive rim compositions, suggests that the reactivation of a relatively cold tephritic mush was not triggered by a single episode of mafic magma injection shortly before the eruption.

Within this context, and in order to place additional constraints on the pre-eruptive conditions of this eruption, we conducted crystallization experiments on three representative samples emitted during the first month of the 2021 La Palma eruption. Experiments were performed over a wide range of temperature (1150-920 °C), pressure (100-400 MPa), and $H_2O$-$CO_2$ ratios. These new experimental results, combined with detailed petrological and geochemical data from the erupted products, olivine diffusion chronometry, and relocated precursory seismicity, allow us to: (1) place tighter constraints on magma storage conditions, (2) assess the ability of existing petrological tools to capture these conditions, and (3) propose a conceptual model for the magmatic processes and temporal evolution of the ~10 km-deep reservoir that fed the early stages of the 2021 La Palma eruption.

For further information see Andujar et al. (2025), Journal of Volcanology and Geothermal Research, 463, 108327.

# Recent unrest phases at Vulcano Island (Italy) in the regional volcano-tectonic framework: insights from GNSS and InSAR observations

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Vulcano Island (Aeolian archipelago, Italy) is an active volcanic system characterized by persistent hydrothermal activity and a complex long-term interplay between magmatic, hydrothermal, and tectonic processes. In 2021-2023 the island experienced its most recent unrest episode, marked by increased fumarolic activity, seismicity, geochemical anomalies, and ground deformation. Understanding the sources and mechanisms driving these signals is essential for interpreting unrest dynamics in hydrothermal-dominated volcanic systems.

In this study, we analyze GNSS and InSAR time series spanning 2016-2023, covering both the latest unrest episode, along with another minor unrest in 2018, and the intervening periods. The datasets are analyzed jointly and independently through deformation source modeling under purely elastic and thermo-poro-elastic (TPE) rheologies. To better simulate deformation associated with hydrothermal processes, we implement the cylindrical and spherical TPE sources that account for deformation induced by pore-pressure and temperature changes within a hydrothermal reservoir. We also include the continuous GNSS station LOSV located in southern Lipari Island, which records transient displacements synchronous with those observed on Vulcano. Modeling results indicate that the 2018 unrest was driven by an inflating source located west of Vulcanello, in the NW part of the island, at about 3.8 km depth, with a cumulative volume increase of about $0.9 \cdot 10^6$ $m^3$, likely corresponding to the shallowest magmatic storage level feeding the hydrothermal system beneath La Fossa cone. The 2021-2023 unrest instead involves a shallower source (0.5-1 km depth) beneath La Fossa cone, with a cumulative volume change of $0.02\text{-}0.2 \cdot 10^6$ $m^3$, consistent with hydrothermal pressurization driven by the injection of hot magmatic fluids. Residual deformation patterns and synchronous displacements at Lipari suggest the superposition of additional deformation processes related to an additional deformation source and/or to regional tectonics and stress perturbations associated with the Aeolian-Tindari-Letojanni fault system.

# Timescales and magma dynamics of the plumbing system feeding a Plinian eruption: the 79 CE eruption of Somma-Vesuvius, Italy

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Plinian eruptions are the most common high impact explosive events, causing severe local impacts and influencing human settlement or migration and global climate. Understanding their pre-eruptive processes and timescales is crucial for forecasting eruptions and mitigating hazards. The iconic 79 CE Somma-Vesuvius eruption (Italy) is considered the archetype of Plinian eruptions. However, knowledge of its plumbing system architecture and pre-eruptive magmatic processes remains incomplete. Chemical and isotopic data, clinopyroxene zoning analysis, and numerical modelling reveal a vertically extended plumbing system with deep mafic magma batches refilling a tephri-phonolitic reservoir multiple times before the eruption. Diffusion modelling constrains recharge events in timescales fromdecades to less than a year, which align with historically well-documented seismicity ("non desiit enim assidue tremere Campania", Seneca;" Praecesserat per multos dies tremor terrae", Pliny the Younger) preceding the eruption. These findings enhance our understanding of volcanic behaviour, aiding in hazard assessment and risk mitigation for future similar eruptions.

# Large effusive eruptions of Bracciano Caldera (Sabatini volcanic system, Italy)

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Large effusive eruptions can generate extensive lava flows fields representing significant volcanic hazards, particularly in densely populated regions. However, the processes that generate these eruptions and their pre-eruptive storage conditions remain debated. A key question is whether large effusive eruptions are fed directly by deep reservoirs or require prolonged accumulation of large magma volumes in shallow crustal storage.

Here, we investigate a large-volume effusive eruption occurred in the Sabatini Volcanic District, around 341 ka, preceding its most recent caldera-forming phase. Petrological observations, thermobarometry, and experimental constraints indicate that magmas ranging from phonotephrite to tephriphonolite in composition were initially stored at depths higher than12 km (higher than 300 MPa) before ascending to 6 km (150 MPa), where they opened a new pathway and formed a transient shallow reservoir. The phenocryst assemblage-clinopyroxene, leucite, and titanomagnetite-equilibrated at 150 MPa prior to eruption.

Petrological evidence suggests that the first large magma batch resided only briefly within the newly formed shallow reservoir, whereas two subsequent batches were erupted after longer storage intervals. Mineral assemblages and clinopyroxene textures indicate the development and later remobilisation of a feldspar-rich crystal mush prior to eruption. All magma batches record similar pre-eruptive conditions, with temperatures of 1150 °C, pressures around 150 MPa, and low dissolved water contents (around 1 wt%).

These observations support a model in which magma accumulates within long-lived, deep crustal reservoirs dominated by high-crystallinity mushes. Repeated injections of parental magma progressively favoured magma remobilisation and ascent towards shallow crustal levels, where magma may be temporarily stored before eruption. Shallow reservoirs are therefore ephemeral features that are assembled rapidly by deep recharge and subsequently drained during eruptions.

Understanding this deep-to-shallow magma transfer highlights how large effusive eruptions can be triggered rapidly following deep recharge, with important implications for volcanic hazard assessment.

# S05 - TRANSDISCIPLINARY APPROACHES TO VOLCANO MONITORING AND HAZARD ASSESSMENT: AI, SEISMOLOGY, GEODESY, AND REMOTE SENSING

Conveners:

Roberto Manzo, Umberto Tammaro, Claudio Martino, Marius Isken

# On the tilt measurements to tectonic earthquakes in Neapolitan Volcanic District

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Tiltmeters are crucial instruments for monitoring ground deformation in volcanic areas; however, characterizing their response can be challenging. The Osservatorio Vesuviano (OV-INGV) has deployed a network of tiltmeters in the Neapolitan volcanic areas (Campi Flegrei, Vesuvius, and Ischia), which have been continuously recording data since 2015. Over this extended monitoring period, peculiar behavior has been observed in the response of these instruments to large tectonic events. In particular, during the 2016 Central Italy seismic sequence, the signals recorded by the tiltmeters exhibited unusually large amplitudes and long durations.
To characterize the instrumental response, we analyzed the amplitudes and durations of the tiltmeter signals and compared them with the seismic signals recorded on the days of the main events of the sequence. Because seismic sensors (velocimeters and accelerometers) and tiltmeters operate in different frequency bands, the seismic signals were appropriately processed. Following the procedure proposed by Lippiello et al. [2025, Toward recognizing the waveform of foreshocks, Geophysical Research Letters, 52, e2025GL115466], we computed the base-10 logarithm of the Hilbert transform of the seismic signal, obtaining the quantity μ(t). We compared the maximum value of μ(t) with the maximum measured tilt and found a correlation between the two quantities. In addition, we compared peak ground velocity (PGV), peak ground displacement (PGD), and manually picked signal durations from the seismic records with the maximum recorded tilt and the signal duration observed in the tiltmeter data. This analysis revealed linear relationships between the seismic measurements and the tiltmeter responses, particularly for borehole tiltmeters.

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# IT infrastructure as a scientific instrument for Real-Time volcano monitoring and crisis governance during Campi Flegrei unrest

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In volcanic regions experiencing unrest and hosting high population density, digital infras tructure is not merely a technical backbone but a scientific instrument enabling reliable inference and crisis governance. We present the infrastructure developed at INGV - Osservatorio Vesuviano to sustain real-time surveillance of Vesuvius, Campi Flegrei, Ischia, and Stromboli, with particular focus on the ongoing unrest at Campi Flegrei, characterized by persistent ground uplift and recurrent seismic events and swarms.

The system is designed as a high-availability, risk-aware virtualized ecosystem based on a hybrid, multi-technology virtualization cluster with inter-cluster failover capabilities. This heterogeneous architecture reduces systemic vulnerability and ensures service continuity under mission-critical conditions. Logical domain segregation, network segmentation, and security-by-design principles inspired by Zero-Trust paradigms limit failure propagation, acknowledging that digital disruption during volcanic crises directly impacts scientific interpretation, operational response, and societal trust.

Operational resilience is reinforced through geographic redundancy: a fully equipped backup data center and monitoring room have been established at the historical Ercolano site, outside the highest-risk sector of Campi Flegrei. This mirrored infrastructure guarantees full surveillance operability and decision-support continuity in severe crisis scenarios affecting the primary operational area.

Beyond virtualization, the infrastructure embeds a distributed real-time processing platform based on asynchronous worker pools communicating via high-performance messaging queues. This architecture enables streaming ingestion and parallel processing of multi-parameter datasets, including seismic, tide gauge and geochemical observations. AI-driven workflows are integrated directly into live data streams, including near-real-time seismic phase recognition, event detection, and location using deep neural networks [Cantiello et al., 2026]. Such integration enhances sensitivity to low-magnitude seismicity typical of unrest phases, improving pattern recognition within large, heterogeneous datasets.

A containerized orchestration layer supports scalable processing of data and provides an AI-ready environment for machine learning deployment and multi-sensor data fusion. In this framework, computational infrastructure actively shapes scientific inference by enabling the synergy between physics-based models and data-driven approaches advocated in transdisciplinary volcano monitoring [Cantiello et al., accepted].

A dedicated governance layer is implemented through an asynchronous RESTful engine [Di Filippo and Peluso, 2022] that decouples computationally intensive post-processing from core surveillance systems. This engine manages automated generation of above-threshold seismic communications, periodic bulletins, shakemaps for high-energy events [Martino et al., 2025], and institutional reports transmitted to the Italian Civil Protection Department (DPC), in accordance with operational protocols for seismic swarms and escalation phases.

The microservice-based architecture preserves real-time analytical performance during peak activity and has been repeatedly stress-tested throughout the ongoing Campi Flegrei unrest,

particularly during the most intense seismic swarms, without compromising surveillance continuity. The resulting system represents a transdisciplinary operational framework in which infrastructure design, AI-based seismic analysis, multi-sensor integration, and hazard governance converge into a unified model. In the context of Campi Flegrei unrest, cyberinfrastructure it self functions as a resilient scientific instrument, enabling robust inference, rapid response, and continuity of decision-support capabilities under extreme and evolving conditions.

# Towards automatic high-resolution earthquake analysis of the Campi Flegrei caldera using a data-driven approach

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Active calderas exhibit complex and rapidly evolving seismic patterns that provide key information on subsurface processes and volcanic unrest. Improving the resolution and completeness of earthquake catalogues is therefore essential for interpreting the dynamics of these systems, particularly in densely populated urban regions such as the Campi Flegrei caldera (southern Italy). In recent years, this volcanic system has experienced renewed ground inflation and intense seismic activity, emphasising the need for enhanced monitoring strategies capable of resolving low-magnitude events and subtle spatio-temporal variations in seismicity.
Here we present the first application of the data-driven framework Qseek [Isken et al.2025] to the Campi Flegrei caldera, aimed at producing a high-resolution, automatically generated earthquake catalogue. Qseek combines advanced ML-driven first-arrival annotation, detection, localisation, and automated relocation techniques to identify and characterise seismic events with improved sensitivity and spatial accuracy. By leveraging continuous waveform data from multiple seismic networks, the data-driven method enables the reconstruction of seismic activity with significantly greater detail compared to standard operational approaches. As an initial step, the workflow is applied in an offline configuration to recent years of seismic data from Campi Flegrei in order to evaluate its performance and validate the resulting catalogue against the operational catalogue provided by INGV. Preliminary results indicate a substantial increase in the number of detected earthquakes and a sharper definition of hypocentral clustering, allowing to image previously unresolved structures and migration patterns of seismicity to emerge. Building on this validation phase, we present the first preliminary outcomes from the implementation of the workflow in a near-real-time configuration. Early tests demonstrate the feasibility of rapidly processing incoming data streams and generating updated earthquake locations, providing a foundation for improved tracking of seismic activity during periods of volcanic unrest.
This study represents the first deployment of the Qseek methodology at Campi Flegrei and highlights its potential to substantially enhance the interpretative capability of seismic monitoring in active calderas. By enabling more detailed observations of the temporal and spatial evolution of seismicity, this approach offers new opportunities to investigate the mechanisms driving volcanic unrest and supports the development of next-generation real-time monitoring systems for volcanic hazard assessment.

# Real-Time Multidisciplinary Volcano Monitoring with a Scalable Data-Driven Computing Architecture

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In volcano monitoring, in order to make surveillance increasingly effective, a multi-parameter approach is essential. Indeed, it is not only necessary to monitor purely seismic parameters, but also geodetic, geochemical, thermal, meteorological, tidal, optical, and even radio emission parameters. The number of parameters observed, sampled, and acquired therefore tends to grow both in type and in data size, also due to the expanding sensor network.
Obviously, data shouldn't simply be acquired and stored for offline operations; to make surveillance effective, it must be processed as quickly as possible, almost in real time. Analysis, correlations between physical phenomena, and the resulting inferences are increasingly necessary, with the new frontiers of research and technological development, especially through the use of artificial intelligence techniques. The need, therefore, is to be able to process large amounts of data, perform increasingly complex operations on them, and obtain results in the shortest possible time to provide rapid information for surveillance purposes, especially in highly anthropized areas.
In this context, the need arose to design a logical system architecture, implementable using a hardware/software platform, that could then ensure simple integration of modules that perform the basic analysis and correlation operations on the application domain signals. The main requirements to be met were: rapid, near-real-time response times; scalability to accommodate the increase in the flow of data to be analyzed or the complexity of the operations to be performed on it; the loosest possible coupling to allow developers to focus on the single problem while being able to abstract the behavior of the other components; ease of integration with existing components; and ease of development even for non-IT professionals.
An architecture was therefore designed [Cantiello et al. 2026] based on the concept of completely independent workers, which follow a publisher/consumer approach, perform single, specific tasks, and communicate using a high-performance distributed messaging subsystem. The workers are dynamically orchestrated based on the physically available resources and the workload they support. Produced and consumed messages are each labeled with a topic that characterizes their information content. Each worker can therefore assume the role of producer, consumer, or both and operates on appropriate message queues associated with the topics. The model is therefore service-oriented, yet completely data-driven. Data availability triggers service execution. Each new worker added does not disrupt the operation of existing workers precisely because of the loose coupling.
A hardware/software platform was then developed on this architecture, incorporating individual workers into software containers and orchestrated using Kubernetes. Apache Kafka was used for the real time messaging subsystem. The entire interface between the software components and messaging management was incorporated into a Python library to further abstract the relationship with the infrastructure and thus facilitate worker development by researchers without adequate IT skills. The library also transparently exposes metrics for each developed worker to measure its performance in terms of resource usage and messages processed.
The platform has been in use at the Vesuvius Observatory's monitoring room for over a year. Some services currently running on legacy architectures are being migrated to it. In parallel,

innovative modules have been developed, such as the calculation of peak ground acceleration [Martino et al. 2025] maps for significant seismic events, the calculation of magnitude values, and the automatic detection of seismic signal phases due to earthquakes and their localization using artificial intelligence techniques [Cantiello et. al 2026].
The initial results since the platform's adoption are undoubtedly positive: response times have proven to be in line with those expected for a near-real-time system, and the use of computational resources is low and in line with the possibilities for future expansion.

# Interdisciplinary, Multidisciplinary or Transdisciplinary approach building resilient societies: Insights for DRR from the CORE Project

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It is well known that disciplinary expertise has played a key role in advancing knowledge in Disaster Risk Reduction (DRR) respect to various hazards including volcanic hazard. Interconnected disciplinary expertise (multidisciplinary and interdisciplinary) has further enriched the understanding of hazards and risks. However, this understanding cannot comprehend multidimensional, fundamental, and global issues like DRR.
A successful DRR strategy depends on cooperation between scientists, policymakers, and practitioners to mitigate risks and strengthen societal resilience. All this indicates to venture outside the boundaries of the single disciplines seeing forward a transdisciplinary approach to go beyond the disciplinary silos by co-creating knowledge and solutions in partnership with those affected by disasters. The transdisciplinary approach offers a paradigm shift in how we conceptualize and address disaster risk. By embracing complexity, collaboration and co-creation, we can forge a path towards a more resilient and equitable future for all.
Here, we show some results obtained by the H2020 CORE project that analysed case studies from Europe and beyond, investigating what went wrong, spanning both pre-event preparedness and post-event recovery and identifying best practices, enabling scalable and adaptable resilience strategies across diverse contexts. The project also fostered long-term relationships between scientists, policymakers, and practitioners, ensuring sustained engagement and continuity despite personnel changes.

# CarlOS: a real-time microservice-based operating system for seismic data acquisition, processing and AI-ready volcano monitoring

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Real-time access to high-quality seismic data is fundamental for effective volcano monitoring and rapid hazard assessment. Here we present CarlOS (Continuous Acquisition and Real-time Linked Operating System), a lightweight operating system designed for real-time acquisition, management and analysis of seismic data from field stations. The system has been developed to operate primarily with the GILDA (Geophysical Instrument for Low power Data Acquisition) seismic station, an in-house digitizer developed at the Osservatorio Vesuviano, but its modular architecture allows easy adaptation to a wide range of digitizers, including experimental systems. CarlOS runs on industrial-grade PCs to ensure robustness and resilience in harsh environmental conditions typical of volcanic monitoring deployments. The system acquires seismic signals continuously and distributes them externally through the SeedLink protocol, enabling seamless integration with existing seismological infrastructures. In case of network interruptions, the data stream is internally buffered and automatically recovered, ensuring data continuity and availability. In addition to data acquisition and distribution, CarlOS provides real-time waveform analysis tools including spectral analysis, power spectral density estimation and automatic detection of P and S phases. All functionalities are accessible through a user-friendly web interface based on internally developed microservices.

The system is designed as a field-ready front-end platform for the implementation of artificial intelligence algorithms aimed at early detection of anomalous seismic patterns and improved volcano monitoring. CarlOS therefore represents a flexible and scalable solution for integrating real-time seismic observations with next-generation AI-based hazard assessment frameworks.

# Understanding of Strong Coupling Between Land-Ocean-Atmosphere-Meteorological Parameters Associated to the Volcanic Eruptions Using Multi Satellite Data

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Volcanic eruptions are sudden, often violent events that occur globally on both land and in the ocean, significantly impacting the geosphere, hydrosphere, atmosphere, and various meteorological parameters. As some of the deadliest natural disasters in geological history, past eruptions have been delineated as significant archaeological and historical sites, often located using airborne and ground-based geophysical surveys. Now, ocean and land have dense network of observing systems, Ocean (Buoys and ARGO floats), Land (Automatic Weather Stations - AWS, Seismographs, GNSS, and AERONET). These systems provide continuous local and regional data that are integrated using Geographic Information Systems (GIS) to provide a global perspective. Specifically, seismological observatories monitor volcanic earthquakes associated with magma chamber movement, tracking both coseismic activity and eruptions.
Over the last several decades, the development of multi-satellite constellations operating in optical and microwave frequencies has revolutionized our capabilities. These sensors detect subtle changes around vulnerable locations during the preparation, occurrence, and post-disaster phases, providing critical data for evacuation planning and hazard mitigation.
In this talk, we will discuss three recent major events:

- 2020: Taal (Philippines)
- 2022: Hunga Tonga-Hunga Haapai (Tonga)
- 2025: Hayli Gubbi (Ethiopia)

All three eruptions profoundly affected meteorological and atmospheric parameters. Satellite observations revealed massive ash plumes governed by wind intensity and direction, with ash spreading over 100 km and plumes dispersing beyond 1000 km. Pronounced changes were observed across:

- Land and Air: Surface and atmospheric temperature shifts
- Meteorology: Relative humidity, water vapor, and cloud cover
- Atmospheric Composition: Aerosol Optical Depth (AOD), Angstrom exponent, greenhouse gases, $SO_2$, and total ozone column
- Oceanography: Changes in ocean color, vertical chlorophyll, and salinity profiles

The integrated data from ground and satellite observations demonstrate a strong coupling between the land, ocean, and atmosphere during volcanic activity. These datasets are vital for understanding the timing of magma initiation and the onset of eruptions, which is essential for early warning systems. Finally, we will present the application of the joint NASA-ISRO (NISAR) mission data in analyzing the 2025 Hayli Gubbi eruption, highlighting how high-resolution radar imaging enhances our mitigation strategies.

# Analysis and modelling of non-stationary components of the gravity field at Campi Flegrei caldera from nearly two years of superconducting gravity recording

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The investigation of subsurface mass redistribution processes in active volcanic areas is a key challenge as the occurrence of these phenomena can cover a wide range of spatial and temporal scales. In this context, gravity observations represent a powerful tool, especially when used jointly with other geodetic techniques such as GNSS and InSAR, as they can reflect mass and density changes related to magma dynamics and fluid migration within the crust.
In October 2024, a superconducting gravimeter (SG) iGrav029 was installed at Rione Terra site in Pozzuoli, the central sector of the Campi Flegrei caldera (CFc), with the aim of fostering the gravity monitoring of CFc. This was established as part of a scientific collaboration between the INGV-OV, the DiSTAR-UNINA and ITES-Strasbourg (France). The decision to install an SG stems from its unique characteristics of very low instrumental drift and high precision. In an active volcanic area such as the CFc, which is known worldwide for the episodes of large ground deformations, this type of gravimeter can provide information on small and the short-term gravity variations which can hardly be observed by discrete time-lapse gravity surveys.
We report on the analysis of nearly two years of continuous gravity observations acquired with the iGrav029. Target of the analysis is to separate signals related to volcano dynamics from all the other relevant environmental effects. Aside the tides, the most significant effects recorded by the iGrav029 are related to the atmospheric pressure variations and non-tidal ocean loading (NTOL): both can generate gravity signals with magnitudes comparable to those expected from volcanic processes.
We examine the instrumental drift of the SG in detail. Although it is much smaller than that of spring gravimeters, it is a critical aspect for interpreting long-term gravity records on volcanoes. Here, SG observations are compared with relative gravity measurements acquired using a Scintrex CG-6 spring gravimeter. The latter were collected during periodic time-lapse gravity campaigns conducted at a benchmark close to the iGrav029 installation site and provide gravity differences with respect to a stable reference point located outside the caldera; relative gravity measurements are routinely corrected for drift during each survey. We find an excellent agreement between the SG and Scintrex gravity time series. After carefully modelling and removing all these non-volcanic contributions, a long-term gravity decrease of about 50 microGal in the time span from October 2024 to March 2026 is observed, which is correlated with the observed ground uplift. The relationship between gravity variations and vertical ground displacement is explored by analysing the variability of their ratio over time, as it can provide insights into the processes driving unrest of the caldera.
Finally, a forward modelling, including a coupled solution for gravity and surface deformation (as observed from GNSS and InSAR data), is realized to obtain temporal mass variations compatible with the source of unrest. In this contribution we demonstrate how an iGrav SG can improve the volcano monitoring by providing high resolution mass variations with unprecedented precision.

S05 - Oral Presentation

# Unveiling the volcanic breath through seismic ambient noise polarization on Piton de La Fournaise, La Réunion

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Ambient seismic noise polarizes in the horizontal plane as an effect of the presence of pervasive fracture fields in the upper crust. Variations in the acting local stress field, as well as the presence of pressured fluids can strongly affect polarization strength. We investigate temporal variations of polarization on the Piton de la Fournaise volcano, using continuous seismic recording acquired in the period 2011-2024. We find recurrent and unambiguous trends of polarization strength during eruptive periods. Few weeks before eruptions, an increase of polarization is observed, as the effect of variations in the local stress field due to magma rise which affect the opening of existing fracture. Similarly, before the end, the closure of the dike probably causes a loss of polarization (depolarization). Our findings show that noise polarization has the potential to monitor in real-time crustal processes on an active volcano during eruptions.

# A Multi-Parametric Approach for Real-Time Monitoring of Seafloor Deformation in shallow water environment

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Monitoring seafloor deformation in shallow waters is crucial for understanding volcanic dynamics in active and densely populated areas such as the Campi Flegrei Caldera. Indeed, a significant portion of the uplift associated with the bradyseism phenomenon also occurs in the submerged sector of the Gulf of Pozzuoli. Although recent studies have demonstrated the effectiveness of seafloor deformation measurements in this area using bottom pressure sensors, data processing has historically required complex post-processing analyses to compensate for oceanographic factors, particularly for the density variations along the water column. This computational delay has hitherto precluded the use of such networks for real-time monitoring purposes.

In this work, we present a novel methodology that overcomes these limitations, enabling real-time monitoring of seafloor deformation for the first time. Our approach is based on the integration of data acquired by the seafloor pressure sensor network with a specific instrumental and analytical configuration, consisting of three key elements: (1) a remotely located tide gauge, outside the area subject to volcanic deformation; (2) a barometer positioned near the marine sensor network; and (3) the implementation of a prediction model for the density variations along the water column during the time. This model has been obtained through previous CTD campaigns and the use of artificial intelligence algorithms to predict density trends.

This method allows for the isolation and extraction of the purely geodetic signal with unprecedented efficiency. Specifically, the subtraction of regional sea-level data (provided by the remote tide gauge) and local atmospheric pressure (provided by the barometer), combined with the compensation of thermohaline effects using the predicted water density variation, enables the instantaneous filtering of the background signal. Through this processing, we are able to convert the seafloor pressure measurement into a vertical deformation measurement, effectively allowing the pressure sensors to operate as true tide gauges providing real-time data.

The application of this methodology to data from the Gulf of Pozzuoli demonstrates how the use of the predicted density variation drastically speeds up analyses, eliminating the need to wait for complex oceanographic profiles measured in situ. The results confirm that the precision in extracting the vertical deformation rate remains high, making the data immediately usable.

In conclusion, this innovative method improves the approach to marine geodesy in the Campi Flegrei, allowing the evolution of offshore bradyseism to be tracked with the same timeliness as onshore networks (like GNSS, SAR) and providing a new, crucial operational tool for early warning systems and volcanic risk assessment.

# The Application of Remote Sensing Data (SAR, Thermal and Optical) and Geodetic Modeling to Investigate the Volcanic Activity at Semeru Volcano (Indonesia)

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Semeru (Indonesia) is a persistent eruptive volcano, but its volcanic activity remains poorlyconstrained. Here we used a combination of different remote sensing data to improve the understanding of Semeru. By differencing high resolution (2m) Digital Elevation Models (DEM) derived from optical data (EarthDEMs), we estimated a bulk volume of about 43.5 millions of cubic meters of lavas erupted from 2014 to 2020. Thermal data from MIROVA show multiple peaks in the volcanic radiative power and in the cumulative Volcanic Radiant Energy (VRE) related with lava flow extrusions. Time series of deformation, obtained with Synthetic Aperture Radar Interferometry (InSAR) from Sentinel 1 data, show on both orbits negative line of sight displacements of the SE flank from 2014 to 2023. The observed displacements can be related to surface processes or to a limited deflation of a shallow (less than 2 km) reservoir, modeled with a Boundary Element Method. We used the volume estimated by EarthDEMs to calibrate the VRE and to calculate the erupted volume of lava from VRE for periods not covered by EarthDEM, allowing in the future the near real time estimation of volumes from MIROVA data. Erupted volumes of lava over the time reveal a steady state activity. Our data suggest that the persistent volcanic activity at Semeru is fed by deep portions of the magmatic system, while the possible shallow reservoir is a hydrothermal or an ephemeral magma reservoir. This study highlights the importance of using different remote sensing data to monitor, quantify, and interpret the volcanic activity in poorly monitored and studied volcanoes.

# Monitoring the 27 December 2025 Mount Etna Volcanic Cloud Using SEVIRI and FCI: A Detection and Quantification Cross-Comparison Experiment

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The detection and monitoring of volcanic clouds are essential for hazard assessment and aviation safety. In this study, we apply a neural network (NN) model, trained on data from the Spinning Enhanced Visible and Infrared Imager (SEVIRI), to detect the volcanic cloud generated during the Mount Etna eruption of 27 December 2025. The analysis evaluates the model's ability to generalize across different satellite instruments, by testing its application to observations acquired by the Flexible Combined Imager (FCI), which is onboard the Meteosat Third Generation (MTG) platform. In addition, volcanic cloud quantification is performed using the Volcanic Plume Removal (VPR) algorithm, with the neural network-based volcanic cloud detection used as input. The main objectives of this study are to evaluate the cross-instrument applicability of the neural network model and its adaptability to next-generation geostationary sensors, and to present the first volcanic cloud quantification analysis using FCI data, comparing the results with those obtained from SEVIRI observations.
The results demonstrate that the model successfully detects volcanic cloud structures in both SEVIRI and FCI observations, with a strong correlation between the quantification estimates. This approach represents a significant step toward the development of a near-real-time monitoring system, enabling automated detection and subsequent quantification of volcanic clouds.

# Rethinking volcanic heat from space: a new thermal framework for global heat budget revision, activity classification, and eruption precursor detection

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Satellite-derived volcanic heat flux has long been applied to infer subsurface magmatic processes, yet current space-based approaches capture only a fraction of the total thermal signal. By focusing predominantly on high-temperature eruptive sources, existing methodologies systematically overlook moderate- and low-temperature emissions, leaving global volcanic heat budgets incomplete. Here we propose a novel framework that merges Mid-InfraRed (MIR; 3.5-4.5 µm) and Thermal-InfraRed (TIR; 10-12 µm) satellite observations to retrieve volcanic thermal output across the full physically relevant temperature spectrum.

The chief parameter here introduced is the Total Volcanic Radiative Power (VRP_Tot), defined as the combined MIR- and TIR-derived radiative power (VRP_MIR + VRP_TIR). Unlike conventional single-band retrievals, which incur systematic errors exceeding 90% outside their optimal temperature range, this formulation maintains accuracy within ±20% over the 273-1500 K interval. We further introduce VRP_Ratio, a dimensionless diagnostic index that encodes the thermal structure of a volcanic system and provides a physically grounded basis for classifying hydrothermal, dome-building, open-vent, and effusive activity within a single, coherent parameter space.

Application to a suite of representative volcanoes demonstrates that MIR-only inventories underestimate total thermal output by factors of 2-20 for moderate-temperature systems, implying that current global volcanic heat flux inventories may be substantially revised upward. At Sabancaya volcano (Peru), VRP_Ratio time series reveal shifts in thermos-structural conditions several months before the November 2016 eruption, constituting clear precursory signatures that single-wavelength methods fail to resolve.

Beyond correcting long-standing inventory biases, this framework enhances real-time volcano surveillance and advances the early recognition of eruptive transitions. Its transferability across diverse volcanic settings and spectral platforms positions it as a broadly applicable tool, with implications extending from volcanology and hazard assessment to climatological modelling and the characterisation of planetary volcanism.

# Prometeo: a real-time remote-control system supporting the operability of the Osservatorio Vesuviano seismic network

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The effectiveness of volcano monitoring strongly depends not only on the quality of geophysical measurements but also on the continuous operability of the technological infrastructure enabling data acquisition and transmission. Seismic networks deployed in active volcanic environments consist of geographically distributed stations operating under challenging environmental and logistical conditions, where failures in power supply, communication systems, or instrumentation may compromise data availability and reduce situational awareness during volcanic unrest.
We present PROMETEO, a remote-control and infrastructure monitoring system developed at the INGV - Osservatorio Vesuviano to provide real-time knowledge of the operational status of stations composing the Osservatorio Vesuviano seismic network. The system supervises the technological layer underlying geophysical monitoring, supporting the continuity and reliability of seismic observations across the Campanian volcanic district, including Mt. Vesuvius, Campi Flegrei, and Ischia Island.
PROMETEO adopts an Internet of Things architecture integrating heterogeneous diagnostic information through standard communication protocols such as MQTT, SNMP, and MODBUS. The platform continuously acquires parameters related to energy systems, network connectivity, environmental conditions, and device performance, which are centralized within a supervisory environment enabling real-time visualization, historical analysis, and automated alerting.
The multiparametric approach allows operators to rapidly discriminate between infrastructural anomalies, connectivity disruptions, and power-related issues, significantly reducing diagnostic time and unnecessary field interventions, particularly for stations located in remote or difficult-to-access areas. Long-term tracking of infrastructure parameters supports preventive maintenance strategies and improves network resilience.
By providing a unified operational overview of station health, PROMETEO enhances control-room situational awareness and directly supports volcano monitoring by ensuring data continuity, a fundamental prerequisite for seismic interpretation, multiparametric data integration, and hazard assessment. The system demonstrates how infrastructure remote-control represents a key operational component of modern volcano observatories, contributing to the robustness and effectiveness of monitoring networks in densely populated volcanic regions such as southern Italy.

# Volcanic deformation monitoring in Northern Ecuador using the DInSAR technique

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In Ecuador, the ground-based monitoring network covers only 12 of the 84 identified volcanoes. In this context, the DInSAR technique emerges as an essential geodetic tool for establishing baseline deformation data with millimetric precision. Given that many of these systems host vulnerable populations on their flanks—such as the Guagua Pichincha, Rucu Pichincha, and Cayambe volcanoes—or even within their calderas, as in the case of Pululahua, radar interferometry provides a non-invasive solution to overcome access and monitoring constraints. Consequently, this study analyzes the surface deformation of these four volcanoes using the DInSAR technique during the 2016-2024 period, aiming to provide technical mapping to document the behavior of these volcanic edifices. To achieve this objective, the research was developed in three phases: i) a literature review to characterize eruptive histories and exposed populations, alongside the acquisition of Sentinel-1 scenes in both ascending and descending orbits; ii) generation of interferograms (IFGs) by applying orbital, topographic, and geometric corrections through SNAP software workflows; and iii) generation of cartographic material and time series based on the Line-of-Sight (LOS) implemented in RStudio. The results indicate low-magnitude LOS deformation in the Pichincha Volcanic Complex (Guagua Pichincha and Rucu Pichincha) and Pululahua, with inflation and deflation signals generally below ±3 cm. In contrast, the Cayambe volcano exhibits patterns consistent with minor subsidence. These findings exhibit the utility of DInSAR as a fundamental geodetic tool for establishing activity thresholds in volcanoes with limited instrumentation. In conclusion, the identified LOS variation patterns show consistency with recent activity reports from the Instituto Geofísico for systems such as Guagua Pichincha, suggesting the technique's potential for regional monitoring. However, as a preliminary analysis sensitive to atmospheric noise, these results do not replace in-situ monitoring but rather serve as a strategic reconnaissance tool. This study demonstrates that DInSAR is fundamental for optimizing the planning of terrestrial geodetic networks, allowing for the prioritization of instrument placement in detected deformation zones and establishing a systematic framework for the surveillance of volcanoes with sparse instrumental coverage.

# Integrated Long-Term Geodetic Observations of the Pernicana Fault System (Mount Etna)

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Mount Etna, located along the eastern coast of Sicily, is one of the most active volcanoes in the World and represents a complex geodynamic system where volcanic and tectonic processes interact. The regional tectonic setting is controlled by the N-S compressive regime related to the Africa-Eurasia convergence and the WNW-ESE extensional regime reasonably associated with the Malta Escarpment and the Ionian roll-back. Within this framework, the eastern flank of the volcano undergoes a well-documented eastward motion, whose relationship with eruptive and magmatic activity is still under investigation.

The Pernicana Fault System (PFS) marks the northern boundary of Etna's mobile eastern flank and plays a key role in accommodating this deformation. The system consists of discrete segments arranged in a right-stepping en-échelon configuration forming a left-lateral shear zone that dissects the entire north-eastern flank of the volcano. Its kinematics varies along strike: the western segment is associated with shallow seismic crises (M around 4.0) characterized by oblique dip-slip and left-lateral motion, whereas the eastern segment mainly exhibits aseismic creep with dominant left-lateral displacement.

The dynamics of the PFS have been investigated using a multidisciplinary geodetic approach integrating leveling, Electronic Distance Measurement (EDM), tiltmeters, GNSS observations, and InSAR data. Long-term geodetic monitoring began in the 1980s with the installation of a 150 km leveling network including about 200 benchmarks, some of which cross the Pernicana fault. GNSS observations, initiated in 1988 and progressively expanded into a dense network of more than seventy stations. Two local GNSS networks installed across the eastern segment of the fault further constrain the displacement field in the aseismic sector.

InSAR data, available since the late 1990s, allow the surface trace of the Pernicana fault to be mapped from the north-eastern rift zone to the Ionian coastline. Integrated geodetic observations indicate a left-lateral transcurrent motion along the fault with a long-term rate of approximately 20-30 mm/yr. Time series from GNSS and InSAR datasets also reveal episodic accelerations in fault motion associated with seismic crises and eruptive activity.

The integration of these long-term geodetic datasets provides robust constraints on the deformation pattern of Mount Etna and improves our understanding of the role of the Pernicana Fault System in controlling eastern flank instability and its relationship with magmatic processes.

# A long-lasting inflation at Mt. Etna volcano: revisiting the post 1991-1993 eruption time interval

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Following the voluminous 1991-1993 eruption, Mount Etna experienced a period of low volcanic activity. A vigorous pressurization of the plumbing system of the volcano started in September 1993 as clearly documented by geodetic observations. This build-up phase ultimately culminated in the 2001 eruption. Leading up to this event, the volcano was highly restless, exhibiting frequent explosive activity at its central craters, summit lava flows, and notable seismic swarms on its western flank, particularly in January 1998 and April 2001.
We revisited such vigorous pressurization by taking into account all available continuous and episodic GNSS observations collected during the 1994-2001 time interval. To this aim, we reprocessed all GNSS raw data by using the GAMIT/GLOBK code, aligning both time series and velocity field to a local reference frame, in order to remove the regional deformation pattern. We inverted the resulting surface velocity field to get new insight on the pressurizing source by adopting different analytical models.
We framed achieved results in the general context of the eruptive cycles (inflation-eruption-deflation) characterizing Mt. Etna volcano in the last decades as well as providing also new insight on the long-term volcanic hazard assessment.

# Stromboli's explosions from land and sea: Insights from Ocean Bottom Seismometers Data

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Stromboli volcano is characterized by persistent explosive activity punctuated by major and paroxysmal eruptions, whose precursory signals remain difficult to detect. One of the main challenges lies in identifying deeper seismic sources, often masked by surface activity and volcanic tremor recorded by onshore stations.
To improve the detection and characterization of such signals, four offshore Ocean Bottom Seismometers (OBS) were deployed between May and September 2024, complementing the permanent onshore monitoring network. However, independent clock drifts affecting OBS recordings can significantly bias multi-station analyses and source localization.
In this study, we estimate and correct OBS clock drifts by computing cross-correlation time lags between offshore and onshore seismic stations. The results reveal approximately linear drifts for all instruments, allowing for a consistent time correction of continuous seismic data.
Using the corrected dataset, we do a preliminary localization of volcanic tremor based on RMS amplitude measurements from the onshore network. A grid-search inversion approach is applied to constrain the spatial distribution of tremor sources.
Our results highlight the importance of accurate timing for integrating offshore and onshore datasets and provide first-order constraints on tremor source location at Stromboli. This work represents an initial step toward a combined analysis of multi-sensor data, with the aim of improving the detection of deeper processes potentially involved in the build-up to major explosive events.

# EtnaMonitor: reducing false alerts in real-time volcano monitoring from public feeds using hysteresis, cooldown policies and AI-assisted development

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Real-time volcanic monitoring systems serving non-specialist audiences face two challenges rarely addressed in the literature: data availability exclusively in visual format (PNG charts) rather than structured numeric feeds, and alert fatigue — user desensitization caused by redundant notifications during prolonged eruptive episodes.

We present EtnaMonitor (etnamonitor.it), an operational real-time monitoring platform for Mount Etna developed and managed by an independent researcher. The system integrates: (1) INGV volcanic tremor data automatically extracted from PNG images via computer vision (coverage: 93.5% per execution cycle, resolution: ~7 minutes); (2) NASA FIRMS thermal hotspots; (3) Copernicus Sentinel-2/1 satellite imagery; (4) an intelligent alerting engine based on hysteresis, per-user cooldown, and personalized thresholds; (5) automatic Telegram notifications.

We report results from 5 months of operation (October 2025 - March 2026) across 133 registered users. The smart alerting policy reduced notification volume by 97.6% compared to a naive fixed-threshold baseline (483 alerts sent out of 20,049 potential triggers), while maintaining 100% coverage of 5 significant volcanic events independently confirmed by INGV bulletins: NE Crater paroxysms on 24 December 2025 (first paroxysmal activity after 28 years), lateral eruption in Valle del Bove on 1-9 January 2026 (peak: 43 alerts in one day, lava front at 1,360m), sub-terminal eruption of SE Crater on 18-24 February 2026, explosive event with ML 4.5 earthquake on 4 March 2026, and tremor spike on 15 March 2026.

The platform was developed entirely through AI-assisted vibe coding with multi-LLM orchestration (Claude Sonnet, ChatGPT, GitHub Copilot), representing a documented case of an operational scientific monitoring system built through structured prompt engineering by a single developer in 3-6 months.

As of 20 March 2026, a point-by-point persistence layer (tremor_readings table, PostgreSQL) is operational, accumulating the dataset required for training a HistGradientBoosting classifier for tremor escalation prediction over the next 6 hours (target: ~30,000 samples by June 2026).

This work documents a transdisciplinary approach combining computer vision, smart alerting, and AI-assisted development methodologies for volcano monitoring from public feeds, with operational validation on real confirmed events.

# UAV Radiometric TIR Orthomosaics for Surface Heat-Flux Quantification in Quiescent Volcanic-Hydrothermal Systems: A Case Study at Pantelleria Island (Sicily Channel Rift, Italy)

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Accurate quantification of surface heat loss from quiescent volcanic-hydrothermal systems is essential for closing subsurface energy budgets, identifying structurally controlled upflow zones, and detecting thermal precursors to volcanic unrest. Satellite thermal products lack the spatial resolution required to resolve individual diffuse degassing structures, while ground-based heat-flux grids rarely achieve sufficient areal coverage for reservoir-scale inference. Here we present a reproducible UAV-based workflow that retrieves volcanic radiative power (VRP) and apparent heat-flux density from radiometrically calibrated thermal infrared (TIR) orthomosaics, providing a practical tool for geothermal targeting in active volcanic terrains. Pantelleria Island (Sicily Channel Rift, Italy) - a high-enthalpy geothermal system within the Cinque Denti caldera, with subsurface temperatures exceeding 490 °C at 2 km depth and persistent fumarolic discharge governed by NW-SE and NE-SW fault systems - served as the test site. Pixel-scale heat flux was derived from surface temperature rasters using the Sekioka and Yuhara (1974) energy-balance approach, which partitions total heat loss into a radiative term (Stefan-Boltzmann law) and a sensible convective term (Newton's law of cooling). Favara Grande yields coherent thermal anomalies up to ~74 °C and an integrated surface thermal power of ~8 MW across ~0.18 $km^2$, with core heat-flux densities of $10^1$-102 W $m^{-2}$. Cuddia di Mida exhibits spatially restricted anomalies and an order-of-magnitude lower output (~0.2 MW across ~0.03 $km^2$). This quantitative contrast confirms fault-focused hydrothermal discharge at Favara Grande, consistent with independent geochemical and isotopic evidence for deep magmatic fluid ascent. The resulting heat-flux rasters constitute a reproducible baseline for multi-temporal monitoring and for integration with soil $CO_2$ flux mapping, fumarole chemistry, and deformation datasets in future assessments of hydrothermal variability at Pantelleria.

# Implementation and performance of a GNSS RTX network for rapid ground deformation monitoring in the Campi Flegrei caldera

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Monitoring ground deformation in active volcanic areas is essential for understanding the dynamics of volcanic unrest and supporting hazard assessment efforts.
The Campi Flegrei caldera (southern Italy) has recently experienced renewed bradyseismic activity, characterized by significant ground uplift, increased seismicity, and continuous gas emissions. Within this context, improving the spatial density of geodetic observations is critical for a more refined characterization of deformation patterns within the caldera.
To complement the spatial coverage of the existing permanent GNSS network (39 stations), a temporary monitoring network based on the GNSS RTX (Real-Time eXtended) positioning technique was designed and implemented between March 2024 and March 2025. The RTX technology, which provides centimeter-level accuracy in real-time through global satellite corrections, was integrated with standard post-processing analysis to ensure highest precision in measuring the East, North, and Vertical (Up) components of displacement.
This new GNSS RTX network currently consists of 30 survey benchmarks distributed across the caldera, with a specific focus on areas exhibiting the highest deformation rates and sectors with anomalous patterns (e.g., the Monte Olibano - Accademia area). Repeated measurement campaigns were carried out approximately every 2-3 months. Preliminary results from benchmarks located in the maximum deformation area show displacement trends consistent with permanent stations observations, thereby confirming the reliability of the RTX technique in detecting centimetric-scale displacements.
These results underscore the effectiveness and versatility of GNSS RTX measurements as a solution for temporary geodetic monitoring. The system allows for the rapid deployment of dense observation networks in volcanic areas, thereby providing valuable complementary data for the spatio-temporal analysis of ground deformation in the Campi Flegrei caldera.

# Multi-temporal deformation analysis for monitoring hydrothermal systems in Great Geysir, Iceland

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Located within the Haukadalur geothermal field in Iceland, the Great Geysir hydrothermal system evolves within a dynamic environment defined by the interplay between active rifting and high-enthalpy hydrothermal processes. As a quasi-dormant system, it exhibits high-frequency surface deformation signals linked to internal pressure fluctuations; however, characterizing these signals is challenging due to the overprinting of regional tectonic spreading and extreme atmospheric noise typical of high-latitude volcanic settings. This study analyzes surface deformation for the 2015-2026 period by integrating InSAR time series (ascending and descending orbits) to determine whether the observed kinematics are driven by localized internal pressurization (geyser activity) or the regional tectonic regime.

To achieve the objective of this study, the following multi-phase methodology is implemented: i) acquisition of Sentinel-1 imagery in ascending (Path 16) and descending (Path 09) orbits, followed by interferometric processing with orbital and atmospheric corrections; ii) generation of displacement time series anchored to continuous GNSS stations (IMO/EPOS) to ensure absolute geodetic precision; and iii) decomposition of displacement vectors into vertical and horizontal (E-W) components. The resulting deformation rate maps and time series are expected to provide the geodetic constraints necessary for integration with future field-based geophysical data. This correlation will link surface deformation patterns with subsurface structural architecture, enhancing the understanding of the geomechanical behavior of quasi-dormant volcanic systems.

# Integrated Thermal-Optical UAS Mapping of the Alalobad Hydrothermal Field (Afar, Ethiopia): Fault-Controlled Heat Discharge, Extremophile Niche Partitioning, and Biosignature Detection in a Mars Analogue Setting

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Integrated UAS surveys combining calibrated long-wave infrared (LWIR) thermography (FLIR Vue Pro 640; 7.5-13.5 µm), high-resolution RGB photogrammetry, and ground-based microbial characterization were conducted at the Alalobad geothermal field (Tendaho Graben, Afar Depression, Ethiopia) to characterize surface thermal anomalies, fault-controlled hydrothermal discharge, and extremophile biodiversity within a planetary analogue framework for ancient Martian hydrothermal environments. Structure-from-Motion photogrammetry with differential GNSS produced co-registered digital surface models and thermal mosaics (absolute temperature uncertainty ±1.5-2 °C), resolving discrete anomalies spanning 26-92 °C along NE-SW fault intersections spatially coincident with fumaroles, degassing zones, and microbial mats. Thermal zonation reveals ecologically coherent temperature windows for distinct microbial guilds: thermophilic cyanobacteria and chemolithotrophic bacteria dominate 40-70 °C; sulfur- and iron-oxidizers peak at 60-80 °C; thermotolerant algae occupy marginal 25-45 °C environments. Phototrophic communities produce diagnostic pigment assemblages - chlorophylls, phycobiliproteins, and photoprotective carotenoids - whose spectral signatures are detectable in RGB imagery and constitute measurable surface biosignatures. Integration of LWIR data with RGB colour and texture metrics, microscopy, and shotgun metagenomics enables semi-automated discrimination of microbial community types, providing a quantitative biosignature detection framework. Surface heat-flux budgeting yields densities of 35-110 W $m^{-2}$ and a total thermal output of ~2.7 MW, consistent with a vapor-dominated reservoir. Angular ejecta blocks encrusted by extremophile biofilms and silica sinter coatings represent high-preservation-potential microhabitats directly relevant to fossil biosignature formation on Mars. Comparative analysis with Home Plate, Nili Fossae, and Eridania Basin confirms morphological and habitability-index convergence, validating Alalobad as a ground-truth living laboratory for Mars exploration.

This work was conducted within the framework of the HELENA Project (ASI, Contratto N. 2023-9-U.0).

# Earth Observation for Hazard Monitoring and Risk Assessment: Insights from the February 2025 Mount Etna Eruption

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Earth Observation (EO) has become a key tool in modern volcanology, enabling near-real-time monitoring of eruptive activity and improved assessment of interacting volcanic hazards. This study presents a multi-sensor satellite analysis of the February 2025 eruption of Mount Etna (Italy), demonstrating how integrated EO observations can contribute to hazard assessment and crisis monitoring in one of the world's most active and densely monitored volcanic regions. The eruption is particularly notable as the first major Etna event fully observed using the operational Meteosat Third Generation Imager (MTG-I), whose improved mid-infrared spatial and temporal resolution provides new opportunities for high-frequency thermal monitoring of volcanic activity.

Near-daily coverage of multispectral imagery documented effusive activity and lava flow propagation, allowing detailed reconstruction of flow evolution, emplacement rates, and spatial distribution of lava inundation. Thermal anomaly tracking using different kinds of multi-sensor data enabled estimation of magma discharge rates and eruption intensity, providing key parameters for hazard assessment during ongoing activity. Concurrently, eruptive plume dynamics and volcanic gas emissions were analyzed using satellite observations, including $SO_2$ measurements, to characterize the explosive component of the eruption and its atmospheric impacts, relevant for both aviation safety and regional hazard assessment. Furthermore, high-resolution post-eruption multispectral imagery generated an updated digital surface model, from which it was possible to estimate the thickness of the deposit and the erupted volume.

By integrating multi-sensor EO observations across effusive, explosive, and atmospheric hazards, this work illustrates how satellite-based monitoring can support multi-hazard characterization during eruptive crises and contribute to the development of quantitative datasets useful for hazard modelling and risk assessment. These results highlight the role of advanced Earth Observation systems in strengthening monitoring capabilities and providing actionable information that can support civil protection authorities and decision-makers during volcanic crises.

# Characterizing Ambient Seismic Noise in the Campi Flegrei Caldera: Implications for Volcano Monitoring in Urban Environments

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Urban volcanic systems pose significant challenges for seismic monitoring due to high levels of anthropogenic noise that can obscure weak volcanic-related signals. This issue is particularly critical at Campi Flegrei caldera (southern Italy), one of the most active and densely populated volcanic areas in Europe, where reliable detection of low-magnitude seismicity is essential for understanding ongoing unrest and improving hazard assessment. In such environments, a detailed characterization of ambient seismic noise represents a key step toward optimizing monitoring strategies and enhancing the detectability of volcanic signals. In this study, we analyze the spectral characteristics and spatial variability of ambient seismic noise across the Campi Flegrei seismic network using Power Spectral Density (PSD) analysis. Continuous recordings from several broadband stations belonging to both permanent and temporary networks managed by the INGV-Osservatorio Vesuviano were examined over a period of one year. The PSD distributions were compared with the global low- and high-noise reference models to evaluate station performance and quantify background noise levels across different frequency bands.

Results highlight strong spatial variability in seismic noise conditions within the caldera. Stations located near urban infrastructures, transportation routes, or installed at the surface show significantly higher noise levels compared to buried or better-shielded installations. Anthropogenic activity dominates the higher-frequency bands, while natural sources such as oceanic microseisms contribute to lower-frequency noise. These differences directly influence the capability of the network to detect and characterize low-magnitude volcano-tectonic events and other subtle signals associated with hydrothermal or magmatic processes. The analysis demonstrates the importance of continuous and site-specific noise characterization for improving volcano monitoring in densely urbanized environments.

In highly complex volcanic settings such as Campi Flegrei, integrating detailed environmental noise characterization with advanced analysis tools can significantly enhance the reliability of monitoring systems and improve the interpretation of subtle geophysical signals relevant for volcanic hazard assessment.

# S06 - HUMANS AND VOLCANOES: A LONG HISTORY OF INTERACTION

Conveners:

Daniele Musumeci, Stefano Branca, Sandro de Vita, Franco Foresta Martin

# Power and gaze: the human experience of volcanoes across myth, philosophy, literature, and geoethics

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Volcanoes assert themselves as true anthropological and cultural topoi, symbols of nature's power and, at the same time, mirrors of human fragility and aspiration. The awe with which humans have long approached their force has generated mythological, literary, philosophical, and scientific experiences and practices of great fascination and marked cultural interest, revealing how fear and wonder can become drivers of knowledge and responsibility.
In this contribution, an attempt will be made to offer an exemplary synthesis of some of these anthropological practices, ranging from myth and its role in the development of scientific thought, to literature and philosophy, with particular attention to the concept of the sublime and to the function of wonder/tháuma as both a cognitive and emotional experience.
From this perspective, volcanoes are not only objects of study or threats to be managed, but also instruments of geoethical reflection, as they invite recognition of our belonging to nature, our finitude, and the need to establish relationships with the environment based on respect, care, and shared responsibility. Wonder, far from being a mere irrational feeling, thus becomes a driver of prudent behaviour, social awareness, and sustainable practices, integrating scientific knowledge and cultural sensitivity in coexistence with natural forces.

# Polynesian Geomyths as Early Records of Volcanic Processes

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Traditional Polynesian oral narratives represent a rich and largely underutilized archive of observational knowledge related to volcanic activity and landscape evolution. Long before the formal development of volcanology as a scientific discipline, island communities living in close proximity to active volcanoes developed explanatory frameworks that translated recurring volcanic phenomena into symbolic stories. This study examines the conceptual overlap between Polynesian mythological traditions and modern volcanological understanding, emphasizing how myth functioned not merely as cultural expression, but as a structured means of recording and transmitting environmental knowledge across generations.

Focusing on selected mythological figures, including Pele, Maui, Moo, Hopoe, and Ru, we analyze how specific narratives reflect direct observations of volcanic and hydrothermal processes. These accounts encode phenomena such as mantle hot spot volcanism, submarine eruptions, lava water interactions, hydrothermal circulation, basalt weathering and erosion, and the formation and dispersal of pumice. Rather than abstract speculation, these myths appear grounded in lived experience, using metaphor and personification to convey the dynamics, hazards, and long term evolution of volcanic landscapes. The symbolic language employed in these traditions enabled complex geophysical processes to be communicated in an accessible and memorable form within non literate societies.

Placing these narratives within the broader historical evolution of volcanology reveals a striking temporal contrast. While European scientific interpretations of volcanic activity began to emerge between the seventeenth and nineteenth centuries, key concepts such as mantle plumes, hot spot chains, and hydrothermal systems have only been fully developed in recent decades. Polynesian geomyths, by comparison, preserve observational insights that predate modern scientific frameworks by centuries or millennia. This work argues for the value of integrating volcanology with anthropology, geomythology, and indigenous knowledge studies, promoting a more inclusive understanding of how humans have interpreted and adapted to volcanic environments.



S06 - Oral Presentation

# The 1776 and 1790 landslides in the Niscemi town (Caltanissetta, Italy): historical evolution and spatial reconstruction

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The recent reactivation of a giant landslide in Niscemi town (Caltanissetta) in January 2026 has brought attention back to a complex geomorphological setting, already affected by a similar event in 1997. However, the evolution of this slope instability dates back centuries. Historical sources (including the contemporary memoirs by Saverio Landolina Nava and later 19th-century chronicles) document that, as early as 1790, a massive landslide had severely struck the area, reaching the outskirts of the town. Nevertheless, the exact spatial extent and the chronology of events preceding the 18th-century collapse have remained partially unexplored until now.
The present work proposes a critical analysis of the contemporary sorces and later historiographical works in order to define the extension of the 1790 landslide and revise its chronology. The review of known archival sources allowed, so far, to rule out a seismically induced triggering during the catastrophic Val di Noto earthquake of January 1693 (Mw 7.4). Instead, the research allowed us to backdate the first evidence of instability to 1776 in the Sante Croci neighborhood, identifying this episode as a prelude to the more severe and well-documented event of 1790.
Through a multidisciplinary approach integrating the analysis of textual historical sources, historical cartography, current geological knowledge, the use of Geographic Information Systems (GIS) and a reconstruction of the marked demographic increase recorded in the riveli (censuses) between 1651 and 1861 in Niscemi, we can define the original extent of the historical landslide and discuss some possible co-factors able to explain the instability of the slope beneath the historical center of the city.

# Preserving Volcanic Structures and Eruptive Effects for Educational, Tourism, and Scientific Purposes

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Volcanoes hold a powerful attraction for humanity while simultaneously offering development opportunities for many sectors that are not always fully embraced. Their presence can yield well-known benefits, such as energy production, soil fertility, and the creation of unique landscapes, but can also lead to disasters. Between these two extremes lies a range of opportunities to deepen our knowledge of volcanic regions, explore their needs, and improve their utilization. Preserving extinct or dormant cones - and, where possible, their products - provides a foundation for research and education, as well as an economic boost for areas often overlooked by mainstream tourism.

In recent decades, a growing commitment to the tourism sector has been paired with the realization that addressing, rather than erasing, the damage caused by eruptions allows for the creation of true open-air museums. Areas beyond urban recovery are becoming exemplary warnings and vital planning tools for the future of territories threatened by volcanic activity.

Many virtuous examples in this field deserve study. Smaller volcanic areas are often the most ingeniously valorised through significant itineraries and museums (such as the Chaîne des Puys in France, the Garrotxa region in Spain, and the islands of Lanzarote in the Canaries and Faial in the Azores). In regions where activity is more widespread (such as Japan, Indonesia, the Philippines, Iceland, and various South American countries), priority is often given to urgent issues like forecasting and disaster management. Yet, even in these areas - despite varying economic contexts - the work of field-based volcanological dissemination is not neglected, often showcasing rare competence and effectiveness.

In a country like Italy, which possesses vast volcanic areas and a dynamic tourism industry, international experiences can help improve the proper use of a natural resource that is often unfairly perceived as a disadvantage.

# Emilia Poli Marchese's Research on Volcanic Environments: A Comparison between Mount Etna and Mount Fuji in the History of Botany

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This study offers a historical and scientific examination of the relationship between volcanology and botany, comparing Mount Etna and Mount Fuji, drawing on the pioneering research of Emilia Poli Marchese. Focusing on the investigation of Etnean volcanic environments and the comparative analysis of the two volcanic structures, this work traces the progressive integration of geomorphological analysis with phytosociological research during the latter half of the twentieth century.
Mount Etna and Mount Fuji were selected for this comparative study as they represent the highest volcanoes in Europe and East Asia, respectively, and are situated at nearly the same latitude. The literature demonstrates that the lava substrate is not merely an inert support, but functions as a dynamic matrix that influences plant succession, colonization processes, and vegetation adaptation strategies. The comparison between Mediterranean and temperate environments underscores bioclimatic and biogeographical distinctions, while also revealing a common ecological paradigm rooted in the principle of primary succession and the conceptualization of the volcano as a natural laboratory.
Through this comparative analysis, a history of science emerges in which the volcanic edifice becomes a privileged epistemic space, where field observations and theoretical systematization intertwine, thereby contributing to a redefinition of the relationships between the Earth's endogenous dynamics and the floristic-vegetational component.

# The Etna landscape in Sicily and the socio-spatial construction of "disaster"

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This paper aims to explore the concept of socio-territorial vulnerability, drawing on the specific contributions of the sociology of disasters. The origins of this field of study date back to the early 20th century, emphasising the importance of a sociological analysis focused on examining the historical and cultural processes, as well as the natural ones, that may lie at the root of certain extreme events. The broad categories of sustainability, socio-territorial vulnerability and resilience now serve as guiding principles in shaping the contribution that environmental and territorial sociology - in a rather distinctive way - can make to the examination of 'disaster' in large urban centres. This latter term, as demonstrated by the scientific debate, is the result of a distinctive 'grammar' in which 'danger', 'vulnerability' and 'risk' engage in a constant dialogue with the urban landscape, calling for a sociologically oriented, mixed-methods approach, where, alongside the analysis and representation of indicators relating to the fragility and exposure to danger of local populations, qualitative social research techniques help to explore the boundaries of this complex framework.
More specifically, the critical reference to the paradigm of the 'vulnerability of places' [Cutter, 2003] appears to have significant practical relevance in examining the political and social transformations currently affecting—though not exclusively—large contemporary urban centres. In the second part, the study aims to focus more specifically on the city of Catania. This context is characterised by various 'catastrophes' which, over time, have shaped the urban fabric and whose historical traces remain vivid to this day, not only in the Etnean landscape but also in the strong sense of identity that binds the people of Catania to their mountain, Etna.
Alongside the image of the resilient 'phoenix', however, there are signs of an urban development that is at times unsustainable, characterised by urban planning schemes and distinctive socio-spatial dynamics that are filling the vacant spaces to the north and south of Catania city centre and, subsequently, the volcanic and agricultural areas near Mount Etna. The (natural and anthropogenic) processes of 're-territorialisation' and 'de-territorialisation' of the landscape [Raffestin, 1984] will shape the face of the contemporary metropolitan city in its morphological and socio-functional structure - through accelerated building expansion and ever-increasing land consumption - alongside which, however, a social construction of the disaster will emerge, drawing on imaginaries of faith and symbolic-narrative elements that re-propose a distinctive 'historical memory' of the catastrophe. Natural and social elements will thus become intertwined, inviting us to explore even more closely the ways of inhabiting a "context at risk" and opening up a broader and more careful reflection on the potential intersections between policies, techniques, practices and knowledge underpinning any possible development strategy in vulnerable contexts.

# Mount Etna through Emily Lowe's eyes: perception of volcanic risk between wonder and danger

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Between the 18th and 19th centuries, Mount Etna was one of the most visited destinations of the Grand Tour, attracting travellers, intellectuals and proto-scientists from all over Europe. The diaries, travel memoirs and letters left by these observers form a narrative collection of great interest, not only from a literary point of view, but also from a scientific one. In these writings, the perception of volcanic risk is processed, translated into accessible language and shared with an educated audience, anticipating in its forms and intentions the modern practices of risk communication. One of the first women to climb the volcano — if not the very first — accompanied only by her mother and a guide, was Emily Lowe, author of a travel account with a remarkably telling title: Unprotected Females in Sicily, Calabria, and on the Top of Mount Etna (1859) [Lowe E., 1859, Routledge, Warnes and Routledge, London-New York]. The British traveller offers a direct and detailed account of the volcano in the mid-nineteenth century. She describes the weather conditions, the layout of the route and the real dangers of the climb, from the overwhelming heat to the icy snow of the night descent, providing the reader with clear practical advice on how to face the journey safely.

The text reveals a constant tension between real danger and an irresistibly fascinating challenge. Lowe conveys to her readers the surprising and perilous relationship that can exist between human beings and nature, between fear and wonder, closing her account with an explicit invitation to "adventurous young ladies" to follow in her footsteps. In doing so, she anticipates one of the most pressing challenges in volcanology today: communicating risk to a non-specialist audience while keeping curiosity alive, without underestimating the danger. The connections between past and present models of scientific communication suggest how the collective image of Etna has been shaped over time through the public telling of eruptions and fear, showing how history has contributed to influencing the perception of risk still today.

# Risk Faults: Relocation, Displacement, and Homemaking on the Slopes of Mount Etna

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The analysis focuses on post-seismic experiences in the Mount Etna area, a territory historically marked by a plurality of catastrophic events (earthquakes, eruptions, landslides) that have contributed to shaping settlement patterns, moral economies, and local cosmologies. Rather than considering such events as absolute ruptures, we interpret them as moments of intensification of pre-existing dynamics: configurations of housing precarity, informal practices of resource access, gender and class hierarchies, and ambivalent relationships with the State and techno-scientific institutions.

This study conceptualizes the earthquake not as a time-bound natural event, but as a historical-anthropological process produced at the intersection of geophysical forces, institutional apparatuses, and everyday practices. From this perspective, the earthquake is understood as a "revealing event" that discloses and makes tangible structural vulnerabilities, power asymmetries, and deeply ingrained inequalities, as well as a critical mechanism capable of highlighting the anomalies of risk governance regimes that organize social life before, during, and after the crisis.

In the wake of a critical anthropology of risk, the paper examines the ways in which disaster temporarily suspends the symbolic and normative order, opening spaces for the renegotiation of belongings and authorities. The emergency and reconstruction phases are analyzed as arenas in which legitimacy, rights, and responsibilities are redefined: amidst rhetorics of resilience, practices of situated solidarity, and conflicts over access to compensation and public interventions.

In the Etna area the risk translates into an intense activity of symbolic and social re-anchoring: religious rituals, commemorative practices, genealogical narratives of the disaster, and civic mobilizations operate as mechanisms for the reconstitution of presence. The crisis, far from being a mere parenthesis, becomes a generative moment in which the very conditions of subjectivity and belonging are redefined.

Methodologically, the article is based on a multi-level ethnography that combines participant observation, in-depth interviews, and the analysis of normative and media apparatuses, to grasp the disaster as a relational field in which human and non-human actors co-produce scenarios of crisis and reconstruction. Through this lens, the earthquake in the Etna area emerges not only as a collective trauma, but as a generative process that reorganizes temporalities, spatialities, and political imaginaries, contributing to redefining the very conditions of citizenship and dwelling in a structurally exposed territory.

# The puzzling case of the tuff maiden sculpture from the Bronze Age village of Ustica (Italy): joke, hoax or sensational discovery?

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The archaeological excavations carried out in 1991 at the Middle Bronze Age Faraglioni Village, on the island of Ustica, brought to light a small tuff sculpture representing a stylized female figure. The excavation was led by the American archaeologist Robert Ross Holloway, who described the find as the first known example of a Middle Bronze Age sculpture discovered in Sicily.
However, two years later, a letter circulated among several recipients claimed that the sculpture was actually a fake, secretly planted at the site as a prank. This allegation triggered a heated dispute between Holloway—who defended the authenticity of the object and interpreted the claim as an attempt to undermine his work—and Giovanni Mannino, a previous excavator at Faraglioni, who maintained that the piece was not genuine. The question has remained unresolved for more than thirty-five years, with no scientific investigation carried out to settle the matter.
This study marks the beginning of a multidisciplinary scientific effort aimed at providing decisive evidence, or at least robust clues, supporting or refuting the two opposing hypotheses.
Preliminary findings from non-destructive elemental analysis conducted using portable X-ray fluorescence (pXRF) indicate that the stone used for the sculpture likely originated from the tuffs of Mount Falconiera, a volcano located about one kilometer east of the Faraglioni settlement and inactive for more than 130,000 years. This interpretation is supported by the shared Na-alkaline hawaiite geochemical signature of both the sculpture material and the volcanic deposits of Mount Falconiera.
The same analysis also shows that some samples of Falconiera tuff, which were lightly incised with modern metal tools, exhibit contamination from trace elements associated with those tools. By contrast, no comparable contamination has so far been detected on the Holloway's sculpture. However, although these findings indicate that the sculpture does not exhibit clear evidence of having been worked with modern tools, further analyses are still in progress to detect even minimal traces of modern metal alloys.
In addition, drawing on studies of the composition of metal alloys used during the Middle Bronze Age for toolmaking, it may be useful to investigate whether traces of similar alloys can be detected on the Holloway's sculpture. If such traces were indeed identified, this would open the way to a dual hypothesis:

1. the sculpture was actually worked during the Bronze Age and would therefore be authentic;
2. alternatively, the creators of a forgery would have had to use tools made from the same types of alloys employed in the Bronze Age.

If, on the other hand, no traces of any kind were found, it would be highly likely that they hadbeen leached away over the long millennia of burial, thereby strengthening the hypothesis that supports the object's authenticity.
Moreover, additional archaeological collaborations will soon be activated, in order to compare the shape and style of the sculpture with those of similar artefacts from the same period and to perform a detailed use-wear analysis.

# The long reconstruction of the Val di Noto following the 1693 earthquake: new towns, reconfigurations, and continuities

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According to the Italian Seismic Catalogue, the earthquake that devastated the Val di Noto in 1693 holds the record as the highest magnitude event (Mw 7.4) to have occurred in Italy over the past two thousand years. The entire southeastern sector of Sicily suffered incalculable damage: 70 towns reported damage equal to or greater than degree IX on the MCS scale, and dozens of cities, including Catania, were entirely razed to the ground. According to historical sources of the time, there were at least 50,000 casualties.
Scientific and historical literature on the subject has often focused on the Late Baroque reconstruction of the cities and the demographic and economic boost of certain urban centers, overlooking the continuities, the social costs of the tragedy, and the long-term legacy of the event in our present.
By intersecting historical-institutional analysis with the use of Geographic Information Systems (GIS) and historical seismology data, this contribution aims to fill this gap, testing the now-consolidated narrative and tracing the marks of the reconstruction in today's cities. The analysis of disaster governance processes and a long-term reading of demographic and economic trends highlight, in fact, how the earthquake did not always trigger a radical mutation of ongoing socio-economic processes, but rather acted as an accelerator of long-term trends.
The historical socio-spatial investigation reveals, instead, how in some cases, the reconstruction produced not only a radical reconfiguration of urban space but also a new social geography, which exacerbated existing inequalities and generated new vulnerabilities from a seismic perspective, the scars of which are still visible today.
As test cases, we also focus our attention in the managing of emergency and rebuilding in Catania and Noto, to investigate the reconfiguration of power and the conflicts behind the magnificent late baroque churches and palaces.
The answers provided by this investigation, while focusing on the early modern period, do not end in the past. They represent a solid starting point for the comparative analysis of subsequent institutional responses to major seismic events that struck Sicily in the contemporary era (Messina 1908, Belice Valley 1968). The ultimate goal of this work is to trace the continuities and discontinuities in emergency practices in order to build a body of critical knowledge that can prove useful for modern policymakers and administrators, who are called upon to face the complex challenges of urban planning and seismic risk prevention.

# The affective afterlives of volcanic eruptions through the geopoetics of music: Geology, emotion, and song in more-than-human worlds

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Volcanic eruptions produce threshold moments where geology and emotion intertwine through lived experience [Bachelard 1964]. Across cultures and time, these pervasive events are experienced, processed, sounded, and preserved through voices, pleas, stories, and songs that reflect deep emotional registers [Pérez de Arce 2007; Stoffle and Van Vlack 2022; Salazar and Salas 2024]. The reverberations of an eruption linger long after the event, inspiring music that allows people to reflect upon and navigate their experiences across time and space. As a temporal and spatial art form [Schafer 1967], music becomes an integral component of the soundscapes of volcanic eruptions, revealing the entangled rhythms of people's life and volcanic vitality, understood as the interaction of human and more-than-human forces [Lefebvre 2013]. Analysing these musical narratives provides a compelling lens for interpreting the intersection of geology and emotion, serving as a distinct form of cultural, historical, and spatial knowledge in a more-than-human world [Grosz 2008; Lorimer 2013; Luciano 2024].

In volcanic contexts, humans and volcanoes mutually affect one another, creating an emotionally charged sphere where more-than-human forms of sociality and connection emerge [Tsing 2013]. Songs, I argue, capture this 'becoming,' offering a unique frame to explore how people emerge from an eruption shaped by interactions on a more-than-human scale. This research posits that a wide array of songs about eruptions offers a unique analytical frame through which to explore these connections, navigating the volcano's enduring role as an agent of inspiration and imagination, even amidst disaster [Alexander 2012].

What do music and songs about volcanic eruptions reveal through their geographical and emotional content? In this research, I explore the emotional geographies and the generative experience of volcanic eruptions through place-based specific analysis of song lyrics. I argue that, along with music's sensory nature, lyrics constitute a geopoetic and spatial practice, encompassing micropolitical, textual, and contextual dimensions of lived experiences. Their interpretation can contribute to spatial knowledge of eruptions, situated emotions, and the historical encodings of disaster afterlives. Through ethnographic and thematic analysis of twenty song lyrics about ten volcanoes - namely, Paricutin, Mount St. Helens, Soufriere Hills, Fogo, Fuego, Tajogaite, Lonquimay, Calbuco, Chaitén, Hudson -, I trace emotional geographies that span from grief to hope, with narratives that recall sensitive moments of what was lost, loved, yearned for, and reclaimed, framing eruptions as more than geological events; eruptions become emotional, historical, and lived. Crucially, the song lyrics map and document a more-than-human healing process, following rupture, negotiation, and reconciliation with a volcano. Ultimately, the research probes the potential of songs as geo-located artefacts for affective storytelling, understood as a form of affective communication of risk, through close readings of the intimate interplay between geology, place and emotion, and its role - often overlooked - in shaping eruption experience. By articulating the emotions and lived experiences tied to specific volcanic territories, the lyrics provide lasting place-based narratives (for further emotional, geographical, ethnographic and historical analysis within volcanology). These narratives, in turn, are essential for understanding the changing and enduring human-volcano interactions as people in different regions navigate the afterlives of disasters and their lives eruption after eruption.

S06 - Oral Presentation

# Distinguishing obsidian from obsidian-like glass: an archaeometric study of black-appearing fragments from Ustica (Italy)

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This study presents the archaeometric investigation of nine black-appearing, obsidian-like glass fragments recovered from the surface of an intensively cultivated agricultural field on the island of Ustica (northern Sicily, Italy). The context is characterized by the recurrent emergence of prehistoric, Roman, and late Roman tiny ceramic fragments, following field ploughing and heavy rainfall.

The nine glass fragments were recovered incidentally during routine agricoltural field cleaning operations and were initially mixed with numerous pieces of clearly modern, synthetic glass, all together destined for disposal. Although initially indistinguishable from natural obsidian based on their macroscopic appearance, the fragments were selected for analysis due to their glossy surface and conchoidal fracture.

A combined approach based on optical microscopy and non-destructive portable X-ray fluorescence (pXRF) analysis was employed to assess their nature. Microscopic observations revealed diagnostic features of artificial glass production, including gas bubbles and internal heterogeneities. Furthermore, transmitted-light observations allowed the identification of two distinct chromatic groups: a red-purple group and a dark green group.

Elemental data obtained by pXRF, although limited by the inability to measure light elements such as Na, K, and Ca, were interpreted using trace element proxies. In particular, Rb and Sr were used as qualitative proxies for potassium and calcium, following established methodologies. The resulting Rb/Sr ratios indicate a soda-lime-silica composition consistent with natron-based glass. The combined use of Rb/Sr and Mn/Fe systematics allowed the identification of two compositional subgroups corresponding to the observed chromatic variability, reflecting different contributions of manganese and iron as chromophores.

The absence of geochemical signatures typical of volcanic glass, together with the optical and microstructural evidence, allows a clear exclusion of natural obsidian.

The analyzed fragments are therefore interpreted as artificially produced, black-appearing glass belonging to the Roman and late Roman tradition of vitrum obsianum, a material designed to imitate the aesthetic properties of natural obsidian. Their occurrence on Ustica, an island without local glass production, supports their attribution to imported goods circulating within Mediterranean exchange networks.

More broadly, this study demonstrates that pXRF, when combined with a proxy-based interpretative framework, represents an effective non-destructive tool for distinguishing natural obsidian from visually similar artificial glass in archaeologically decontextualized assemblages.

# Life and Diet in Late Antique Puteoli: Preliminary Isotopic Insights from the Early Christian Necropolis of San Vito (Phlegraean Fields, Pozzuoli, Italy)

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The Late Antique-Early Christian necropolis of San Vito, located along the ancient Via Campana-Capuana in Puteoli (modern Pozzuoli), in the volcanic landscape of the Phlegraean Fields (Campi Flegrei), offers a rare and well-preserved window into the lives of a community living at the crossroads of commerce, culture, and faith. Puteoli from its deduction as a Roman colony in 194 BC served as one of the principal ports of Rome, a dynamic hub where goods, people, and ideas from across the Mediterranean converged. Within this geologically active and environmentally distinctive setting, the necropolis-dated between the 2$^{nd}$ and early 6$^{th}$ centuries CE-preserves one of the earliest and most significant testimonies of Christianity in the region.

The funerary complex, characterized by hypogean chamber tombs, superimposed loculi, and well-preserved arcosolia, includes decorated burial spaces such as the "Good Shepherd" tomb, as well as epigraphic evidence documenting early Christian communities. These archaeological features provide a crucial contextual framework for interpreting the individuals buried within a landscape shaped not only by human history but also by long-term volcanic processes.

This paper presents the first results of an ongoing isotopic investigation aimed at reconstructing dietary habits and broader aspects of lifestyle within this community. Eight individuals from the paleochristian sector of the necropolis were analyzed through stable isotope measurements ($\delta^{13}C$ and $\delta^{15}N$) of bone collagen, extracted following standard protocols and measured by EA-IRMS at the University of South Florida. The good preservation of collagen, confirmed by reliable C/N ratios, ensures the robustness of the dataset.

The emerging picture is one of both continuity and diversity. Most individuals display isotopic signatures consistent with a diet largely based on terrestrial C3 resources, including cereals and legumes, complemented by moderate consumption of animal protein- patterns consistent with a late Roman urban population. However, significant individual variability is evident. One individual shows elevated $\delta^{15}N$ values indicative of high protein intake, likely from terrestrial or freshwater sources; another reflects a protein-poor diet. Particularly notable is one individual whose isotopic values indicate a substantial contribution of marine resources, suggesting differentiated access to food or closer engagement with coastal subsistence activities.

Such variability, even within a limited funerary sample, points to a socially and economically heterogeneous community. Differences in diet may reflect social status, occupational specialization, or varying degrees of integration into the commercial and environmental networks of Puteoli. In a volcanic coastal setting such as the Phlegraean Fields, where natural

resources, landscape dynamics, and human activity are tightly interconnected, these data acquire additional interpretive significance.

By integrating isotopic evidence with funerary archaeology, epigraphy, and the geological context of the Campi Flegrei, this study contributes to a broader interdisciplinary understanding of human-environment interactions in Late Antiquity. It highlights how bioarchaeological data can inform not only on diet and mobility, but also on the ways communities adapted to and exploited complex volcanic landscapes.

As the dataset expands, future work will refine these interpretations and further explore the relationships between environmental setting, resource availability, and social differentiation-demonstrating the value of archaeometric approaches within volcanological and geoarchaeological research frameworks.

# Socio-territorial approach for studying vulnerability and opportunities: the cases of Catania and the Strait of Messina

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In the socio-territorial approach, vulnerability does not simply equate to exposure to a risk - whether physical, environmental or infrastructural - but rather to a relational and structurally produced condition that concerns the capacity of urban contexts to maintain housing functions, social complexity, accessibility to services and the continuity of shared meanings. Numerous theoretical and empirical studies emphasise that vulnerability must be understood as a relational and processual condition, produced by the interaction between economic, social, institutional and cultural factors [Harvey D. 2012, Rebel Cities: From the Right to the City to the Urban Revolution, London, Verso; De Lucia C., Salata S. 2020, "Centri storici, vulnerabilità e resilienza urbana", Territorio, 93: 45-58]. From this perspective, vulnerability emerges as the outcome of specific modes of production and management of urban space. Following the theoretical framework of Henri Lefebvre [1974, La production de l'espace, Paris, Anthropos], urban space is the result of a social production that reflects power relations, economic logics and everyday practices. Cities, as complex spaces of high symbolic and cultural density, are particularly exposed to processes of selective appropriation and economic valorisation.

In this context, vulnerability manifests itself as a crisis of habitability and social reproduction, which is reflected in the gradual decline in permanent residence, the loss of functional diversity and the weakening of local communities. Vulnerability can, therefore, be understood as a systemic condition affecting multiple dimensions simultaneously: a) the social dimension, through processes of exclusion and displacement of the resident population; b) the economic dimension, through functional specialisation and dependence on volatile economies; c) the cultural and symbolic dimension, through the selection and simplification of urban narratives; d) the institutional dimension, linked to the fragmentation of governance and the rigidity of planning tools.

This empirical study of the cities of Catania and Messina is part of this line of research on vulnerability. The study was launched in 2023 as part of the Erasmus+ project "Osez: Des Collectifs de travail pour mieux comprendre le changement" and continued within the framework of the ongoing project entitled "Socio-Territorial Morphology and Attractiveness of Metropolitan Areas in Southern Italy" (MOSTRAMI), part of the PIACERI programme at the University of Catania.

Both cities are the capitals of metropolitan areas that are vulnerable both from a geophysical perspective - due, respectively, to the presence of Mount Etna and the fault line running through the Strait - and from a socio-territorial perspective (social, economic, cultural and institutional). Both are emblematic of modernisation processes that characterise the recent past of many urban contexts in Southern Italy. Their history is marked by opportunities and challenges that alternate, intertwine and clash, resulting in contradictory distinctive features. They possess a typically southern cityscape with a historic centre that remains densely populated and significant due to the presence of diverse urban functions that attract varied populations. They are characterised by a lack of robust planning, which has led to significant socio-territorial inequalities and inadequate protection of cultural and landscape heritage, as well as by the development of the informal economy, which often spills over into criminal activity [Cassano F. 2007, Il pensiero meridiano, Roma-Bari: Laterza; Casavola, P., Trigilia, C. (a cura di), (2012). La

nuova occasione. Città e valorizzazione delle risorse locali, Roma: Donzelli Editore].
Using digital mapping tools (Geographic Information System), the first part of the research sought to reconstruct the socio-territorial morphology of Catania and Messina, namely the processes of transformation that have affected the socio-demographic and economic structure over the last decade, with a close focus on both the critical issues and the existing potential.
In the second part of the research, the concept of socio-territorial fragility "was operationalised" through the construction of a composite index comprising various indicators, including young people not in education, employment or training (NEETs), the proportion of the population with low educational attainment, households in financial hardship, the youth unemployment rate, and low-income households.
The main findings of the research highlight the specific characteristics of the two Sicilian areas, which serve as a starting point for rethinking policy guidelines for a virtuous model of local governance that addresses social and material vulnerabilities in order to mitigate their effects in the near future.

# Campi Flegrei: integrating marine and onland geo-archaeological data to reconstruct the evolutionary processes of the caldera

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The Campi Flegrei caldera represents one of the most complex volcanic and geoarchaeological contexts in the Mediterranean, characterized by bradyseismic processes that have profoundly influenced both the coastal landscape and human settlement over the millennia. This paper aims to analyse and compare geoarchaeological data from submerged contexts and those acquired in terrestrial environments to integrate and reconstruct the morphological and settlement evolution of the area.
The intense caldera activity that has characterised the area has produced significant transformations of the landscape, upon which communities have acted through works designed to counteract and compensate for the changes induced by such activity. Through the joint examination of stratigraphic evidence, archaeological structures, palaeoenvironmental indicators and geomorphological data, it emerges that the transformations of the territory are the result of a close interaction between natural processes (volcanism, subsidence and ground uplift) and human activities. Submerged sites, in particular, provide crucial information on changes in relative sea level and the chronology of bradyseismic events, whilst terrestrial data—which in some cases preserve traces of marine transgression—allow these dynamics to be contextualised within phases of settlement and urban development.
A comparison of these two categories of data highlights interpretative convergences and discrepancies, emphasising the importance of a multidisciplinary approach for a more accurate reconstruction of the ancient landscape. The study also contributes to improving our understanding of current geological risks in the Phlegraean area, offering methodological insights for future integrated research in dynamic coastal contexts.



S06 - Oral Presentation

# Volcanic Forcing and Climate Impact: analysis of time series of meteorological data in the last two centuries in Italy

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Volcanic eruptions are primary drivers of natural climate variability. The injection of sulfate aerosols into the stratosphere creates a shield against incoming solar radiation, triggering a rapid and temporary regional or global cooling. Historically, this climatic forcing has acted as a catalyst for severe socio-economic disruptions, contributing to crop failures, famines, and the outbreak of major pandemics. While paleoclimatic literature heavily relies on indirect proxy data, such as polar ice cores, to quantify past temperature variations, this study provides direct instrumental evidence. By analysing the continuous historical series of maximum and minimum temperatures from the Brera Astronomical Observatory (1763-2023), we examined the thermal anomalies correlated with 18 major eruptive events featuring a Volcanic Explosivity Index (VEI) greater than 5 (spanning from Laki in 1783 to Pinatubo in 1991). The results clearly quantify the magnitude of the local post-eruptive temperature drop in Italy, instrumentally confirming the strong impact of volcanism on the climate and highlighting the historical vulnerability of human societies to sudden meteorological fluctuations.

# The use of hawynofiro lavas as aggregate in the mortars of the city walls of Melfi (Potenza) Basilicata Region - Italy

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This paper reports the preliminary results of an archaeometric study conducted on the stone materials constituting the city walls of Melfi-PZ (Basilicata - Italy).
The walls of Melfi were built to protect the city in the Byzantine era (XI century AD) and remodeled between the Norman and Aragonese periods (XII -XIII centuries AD). They accompanied the urban and political development of the city, playing a strategic role in the territorial control.
During a sampling campaign, in order to characterize the stone materials used to build the walls, a total of eleven samples were collected from areas that were as representative as possible of the different construction phases of the city walls. These samples were divided by type as follows: eight mortars and three samples from the masonry blocks of different types: pyroclastic rock, lava, and limestone. In addition, three samples of in-situ lava were collected.
A multi-analytical approach was adopted to characterize mortars and masonry. In addition, lava samples were also studied with the aim to obtain provenance information on the possible raw materials. Mineralogical petrographic and microchemical data were obtained using a Polarized Optical Microscopy (POM), a Scanning Electron Microscope (SEM model FEI Quanta 200F) and an Electron Microprobe with associated microanalysis (EMPA-WDS model JEOL-JXA 8230, equipped with five WDS spectrometers).
Petrographic studies of mortar samples allowed us to identify three distinct groups based on the morphological characteristics of the aggregate and the presence/absence of lime lumps.
In all samples, the aggregate consists exclusively of lava rock fragments and single crystals.
The rock fragments have a porphyritic texture with phenocrysts of feldspathoid and pyroxene immersed in a microcrystalline groundmass rich in microcrystals of feldspathoids, pyroxenes and oxides. The feldspatoid is a hauyne with a very low $Na_2O$ content (about 3% wt), rich in $SO_3$ and $Cl_2O$. Pyroxene is an iron-rich augite with a high $TiO_2$ content (between 2 and 5% wt).
Microchemical analysis allowed us to compare the characteristics of the crystals in the mortars with those of the phenocrysts in the lava samples. The results show the geochemical similarity with the rock lava sample highlighting the local provenance from volcanic products of Mt. Vulture.
In conclusion the types of rock fragments present in the aggregate of all mortar samples are consistent with the lithologies outcropping in the area, confirming the use of local raw materials for their production. The absence/presence of lime lumps would indicate the use of different workers, probably at different times.
The study is still in progress with the aim of understanding the possible use of local raw materials also for the binder production.

# Mass tourism in fragile geological settings: anthropogenic impact in the Alcantara Gorges (Sicily)

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The Alcantara Gorges, formed between 8,000 and 10,000 years ago, are one of the most iconic geological sites of Sicilian volcanism. Their morphology, characterized by spectacular basalt columns, is the result of the cracking of lava flows during their rapid cooling after being emplaced and of the slow erosion by riverine water. The valley's identity is deeply linked to the watershed of the river of the same name, whose historical stratification is evidenced by the place name of Arabic origin "al-Qàntarah", the arched bridge. This name reflects the strategic importance of crossing infrastructure in a geomorphological context characterized by deep lava incisions.

The Alcantara stands out in Sicily's hydrographic landscape for the significance and regularity of its flow. The watercourse extends for 48 km from the southern slope of the Nebrodi Mountains (Floresta area) to the broad delta in the Ionian Sea, near Capo Schisò. Its longitudinal profile, characterized by a right-angle change in direction near Randazzo, defines its primary hydro morphological structure.

From a geological perspective, the valley represents a complex system situated at the confluence of the Peloritane metamorphic units, the Nebrodi sedimentary ranges, and the Etna volcanic system. This geological feature results in a differentiated hydrological response and environmental fragility along the river's course.

Established in 2001, the Alcantara River Park is Sicily's newest protected area. With a resident population of over 52,000 people spread across 12 municipalities, the Park must balance significant local human pressure with high tourist demand.

The protection regime is divided into four functional levels that combine conservation and development: while Zones A and B are dedicated, respectively, to the strict protection of ecosystems and the controlled management of natural resources, Zones C and D serve as buffer zones focused on tourism and the transition to human activities compatible with the Park's objectives.

However, high seasonal tourist pressure raises critical questions regarding ecosystem resilience and the coexistence of mass tourism with natural risks.

This study, conducted as part of a doctoral project on the biogeochemical characterization of the Simeto and Alcantara river basins, proposes an integrated methodology for assessing the indirect anthropogenic impact on the Alcantara Gorges. Although the study is in a preliminary phase, the research hypothesis is based on the correlation between the intensity of tourist flows and variations in specific biogeochemical indicators (e.g., nutrients, emerging pollutants, key physicochemical parameters such as EC, T, $O_2$, Eh, and pH); as well as major dissolved constituents and trace elements in river waters during seasonal peaks.

Water samples were collected from various river sections, including the mouth, the main springs, and several wells, with the aim of distinguishing the geogenic contribution, resulting from the weathering of silicates, from seasonal anthropogenic inputs.
Although the research is still in its early stages, preliminary results indicate that mass tourism may represent a significant anthropogenic driver, capable of temporarily modifying the biogeochemical balance of this highly vulnerable environment.
It is hoped that the results obtained will contribute to the development of scientific tools for sustainable land management and support more effective risk communication in vulnerable contexts.

# Geomorphological and volcanological research on the sea caves of Ustica: from prehistoric finds to sea-level change studies

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The geomorphological research on the sea caves of Ustica, a small volcanic island in the southern Tyrrhenian Sea, has developed significantly over the past century, combining geo-volcanological observation, marine studies, and advanced dating techniques.
Early explorations in the caves such as Grotta Azzurra and San Francesco Vecchio focused mainly on archaeology, since these cavities contained prehistoric remains from the Copper and Bronze Ages. Earlier volcanic studies had already identified the Falconiera tuff cone, formed about 130,000 years ago, as a major geomorphological structure influencing local cave development. Only later, in the twentieth century, did scientists begin to analyze them in terms of geomorphology [e.g. Colantoni er al., 1990; Mannino and Ailara, 2014, 2016; Furlani et al. 2017; Antonioli et al. 2023; Furlani and Foresta Martin, 2019; Foresta Martin and Furlani, 2021], recognizing their role in reconstructing sea-level changes and tectonic movements.
The presence of marine fossils and stalactites both above and below the current sea level offered crucial evidence for vertical crustal movements. Modern studies, as part of the Geoswim project, mapped the entire island's coastal system through swimming surveys. These analyses revealed that the western side of Ustica had uplifted more than 30 centimeters in the early 1900s due to localized seismic activity
Geomorphologists emphasized the importance of these caves as natural archives of sea-level oscillations throughout the Holocene and Late Pleistocene. In some areas, like the central part of the island, submerged stalactites indicated a long-term subsidence phase, while eroded fossil crustaceans at higher elevations marked ancient shorelines. Together, these findings defined Ustica as a key site for Mediterranean coastal geomorphology. Moreover, the island represents the most studied volcanic island in terms of geomorphology.
The integration of volcanic, tectonic, and marine data now allows scientists to interpret Ustica sea caves not only as volcanic or erosional features but also as sensitive indicators of climate change. Today, Ustica's coast is considered a natural laboratory for studying interactions between volcanic landforms, sea-level fluctuation, and human prehistory, bridging geology, archaeology, and climate science in one of the Mediterranean's most evocative landscapes.

# S07 - TOWARDS OPEN SCIENCE IN VOLCANOLOGY: DATA COLLECTION, ARCHIVING, SHARING AND REUSE

Conveners:
Marina Bisson, Lucia Cacciola, Rossana Paciello, Gabriele Tarabusi

# An Overview on the Management of the Volcanological Data

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Volcanological datasets are inherently heterogeneous, encompassing a wide spectrum of sources and formats. They derive from field-based observations, ground-based and remote sensing instrumentation, permanent monitoring networks as well as temporary campaign deployments. These datasets include geochemical analyses, geophysical time series, imagery, video recordings, and other diverse data types. Their collection, processing, and storage occur under differing objectives, levels of infrastructure, and institutional frameworks, and are overseen by a variety of organizations worldwide, including observatories, universities, and research institutes. Within this context, volcanologists have developed a range of approaches to data management, reflecting the specific purposes of data acquisition, such as scientific monitoring, hazard assessment and civil protection, and research-oriented investigations.
Advances in technology have further increased the complexity of data management practices. In recent decades, both the volume and the quality of acquired data have grown substantially, while formerly analog records are now routinely digitized, leading to the generation of larger and more intricate datasets.
Moreover, the adoption of the Open Science paradigm, together with compliance with the FAIR principles (Findability, Accessibility, Interoperability, and Reusability) introduces additional technical and governance-related challenges aimed at improving data accessibility within the volcanological community.
This contribution provides an overview of current strategies and best practices in volcanological data management and dissemination, as highlighted in a recent Special Issue of the Bulletin of Volcanology. Key topics include data standardization and interoperability, data archiving, long-term curation, and the infrastructures that support both scientific research and monitoring activities.

# A database for the identification of tectonic structures at Mt. Etna via soil gas prospecting

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This study provides an integrated approach to identifying tectonic structures in the Mt. Etna area by leveraging geochemical data and GIS technology. The primary objective was to create a database whose purpose was to update the existing structural maps of the volcano. This goal was achieved primarily through a critical review of literature data and then through the implementation of new measurement surveys.

The research involved an extensive bibliographic search, primarily using the Science Direct database, focusing on volcanic degassing from soils. From this search, 24 relevant papers were selected to refine the structural framework of Mt. Etna. The data collected are heterogeneous, encompassing area prospecting and profiles through exposed, hidden, or buried tectonic structures.

To manage this information, a geochemical GIS was developed using QGis, an open-source platform. This system supports the storage, editing, and analysis of geospatial data. Key features of the data integration include: a) Data Volume: Approximately 12,000 measures from existing literature were used to populate the GIS; b) New Measurements: The database was further enriched with 3,600 new, unpublished $CO_2$ flux data points collected from the Fleri and Ragalna areas; c) Mapping Techniques: Surface distribution of soil $CO_2$ emissions was mapped using interpolation methods such as Ordinary Kriging, Natural Neighbor, and Sequential Gaussian Simulations.

The analysis revealed a statistically sound correlation between anomalous soil $CO_2$ and radon emissions and tectonic structures, including those previously hidden or unknown. These degassing structures are characterized by high ground permeability and are capable of producing ground motion.

Despite challenges regarding the lack of papers with tabulated data useful for populating the GIS, the heterogeneity of older data and the difficulty of integrating various methodologies, the project successfully established a comprehensive bibliographic and geochemical database. Ultimately, this research demonstrates that soil gas surveys are an essential tool for defining the complex tectonic network of Mt. Etna.

# Advancing Open Science in Volcanology: OEDataRep - the FAIR compliant Data Repository

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Research and monitoring activities at the INGV - National Institute of Geophysics and Volcanology - continuously generate a large volume of heterogeneous data ranging from seismic and volcanic monitoring (e.g., seismic waveforms and tremor), deformation and geodetic time-series, geochemical measurements, eruption/event catalogues, to geophysical modeling outputs. Given the scientific community's increasing adoption of the "Open Data" philosophy and the "Open Access" model for research products, adhering to the FAIR principles (Findable, Accessible, Interoperable, Reusable) for scientific output has become a strategic priority. Achieving these goals requires effective Research Data Management (RDM) infrastructures capable of supporting the publication, discovery, and reuse of scientific datasets.
In response to this need, this work introduces OEDataRep, the INGV Osservatorio Etneo Open Data Repository. It is specifically designed to support FAIR-compliant publication, ensuring the discovery, and long-term preservation of published datasets produced at the INGV Osservatorio Etneo. The repository is built upon InvenioRDM, the open-source “turn-key” Research Data Management Repository framework developed by CERN.
Leveraging the open-source nature of the InvenioRDM framework, OEDataRep was extended to address the needs of the scientific community at the INGV Catania department regarding specific temporal datasets. This research and development initiative led to the integration of the data repository itself with two key institutional software platforms: the Metadata Editor and the TSDSystem. The former is the official INGV software used by researchers to define, edit and validate dataset metadata before publishing them into the institutional INGV "Data Registry" catalog. The latter is the Time Series Database System, designed to collect time-series from several sources, standardize them within a unique and coherent database structure, and provide efficient access through dedicated REST API.
Through the interoperability of these three software, researchers interact with the Metadata Editor web based interface to provide the dataset metadata and submit the related files to the data repository. Once the submission is completed, if the published dataset includes time-series data, the repository acts as a client of the services exposed by the TSDSystem, so temporal data are not only deposited in the repository but are also atomically ingested into the TSDSystem database. Conversely, the same time-series data can be dynamically retrieved from the TSDSystem and visualized within the dataset landing web page on the repository, ensuring consistency between the archived dataset and the underlying time-series infrastructure.
This integration ensures time-series data are readily accessible via modern APIs, thus maximizing interoperability and reusability in full compliance with FAIR principles.
The successful implementation of the OEDataRep generalist approach has prompted a recent exploratory analysis at the national level within INGV. This analysis aims to evaluate the potential for adopting a unified data management solution across the entire institution.

# IPSES: The Italian Platform for Solid Earth Sciences as a catalyst for Open Science and data reuse

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Volcanological research relies on intrinsically heterogeneous datasets, ranging from multiparametric time series and geochemical measurements to satellite imagery and complex modeling results. Historically, these valuable resources have suffered from fragmentation across different institutions and projects, often archived using diverse standards. This fragmentation hinders accessibility, interoperability, and the ultimate reuse of data. To overcome these limitations and fully embrace the Open Science paradigm, the Italian National Institute of Geophysics and Volcanology (INGV), within the framework of the PNRR "Monitoring Earth's Evolution and Tectonics" (MEET) project, has developed IPSES (Italian Platform for Solid Earth Sciences).

While IPSES offers immense value to volcanology, its scope extends far beyond a single discipline, encompassing the entire spectrum of geosciences and Solid Earth sciences. Crucially, IPSES does not operate as a traditional data archive or a centralized repository. Instead, it functions as a federated aggregator and a single point of access. The physical data remains securely hosted and maintained by the original data providers, who make it available through shared interoperability standards. Built strictly upon the FAIR (Findable, Accessible, Interoperable, and Reusable) principles, the platform represents a significant technological leap in data management strategies, facilitating cross-disciplinary research and bridging the gap between volcanologists and the wider geophysical community.

From an architectural perspective, IPSES is a cloud-native, microservices-based platform currently deployed on a commercial cloud infrastructure. It ensures European-level interoperability by leveraging the EPOS ICS-C backend architecture and adopting standard metadata profiles (DCAT-AP), cross-disciplinary OGC (Open Geospatial Consortium) standards, and specific data formats (e.g., QuakeML, GeoJSON, CoverageJSON). A key innovation for data discoverability is the integration of advanced semantic search capabilities, utilizing ChromaDB for vector embeddings, which allows researchers to query complex RDF metadata using natural language.

For the end-user, IPSES offers a comprehensive Web GUI where scientists can discover, filter, and visualize spatial and temporal datasets through interactive maps, 3D models, image galleries, video streams, and time-series charts. Furthermore, the platform goes beyond data aggregation and discovery by introducing a Virtual Research Environment (VRE). Based on JupyterHub, the VRE provides authenticated users with a secure, persistent workspace. Through a dedicated Python library ("pyipses"), researchers can programmatically access their saved bookmarks from the GUI workspace, download heterogeneous datasets directly from the distributed providers into their JupyterLab environment, and immediately apply standard scientific Python libraries for advanced data processing and modeling.

The platform features metadata ingestion pipelines allowing authorized users to register new resources, enriching the catalog dynamically. A fundamental publication constraint is enforced for any institution wishing to join the IPSES initiative: all contributed data must be publicly accessible via standard web services, uniquely identified and metadated using DataCite DOIs, and released under open licenses compatible with Creative Commons CC BY 4.0. This strict policy ensures that the expanding catalog maintains high standards of openness and quality.

In conclusion, IPSES provides the volcanological and broader geosciences communities with a comprehensive, FAIR-compliant ecosystem. By bridging the gap between distributed data providers, advanced discovery tools, and active data analysis through its VRE, IPSES actively fosters data sharing, reproducibility of results, and multidisciplinary collaborative research, effectively translating the theoretical goals of Open Science into practical, everyday tools for researchers.

# Data model for the multidisciplinary cataloguing of volcanic ash

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Studying the morphology and componentry of volcanic ash is fundamental for understanding magma ascent dynamics, fragmentation mechanisms, and syn-eruptive processes within the conduits. This work set out to develop a conceptual model for cataloguing data related to the explosive activity monitored by the INGV-OE of Catania on the Etna and Stromboli volcanoes. The samples investigated in this study (included in a basic database created and managed by L. Miraglia) have been analysed within the INGV-OE surveillance activity in order to obtain quantitative and qualitative data.

In the sedimentology laboratory, granulometric and shape analyses are performed using the CAMSIZER® optical analyser. The extraction of specific geometric parameters - including mean size, median, sorting, sphericity, aspect ratio, symmetry, and convexity - enables quantifying the complexity of the sample. Cross-referencing these metrics makes it possible to identify specific "morphological domains" directly related to the eruption energy, distinguishing, for example, the scoriaceous and irregular ash particles, erupted during paroxysmal activity, from spherical ones, usually associated with more continuous degassing phases.

Concurrently, observations conducted under a stereomicroscope (Leica M205A) allow for the textural characterization of the sample. Clasts are categorized into three main classes: juvenile material, lithics and free crystals. Particular focus is given to juvenile particles, which can be further classified based on specific physical features, such as lustre, colour, internal texture and external morphology, and shape (e.g. fluidal, spongy, or blocky). The integration of these textural data provides crucial evidence regarding decompression paths, the degree of crystallization, and magma cooling rates just prior to the eruption.

The aim of this work is to create a data model that combines analytical-quantitative rigor with the features acquired from the high-definition images of the clasts. The association of shape parameters and images analysis fits into the recent trend of digital volcanology, paving the way for future Artificial Intelligence applications (such as Convolutional Neural Networks), capable of automating ash classification and calculating objective "mixing ratios" between shapes.

The metadata definition process facilitates data organization according to FAIR principles and Open Science policies, aligning with the INGV data policy and recent global standardization initiatives [Benet et al.,2024]. This data model has been used to expand the GEOCHEM database [Cacciola et al., 2025], implemented inside the Osservatorio Etneo. By encouraging community-wide contribution, this framework supports volcanic monitoring and helps improve hazard assessments.

# GeoChem: a volcanic data model for solid and gas samples within the European volcanological community framework

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Volcanology is an intrinsically multidisciplinary field where understanding eruption dynamics requires the integration of diverse datasets, including geophysical, geological, and geochemical observations. In recent decades, advances in analytical chemistry and sampling techniques have significantly increased the volume and variety of available data across different geochemical spheres. However, to optimize their usefulness, these data must be reproducible, reusable, and managed through transparent methodologies.

Historically, volcanological data have been fragmented across institutions and projects, often archived using heterogeneous standards that hinder comparison and integration. While communities such as seismology have long-established standards, the geochemical community has only recently adopted collaborative approaches to establish the metadata standards necessary for making data FAIR (Findable, Accessible, Interoperable, and Reusable).

To address these limitations, we present GeoChem [Cacciola et al. 2025], a comprehensive conceptual data model and relational database schema designed for the volcanological community.

GeoChem was developed as part of the EUROVOLC project and the EPOS research infrastructure and provides a standardized framework for both solid and fluid geochemical samples; the core of the model consists of a four-level hierarchical structure; these levels represent the main entities and allow for the organization of information from sampling to the analysis, while providing detailed metadata on individual measurements, including units of measurement, precision, and instrumentation.

The model was developed to address the need to organize samples collected during monitoring activities and is based on data collected and analyzed by the INGV - Etna Observatory and the INGV - Palermo Section.

GeoChem, initially, was used to manage petrological data collected by the Etna Volcano Observatory [Corsaro et al. 2013], specifically bulk rock samples and the analyses performed on them, as well as chemical analyses of fumaroles—particularly those related to fumaroles, gases, and soda solutions—collected using Giggenbach bottles during the field campaign conducted in São Miguel (Azores, Portugal) in February 2019.

To demonstrate the model's scalability and interoperability, the model is under continuous development and expansion to include and manage new types of samples, such as volcanic ash, and the heterogeneous analyses performed on them, as well as to incorporate data from other European volcanic systems.

A key collaboration has been initiated with the CSIC (Spanish National Research Council), within the framework of EPOS under the Volcano Observations Thematic Core Services, to integrate geochemical data from the El Hierro volcano in the Canary Islands.

The GeoChem system enhances the user's ability to discover and share data through specialized functionalities, including RESTful API web services already integrated into the EPOS Platform. Data providers are supported by web masks for standardized entry, while the broader community can access complex datasets through intuitive interfaces.

The evolution of GeoChem from a localized repository to a European-wide tool represents a pivotal step toward Open Science in volcanology. By providing a shared standard for data representation and management, the model fosters scientific collaboration and networking. The integration of diverse datasets ranging from Etnean ash layers to El Hierro's submarine products validates the model's robustness. Future perspectives include extending the model to manage real-time data streams and emerging technologies, ultimately supporting more accurate volcanic forecasting and more effective risk mitigation strategies on a global scale.

# Overcoming fragmentation in volcanological community: The EPOS VOLC TCS framework for FAIR data management and Open Science

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Volcanological data are inherently heterogeneous, encompassing multiparametric time series, geophysical, geochemical, and geological observations. This diversity, while representing a rich resource for advancing our understanding of volcanic processes and improving hazard assessment, often leads to fragmented archiving and disparate data management strategies. To fully embrace the paradigm of Open Science and adhere to FAIR principles, the volcanological community must overcome significant technical and policy challenges regarding data standardization, long term curation, and access. The Volcano Observations Thematic Core Service (VOLC TCS) represents a federated, pan-European approach to these very challenges, operating as one of the ten thematic core services within the European Research Infrastructure Consortium for the European Plate Observing System (EPOS ERIC). The primary objective of the VOLC TCS is to implement a robust technical, financial, and legal framework to strengthen the European volcanology community comprising Volcano Observatories (VOs) and Volcanological Research Institutions (VRIs) and to provide virtual access to diverse data, data products, software, and services from European volcanoes and overseas territories. Managing this wealth of information has required navigating complex challenges. Key efforts have focused on resolving the great heterogeneity of volcanological data regarding technical characteristics and legal aspects, such as varying data policies and diverse usage purposes ranging from scientific research to early-warning and crisis response. Furthermore, ensuring the consistency of VOLC TCS products with the broader EPOS service provision, which merges services from different Earth Science communities, has been a critical step. To achieve this harmonization, a rigorous technical process was undertaken to align various datasets by adopting common data formats and defining metadata according to the overarching standards of the EPOS Integrated Core Services. This involved a detailed metadata definition process associating a conceptual model to create a structured database where information is natively stored, managed, and updated. This strict standardization ensures true interoperability across disciplines, smoothing the integration of volcanological data with services defined by other domains, such as seismology and GNSS. Currently, VOLC TCS exposes its interoperable services through the EPOS Data Portal, adopting Open Access criteria and licenses defined in the EPOS Data Policy. Furthermore, to tackle the fragmentation of diverse datasets, the community has implemented the VOLC TCS Gateway, which proposes a unique access point for volcanological services. Crucially, it exposes both the fully EPOS compliant services and those services that are not yet compliant but hold significant importance for the scientific community. This Gateway also acts as a bridge, interfacing with institutions outside the EPOS perimeter and integrating with data infrastructures operating at a global level. Based on the experience gained so far, the VOLC TCS continues to propose future actions to address technical challenges, foster community integration, and ensure the mid-to-long term sustainability of interoperable, FAIR-aligned volcanological services.

# A relational geo-spatial database for Stromboli volcano: challenges and perspectives

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The persistent mild-explosive activity of Stromboli volcano (Aeolian Archipelago, Southern Italy) is episodically interrupted by much more energetic and dangerous episodes called paroxysms. The Istituto Nazionale di Geofisica e Vulcanologia (Italy) set up the interdisciplinary UNO Project (UNderstanding the Ordinary to forecast the extraordinary), aimed at understanding when the Stromboli volcano is about to switch from the ordinary to the extraordinary (dangerous) activity. The UNO Project includes an outstanding variety of research activities, including the collection of new data within the timeframe of the Project (2019-2025). Key to the success of the Project is the collection of integrated high spatial and temporal resolution data and their joint analyses in a shared relational geo-spatial database. Here, we present the development of this database, focusing on the preparatory work and the design of the logical model. Several hints and examples are provided to bridge the gap between the standard perspective of field volcanologists and the technical issues and caveats governing the domain of relational geo-spatial databases.

# PEOS: an open and FAIR Earth Observation e-infrastructure for volcanological data integration and reuse

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Volcanological research and monitoring increasingly rely on heterogeneous datasets generated by multiple observational systems, including satellite observations, ground-based monitoring networks, in situ measurements and numerical modelling. In recent decades, Earth Observation data have become a fundamental component for analysing volcanic processes and related hazards, enabling the detection and quantification of surface deformation, thermal anomalies, volcanic ash clouds, plume dynamics and gas emissions. Despite their scientific and operational relevance, these datasets and the derived products are often fragmented across institutions and projects, archived according to heterogeneous standards and managed through independent technological environments. Such fragmentation limits data discoverability, accessibility, interoperability and long-term reuse, posing significant challenges for the volcanological community in the context of Open Science and FAIR data principles.

Within the framework of the MEET project (Monitoring Earth's Evolution and Tectonics), Work Package 9 addresses these challenges through the development of PEOS, the Platform for Earth Observation from Space. PEOS is developed within the Earth Space Observation Center (COS) of the Istituto Nazionale di Geofisica e Vulcanologia, which coordinates the institute's activities in remote sensing applications and space technologies for geophysical monitoring. The platform provides an integrated technological environment designed to support the ingestion, management, processing and dissemination of Earth Observation data and value-added products relevant to natural hazard monitoring and environmental applications.

PEOS is conceived as an open, modular and expandable e-infrastructure capable of hosting heterogeneous processing modules and integrating different categories of datasets within a shared technological framework. The platform supports automated data ingestion, execution of scientific processing chains and publication of standardized outputs through interoperable services. Within the volcanological domain, the platform integrates algorithms and products for the detection and quantification of volcanic thermal anomalies, satellite-based observations of volcanic ash clouds and plume height, and surface deformation analyses obtained through the integration of SAR interferometry and GNSS measurements. Additional datasets include digital surface models derived from high-resolution optical imagery as well as ground-based observations used for calibration and validation of satellite-derived products.

Beyond the generation of specific products, PEOS aims to transform heterogeneous Earth Observation processing outputs into interoperable digital resources accessible to a broader scientific and operational community. To achieve this objective, the platform promotes the harmonization of heterogeneous workflows through standardized output formats, shared metadata descriptions and interoperable service interfaces that enable automated dissemination through dedicated APIs. From an Open Science perspective, PEOS contributes to the practical implementation of FAIR principles. The EPOS-DCAT-AP specification [6], an extension of the DCAT application profile for research infrastructures, is adopted in order to provide machine-readable, standardized descriptions of the data-products and access-services made available by the Platform. The access services are developed according to OpenAPI specification (openapis.org) and implements OGC standards (ogc.org). The platform is

also designed to interoperate with other National and European research infrastructure such as IPSES (Italian Platform for Solid Earth Science) and EPOS, the European Plate Observing System. By providing a technological environment capable of harmonizing heterogeneous Earth Observation workflows and enabling interoperable access to satellite and ground-based derived products, PEOS contributes to reducing fragmentation in volcanological data management and supports more effective data sharing, integration and reuse for both scientific research and operational hazard monitoring. The platform represents a concrete step toward the development of FAIR-compliant digital infrastructures able to support multidisciplinary research and to strengthen the role of Earth Observation data within the broader Open Science ecosystem.

# A satellite-derived dataset of Volcanic Radiative Power for global analysis of volcanic activity (2000-2025)

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We present a global, harmonized dataset of Volcanic Radiative Power (VRP) derived from mid-infrared (MIR) satellite observations spanning 2000-2025 and covering 170 active volcanoes worldwide. VRP measurements are retrieved from MODIS and VIIRS sensors and processed using the MIROVA system, with a dedicated cross-sensor harmonization to ensure temporal continuity and interoperability across the 25-year record. To improve data quality and reusability, volcanic thermal sources are identified using sensor-specific thresholds combined with an unsupervised machine learning algorithm that reduces false detections while preserving sensitivity across six orders of magnitude. The resulting dataset is provided in a standardized and consistent format designed to facilitate integration with other volcanological datasets and support multi-scale analyses. By ensuring consistency, accessibility and long-term continuity, this dataset contributes to ongoing efforts toward FAIR (Findable, Accessible, Interoperable and Reusable) data practices in volcanology. It is intended for reuse in studies of volcanic activity, hazard assessment, long-term trend analysis ranging from individual volcano characterization to regional and global comparisons.

# The EPOS Volcanological Software Catalog: a Service to the community

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Scientific products, and specifically scientific software, are being more and more requested as services from a variety of stakeholders, including fellow researchers, students, policymakers as well as the general public. Volcanological software is no exception, as testified by recent EU-funded initiatives such as EUROVOLC and ChEESE, focused on using HPC solutions to model hazard and risk; Geo-INQUIRE, devoted to making geo-scientific products (data, software, infrastructure) available to foster curiosity-driven research; DT-GEO, aimed at creating Digital Twins for geophysical extreme events. These efforts have been coordinated and favored by EPOS (European Plate Observing System), a European Research Infrastructure Consortium (ERIC) committed to enabling excellent science through the integration, accessibility, use and re-use of Solid Earth science data, research products and services.
Volcanological software applications have now a widespread use, and range from relatively simple, one-dimensional and fast models to solve approximate equations of motion for e.g. plume dispersion dynamics, to more complex computational fluid dynamics frameworks to describe the full three-dimensional evolution of pyroclastic density currents or magmatic dynamics at crustal depth.
In this work we present a catalogue of volcanological software consisting of a dedicated web portal, providing information to an EPOS service. The portal includes a growing number of numerical models targeting a variety of volcanic processes, from magmatic source to eruption and tephra dispersal; metadata are exposed to the wider Solid Earth Sciences community through a specific service within the EPOS Platform. Effort has been put into providing a comprehensive presentation of the simulation tools, including validation benchmarks, examples of use and detailed documentation, to allow for their widest dissemination and use. Some of the less computationally-intensive software is also equipped with the ability to be run online.
The portal is mainly addressed to the research community, with the main aim of fostering feedback between modelers and the wider volcanological community that can benefit from the use of the tools provided. Cross-fertilization is indeed crucial to advance in such interdisciplinary subjects as volcanic processes and hazard, and must be fostered by openly sharing resources and tools, and providing support for their responsible use.

# Strain data collection at Stromboli volcano: sharing strategies on the EPOS data portal

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Starting in 2006 on the island of Stromboli a volumetric strainmeter, installed on the north-eastern side of the island, near the village of Stromboli (SVO dilatometer), has provided continuous strain data, representing a valuable resource for advancing the understanding of volcanic processes, improving hazard and risk assessment, and supporting scientific research.
Due to their high dynamic, and since their output responds to input over a wide frequency range, strainmeter data are prone to be affected by anthropic noise, changes in atmospheric pressure, tides, rainfall, underground water movements, changes in underground temperature, earthquakes, as well as other crustal movements: in order to thereby obtain cleaner strain data, several kinds of procedures have been developed over time by geophysicists to remove the unwanted ("spurious") signals from the actual recordings, capable of representing the actual changes of the local strain in proximity to the installation site.
Strategies for managing strain data have been designed to enable access for universities, research centers and observatories, in the context of the growing international commitment to Open Science: this effort has been achieved by the integration of strain data within Thematic Core Service Volcano Observation (VOLC-TCS) that offers, within the European Plate Observing System (EPOS), long-term access to data, products and services.

# An online database named ‘RESPIRA - Remote sEnsing obServations of source Parameters and data IntegRation at EtnA'

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Eruption Source Parameters (ESPs) are fundamental for quantifying explosive activity and serve as inputs for volcanic ash dispersal models used to forecast tephra fallout deposits and assess associated hazards. These parameters include column height, measured via sensors such as radar, lidar, calibrated visible cameras, and satellite radiometers; total grain-size distribution (TGSD), which usually requires the analysis of tephra deposit samples; mass eruption rate (MER), which is either retrieved through sensor-based techniques (radar and cameras) or estimated via analytical modelling from values of column height. Accurate ESP estimation is particularly crucial for densely populated regions like Mount Etna (Italy). Since 1986, 141 paroxysmal episodes at Etna have been monitored using various sensors. However, despite the amount of data in the scientific literature, a standardized and integrated dataset is not available.
In this work, we present RESPIRA (Remote sEnsing obServations of source Parameters and data IntegRation at EtnA), a new online dataset comprising ESPs derived from scientific literature, new multi-sensor analyses, and established mathematical formulations. This comprehensive collection significantly enhances the characterization of different processes occurring during paroxysms of Etna. RESPIRA will facilitate statistical analyses of ESP recurrence, the identification of new eruptive scenarios, and the investigation of complex interactions between eruption columns and the atmosphere.

# From static hazard maps to an interactive multi-hazard geospatial analysis platform enabling collaborative digital workflows

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The increasing availability of probabilistic hazard datasets in solid Earth Sciences requires digital environments that go beyond static map visualization, enabling in-depth spatial analysis, data comparison across multiple hazard contexts, and data download in standard formats.
In this work, we present a web-based geospatial platform properly designed to support interactive exploration, analysis, and dissemination of hazard data (maps and curves), while remaining extensible to any type of GIS layer. The platform performance is tested using Mount Etna as a case study and integrates volcanic and seismic hazard assessments derived from established probabilistic models for different hazardous events and their metrics, including lava flow invasion, ground load from volcanic ash fallout, and seismic intensity [Cappello et al., 2025; Scollo et al., 2025; D'Amico et al., 2025]. Hazard datasets originally provided in NetCDF format are here processed and stored in a spatial database, allowing consistent management of both raster and vector representations of exceedance probabilities across different spatial resolutions. Aside from the standard spatial queries, the system enables advanced analytical interactions, such as point-based interrogation of hazard layers with on-the-fly visualization of probability percentiles across different hazardous events and specifically different thresholds in their metric. Users can also extract and download hazard matrices and map products, supporting quantitative comparison and further offline analysis. By combining geospatial data management with interactive analytical tools, the platform allows researchers from different disciplines to explore complex spatial information in a transparent and reproducible manner. The adoption of standardized web services and modular workflows enhances interoperability and facilitates integration with external infrastructures. Designed in accordance with FAIR data principles, the platform represents a flexible digital geoscience tool that can be extended to additional hazard domains and GIS workspaces. This work proves how interactive geospatial analysis workflows can enhance the scientific use of probabilistic hazard information and foster collaboration among hazard modelers, Earth scientists, and stakeholders, in line with the objectives of the EPOS European research infrastructure.

# S08 - GEOPHYSICAL CHARACTERIZATION OF VOLCANIC SYSTEMS: STRUCTURE, DYNAMICS, AND MONITORING

Conveners:

Maria Giulia Di Giuseppe, Antonio Troiano

# Three-dimensional thermo-fluid dynamic modeling of Pantelleria Island (Sicily, Italy) constrained by geophysical data for geothermal resource assessment

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Pantelleria Island (Sicily Channel, Italy) represents a particularly promising area for geothermal explorations due to its high thermal gradients and widespread hydrothermal manifestations, including diffuse $CO_2$ emissions, fumaroles, and thermal springs. Assessing its geothermal potential requires a robust preliminary characterization of the subsurface to define the extent and physical properties of potential reservoirs. Prior to undertaking costly and technically demanding operations such as deep drilling, numerical modeling represents a crucial tool for guiding and optimizing exploration strategies.

In this study, we present a three-dimensional thermo-fluid dynamic model of Pantelleria Island developed using the TOUGH2 simulator. The model is based on a petrophysical framework constrained by new geophysical data, integrating a resistivity structure derived from an audio-magnetotelluric survey down to approximately 1800 m depth and rock density information obtained from the inversion of gravimetric data. These complementary datasets provide key constraints on the subsurface architecture and physical properties of the volcanic system.

The simulations reproduce the steady-state distribution of temperature and fluid pressure, providing insights into fluids pathways, heat distribution and the role of major volcano-tectonic structures in controlling hydrothermal circulation. The resulting thermo-fluid dynamic model allows the identification of areas characterized by favorable conditions for geothermal exploitation. This approach provides a quantitative framework for assessing zones with significant geothermal potential and for evaluating possible fluids extraction and reinjection scenarios.

# Continuous Electromagnetic Monitoring at Campi Flegrei Caldera

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The Campi Flegrei caldera (southern Italy) is currently experiencing a prolonged phase of unrest characterized by ground uplift, intense degassing, and increasing seismicity. Although the area is monitored by an extensive geophysical and geochemical network, continuous electromagnetic observations remain limited.
In volcanic environments, magnetotelluric (MT) monitoring has the potential to detect temporal variations in subsurface electrical resistivity associated with fluid circulation, temperature changes, and hydrothermal processes. However, the interpretation of such temporal variations critically depends on the ability to distinguish signals associated with subsurface dynamics from those generated anthropogenic electromagnetic noise, which is a particularly challenging task in a densely urbanised area such as the Campi Flegrei caldera.
To address this issue, we analyzed continuous MT datasets acquired at three sites located at increasing distances from the caldera center. The analysis focuses on the temporal variability of magnetotelluric responses to evaluate their stability over time and to identify site-dependent noise contributions.
The results reveal different levels of temporal variability among the three sites. A comparative analysis of these variations helps discriminate between signals likely related to local anthropogenic noise and those potentially associated with ongoing unrest at Campi Flegrei. Overall, this approach provides a framework for assessing the reliability of temporal MT variations and for improving the interpretation of continuous electromagnetic monitoring in active caldera systems.

# Thermal structure and magmatic controls on the Sabatini volcanic system (central Itay): insights from geophysical constraints and time-dependent modelling

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The Tyrrhenian margin of central Italy is characterized by widespread magmatism, metasomatism and elevated heat flow. Within this framework, the Sabatini Volcanic District (SVD) stands out for its persistent thermal anomaly [Della Vedova et al., 2001], reflecting the long-term imprint of a Quaternary magmatic system. This study investigates the present-day thermal state and crustal architecture of the SVD for reconstructing the evolutionary trajectory and post-caldera dynamics, by integrating geophysical observations with 3D time-dependent thermal modelling. Our conceptual model includes volcanic deposits and the allochthonous Tolfa flysch as primary caprock units. These units overlie a Mesozoic-Cenozoic carbonate reservoir [Buonasorte et al., 1991]. The deeper crust is represented by micaschists and gneisses, a mafic lower crust, and a peridotitic mantle, consistent with geological analogues found in Larderello [Gola et al., 2017]. Geophysical constraints are combined with thermobarometric estimates, petrological evidences and borehole data to define magma emplacement depths. Volcanic ages were used to parametrize timing of intrusions through smoothed on-off functions. We developed a 3D time-dependent conductive model to simulate the thermal evolution of the crust over the last 800 k.y. [Marra et al., 2020]. The workflow involved: (i) refining of the existing stratigraphic datasets [Petracchini et al., 2015] at crustal and lithospheric scales; (ii) defining of boundary conditions, including surface temperatures, basal heat flow and lithothermal properties; (iii) identifying of the deep and shallow heat sources through analysis of the available 3D tomographic images [Magnoni et al., 2022] and thermobarometric estimates of volcanic products [Giordano and Caricchi, 2022]; and (iv) integrating all constraints into the modelling environment (Comsol v. 6.3). Initial conditions were established using steady-state geotherms calibrated against mantle xenoliths from the nearby Torre Alfina district [Conticelli and Peccerillo, 1990]. Our simulations reproduce the thermal structure of the Cesano-Sabatini geothermal field only when, in addition to the deep magmatic source, multiple shallow heat sources are also included. This specific configuration agrees with seismic tomography, suggesting a composite magmatic system rather than a single intrusive event. Ultimately, our findings highlight the role of multi-level magmatic bodies in sustaining long-term thermal anomalies in post-caldera volcanic systems. The integration of geophysical imaging and thermal modelling provides new constraints on the structure and evolution of the Sabatini crustal system and offers a robust framework for future convective simulations that include fluid-rock interaction.

# MEDUSA: 10 years of continuous monitoring of the Campi Flegrei area

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Since spring 2016, MEDUSA — a permanent, multi-parameter marine monitoring infrastructure — has contributed significantly to the real-time monitoring of the Campi Flegrei volcanic area. The infrastructure consists of four equivalent marine systems, each comprising an elastic buoy (hosting a geodetic GNSS receiver on the top) and connected through a cable to a seafloor module. The module is equipped with oceanographic and geophysical sensors including a bottom pressure recorder (BPR), a low-frequency hydrophone, and a broadband seismometer. One of the buoys is also equipped with a tide gauge.

The analysis of local earthquake recordings using hydrophones has allowed the definition of a useful equation for magnitude calculation. This method could be easily exported to other volcanic areas where submerged volcanoes are monitored by networks of hydrophones and seismic sensors on land. The proposed approach indeed allows magnitude measurements of small-magnitude earthquakes occurring at sea, thus adding useful information to the seismicity of these volcanoes. Furthermore, data from the seismometers contribute to the correct determination of hypocentral parameters for earthquakes occurring in the Gulf of Pozzuoli and to the definition of their focal mechanism parameters.

With the GNSS and tide gauge, it has been possible to determine the trend of bradyseism even in the submerged part of the caldera. Since 2016, a vertical uplift has been highlighted at the buoy closest to the city of Pozzuoli, CFB1, with approximately 95 cm. Decreasing values are observed at the sites of the other buoys, approximately 77 cm at sites with intermediate distance, down to 30 cm for the most distant buoy located about 2.5 km south of the city of Pozzuoli. The data obtained from the tide gauge are in perfect agreement with those from the GNSS installed on the same buoy.

In parallel, an original methodology was developed for determining seafloor ground uplift using measurements obtained with BPRs. This methodology uses BPR and tide gauge data to determine variations in seawater density over time and combined with atmospheric pressure measurements, it is possible to convert the pressure measured at the seafloor into variations in the water column height, analogous to a tide gauge. This measurement is then compared with a reference tide gauge located in an area outside the volcanic zone and considered stable. In this way, a new method has been developed to extend the measurement of seafloor deformation even to sites distant from the buoys.

This unique MEDUSA infrastructure enables continuous measurement of seafloor deformation, obtaining a complete map of the deformation field within the caldera's marine sector. Data collected over the past decade continue to provide vital contributions to the development of new interpretative models for the Campi Flegrei volcanic complex. In this presentation, we will discuss the acquisition of seismic (broadband velocimeters, accelerometers, and hydrophones), geodetic (GNSS and pressure sensors), and oceanographic (tides, currents) data, alongside a comprehensive collection of data analyses.

S08 - Oral Presentation

# Multiparametric reciprocity-based volcanic monitoring with ambient seismic noise

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Seismic monitoring enables the study of the dynamic processes within volcanic systems and the evolution of the volcanic cycle. Although the volcanic seismicity has traditionally played the leading role in volcanic monitoring, most volcanic cycles span long periods of seismic quiescence where seismo-volcanic events are scarce or even absent. This is a critical disadvantage in the study of volcanic systems because many geodynamic processes can be taking place in depth aseismically, hence limiting the detection of changes in the magmatic conditions and compromising the interpretation of the volcanic cycle. In order to perform a thorough volcanic surveillance, the seismic monitoring requires an adequate level of both measurement repeatability and time-continuity over long periods of time that naturally include seismic quiescence. In this respect, seismic methods based on the use of ambient noise facilitate the repeatability conditions in the seismic-monitoring measurements. By using ambient noise we are exploiting an alternative source of seismic information independent of the local seismicity, thus providing additional value and complementing the seismic study of the geodynamic processes in the subsurface. Most noise monitoring methodologies are conducted by means of cross-correlation and analysis of the correlated scattered wavefield (or seismic-coda wavefield). The seismic-coda analysis is of great advantage in this particular case, since it detects perturbations in the crustal mechanical properties, in terms of relative seismic-velocity changes, with a much higher sensitivity than that of standard noise tomographic approaches. However, this analysis is not exempt of inaccuracies, being prone to the creation of signal artifacts, reliance on the assumption of the medium with homogeneous scattering properties, and eventually lack of control over the volume of crust sampled beyond the monitoring target. This aspect can cause a bias in the interpretation of the dynamic processes of the subsurface, creating uncertainty in the seismic results when other sources of crustal perturbation are present in the area (such as neighboring volcanic structures and/or seismogenic faults).

In the present abstract an alternative approach is proposed to monitor the volcanic system that exploits the ambient-noise wavefield without the drawbacks of the cross-correlaton methods. In the proposed approach we exploit the principles of seismic reciprocity and seismic imaging techniques employed in exploration geophysics without compromising the characteristic robustness of ambient-noise methods. One significant advantage includes the accuracy improvement of the monitoring by implementing seismic processing tools that limit the extent of the crust volume to be analyzed. This prevents our measurements from being affected by seismic perturbations that originate from outside of the target volcanic system. This new approach focuses on the most dominant ambient noise waveforms (Rayleigh- and Love waves) and their combined analysis in the aim of enhancing the use of coda-wave analysis beyond what cross-correlation can provide. Working with both types of waveforms jointly makes it possible to translate the observed relative seismic-velocity variations into actual changes in the crustal bulk- and shear- moduli, separately. Furthermore, this approach enables also to perform the analysis of seismic attenuation and to constrain the estimation of the respective Q-factor of both bulk- and shear- moduli. The resulting time-lapse monitoring of these two elastic parameters and their respective Q-factors helps constrain the understanding of the geodynamic processes inside the volcanic system: this multiparametric approach establishes a new insight for the

identification and differentiation of seismic perturbations produced by variations in the magma chamber conditions, changes in the magma physical/chemical properties, or fluctuations in the magmatic-fluid interaction with the host rock and overburden. Lastly, this reciprocity-based method enables all these analyses to be implemented in a tomographic setting for each of the corresponding parameters, thus extending the monitoring into a 3D imaging.
This work presents the advantages of implementing methodologies based on seismic reciprocity for the monitoring of volcanoes and other geological features that pose a hazard risk.

# Absolute and relative gravity measurements at Etna volcano (Italy) in the period 2009 - 2025

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A 17-year time series (2009-2025) of repeated absolute gravity measurements from Mt. Etna (Italy) is presented and analysed to constrain volcano-related mass redistribution at depth, occurring over time scales of months to years. Intense eruptive activity occurred at the summit craters during the study period, including more than one hundred lava fountain episodes, thus providing an exceptional framework for investigating the interplay between the processes governing eruptive cycles and the gravity changes observed at the surface.
Absolute gravity measurements were carried out approximately on an annual basis, using the Microg LaCoste FG5#238 gravimeter. To enhance the temporal resolution, relative gravity observations were carried out at selected stations, using Scintrex CG-5 and CG-6 gravimeters, at sub-annual intervals and, in some cases, through nearly monthly campaigns. The combined dataset reveals cycles of gravity increases and decreases, affecting the entire volcanic edifice and associated with periods of intense lava fountain activity.
Gravity changes up to 2015 were interpreted as due to magma recharge (2009-2011) and discharge (2011-2014), involving a storage zone at ~ 5 km b.s.l.
The present study represents both a continuation of earlier work and a comprehensive reappraisal of the entire observation period. The results confirm the high potential of gravity studies for improving the detection of unrest and the identification of processes that may precede eruptive activity.

# Imaging hydrothermal systems in the Aeolian Islands: electrical resistivity constraints on subsurface structure and fluid pathways

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The Aeolian archipelago (Southern Italy) represents a complex volcanic system where magmatism, tectonics, and hydrothermal circulation interact to control fluid migration and geothermal potential. Constraining the geometry of hydrothermal systems and their permeability architecture is essential for understanding both subsurface processes and surface manifestations relevant to volcanic monitoring and geothermal assessment.
As part of the IRGIE project (Inventario delle Risorse Geotermiche delle Isole Eolie), we present a large-scale 3D Audio-Magnetotelluric (AMT) investigation to image the electrical patterns in the subsoil and identify fluid pathways across Lipari, Salina, Vulcano, and Panarea. The dataset includes 153 AMT soundings, inverted using a 3D approach to obtain robust models of subsurface resistivity at depths of several kilometres.
The resulting models highlight a strong variability in the electrical structure, reflecting different volcanic and hydrothermal conditions. At Vulcano, a resistive body beneath La Fossa crater is interpreted as a conduit-like structure connected to deep magmatic fluids, surrounded by a shallow conductive cap associated with hydrothermal alteration. At Panarea, conductive anomalies aligned along NE-SW structures reveal fault-controlled hydrothermal circulation, consistent with active degassing and submarine venting. Lipari exhibits a heterogeneous resistivity pattern, with localized conductive domains associated with shallow hydrothermal systems, suggesting a waning but still active geothermal regime. In contrast, Salina is dominated by resistive structures related to cooled volcanic units, although localized conductive features indicate fluid circulation and potential low-enthalpy resources.
These results demonstrate how AMT imaging provides key constraints on the structural and physical controls governing hydrothermal systems in volcanic environments. The integration of geophysical observations within a broader geological and volcanological framework allows linking subsurface architecture to fluid circulation processes, offering a quantitative basis for geothermal assessment and improving the interpretation of geophysical monitoring signals in active volcanic systems.

# 3D gravity modelling of Pantelleria Island: insights into the geothermal system

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Although Italy holds a substantial geothermal potential, this renewable resource remains largely underexploited. All geothermal projects, from local low-enthalpy applications to large-scale high-enthalpy exploitation, require a preliminary resource assessment phase aimed at defining the spatial extent, volume, and physical properties of the reservoir. Pantelleria Island, located within the Sicily Channel rift system, represents a prime candidate for such exploration. Deep boreholes have documented geothermal gradients exceeding 200 °C/km and temperatures of 250-265 °C at approximately 1.2 km depth within the Cinque Denti caldera, while active $CO_2$ degassing, fumarolic fields, and hot springs confirm the presence of an active hydrothermal system. Despite this potential, the structural controls on the geothermal reservoir remain poorly constrained at depth.

In the framework of "PANTA REI" project, a new high-resolution gravity survey was conducted. This allows adding approximately 130 stations to the existing on-land data and integrated offshore measurements extending up to 20 km from the coast. The resulting dataset comprises about 630 stations, with an average density of ~3.5 stations/km². Due to the high lithological heterogeneity between intra- and extra-caldera sectors of the island, a dual-domain density approach was adopted for terrain correction: 2300 kg/m³ for caldera infill deposits and 2700 kg/m³ for the outer domain. This approach enabled the computation of a new Bouguer anomaly map, with values ranging from ~64 to 90 mGal on land. Regional-residual separation was performed using the fractional-order vertical derivative method [Florio et al., 2023], allowing an efficient isolation of the effects of local sources. Boundary analysis, carried out using the Enhanced Horizontal Derivative [Fedi & Florio, 2001], delineates some sharp lateral density contrasts aligned with the major volcano-tectonic structures, including the Cinque Denti and La Vecchia caldera rims, as well as the Montagna Grande and Zinedi faults.

The residual anomaly field was used as input for a 3D gravity inversion implemented using the SimPEG Python library [Cockett et al., 2015]. A Sparse IRLS (Iteratively Reweighted Least-Squares) regularization was applied on an adaptively refined mesh, with density contrasts bounded within ±500 kg/m³ and depth weighting. The inversion was constrained by prior information from deep borehole stratigraphy [Chierici et al., 1995] and seismic reflection data [Civile et al., 2008], guiding the solution toward a geologically consistent model. The resulting 3D density contrast model images a high-density body (300 - 500 kg/m³) in the southeastern sector of the island, extending up to ~1 km below sea level and interpreted as a shallow syenitic intrusion consistent with well log data. A broad low-density zone beneath Montagna Grande reflects caldera-fill deposits and a highly fractured volume associated with the resurgence.

These results might contribute to providing a quantitative framework for characterizing the structural controls on Pantelleria geothermal system, mapping potential fluid pathways, and constraining the geometry and physical properties of the reservoir. By resolving the density

architecture of the caldera, this study provides key input for ongoing numerical simulations of geothermal exploitation and contributes to resource assessment strategies. Overall, the results highlight the value of integrated high-resolution gravimetry and constrained 3D inversion for geothermal exploration in volcanic environments.

# Geodetic, topographic and UAV monitoring for the assessment of geological hazards of the Santa Barbara mud volcano, Caltanissetta (Sicily)

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Geodetic and topographic monitoring integrated with aerophotogrammetric techniques represents a fundamental tool for defining the kinematics and dynamics of active geological processes such as uplift, subsidence, and surface deformation. In this context, remote sensing plays a key role in the assessment and monitoring of natural hazards. The design of a monitoring system must be based on the analysis of spatial and temporal factors controlling deformation rates, starting from preliminary structural and stratigraphic geological investigations and integrating geomorphological, hydrological, and geotechnical studies.
The Santa Barbara mud volcano is located in the city of Caltanissetta, in the central sector of Sicily. On August 11, 2008, a paroxysmal event caused several damages to the nearby infrastructures within a radius of ~2 km from the emission vent. The main precursors of paroxysmal events, in mud volcanoes, include ground deformation processes (e.g., inflection) and formation of fractures on surface with different sizes (from centimetric to decametric scale).
In this work, we present an integrated methodology for monitoring deformation processes that may act as precursors to paroxysmal events at the Santa Barbara mud volcano. The proposed approach includes: (i) data acquisition from discontinue and permanent station; (ii) UAV-based aerial photogrammetric surveys processed using the Structure-from-Motion (SfM) algorithms, and (iii) analysis of surface deformation through multi-temporal point cloud comparison using the M3C2 algorithm in CloudCompare software. For each flight a set of Ground Control Points (GCPs), measured with a theodolite total station (TTS), were used to improve the positional accuracy of the obtained model [Brighenti et al., 2021].
The GNSS data were used to perform a deformation analysis for the period 2016-2025. Our results suggest that the investigated area exhibits a general motion toward ESE with velocities ranging between 5 mm/yr and 12 mm/yr. The GNSS permanent station, located in the north sector of the area, appears to be stable with a motion of ~ 3.3 mm/yr to the north, a typical regional velocity in central Sicily. The western sector of the area shows a northeastward motion of ~1 mm/year, whereas the points located in the eastern sector of the mud volcano show a predominant trend of motion of about 10.34 mm/year toward ENE in the period 2017-2024. Additionally, UAV photogrammetric surveys conducted between 2020 and 2025 reveal an average subsidence of approximately 0.15 m, with maximum values of 0.24 m, the latter occurring along the incisions of the drainage network.

# Magnetic anomaly characterization of the polygenetic Martignano Lake maar, Sabatini Volcanic District (Central Italy)

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This study presents the first high-resolution magnetic survey and three-dimensional inversion of the Martignano maar, a polygenetic volcanic structure located within the Sabatini Volcanic District of central Italy. Magnetic data were acquired across the lake surface using a boat-mounted Overhauser magnetometer and complemented by drone-borne surveys employing an optically pumped magnetometer over the surrounding emerged areas. The combined dataset provides dense spatial coverage of the maar and its rims, enabling detailed analysis of the magnetic signature associated with the volcanic structure. The reduced-to-observation magnetic anomaly map reveals a coherent anomaly ranging from -960 to +270 nT, characterized by a dominant negative signal spatially coincident with the crater. This pattern reflects a strong magnetization contrast between the weakly magnetized crater infill, composed of pyroclastic deposits, volcaniclastic sediments, and lacustrine material and the more strongly magnetized volcanic plateau hosting the maar.

To investigate the subsurface structure responsible for the anomaly, we performed a three-dimensional magnetic inversion formulated in terms of magnetization contrast relative to the surrounding volcanic background. The inversion employs a compactness-constrained greedy algorithm designed to recover coherent source bodies while minimizing model non-uniqueness. The preferred solution images a well-defined funnel-shaped low-magnetization domain beneath Lake Martignano. This structure widens at shallow to intermediate depths and progressively narrows downward within the volcanic sequence, forming a geometry consistent with the expected architecture of a maar-diatreme system produced by repeated phreatomagmatic explosions.

The model indicates that the main magnetic signal originates from the deeper, brecciated diatreme zone, whereas the shallow crater infill contributes little to the observed anomaly because of its limited magnetization contrast with the surrounding volcanic deposits. The geometry of the recovered structure is also compatible with the polygenetic eruptive history previously proposed for the Martignano maar, suggesting that the present crater may result from the interaction and partial coalescence of multiple eruptive centres.

These results provide the first geophysical constraint on the internal architecture of the Martignano maar and demonstrate that high-resolution magnetic surveys combined with contrast-based inversion can effectively resolve diatreme-scale volcanic structures under favourable geological conditions. The methodology offers a robust framework for investigating concealed maar-diatreme systems and contributes to improving the understanding of subsurface volcanic architecture in the Sabatini Volcanic District and comparable volcanic settings worldwide.

# Analysis of tilt changes associated with lava fountains at different craters of Mount Etna

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Mount Etna is one of the most active volcanoes in the world, with frequent eruptions occurring mainly from its summit craters: Voragine (VOR), North-East Crater (NEC), Bocca Nuova (BN), and South-East Crater (SEC). Summit eruptions are usually characterized by Strombolian activity of varying intensity, often evolving into highly energetic lava fountains. Since 2011, approximately 130 lava fountains have been recorded. Most of them occurred at the SEC, while a smaller number originated from the Voragine, specifically four in December 2015, two in May 2016, and six between July and August 2024. Most recently, in December 2025, the NEC produced two lava fountains, marking the first such episodes at this crater in almost 30 years; the previous event occurred in March 1998. These events, causing the formation of dispersed ash plumes and fall-out deposits, may pose serious hazards to aviation and, more generally, to the population.
To better understand the dynamics driving these events, we analyzed the tilt changes associated with recent lava fountains originating from the three craters. For each crater, we selected events with different energies, using data recorded at the four tilt stations that showed clear signals across all the analyzed lava fountains. Tilt signals allow for the detection of single lava fountains, recording variations of up to 0.1 microradians.
Our ongoing analyses focus on the comparative study of the parameters of the tilt vectors across the selected events. By assessing the consistency or variation of these deformation patterns across the lava fountains produced by the three craters, we aim to investigate the respective changes in the position and volume of the pressure sources. Furthermore, characterizing the tilt patterns of each crater could provide an important tool for volcano monitoring, allowing for the identification of the active crater even when heavy cloud cover precludes direct visual observations.

# Fluid migration along the active submarine hydrothermal system of Panarea: preliminary results from passive hydroacoustic and geodetic data

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Stromboli and Panarea Islands are located in the eastern sector of the Aeolian Arc, a geologically active region where deep subduction processes, crustal tectonic activity and volcanism coexist. A set of recent studies have demonstrated a consistent temporal correlation between seismic tremor variations within the Panarea hydrothermal system and soil degassing rates measured close to the Stromboli's summit area. These findings would suggest a shared magmatic source and fluid migration along a common tectonic structure. However, the temporal and physical relationships between changes in the Panarea hydrothermal system, soil degassing rates at the Stromboli summit area, and transient ground deformation recorded by GNSS remain poorly constrained.
To further investigate these complex dynamics, we propose a multidisciplinary approach that combines passive hydroacoustic and geodetic monitoring to explore the dynamics of fluid ascent. The Panarea Volcanic complex, characterised by one of the most active hydrothermal fields in the Mediterranean Sea, represents an ideal site to evaluate the potential of integrating these techniques. By analysing the multiparametric time series recorded between 2016 and 2018, we focus on specific time windows characterised by intensified submarine hydrothermal venting at Panarea. Specifically, this preliminary analysis compares the high-frequency bands (100-2000 Hz) of sound associated to bubbles' plume, recorded by a hydrophone deployed permanently within the so-called "Black Point" hydrothermal spring area and related to gas flow rate, with transient ground deformation captured by the nearby GNSS stations (CPAN, IPAN).
The result of this preliminary analysis allows us to identify and quantitatively estimate analogous trends, detecting both synchronous variations and time-lagged signals across the datasets.
This work provides new insights into the local cause-effect relationship between hydrothermal fluid migration and crustal deformation. Furthermore, it highlights the potential of an integrated methodological approach to better understand the role of fluids and their interaction with local tectonic structures in complex volcanic settings.

# Source Localization of Continuous Seismic Signals During 2024 Eruptive Activity at Stromboli

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Stromboli is an active open-conduit volcano located in the Aeolian archipelago in the southern Tyrrhenian Sea, Italy. The volcano is characterized by persistent Strombolian activity, occasionally interrupted by more energetic phenomena such as lava effusion, major explosions, and paroxysmal eruptions. Transitions between these eruptive styles may occur over timescales ranging from hours to days, making Stromboli an ideal natural laboratory for investigating the relationship between eruptive activity and geophysical signals.
The activity observed at Stromboli during 2024 provides a valuable opportunity to explore these relationships. During this period, the volcano experienced a progressive intensification of activity, including sustained spattering, lava-flow emplacement, and a paroxysmal eruption. This sequence offers an appropriate framework for investigating how geophysical signals evolve during transitions between different eruptive regimes.
Continuous seismic signals in the 1-10 Hz frequency band represent a significant component of the seismic wavefield recorded at Stromboli. These signals include contributions from different processes occurring in the shallow volcanic system, such as magma movement, degassing, and explosive activity. Despite their relevance for volcano monitoring, constraining their spatial origin remains challenging because of their emergent and continuous nature.
In this study, we analyse seismic data recorded during the 2024 eruptive activity by seven stations of the permanent monitoring network of the Istituto Nazionale di Geofisica e Vulcanologia. Spectral and amplitude analyses are performed in the 1-10 Hz frequency band to characterize temporal variations in signal energy and explore their relationship with eruptive activity. To investigate source location, we apply a method based on the decay of seismic amplitude with distance across the network. This approach allows the centroid of the seismic source to be estimated within a grid of theoretical nodes centred on the Sciara del Fuoco and the summit crater area.
Preliminary observations suggest that both seismic amplitude and the position of the source centroid vary during the different phases of the 2024 eruptive sequence. These results indicate that tracking the spatial evolution of these signals may provide additional constraints on the dynamics of the shallow conduit system and help improve the interpretation of eruptive processes in support of volcano monitoring at Stromboli.

# Insights into the 2008 Etna dike arrest through structural data, energy release patterns, and focal mechanisms

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The propagation of volcanic dikes represents one of the most intriguing and at the same time most critical processes in the field of volcanology. The phenomenon is made complex by the combination of several key factors, such as buoyancy, driving overpressure, magma rheology, crustal layering, topography, which control the final dike propagation. Monitoring volcanic dike propagation and identifying the exact moment of arrest are crucial for real-time risk assessment and civil protection decision-making.

Recently, two methods based on geophysical observables have been proposed to determine whether a dike is near to arrest. The first relies on verifying the energy balance between the expected energy from the initial dimension of the dike and the recorded energy released by the earthquakes produced during the dike propagation [Bonaccorso et al., 2017]. The second method is based on a simple but effective indicator, the occurrence of reverse focal mechanisms during the terminal stopping phase of the dike propagation interpreted as due to the solidification process of the magma intrusion [Bonaccorso et al., 2025].

This study re-evaluates the initial phase of the May 2008 Etna eruption, when a shallow magmatic intrusion migrated northward, critically replicating the geometry and position of the highly destructive 1981 eruption that threatened the town of Randazzo. In particular, we present a comprehensive analysis integrating, for the first time, a detailed field structural investigation of the 2008 non-eruptive (dry) fracture field with high-resolution geophysical monitoring. The structural mapping of surface fractures provides a macroscopic signature of the intrusion's final ascent, allowing for a geometric estimation of the arresting dike-tip depth. This evidence is cross-validated through the Energy Balance Analysis and Focal Mechanisms (FMs) computation, which identifies the occurrence of reverse FMs during the terminal stage. These signals are interpreted as a proxy for the cooling and solidification process of the magmatic body.

Our findings suggest that the real-time detection of reverse faulting, combined with energetic and structural constraints, serves as a robust tool for assessing the propagation state of a dike. This multidisciplinary approach is fundamental for real-time risk assessment and civil protection decision-making, offering a quantifiable framework to identify the transition from dike propagation to arrest.

# Temporal gravity changes in the Campanian Plain and possible interaction with the dynamics of the Neapolitan Volcanoes

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The Campanian Plain (CP) in Southern Italy is a half-graben structure which extends between Apennine Chian and Tyrrhenian Sea, originated by the subsidence of the Mesozoic carbonate platforms during the Mid-Pliocene and Early Pleistocene era. The structure formed in response to the extensional tectonics associated to the spreading of the Tyrrhenian Sea. This process was accompanied by crustal thinning and the development of a deep (more than 3km depth) sedimentary basin. Crustal stretching also led to the Mantle migration and rising of large volumes of magma, resulting in the volcanism within the plain and in the Bay of Naples with the formation of the polygenic apparatus of Mt. Vesuvius and the volcanic fields of Campi Flegrei (CF) and Ischia Island.
The area showed a slow subsidence of few mm y-1 with quite complex spatial patterns during the Quarternary. The origin of these vertical movements is not uniquely attributed: different processes involving interaction between tectonic, volcanic, hydrological and anthropic contributions are invoked to explain the observations. Some authors hypothesised an interaction between the CP and the active CF volcanic system, suggesting that the stress field induced by the major eruptions in the CF produced regional tumescence, subsequent detumescence followed by deformation processes in the caldera (resurgence). It is on the nature of this interaction between local and regional stresses that this work is addressed.
Constraints on the causative mechanisms responsible for the vertical movements may come from coupling geodetic (GNSS and InSAR) and gravity time lapse observations; the latter ones may provide clues on whether the ground movements are accompanied or not by mass changes.
In the frame of the project ESSENTIAL, funded by INGV-Ricerca Libera, we aim to acquire a new set of gravity measurements over the microgravimetric network of the CP. The CP network was established and measured for the first time in 1987/88 by the Osservatorio Vesuviano with the aim to provide a set of 20 gravity benchmarks useful for monitoring the gravity changes in time occurring in the area.
The network extends from Mt. Massico to Sorrento Peninsula (Castellammare di Stabia) and includes CF and Vesuvius encompassing an area larger than 1500 km$^2$.
The plan of the ESSENTIAL project is to use a combination of absolute and relative gravity measurements to obtain a time-lapse picture of the gravity changes throughout the past 35 years. Gravity effects associated to the vertical movements will be taken into account by means of co-located GNSS measurements. Comparisons with available InSAR data will be also considered.
In this contribution we show some preliminary results of a campaign of measurements using a Scintrex CG6 gravimeter: we illustrate the acquisition protocols and the results of the first data analysis.

# Imaging the Casamicciola seismogenic fault through 3D gravity inversion

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Ischia Island, located in the south-western end of Gulf of Naples, is an active volcanic island where the interplay between geothermal fluid circulation and the long-term evolution from caldera resurgence to present-day subsidence is associated with recurrent seismic activity, mainly in the northern sector. Following the Mt. Epomeo Green Tuff eruption (60-56 ka), the island experienced about 900 m of uplift driven by shallow magmatic intrusions and the development of a high-temperature geothermal system. Present-day subsidence and repeated damaging earthquakes (e.g., 1881, 1883, 2017) are concentrated along the Casamicciola seismogenic fault, at the northern base of the resurgent block. Recent studies [De Novellis et al., 2018; Carlino et al., 2022] indicate that this fault, dipping steeply to the south and rooted above the brittle-ductile transition, accommodates differential subsidence of the Mt. Epomeo block and represents a major locus of strain accumulation and release in a densely populated and touristic area.

As part of "MISS Casamicciola" project, a new high-resolution gravity dataset was acquired in 2024-2025, adding about 100 new stations to legacy data, achieving an observation density of ~18 sites/km² around the Casamicciola fault. Using multiple DEMs and an estimate of the reference terrain density derived from both classical and recent approaches, a complete Bouguer anomaly with detailed terrain corrections was computed. The resulting anomaly field, ranging from 65 to 80 mGal, shows high-frequency anomalies superimposed on long-wavelength signals from deeper sources. To isolate shallow contributions and enhance density contrasts, a regional gravity field estimated from a broader dataset was removed, yielding residual anomaly values. Edge-analysis techniques were then applied to the residual field, enhancing lateral density contrasts and highlighting structures likely associated with volcano-tectonic lineaments in the Casamicciola area.

The residual field was inverted using the SimPEG Python library [Cockett et al., 2015] to obtain a 3D density-contrast model of Ischia through Sparse IRLS (Iteratively Reweighted Least Squares) regularization on a topography-refined mesh. The inversion was constrained by activating only cells below topography, applying a depth-weighting function and imposing admissible bounds on density contrasts (±500 kg/m³), thus favouring geologically plausible solutions. In the sector north of Monte Epomeo, the model reveals high-density bodies (possibly related to Green Tuff deposits) to the south, separated by lower-density Quaternary and marine sediments north of the De Novellis et al. (2018) fault plane. The presence of sharp density contrasts across this boundary would support the interpretation of significant lateral density variations consistent with a seismogenic structure, providing new constraints on its geometry.

These results corroborate some previous interpretations of the Casamicciola fault as a lithological and rheological boundary between the faster-subsiding Mt. Epomeo block and the relatively stable northern coastal sector. This interpretation is consistent with independent structural, geodetic, and seismological evidence linking the repeated moderate-magnitude, high-intensity earthquakes to long-term subsidence, the latter might induce stress loading.

By resolving the geometry and density architecture of this boundary, the proposed gravity-based model provides key input for thermo-mechanical and multiphysics simulations of the deformation processes presently ongoing. Overall, this study highlights the effectiveness of high-resolution gravimetry and 3D inversion in imaging shallow seismogenic faults in volcanic environments. It also contributes to establishing a quantitative framework to refine seismic hazard assessment and risk mitigation strategies for the Casamicciola area and the wider Ischia caldera system.

This work was carried out within the PRIN 2022 PNRR project MISS Casamicciola (Multidisciplinary Investigations of the Seismogenic Structure of Casamicciola area, Ischia Island), under the Italian National Recovery and Resilience Plan (PNRR), Mission 4, Component 2, Investment 1.1, funded by the European Union - NextGenerationEU (CUP E53D23021900001).

# S09 - ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING FOR NEW DISCOVERIES IN VOLCANOLOGY

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# Predicting Volcanic Thermal Conditions via LSTM-SGAN Modeling from Multi-Sensor Satellite Time Series: Insights from the Vulcano Case Study (2016-2024)

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Surface heat transfer in volcanic systems is a continuous phenomenon that reflects the dynamic balance between the magmatic system and the surrounding rocks. In volcanoes, part of the magma's energy sustains fluid circulation, leading to elevated ground temperatures. Heat is mainly transported through conduction, convection, and radiation, each detectable through dedicated monitoring techniques. Convection is expressed in fumaroles and diffuse degassing zones, where moderate thermal anomalies point to conductive heat transfer, while radiative fluxes can be quantified using multispectral instruments.

On Vulcano Island, the continuous monitoring network has detected transient changes in heat flow from the active cone, associated with increased seismicity and ground deformation. Analysis of the resulting time series enabled the definition of three volcanic thermal states - Background, Minor Crisis, and Unrest - each corresponding to distinct thermal patterns observed at the La Fossa crater.

Building on these observations, we introduce a two-step methodology to forecast volcanic thermal states using Artificial Intelligence applied to satellite-based remote sensing. In the first step, Long Short-Term Memory (LSTM) neural networks predict future values of time series derived from multisensor satellite imagery. In the second step, a Semi-Supervised Generative Adversarial Network (SGAN), trained on the same satellite observations, classifies the LSTM-predicted sequences into volcanic thermal states.

The input time series include well-established satellite monitoring products, such as the Normalized Thermal Index (NTI) and Volcanic Radiative Power (VRP) from the VIIRS sensor, together with the NDVI, NDWI, and NDMI environmental indices produced from the Sentinel-2 MSI instrument. This framework leverages the temporal forecasting abilities of LSTM models and the robust classification performance of SGANs in settings with limited labeled data, enabling prediction of volcanic thermal state evolution solely from Earth Observation datasets. Preliminary results show that the combined LSTM-SGAN approach can reliably forecast and classify thermal states across multiple future time horizons.

# From DAS Data to Earthquake Localization: An AI-Based Processing Pipeline for Seismic Monitoring at Campi Flegrei

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Monitoring seismicity in active volcanic areas requires methods capable of handling large volumes of data while rapidly identifying and characterizing seismic events. In this study, we present a fully automated processing chain that starts from Distributed Acoustic Sensing (DAS) data and leads to the detection and localization of seismic events using Artificial Intelligence (AI) techniques.
The proposed pipeline consists of three main stages: phase picking, event association, and event localization. First, seismic phase arrivals are automatically identified from the DAS recordings using a deep learning-based picking model [Corsaro et al., "Seismic phases picking with artificial intelligence: A novel approach for distributed acoustic sensing data analysis." GC12-FibreOptic-82, 2024], trained to detect coherent phase patterns along the DAS channels. The detected picks are then associated across channels [Zhu et al., "Earthquake phase association using a Bayesian Gaussian mixture model." Journal of Geophysical Research: Solid Earth, 2022] to reconstruct consistent seismic events in space and time. Finally, a transformer-based model [Corsaro et al., "Deep Learning-Based Earthquakes Localization at Campi Flegrei via Distributed Acoustic Sensing", EGU, 2026] estimates the source parameters of each event, including origin time, hypocentral coordinates and magnitude. This data-driven localization approach leverages the dense spatial sampling of DAS measurements to infer event parameters directly from the distribution of picks along the channels.
Applied to DAS data from the Campi Flegrei area, the proposed pipeline demonstrates how AI-based methods can enhance the extraction and interpretation of seismic information while enabling rapid, scalable, and automated detection and localization of seismicity. Such capabilities represent a key step toward high-resolution and near-real-time monitoring of complex volcanic systems.

# A deep learning-based inversion model for instantly imaging the three-dimensional distribution of volcanic deformation sources

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Forecasting volcanic eruptions relies on rapid identification of where magma is stored and how it moves within the crust. The location and geometry of a magmatic source are typically inferred from ground deformation by applying an iterative optimization process to minimize the error between the estimated and measured displacement fields.
Among the geodetic observations to be inverted, continuous Global Navigation Satellite System (GNSS) measurements are the most commonly used for tracking fast magma movements. Nevertheless, inversion processes can be resource-intensive and time-consuming and, more importantly, can lead to under-constrained inversions when the GNSS station network is sparse and poorly distributed.
To overcome these limitations, we exploit machine learning and propose a shift in perspective: we present a deep learning-based inversion model for rapid imaging the three-dimensional distribution of volcanic deformation sources directly from just a few GNSS stations.
Trained and validated on synthetic displacement fields, the deep learning model requires no prior knowledge of the target volcano or the station configuration during the inference phase. Its potential and robustness have been demonstrated by the retrospective applications to the May 2008 eruption of Mount Etna and the Iceland intrusions in 2023-2024.

# A cluster-based framework for groundmass glasses: toward near-real-time petrological monitoring at frequently erupting volcanoes

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Near-real-time petrological monitoring represents a major frontier in volcanology, offering direct insights into magma composition during eruptions and into the processes driving eruptive activity, with clear implications for hazard assessment and crisis management. Here we develop and test a cluster-based framework using trace-element geochemistry of groundmass glasses from the 2020-2022 paroxysmal sequence at Mt. Etna as a case study. During this period, about sixty-two lava fountains were produced, providing a high-frequency, well-monitored eruptive time series. A dataset of LA-ICP-MS trace-element analyses of groundmass glasses was processed through hierarchical clustering to objectively identify recurrent compositional domains within the erupted products.

Rather than just redefining compositional end-members for each event, this data-driven approach quantifies temporal variations in the relative contribution of established melt populations. Three persistent compositional clusters were identified, including a more mafic domain whose abundance provides a robust geochemical proxy for effective magma recharge through the eruptive sequence. Event-resolved correlations between cluster abundances and physical eruptive parameters, ground deformation signals, and crystal size distribution analysis of erupted products indicate that fluctuations in the mafic cluster fraction reflect changes in magma recharge and transfer efficiency. The novelty of the clustering approach lies in its capacity to condense high-dimensional trace-element information into a limited number of geochemically distinguished groups that can be directly compared with major-element trends, isotopic signatures, mineral-scale records and monitoring signals. This integrated perspective reveals that magma recharge during the 2020-2022 sequence was not confined to isolated peak events, but occurred episodically and progressively, marked by appearances of mafic melts, hybridization during transitional phases, and alternation between slightly evolved and less evolved components throughout the eruptive sequence. In this way, clustering highlights aspects of magma dynamics that remain only partially resolved when individual geochemical proxies are considered independently.

Ultimately, this cluster-based framework can move from retrospective interpretation toward an operational tool for predicting and tracking magma supply. Beyond the specific case of Etna, this study illustrates how large, internally consistent datasets of groundmass glass, analysed through unsupervised learning, can be transformed into objective indicators capable to predict evolving magma dynamics. Although additional technological developments are required for full operational implementation, the framework proposed here represents a concrete step toward integrating high-dimensional glass geochemistry into near-real-time petrological monitoring at frequently erupting volcanoes.

# On the use of the ACE Climate Model Emulator to investigate the climatic impact of volcanic activity

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Volcanic activity can affect the climate system across multiple timescales, from rapid atmospheric fluctuations to long period responses driven by stratospheric aerosol forcing. Rapid evaluation of the atmospheric response to major eruptions calls for approaches that combine physical understanding with efficient predictive tools. Predicting and quantifying these impacts using numerical Earth System Models (ESM) remains computationally expensive, limiting the exploration of uncertainty and sensitivity across different eruption scenarios.
In recent years, machine-learning-based climate emulators have emerged as a promising alternative to traditional numerical models, enabling fast predictions of atmospheric evolution. State-of-the-art emulators, such as the AI2 Climate Emulator (ACE), are trained on outputs from climate model simulations or on reanalysis datasets such as ERA5, which provide realistic representations of the atmospheric state. However, applying such approaches to volcanic forcing poses a challenge. Major explosive eruptions are rare in the historical record, resulting in limited training examples and making it difficult for data-driven models to capture the atmospheric response to these extreme perturbations. Therefore, it remains unclear whether models trained without volcanic forcing can accurately reproduce the atmospheric dynamics associated with volcanic eruptions.
Here, we investigate the potential of machine-learning-based atmospheric emulators for studying the climatic response to volcanic perturbations. We explore the response of the pre-trained ACE model [Watt-Meyer et al. 2025, npj Climate and Atmospheric Science 8.1 (2025): 205] across multiple historical windows characterized by different volcanic and climatic conditions, including periods influenced by major eruptions such as Mount Pinatubo (1991) and background periods without significant volcanic activity. We analyze the temporal evolution of 2 m air temperature and compare global and local mean time series across different initialization periods to evaluate the stability and sensitivity of the emulator. Additional experiments explore ensemble simulations and the consistency of the simulated atmospheric response under different initial conditions. Preliminary results suggest that the emulator response depends on the selected initialization periods and exhibits variable sensitivity in reproducing temperature anomalies associated with volcanic forcing. These analyses also provide insights into how different temporal selections of the training data may influence the model representation of climate responses to volcanic forcings.
These experiments represent a first step toward evaluating the capability of machine-learning climate emulators to reproduce the atmospheric response to major volcanic eruptions. The results highlight both the opportunities and current limitations of data-driven atmospheric models and outline a methodological framework for future ensemble-based sensitivity analyses of eruption scenarios.

# Advanced AI-based downscaling approaches, including emerging quantum-inspired methods, to study volcanic systems and their impacts on climate

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The high complexity of volcanic systems, with an intricate interplay of physical and chemical processes, lead to a variety of eruption styles with different associated hazards. Volcanic activity is diverse, ranging from effusive eruptions, which pose significant risks to proximal areas, to large-scale explosive events with impacts on the atmosphere and global climate. In particular, major explosive eruptions, characterized by the massive injection of sulfur dioxide ($SO_2$) into the stratosphere, have historically driven pronounced surface cooling due to the formation of sulfate aerosols (e.g., the 1991 Pinatubo eruption). The investigation of these processes is often constrained by the limited availability of observational data, as well as by the high computational cost and uncertainties associated with numerical climate simulations. Recent advances in Artificial Intelligence (AI) provide new opportunities to bridge the gap between data availability and model resolution, enabling more efficient and flexible representations of complex geophysical processes. In this context, emerging quantum-inspired and hybrid quantum-classical approaches are also being explored as potential tools to enhance the representation of non-linear relationships in data, although their application remains at an early stage. Here, we present an integrated framework that combines data-driven AI techniques with satellite and reanalysis data to investigate the climatic impacts of large explosive eruptions. The proposed approach is based on AI-driven downscaling and super-resolution methodologies aimed at deriving high-resolution information from coarse-resolution datasets, such as ECMWF ERA5 reanalysis. In particular, we implement convolutional neural network (CNN)-based models to downscale near-surface temperature fields from ~1.0° to ~0.25° resolution, with the objective of better resolving spatial patterns associated with volcanic forcing, using the Pinatubo eruption as a reference case. Preliminary results show that deep learning-based super-resolution approaches are able to enhance the spatial detail of temperature fields and improve the representation of fine-scale variability potentially linked to volcanic aerosol forcing. In addition, different CNN-based architectures (including ResNet and ConvRNN models) are compared to assess their performance in reconstructing spatial patterns and capturing temporal evolution. Exploratory tests with hybrid quantum-classical components are also discussed as a possible extension for handling complex data structures. The integration of observations with AI-based and physics-informed modeling provides a promising framework for improving the understanding of volcanic impacts on climate, with potential applications in climate analysis, hazard assessment, and the development of more efficient predictive tools.

# Enhancing Volcanic $SO_2$ Plume Quantification Using Sentinel-5P TROPOMI and Vision Foundation Model

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Volcanic eruptions release large amounts of sulfur dioxide ($SO_2$) and thermal energy into the atmosphere, influencing atmospheric chemistry, aerosol formation, and the Earth's radiative balance. Monitoring these emissions is essential for understanding eruption dynamics, assessing their climatic impacts, and enhancing early warning capabilities. Satellite-based Earth observation systems, particularly Sentinel-5P with its TROPOspheric Monitoring Instrument (TROPOMI), provide global observations for detecting volcanic $SO_2$ emissions. However, commonly used detection approaches, can lack robustness and have difficulty generalising across different volcanic environments.

Here, we present a zero-shot scene segmentation approach for volcanic plume detection based on the Segment Anything Model 2 (SAM2), a vision foundation model pretrained on large-scale visual datasets. Without any task-specific retraining, SAM2 effectively identifies and segments volcanic $SO_2$ plumes in Sentinel-5P imagery using a dedicated prompting strategy that guides the recognition process. The method performs well across a range of eruptive scenarios, from compact and well-defined plumes (e.g., Mount Etna and Shishaldin) to highly dispersed plumes extending over several hundred kilometres, such as those produced during the Hunga Tonga eruption. Preliminary results show enhanched results with respect, existing methods, while enabling near-real-time processing and eliminating the need for large labeled training datasets. These results demonstrate the potential of general-purpose vision foundation models for scalable and transferable analysis of volcanic emissions from satellite observations. The approach highlights how emerging AI-driven methodologies can support automated, near-real-time monitoring of volcanic activity and opens new opportunities for integrating foundation models into operational volcanic surveillance and Earth observation workflows.

# High-Resolution Thermal and Gas Monitoring of Volcanoes Using Multi-Sensor Super-Resolution and Cross-Modal Learning

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Super-Resolution (SR) models are advanced image processing techniques widely used in satellite-based volcano observation to enhance the spatial detail of remotely sensed data. In this work, we propose a unified deep learning framework that addresses two related but conceptually distinct tasks: (i) thermal-to-thermal super-resolution and (ii) cross-modal reconstruction of volcanic gas concentrations.

Thermal Infrared (TIR) observations are extensively used for monitoring volcanic activity, but their spatial resolution is often insufficient to resolve fine-scale features such as localized hotspots, eruptive vents, and narrow lava flows. Geostationary sensors, such as SEVIRI onboard Meteosat Second Generation, provide high temporal resolution and long-term continuous coverage, albeit at coarse spatial resolution (3 km). The newer Flexible Combined Imager (FCI) onboard Meteosat Third Generation offers improved spatial resolution (1 km), though over shorter time series.

The first task addressed in this study is a thermal-to-thermal super-resolution problem, in which a deep Residual Neural Network (ResNet) is trained to enhance SEVIRI TIR observations by leveraging higher-resolution FCI data. This approach enables the reconstruction of high-spatial-resolution thermal time series from historical SEVIRI archives, preserving their intrinsic high temporal frequency while significantly improving the detection and tracking of small-scale thermal anomalies.

The second task extends beyond classical SR and is formulated as a cross-modal, cross-sensor reconstruction problem. Volcanic gas emissions, particularly sulfur dioxide ($SO_2$), are key indicators of eruptive activity and are commonly retrieved from ultraviolet (UV) measurements acquired by polar-orbiting sensors such as TROPOMI. However, these observations are characterized by low temporal resolution. In this work, we exploit the high-frequency sampling of geostationary TIR observations to infer the spatio-temporal distribution of $SO_2$. A ResNet-based model is trained to learn the relationship between thermal radiances and gas concentrations, enabling the estimation of high-resolution, high-frequency $SO_2$ fields consistent with geostationary acquisition rates.

A key strength of the proposed framework lies in the closure of the spatial-temporal and cross-sensor gap. The model trained to map FCI radiances to $SO_2$ concentrations can be consistently combined with the thermal super-resolution module. In particular, SEVIRI observations can first be enhanced to FCI-like spatial resolution through the SR model and subsequently used as input to the cross-modal network to retrieve the corresponding $SO_2$ concentrations. This sequential application effectively enables the reconstruction of high-resolution gas emission time series from long-term SEVIRI archives, extending quantitative monitoring capabilities to periods preceding the availability of FCI measurements. By combining SR for thermal enhancement with cross-modal learning for gas reconstruction, the proposed framework enables the generation of consistent, high-resolution spatio-temporal datasets that integrate complementary information from heterogeneous satellite platforms, both in the present and in the past.

The methodology is applied to the case study of Mt. Etna, characterized by persistent degassing and frequent Strombolian activity. Results demonstrate the capability of the approach to capture the spatio-temporal variability of both thermal anomalies and $SO_2$ emissions, improving both retrospective analysis and near-real-time monitoring.
Overall, this work highlights how SR techniques can be effectively coupled with cross-modal data fusion strategies to overcome the intrinsic limitations of individual sensors, representing a significant step toward more comprehensive and physically consistent volcanic monitoring from space.

# Detecting volcanic phenomena through QCNN and Satellite Multispectral Imagery

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Recent advances in quantum computing are opening new possibilities for Earth Observation (EO) data analysis. By leveraging quantum mechanical properties such as superposition and entanglement, quantum machine learning (QML) methods introduce new strategies for processing complex datasets. These capabilities have motivated to explore whether quantum-enhanced models can help address long-standing challenges in satellite remote sensing, where the nonlinear relations between spectral and spatial features are complex and need advanced techniques to be unveiled.

EO systems play a fundamental role in monitoring volcanic activity on a global scale. Satellite observations are essential for aviation risk mitigation, hazard monitoring, rapid eruption response, and assessing the environmental and climatic consequences of volcanic events. Data collected from both geostationary and polar-orbiting satellites enable the observation of a wide range of volcanic processes, from the propagation of lava flows to the dispersion of volcanic clouds in the atmosphere. However, reliably classifying volcanic phenomena from satellite imagery remains difficult due to the variability of eruption signals and the relatively limited spectral resolution of some sensors, particularly geostationary instruments.

To address these challenges, this study explores the use of hybrid Quantum Convolutional Neural Networks (QCNNs) for the classification of satellite imagery containing volcanic features observed across different temporal, spectral, and spatial scales. The proposed architectures combine classical convolutional neural networks with quantum computational layers to automatically recognize the volcanic phenomena taking place, using a hybrid learning framework. Specifically, volcanic phenomena, including volcanic clouds, lava lakes, lava flows, and intracrater activities, are automatically recognized using geostationary and polar-orbiting satellite data. Experiments are conducted using datasets acquired from FCI, SEVIRI, Sentinel-2 MSI, and Landsat 8-9 sensors, including images of volcanic clouds (ash, $SO_2$, or mixed compositions), non-volcanic backgrounds, as well as thermal volcanic phenomena, including lava flows, lava lakes, and intracrater activities.

Several QCNN configurations are trained and evaluated, varying the number of qubits and quantum layers in order to analyze their classification performance and computational efficiency. The results are further compared with those obtained from conventional deep learning architectures. The study found that QCNNs outperform traditional models with the same number of trainable parameters and remain robust even when trained on small datasets. The findings indicate that hybrid QCNN models represent a promising direction for volcanological remote sensing and establish a basis for future research, particularly as quantum hardware capabilities and next-generation satellite missions continue to advance.

S09 - Oral Presentation

# Automated Tracking of Explosive Parameters: A High-Frequency Thermal Infrared Workflow for Impulsive Explosions

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Ordinary explosive activity at Stromboli volcano is characterized by high-frequency, impulsive, multi-vent eruptions showing a variety of magnitudes and styles. Manual analysis of over 500 explosions (2019-2024) using punctual, high-frequency multiparametric time series (thermal, UV, acoustic) has revealed that eruptive vigor (velocity, height, frequency) and style scale with geophysical observables, such as degassing and acoustic signals, and vent geometry. To leverage these insights across Terabyte-scale datasets, we present a novel, automated analytical workflow designed to extract key physical parameters with high precision and minimal manual revision.
The approach integrates signal processing and physics-based modeling to quantitatively extract validated eruptive metrics from raw thermal kymographs. A multi-peak detection algorithm based on local prominence in mean column radiance is coupled with adaptive event onset/offset identification. To capture complex Strombolian dynamics, the code employs a dual-modeling: a linear fit isolates the initial gas-thrust phase (0.5 s), while a quadratic fit models the full trajectory of the temperature anomaly. Further, a specific correction addresses field-of-view (FOV) clipping, by identifying and removing artificial "plateaus" in the tracked thermal anomaly front when products exceed the upper frame boundary. In this way the model reduces the underestimation of the initial velocity and maximum height.
The workflow distinguishes actual explosions ($R^2 > 0.8$) from false events through automated quality control. Currently optimized for Type 0 (gas-rich) and Type 1 (ballistic-rich) events, this framework reduces processing time from weeks of manual picking to minutes of automated analysis. This tool enhances the recognition of eruptive patterns and hazard assessment in near-real-time, enabling rigorous comparison with historical datasets. We demonstrate its efficacy using data from the May 2024 Stromboli campaign, where continuous acquisitions yielded a database of over 1,000 events analyzed automatically.

# Kilauea 2024-2025 lava fountains: preliminary insights from satellite observations, machine learning, and ground-based validation

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Lava fountains are one of the most spectacular volcanic manifestations of sustained jets of gas-melt mixtures that can rise several hundred meters above the eruptive vent. These events are typically short-lived, lasting from less than an hour to a few hours. However, in some cases lava fountains can persist for several hours and occur repeatedly during prolonged eruptive sequences. A notable example is the Halema'uma'u crater (Kilauea volcano; Hawai'i), which between December 2024 and March 2026 produced 43 lava fountaining episodes, some lasting more than nine hours. Beyond their eruptive dynamics, lava fountains also represent significant sources of volcanic gases and aerosols that can influence the atmosphere. It is widely recognized that volcanic eruptions are major natural drivers of climate variability and influence atmospheric composition, radiation balance, and global and regional climate systems. While large explosive eruptions dominate global climatic signals, smaller and more frequent basaltic events can produce regional-scale perturbations, especially where topography and geographic isolation modulate the circulation and residence time of volcanic pollutants. Hawai'i represents a uniquely suitable natural laboratory for this purpose: its combination of steep relief, persistent trade winds, and insular setting creates conditions in which volcanic $SO_2$, aerosols, and wind-advected tephra are easy to detect and quantify.

In this study, we focus on the first 39 lava fountain events that occurred in Halema'uma'u crater crater during the period 2024-2025, representing one year of eruptive activity. These events offer a unique opportunity to study how moderate basaltic eruptions affect atmospheric composition and regional climate dynamics in the short term. We used a multidisciplinary approach combining multisensor satellite observations (GOES, TROPOMI, Sentinel-2 MSI) with artificial intelligence algorithms to retrieve key eruptive parameters, including Volcanic Radiative Power (VRP), Time-Averaged Discharge Rate (TADR), erupted volume, cloud height, $SO_2$ mass, and ash dispersion. These satellite-derived measurements are contextualized with local environmental data, including temperature and precipitation, to explore potential short-term atmospheric impacts.

Ground-based observations provide additional constraints, including high-resolution video analysis capturing eruptive precursors, fountain height, plume rise, and ash fall patterns. Video sequences are processed with artificial intelligence-based algorithms to extract time-resolved metrics of eruptive dynamics, generating robust datasets that complement and calibrate satellite measurements.

Here, we present the preliminary dataset and initial observations from this integrated monitoring framework. Our approach yields a high-resolution characterization of lava fountain dynamics, volcanic plume behavior, associated gas and aerosol emissions, and localized atmospheric impacts. By combining satellite data, ground-based video analysis, machine learning-driven

processing, and local environmental data, this methodology demonstrates the potential to enhance monitoring and improve our understanding of volcanic processes in topographically complex island environments. The results lay the foundation for more comprehensive studies of future eruptive episodes and their influence on local and regional atmospheric conditions.

# Advanced AI-Based Techniques for Mapping 400 Years of Mount Etna Lava Flows Using High-Resolution Satellite Imagery

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Effusive eruptions are among the most dynamic and complex volcanic processes on Earth. Dating lava flows is essential for reconstructing the eruptive history of a volcano and for improving theassessment of hazards in exposed areas. Traditional dating methods- such as radiometric techniques, lichenometry, and obsidian hydration - provide reliable estimates but require direct sampling, costly analyses, and long processing times, making them often impractical in remote settings or for real-time monitoring. Over past decades, satellite remote sensing has transformed the study of volcanoes thanks to the ability to monitor vast volcanic areas continuously, non-invasively, and at high resolution. Multispectral sensors such as Sentinel-2 acquire information across the visible, near-infrared, and shortwave infrared regions, revealing reflectance variations, i.e., spectral signatures, associated with the composition, thickness and age, and surface evolution of lava flows. Recent flows, which lack vegetation and are highly exposed, exhibit spectral signatures distinct from those of older flows, which are progressively altered, eroded, or covered by soil and vegetation. Analyzing these signatures makes it possible to distinguish flows of different ages and to trace the eruptive evolution of a volcanic system over time. Here, we propose an innovative approach based on Machine Learning (ML) algorithms for the automatic dating of lava flows using high-resolution multispectral imagery. The case study focuses on Mount Etna (Sicily, Italy), where representative areas corresponding to individual lava flows from the past four centuries were selected. A Random Forest, a supervised ML algorithm, was trained to recognize spectral signatures associated with different chronological classes, distinguishing lava flows from various periods based on their multispectral characteristics. The proposed approach allows the rapid production of detailed chronological maps of lava flows, representing a significant advancement over traditional techniques for dating volcanic surfaces.

# S10 - CHALLENGES AND NEW WAYS TO UNDERSTAND THE DYNAMICS OF CAMPI FLEGREI CALDERA

Conveners:

Guido Giordano, Roberto Isaia

# Longevity, evolution and eruption potential of the Campi Flegrei caldera

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The longevity of volcanic activity at calderas provides first order information on the potential for eruptions of different magnitudes to occur. Yet this parameter is commonly severely underestimated for the limited access to the oldest volcanic sequence, collapsed within caldera depressions and/or buried by younger deposits. In this paper we reassess the longevity at Campi Flegrei, arguably the caldera most at risk on Earth, by determining the age and composition of accessory lithics and xenocrystals. We show that magmatic activity started at least 796 ± 100 ka, extending previous knowledge by more than 500 kyrs. Ages distribution and magma compositions indicate that the Campi Flegrei plumbing system evolved over time reaching thermal maturation for a caldera system in the last 100-150 ka, at an average eruption rate of 9.14 x 10-4 $km^3$/yr, and maintaining its potential for future VEI7 caldera-forming eruptions.

# Birth and growth of a volcano-tectonic fault within the deformation pattern during the current volcanic unrest at Campi Flegrei caldera (Italy)

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In the world, thousands of people are exposed to volcanic risk. Among all volcanic systems, calderas are some of the most complex and dangerous, because when they enter in unrest, we observe variation in hydrothermal system that cause ground uplift, earthquakes, gas changes and we do not clearly understand how this unrest evolves or when it is going to an eruption.
The ongoing volcanic unrest at the densely populated Campi Flegrei caldera is characterized by increasing seismic activity, progressive ground uplift, and geochemical anomalies. These factors raise significant concerns regarding volcanic hazard assessment.
In this study, we analyze the locations of earthquake hypocenters from 2019 to 2025. We use an unsupervised least squares method combined with an iterative Monte Carlo approach to investigate the spatial distribution of seismicity during the current phase of unrest.
The results show that, since 2023, seismic activity has progressively clustered along a preferential plane near the center of the caldera. This structure accounts for more than 50% of recorded seismic events and released seismic energy.
This result indicates a transition from diffuse microseismicity to the early development of a volcano-tectonic fault. This suggests that the caldera rocks may be approaching critical failure conditions. This is a significant change from the symmetric deformation that characterized the uplift phase until 2023.
Furthermore, we used the spatial distribution of GNSS stations to reconstruct the temporal evolution of ground deformation to investigate its relationship with the observed seismicity patterns.
This combined seismic and geodetic analysis provides a new perspective on the evolving deformation regime and has important implications for hazard assessment at Campi Flegrei.

# Neapolitan Yellow Tuff revisited: a new look to stra tigraphy and eruptive dynamics of a complex eruption of Campi Flegrei caldera (Italy)

Roberto Sulpizio[1], Gino Steven Gonzalez Ilama[2], Biagio Giaccio[3], Roberto Isaia[2], Federico Lucchi[4], Jacopo Natale[9], Antonio Costa[5], Pierfrancesco Dellino[1], Daniela Mele[1], Lorenzo Monaco[3], Vincenzo Amato[6], Sebastien Nomade[7], Alison Pereira[7], Giuseppe Siani[8]

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Large explosive eruptions represent some of the most extreme geological phenomena on Earth and provide fundamental insights into the dynamics of silicic magmatic systems. The Neapolitan Yellow Tuff (NYT) eruption of the Campi Flegrei caldera (southern Italy) is the largest magnitude explosive event in the last 15 ky, and is widely considered responsible for the collapse of part of the caldera. Despite decades of investigation, important uncertainties remain regarding the stratigraphic architecture, eruptive dynamics, erupted volume, and the mechanisms of caldera collapse associated with this eruption.

In this study we present a comprehensive reappraisal of the NYT eruption based on new stratigraphic observations, laboratory analyses, and a critical synthesis of previous work. Seventeen stratigraphic sections were investigated from proximal areas inside the caldera to distal locations up to ca. 80 km from the source. The study integrates lithostratigraphic observations with grain-size analysis, componentry, vesicle size distribution from X-ray micro-computed tomography (micro-CT), morphoscopic analysis of ash particles using scanning electron microscopy (SEM), glass geochemistry obtained through electron microprobe analysis, and new radioisotopic ages ($^{14}C$ and $^{40}Ar/^{39}Ar$).

The NYT succession is composed of four main eruptive units recording distinct eruptive stages. Glass compositions range from trachyte to phonolite and define four main compositional clusters (Magmas A-D), indicating the involvement of multiple magma batches within a heterogeneous plumbing system rather than a simple compositionally zoned reservoir. Vesicle size distributions in pumice clasts reveal evidence for late-stage bubble nucleation and suggest magma fragmentation at shallow depths, likely within the upper 2-3 km of the crust. SEM observations of ash particles show a dominance of vesicular pumice fragments with limited occurrence of blocky particles, indicating that fragmentation was primarily controlled by magmatic processes rather than by extensive magma-water interaction.

Integration of field data with borehole stratigraphy allows a new estimation of the erupted volume. Excluding anomalously thick values derived from poorly constrained borehole logs, the best-confidence bulk volume of NYT deposits is estimated at approximately 25 $km^3$, corresponding to about 16 $km^3$ dense rock equivalent. This value is significantly lower than previous estimates exceeding 40 $km^3$ DRE. Thickness distribution and isopach reconstruction suggest a main vent area located in the Agnano Plain sector of the caldera.

These results indicate that the NYT eruption was dominated by pulsatory explosive activity that progressively evolved into pyroclastic density current-dominated deposits. The revised eruptive volume and the spatial distribution of deposits support a piecemeal collapse of the central caldera sector rather than a single piston-like subsidence. This new framework provides improved constraints on the eruptive dynamics and structural evolution of the Campi Flegrei caldera and contributes to a better understanding of large explosive eruptions in resurgent caldera systems.

# Gravity-height variations inferred form time-lapse measurements during the ongoing Campi Flegrei caldera unrest

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We examine long-term time series of gravity changes and height-gravity gradients derived from repeated time-lapse surveys conducted at the Campi Flegrei caldera (CFc) between 2015 and 2025. We take advantage of ground based gravity observations, undertaken twice per year over a network of about 30 benchmarks displayed over the caldera, coupled with ground uplift data as seen by DInSAR and GNSS. The objective is to investigate the origin of the current unrest phase, which has been ongoing since 2005, and to determine whether it is driven by hydrothermal activity, magmatic intrusion, or a combination of both.
To constrain the mass changes and density of the source responsible of the unrest we adopt a comprehensive modelling strategy that employs a coupled solution of the surface displacement and gravity changes induced by an inflating ellipsoidal source in a homogeneous medium. These simulations allow us to predict gravity height gradients as a function of the source parameters overcoming the overly too simplistic spherical approximation. The analysis reveals a strong dependence of gravity gradients on the geometry of the source, implying that gradient value may not be uniquely ascribed to a certain source of density. We also found that a relevant spatial modulation of the gradients is present in case of non-spherical sources.
Finally, we compared the observed gravity gradients with a set of simulated gravity gradients, calculated using the source parameters according to recently published works [i.e. Giudicepietro et al., 2024; Astort et al., 2024] that analyzed the geodetic data in CFc.
Our findings suggest that the present unrest involves mass changes within the source with a density that strongly depends on the source aspect ratio. More oblate sources imply a large contribution of low-density hydrothermal fluids, while ellipsoidal and spherical-like sources may imply presence of magmatic components. More broadly, this study underscores the complexity of interpreting gravimetric data. The proposed approach proves effective for evaluating unrest scenarios in settings where gravity variations are coupled with significant deformation, as observed at Campi Flegrei, one of the world's most hazardous volcanic regions.

# Unrest at Campi Flegrei caldera as a factor for a phreatic/ hydrothermal event within the Accademia-Solfatara area

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Explosive eruptions can occur with different, mechanisms, energy and magnitude, and consequently their impact may involve more or less large areas of the affected territory. Phreatic explosive eruptions are considered to be among those with the lowest magnitude and impact, although unfortunately they have recently caused casualties in several areas of the world. Their unpredictability and the impossibility, to date, of identifying precursor phenomena useful for specific monitoring of these events, greatly increases the volcanic hazard associated with them.

Volcanoes characterized by active surface geothermal systems are environments particularly prone to favor the possibility of phreatic and/or hydrothermal explosive events occurring. Many active calderas host widespread fumarolic and hydrothermal activity as a surface expression of the interaction between hot fluids of deep magmatic origin, surface aquifers, and fault or fracture zones in the shallow crust. The Campi Flegrei caldera has generated during its recent eruptive history phreatic explosive events, concentrated principally in its central sector. The Solfatara volcano was delineated as a result of the succession of phreatic events of varying energy that led to the formation of a maar/diatreme-type structure.

The Solfatara-Accademia area represents the most active hydrothermal sector of the Campi Flegrei caldera, characterized by intense fumarolic activity, shallow seismicity and localized deformation. Past phreatic and hydrothermal events, together with the behavior observed during recent unrest episodes, indicate that this sector may evolve through processes partly decoupled from caldera-scale dynamics, making it a key target for investigating shallow hydrothermal instability. Three-dimensional resistivity models obtained by magnetotelluric (MT/AMT) surveys, performed within INSIDE OUT project, in the framework of the INGV-MUR project Pianeta Dinamico, delineate a complex near-surface architecture characterized by laterally extensive conductive layers, interpreted as clay-rich, low-permeability caps, locally disrupted by resistive structures that connect deeper geothermal reservoirs to the surface. These features define preferential pathways for fluid and gas ascent and highlight strong lateral heterogeneities over short spatial scales.

Time-lapse MT observations reveal temporal variations in electrical resistivity within the uppermost crust, interpreted as changes in fluid circulation, gas flux and permeability conditions in the shallow hydrothermal system. Gravity monitoring showed largest gravity changes in time-span 2021-2025 located in Accademia-Solfatara area, while gravity time-series may suggest cycles of mass accumulation & discharge (with relevant amplitudes). These resistivity and gravity variations spatially correlate with zones of enhanced fumarolic activity, clusters of shallow earthquakes, and localized deformation anomalies in the Accademia sector. The observed patterns suggest a dynamic interplay between fluid ascent, diffusion and self-sealing processes within shallow cap layers, potentially leading to transient pressure build-up at shallow depths, complementing caldera-scale observations and improving the characterization of potentially unstable shallow zones in densely urbanized areas of Solfatara-Accademia.

Integration of structural observations, geophysical imaging and monitoring data, with particular

emphasis on time-lapse magnetotelluric and gravity surveys indicate that the Solfatara-Accademia area represents a structurally controlled, shallow hydrothermal domain whose evolution may play a primary role in the development of localized phreatic or hydrothermal explosive activity as possible eruptive scenario for the investigated area.

# Reservoir configuration, trigger mechanisms, and timescales of shallow magma transfer at Campi Flegrei caldera, Italy

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Since 2005, Campi Flegrei (Italy) has experienced persistent volcanic unrest marked by earthquake swarms reaching magnitudes up to 4.6 and ground uplift rates of 10-30 mm per month, for a total uplift of approximately 160 cm. With around 500,000 residents living within the designated red zone, accurately assessing how this crisis may evolve - and identifying potential eruption-triggering mechanisms - is of critical importance for public safety. In this study, we apply machine-learning clinopyroxene-only thermobarometry [Agreda-Lopez et al., 2024] to pyroclastic samples collected from the opening and upper units of emblematic eruptions spanning diverse ages, styles, intensities, and locations within the caldera.
Clinopyroxenes from opening and upper units display comparable Mg# values, though upper units exhibit more homogeneous distributions. Thermobarometric estimates indicate that all eruptions were preceded by magma storage at shallow depths of 1-2 kbars (4 km). Except for Monte Nuovo and Agnano Monte Spina, clinopyroxenes from opening units also record the extraction of hot magma (1100 °C) from depths exceeding 2.5 kbar (i.e., 8 km). High-intensity eruptions, such as the Neapolitan Yellow Tuff, show bimodal crystallization temperature distributions separated by a clear gap at 900-1000 °C. Only Agnano Monte Spina and Monte Nuovo exhibit petrological evidence for eruptions triggered by external processes, such as elastic crustal weakening [Kilburn et al., 2023]. Notably, the Campanian Ignimbrite displays continuous temperature estimates similar to low-intensity eruptions (e.g., Solfatara, Santa Maria delle Grazie, Averno 1), suggesting that reservoir configuration alone does not control eruption magnitude - and that surface deformation, governed by shallow plumbing dynamics, may not directly correlate with future eruption size. Thermal and statistical modelling were used to estimate the timescales of magma accumulation at 4 km depth preceding the different eruptions. The shallowest magma emplacement depths align with the current source of seismicity and ground deformation, while deeper storage levels match those imaged by seismic and recent magnetotelluric surveys (Isaia et al., 2025), reinforcing strong links between petrological and geophysical data. We infer that the volume of eruptible magma stored within the mid-lower crustal reservoir is a key parameter for estimating future eruption intensity. The timescales of magma accumulation at depth of about 4 km calculated with our approach, suggest that eruptions can be preceded by multidecadal unrest periods. This study provides new constraints on preferred magma pathways and plausible eruptive scenarios - essential for volcanic hazard assessment and risk mitigation.

# The incremental caldera forming of the Neapolitan Yellow Tuff (Campi Flegrei, Italy)

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The Neapolitan Yellow Tuff eruption (NYT; 14.0 ka, 20 km$^3$) is considered the last major eruption of the Campi Flegrei caldera (CFc; Italy), which formed a caldera. Between Masseria del Monte (ca. 30 ka, 18 km$^3$) and the NYT, a succession of pyroclastic deposits have been found in the peripheral area of the CFc and in some cores of distal records. However, it's still not clear how these eruptions occur in the proximal area and thus how to understand their eruptive dynamics. Here, we analysed new proximal outcrops and two new cores located more than 100 km from CFc, where it was possible to identify a number of eruptions prior to NYT. We combined field correlation, componentry, chemical glass composition and isotopic radiometric dating. We found that at least five high-magnitude eruptions (1 km$^3$) in a time span of ca.1 ka preceded the formation of the main NYT eruption. Many of these eruptions show a similar chemical composition and components to the NYT, suggesting a similar source or feeding system for the NYT. The ages also indicate a very short time span for this sequence of eruptions. This new finding may indicate that a series of eruptions can lead to the formation of a caldera, rather than a single large catastrophic event.

# 25 Years of Multi-sensors Thermal Infrared Satellite Time Series for Monitoring the Volcanic Unrest at Campi Flegrei Caldera

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Continuous surveillance of volcanic unrest indicators is essential for understanding the ongoing magmatic and thermal processes. Satellite Thermal Infrared (TIR) data provide a valuable tool for monitoring surface temperature changes in volcanic environments, offering observations over extended time periods.
This study analyzes 25 years of Land Surface Temperature (LST) time series to investigate the thermal signal associated with the volcanic activity in the Solfatara area of Campi Flegrei caldera, located west of Naples (Italy). LST obtained from ASTER (2000-2025, 127 scenes), Landsat 8 and 9 (2013-2025, 154 scenes), and ECOSTRESS (2018-2025, 119 scenes) were integrated to a single time series of 400 clear sky acquisitions, combining the long-term observational capability of ASTER and Landsat with the higher temporal and spatial resolution of ECOSTRESS.
To increase the number of available observations, TIR datasets with different spatial and temporal resolutions were harmonized into a single consistent time series. To ensure reliable thermal signal interpretation, atmospheric correction, image co-registration, and seasonality removal procedures were applied.
Seasonal variation represents a major factor when analyzing LST time series and can mask subtle thermal anomalies related to volcanic processes. This effect was mitigated using a reference thermally stable background area, unaffected by volcanic surface thermal activity. The LST time series was then analyzed to identify long-term trends and possible anomalies associated with documented unrest episodes. In addition, a statistical approach based on standard deviation analysis over Regions of Interest (ROI) centered on the main Solfatara thermal hotspots was applied to detect significant thermal outliers.
Results show thermal anomalies over the entire time series related to the continuous degassing activity in the La solfatara area. Furthermore, thermal data show an increase in both the maximum and the mean temperature above background of the La Solfatara area since 2023, highlighting the onset of a thermal unrest.
These results demonstrate that the integration of multi-sensor TIR datasets represents an effective and reproducible approach for monitoring active volcanic systems. The complementarity of sensors with different spatial and temporal characteristics significantly enhances the capability to detect surface indicators of volcanic unrest, contributing to a more integrated understanding of the Campi Flegrei system and supporting improved hazard assessment strategies.
Future space missions operating in the thermal infrared spectral range will further enhance this capability by combining higher spatial resolution (equal or better than 60 m) with shorter revisit times.

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S10 - Oral Presentation

# Campi Flegrei Nomenclature to forecast volcanic eruption

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The Campi Flegrei volcanic district includes insular (Ischia and Procida Islands) and peninsular volcanic activity (Campi Flegrei volcanic field), and it is linked to the older activity on Ponza Island. The history of this area has been studied in detail since the eruption of the Campanian Ignimbrite (CI, age: 39 ky BP, volume: 200 - 300 $km^3$), which makes one of the most powerful eruptions in Europe. The Neapolitan Yellow Tuff (NYT: age: 15.0 ky BP, volume: 50 $km^3$), another powerful eruption occurred. Activity younger than the NYT can be subdivided in three epochs which include 70 recognized ephemeral eruptions. The volume of these individual eruptions is between 0.4 and 1 $km^3$ (DRE). Probably, the long-lasting magma reservoirs (i.e., CI and NYT) represent eruptions that are fed by deep magma reservoirs. In deep reservoirs (>10 km), magmas stagnate, differentiate and are modified by crustal components (Hercynian basement). The long-lasting reservoirs are also the ones that feed the ephemeral shallow magmatic system (2 - 5 km) that gave rise to the post-caldera magmatic epochs. However, the magmas of the post-caldera epochs are isotopically heterogeneous and consists of several components (i.e., least evolved (as an example the Minopoli eruption, 9500 y BP), CI, and NYT components). There is mixing between ephemeral shallow reservoirs and long-lasting reservoirs leading to explosive eruptions. The concentration of earthquakes and the deformation history suggest that Campi Flegrei could erupt again with an ephemeral eruption, especially if the uplift reaches 5-6 m as in the Monte Nuovo eruption and its associated uplift in 1970-72 and 1983-84. Although, the bradyseism phenomena had started by 1946 AD. It accelerated with much faster uplift during the seventies and eighties and until today. Present estimation envisages three scenarios: A) No eruption- and the bradyseism will stop. B) An eruption like Monte Nuovo eruption will occur around Solfatara volcano. C) The distribution of the earthquakes (ten thousand events) mimic a caldera smaller than NYT but big enough to cause a disaster around the Napolitan area (from Campi Flegrei to Naples).

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# Hydrothermal minerals at submarine discharges: state of the art and strategy approaches with an application to the seafloor “Secca delle Fumose”, Campi Flegrei volcano (Italy)

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Campi Flegrei is a high-risk volcanic caldera in Campania (southern Italy), approximately 8 km in diameter, with nearly half of its area submerged beneath the Gulf of Pozzuoli. Since the repeated episodes of non-eruptive unrest following the last eruption in 1538 AD (Monte Nuovo), and the consequent development of monitoring activities aimed at mitigating volcanic risk in the Neapolitan area, Campi Flegrei has provided a unique natural laboratory for investigating long-lasting volcanic quiescence. However, while extensive monitoring and research activities have been conducted on land, the offshore sectors remain comparatively underexplored. Research in the gulf has mainly focused on monitoring infrastructures developed through the MEDUSA, CUMAS, and LOVE-CF projects, which have improved observations of seismicity, seafloor deformation, and, to a limited extent, fluid emissions.

Submarine hydrothermal venting is known to be an important yet largely unexplored phenomenon in several offshore sectors of Campi Flegrei. While pollution has been extensively investigated in the Bagnoli sector [Romano et al., 2009; Albanese et al., 2010; Trifuoggi et al., 2017; Palkom et al., 2025], scattered studies have focused on the characterization of fluid chemistry, including major gases [Hooker et al., 1985; Orlando et al., 2011; Tedesco et al., 1990], seawater ionic composition [Di Napoli et al., 2011], as well as microbiota and meiofaunal communities [Donnarumma et al., 2019; Baldrighi et al., 2020]. This limited knowledge largely reflects the fact that submarine hydrothermal systems represent one of the most challenging environments to investigate in both volcanology and biological sciences. These environments are also of particular interest because of their potential role in the synthesis of organic molecules, with implications for the origin and evolution of life. Moreover, direct observation and sampling remain difficult as they require complex underwater operations.

In this study we present mineralogical analyses of hydrothermal alteration at the major submarine site of Secca delle Fumose, located in the eastern sector of the Campi Flegrei caldera. This underwater site has been characterized by fumarolic emissions since Roman times and reaches temperatures of up to ~90 °C. We report new mineralogical data on encrustations and suspended materials collected around the vents. Despite the limited amount of sampled material, the adopted techniques — combining X-ray diffraction, infrared spectroscopy, electron microscopy, and energy-dispersive microanalysis (OV-Labs) — allow us to provide the first characterization of hydrothermal alteration products in the offshore sector of the caldera.

These results are integrated with existing geochemical, biological, and ecological information from the literature and compared with the best-studied mineral assemblages of the terrestrial fumarolic fields at the Solfatara crater and the Pisciarelli area. The comparison highlights both contrasts and similarities between submarine and subaerial sulfate environments within the Campi Flegrei volcanic system, contributing to a more comprehensive understanding of hydrothermal processes and fluid circulation in partially submerged volcanic calderas. Such investigations may also be extended to other offshore sectors of the caldera, particularly in conjunction with the installation of new submarine monitoring infrastructures, in order to improve our understanding of seafloor hydrothermal activity.

S10 - Poster

# Offshore multiparametric monitoring of Campi Flegrei: decompositional analysis of MEDUSA geodetic buoy data

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The Campi Flegrei caldera is an active and continuously evolving volcano, with a significant part of its structure submerged beneath the Gulf of Pozzuoli. Although onshore monitoring networks are well developed, the marine sector remains comparatively underexplored despite its relevance to the overall volcanic dynamics.
MEDUSA (Multiparametric Elastic-Beacon Devices and Underwater Sensors Acquisition system) is a permanent marine research and monitoring infrastructure that extends the onshore monitoring network offshore. It consists of four instrumented spar buoys connected to cabled seafloor multiparametric observatories, deployed at depths between 38 and 96 m and at distances of 1-2.4 km from the coastline. Each observatory is equipped with Bottom Pressure Recorder, low-frequency hydrophones, broadband tri-axial Ocean Bottom Seismometer, and auxiliary sensors for orientation, timing (GPS-synchronized), and power monitoring: one site also includes a 3D current-meter and a water temperature sensor. All data are transmitted in real time to the Osservatorio Vesuviano monitoring center and integrated with onshore observations.
In this study, we analysed the time series recorded by CFB3 station, including meteorological parameters, seafloor current-meter and temperature data, with the aim of distinguishing endogenous (volcanic) signals from external forcing. This discrimination is particularly relevant in the context of the volcanic unrest of Campi Flegrei. To highlight long-term patterns and potential anomalies, we applied the STL (Seasonal-Trend decomposition using Loess) algorithm on selected data from 24 May 2017 to 31 December 2020. Our preliminary results show a sort of periodical buffering effect on temperature. In general, during summer the surface water temperature should follow the air temperature pattern (temperatures rise in late spring and during the summer and decrease in autumn with a typical bell-shape), but we observe that water temperature remains low throughout the entire summer season. Moreover, it presents a delay time of about two months in the temperature peak with respect to the air temperature. We interpret this behaviour as the effect of a periodic inflow of colder water in the near-surface layer. The periodical character of this pattern suggests that the related phenomenon is not linked to volcanic dynamics. These findings underline the importance of separating environmental signals from volcanic processes to improve the interpretation of monitoring data and the assessment of volcanic hazard at Campi Flegrei.

# Resolving vents distribution and fault-fluids interactions offshore Campi Flegrei: Evidence from UHR 3D seismic attribute-driven interpretation

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The Gulf of Pozzuoli (southern Italy) hosts the offshore sector of the Campi Flegrei caldera system, an area characterised by ongoing volcano-tectonic deformation, resurgent dome uplift, and pervasive hydrothermal activity. Although the structural framework and geological evolution of this system have been the subject of considerable investigation [e.g., Sacchi et al., 2014; Corradino et al., 2021; Natale et al., 2022], the metre-scale geometry of the apical fault network associated with caldera resurgence and its role in governing shallow fluid ascent remains insufficiently resolved. Conventional 2D seismic datasets are inherently limited in vertical and lateral resolution and areal coverage, precluding the imaging of small-scale tectonic structures. Consequently, the spatial relationship between fault architecture, hydrothermal vent distribution and fluid migration pathways, is still poorly constrained in the submarine sector of the resurgent dome.

This contribution presents the interpretation of ultra-high-resolution (UHR) 3D seismic reflection data acquired within the Gulf of Pozzuoli, which enables metre-scale characterisation of tectonic structures, seismo-stratigraphic units, sedimentary architectures, and fluid-related features. Active fluid ascent pathways are inferred from vertically persistent seismic disturbance zones defined by amplitude blanking, polarity reversals, and bright spots crosscutting primary seismo-stratigraphic boundaries. A comprehensive suite of seismic attributes was systematically applied to the 3D volume to maximise the detectability of both structural discontinuities and fluid-related signals. Discontinuity and structural attributes - including semblance, variance, dip, and azimuth - were employed to support detailed fault delineation [Iacopini et al., 2016], whereas amplitude- and frequency-related attributes - such as RMS amplitude, chaos, spectral decomposition measures, and frequency decomposition — were used to highlight potentially fluid-saturated sediments and migration conduits.

The 3D seismic interpretation resolves the metre-scale fault architecture of the apical area of the resurgent dome, including individual fault strikes, dip angles, spatial extents, segmentation patterns, and overall network geometry. More than 70 predominantly normal faults are identified and organised into distinct strike domains, collectively defining a radial pattern converging toward the resurgence centre. Principal fault orientations are NE-SW, NNE-SSW, and NNW-SSE, with a subordinate ENE-WSW set. Approximately 20 fault segments intersect the present-day seafloor: a subset is concentrated in the western portion of the volume, while others bound the apical graben defining the structural limits of the summit tectonic depression. Within

the graben, pervasive faulting generates minor tectonic depressions and tilted fault blocks, producing a horst-and-graben morphology in the shallow subsurface. In the northern sector of the volume, corresponding to the continental shelf, both tectonic structures and shallower seismo-stratigraphic units are truncated by the seafloor, which acts as an erosional surface. In contrast, tectonic expression is more pronounced along the continental slope, in the southern portion of the seismic volume.

Integrated interpretation and multi-attribute analysis enabled the identification and mapping of 84 vent-related features within the shallow subsurface. These structures display variable geometries, with horizontal dimensions spanning 6 to 55 m and vertical extents reaching up to approximately 90 m. Vents nucleate at different seismo-stratigraphic units and commonly terminate in paleo-pockmark-like morphologies, indicative of episodic fluid discharge and stratigraphically controlled sealing mechanisms. Spatial correlation with the reconstructed fault network reveals that vent distribution is only partially fault-controlled: while a fraction of vents aligns with mapped fault planes, others are laterally displaced from major fault traces, suggesting that additional permeability pathways govern fluid migration in portions of the study area.

These findings imply spatially heterogeneous permeability and temporally episodic hydrothermal discharge within the shallow subsurface, with significant implications for our understanding of hydrothermal circulation and its dynamic coupling with volcano-tectonic deformation during periods of unrest.

# S11 - EXPLOSIVE ERUPTION PRODUCTS, DYNAMICS AND HAZARDS: FROM VOLCANIC PLUMES TO FLOWS INTEGRATING FIELD, EXPERIMENTAL AND MODELLING APPROACHES

Conveners:
Andrea Todde, Ileana Santangelo, Francesco Romeo, Carla Tranquilino

# Investigating the Influence of Atmospheric Conditions on Etna Volcanic Plumes: Insights from Observations and Numerical Modelling

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Volcanic ash released during Etna's paroxysms poses a significant hazard to aviation at nearby airports, with Catania Airport being the most affected. This is because volcanic ash has a relatively low melting temperature compared to the operational temperature of jet engines, and its ingestion can cause engine failure (Vogel et al., 2019). Consequently, accurate forecasts of the volcanic cloud height, ash concentration, and atmospheric dispersion are crucial. To achieve this, plume-rise models are employed, with one-dimensional (1D) models commonly used for operational forecasting. Among these, FPLUME [Folch et al., 2016] is considered one of the most comprehensive, accounting for the effects of wind, moisture, latent heat, and variable entrainment coefficients. FPLUME requires several input parameters for the initial conditions, including the Mass Eruption Rate (MER), the exit ash velocity, the exit ash temperature, the exit water fraction, and the meteorological variables.

Here we present the results from the analysis of 34 Etna eruptions that occurred between 2011 and 2024. MER was retrieved using the Volcanic Ash Radar Retrieval (VARR) technique [Marzano et al., 2012; Mereu et al., 2015], based on data from an X-band weather radar located in Catania. Meteorological soundings were obtained from ERA5 reanalysis dataset. To account for uncertainties in the initial conditions, a Monte Carlo simulation was performed, running 100 FPLUME simulations for each event while perturbing input parameters. The results show that for events with MER larger than $10^6$ kg $s^{-1}$ FPLUME accurately predicts the volcanic cloud heights. However, for weaker events, FPLUME consistently underestimates the cloud height. This discrepancy is more pronounced during eruptions occurring under unstable atmospheric conditions, characterized by high Convective Available Potential Energy (CAPE) and low wind speeds. These findings suggest that for weak paroxysms, atmospheric processes, particularly convection, play a relevant role in determining plume evolution.

A key limitation concerns the parameterization of the entrainment coefficients, which are often overestimated, especially for weak eruptions. To address this issue, we introduce in FPLUME a revised formulation for the shear and vortex entrainment coefficients, with the former expressed as a function of MER and the latter as a function of wind speed. The new parameterizations reduce the discrepancy between observed and simulated cloud heights, with the largest improvement obtained for weaker eruptions.

# Toward the quantitative analysis of plume dynamics and eruptive transitions at Stromboli volcano using AI-derived thermal metrics

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Stromboli volcano is part of the Aeolian Islands archipelago (Italy) and is one of the most active volcanoes in the world. Its persistent activity, termed ordinary, consists of intermittent, low-to-moderate Strombolian explosions, with a rate usually ranging between 5 and 20 events per hour, erupting pyroclastic rocks that fall within the crater terrace located in the summit area. Several active vents open on the terrace and are distributed in two main areas: North and Central-South, often producing spattering from one or more emission points. Occasionally (a few times per year), the explosions can be more energetic and are referred to as “major explosions”, ejecting pyroclastic materials over the terrace up to “Pizzo sopra La Fossa” and beyond. Every few years Stromboli produces its strongest explosions, named “paroxysms”, which can throw light (pumices) and heavy (blocks) materials to long distances, sometime affecting the lower slopes of the island, including densely (in summertime) inhabited areas, and forming pyroclastic flows along the Sciara del Fuoco sometime capable of triggering tsunami.
The automatic detection of the explosive activity of Stromboli volcano and its characterization in terms of event frequency, volume and dispersal of ejected materials can be a powerful tool to identify patterns that may lead to deviations from ordinary activity toward more energetic events. In a previous work, a multi-stage Artificial Intelligence (AI) framework based on convolutional neural networks for classification, object detection, and segmentation was developed and applied to thermal images acquired by the SPT camera mounted on Pizzo sopra La Fossa (900 m a.s.l.), enabling the detection and characterization of explosive events.
In this work, we focus on the analysis of the extracted parameters, in particular on the “delta parameter” defined as the ratio between the pyroclastic dispersal area and that of the poorly-fragmented magma erupted at the early phase of each explosion, which provides a quantitative description of the explosion power. As a case study, we analyze thermal datasets from January 2019 to July 3, 2019, when the larger paroxysmal explosion occurred and was documented by the monitoring sensors network. The evolution of the delta parameter is analyzed to identify variations in eruptive behavior before the paroxysm and its potential role as an indicator of transitions from ordinary Strombolian activity to major and paroxysmal explosions.
This approach highlights the relevance of explosion plume-derived metrics, automatically extracted from thermal imagery, for improving the quantitative analysis of the persistent eruptive activity of Stromboli volcano. Time-series deep learning models are applied to analyze these temporal patterns and to investigate their capability for identifying changes in eruptive behavior associated with high-energy events.

# Statistical modelling of volcanic plume height at Mt. Etna using the seismic tremor

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Explosive volcanic eruptions generate tephra plumes that can reach several kilometers in height, impacting local populations, infrastructure, and aviation safety. Real-time monitoring and forecasting are essential for hazard assessment. While multi-sensor strategies are typically used to determine Eruptive Source Parameters (ESPs), a quick evaluation of Volcanic Plume Height (VPH) is vital for the initial characterization of an explosive activity.
This study develops a statistical model that combines continuous volcanic tremor (VT) signals with plume height and wind velocity above the vent to estimate VPH. We focus on Mt. Etna, Italy, one of the most active volcanoes in Europe, using data from two permanent seismic stations operated by the INGV-Osservatorio Etneo: i) ECPN, located in summit area (about 3000 m a.s.l.) at south-west of crater Bocca Nuova; ii) ESLN sited at an altitude of about 1800 m a.s.l. on southern flank of Mt. Etna. We processed the VT signals to derive a suite of statistical features, including Shannon and Renyi Entropy, Energy, Kurtosis, and Bayesian Regression parameters. Relationships including these parameters, derived from seismic data were tested in order to assess their informativeness about forecasting VPH. Moreover, these models were compared against relationships based on the Mass Eruption Rate (MER) derived from X-band radar data located at V. Bellini Airport, to identify the most sensitive proxies for eruptive intensity.
By analysing fifteen lava fountains occurring between February and June 2021, we derived a statistical relationship to retrieve VPH. Given the near real-time availability of seismic data at volcano observatories, this kind of models have the potential to be operationally implemented. The proposed model can serve as a potential proxy for VPH when direct ground- and/or satellite-based observations are unavailable. The resulting methodology provides a simple tool for a rapid crisis assessment at Mt. Etna and offers a framework applicable to other active volcanoes worldwide.

# Comparison of two methods used to predict mass eruption rate: insights from the 2010 Eyjafjallajökull eruption

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During explosive volcanic eruptions, real-time estimates of the source mass eruption rate (MER) are required to predict tephra dispersal and sedimentation. Observational constraints and physical limitations make it difficult to directly measure MER. As such, modelling approaches have been developed to provide rapid estimates of MER from plume height (PLH) observations, typically in the form of zero-dimensional (0D) relationships or one-dimensional (1D) plume models. 0D relationships may be empirical or theoretical: empirical relationships are derived from regression analyses between PLH and MER from previous eruptions, whereas theoretical relationships emerge from the analysis of fluid dynamics of turbulent jets and plumes. On the other hand, 1D plume models numerically solve the conservation equations for mass, momentum, and buoyancy along the plume axis, and allow additional source parameters to be defined (e.g. vent diameter, temperature, volatile content, and total grain size distribution). A fundamental question to address is whether incorporating additional parameters into the prediction of MER provides more accurate estimates. To address this question, this contribution compares the 1D plume model FPLUME to the 0D relationships contained within REFIR software. MER is predicted for the first and third explosive phases of the 2010 Eyjafjallajökull eruption using PLH observations from C-band radar at Keflavík Airport. The results demonstrate that including additional input parameters does not necessarily improve MER estimates and, within the FPLUME framework, may increase the likelihood of convergence failure due to parameter combination constraints. Instead, model accuracy depends on the robust quantification of key parameters, particularly the entrainment coefficient beta. The results of both models, their implications, and potential areas for development will be presented.

# Unravelling the Stratigraphy and Eruptive Dynamics of the Pietre Cotte and the 1888-90 eruptions activities, Vulcano (Italy)

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The recent evolution (last 700 years) of La Fossa cone (Vulcano island) has long intrigued scientists and sparked debates regarding the origin and timing of products belonging to its various eruptive units. Although very recent, the stratigraphy of these products, the timing of the main eruptions and their characters, and the identification of the source area (s) still remain partly unclear.

In the present work, we aim (i) to reconstruct in detail the stratigraphy of the Pietre Cotte pyroclastic succession, including the deposits of the AD 1888-90 eruptive cycle, which together record the volcanic activity from the XIV century to AD 1890; (ii) to define the processes that control the opening phases of explosive eruptions in intermediate-sialic systems characterized by closed conduits and intense interaction with active hydrothermal systems; (iii) to understand the mechanisms responsible for variations in eruptive style during the eruptions; and (iv) to identify the source area (s). Stratigraphic fieldwork, lithofacies analysis and volcanological interpretation have been carried out, together with laboratory analyses of representative sample components, volcanic-glass geochemistry, thin-section petrography, morphoscopic SEM analyses and X-ray microtomography (μX-CT) investigations. EPMA glass analyses define two distinct compositional domains (trachytic and rhyolitic), with the gap bridged by the products of the 1888-90 eruptive cycle, indicating effective mixing/mingling processes within the shallow magmatic system. Juvenile fragment morphologies are consistent with phreatomagmatic fragmentation and magmatic degassing, with localized hydrothermal alteration. These studies have led to the definition of an updated volcanic succession result of recurring hydromagmatic to magmatic eruptions, with vent-opening phreatic phases, that produced multiple depositional units from fallout and pyroclastic density currents. The Pietre Cotte succession includes distinctive pumice-fallout layers and the well-known rhyolitic lava flow, reflecting a complex eruptive evolution. Based on our stratigraphic data and the re-interpretation of the available historical reports, combined with the available paleomagnetic ages, the rhyolitic lava flow is most likely dated to AD 1739, whereas the pumice fallout layers were likely emitted slightly after in AD 1771. Constraining the precise timing of the main explosive and effusive events is crucial to better understand the dynamics of La Fossa's shallow magmatic-hydrothermal system and the evolution of its most recent eruptive activity, thus providing key insights for volcanic hazard assessment on Vulcano Island.

# Probabilistic assessment of hazard related to pyroclastic currents at Ischia

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The first step towards mitigating the risks associated with pyroclastic density currents (PDCs) consists in quantifying the probability of their occurrence through probabilistic hazard studies. The Island of Ischia constitutes the emerged portion of a large volcanic system, known as the Ischia Volcanic Field (IVC). The last eruption, which occurred in AD 1302, was preceded by centuries of intense volcanic activity, with more than 30 eruptions in the last 10,000 years. At present, the Ischia system is quiescent, but new magmatic intrusions could trigger renewed resurgence, seismic activity and slope instability, potentially culminating in volcanism. The island hosts a permanent population of approximately 60,000 inhabitants, which increases dramatically during summer. This demographic context highlights the urgency of quantitatively assessing volcanic hazards on the island, a topic still poorly addressed in the literature. The aim of this work is to quantify the hazard related to the invasion by PDC on Ischia. We adopted two alternative simplified modeling frameworks (the Energy Cone and the Box model) to study all known explosive eruptions of over the past 10 ky. For each eruption we inverted for potential source parameters and investigated their possible correlations. Vent location uncertainty was addressed adopting a kernel approach based on the spatial distribution of active vents during the past 10 ky. By integrating uncertainties in vent location with dimensional variability of currents, we quantified the hazard associated with PDCs both conditionally, given the occurrence of an eruption, and unconditionally, by estimating the probability of invasion within the next century. This analysis provides a first quantitative estimate of the probabilistic hazard associated with pyroclastic flows for Ischia and demonstrates that the highest probabilities are found in densely populated areas, especially in the area of Casamicciola Terme, Ischia Porto, and Barano. Conditional probability of PDC invasion above 5% includes those areas as well as parts of the NW and SW sectors of the island, between Forio, Panza, and Lacco Ameno, including most of the main populated areas.

# A large-scale slit rheometer for rheological characterization of volcanic mud and granular flows

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Understanding the rheological behaviour of mudflows and granular flows remains a central challenge in volcanic gravity flows research. While laboratory rheometers have traditionally been used to characterize complex materials, their scale and operational constraints often limit their applicability to highly heterogeneous natural flows. Large-scale rheometers represent a promising yet underexplored approach to bridge this gap by enabling measurements closer to real flow conditions.

In this study, we present the construction and implementation of a large-scale slit-type rheometer designed according to the physical principles governing sliding granular materials. The device was designed to reproduce flow conditions at scales significantly larger than conventional laboratory rheometers. In particular, the rheometer enables the monitoring of flow velocity, flow thickness, and normal pressure along the channel, providing the fundamental parameters needed to investigate flow dynamics and rheological behaviour. By prioritizing a modular design and integrating low-cost sensors, the proposed system expands the availability of rheological experimentation to research groups operating with limited resources.

Using the proposed rheometer, we were able to estimate key physical parameters such as shear rate and shear stress. The measurements obtained with the large-scale device were compared with reference data derived from a small-scale commercial Anton Paar rheometer. Despite the differences in scale between the two instruments, the tested materials exhibited consistent rheological trends across both setups. These results suggest that the large-scale slit rheometer is capable of reproducing the fundamental mechanical behaviour of the studied materials, supporting its validity as an alternative and scalable experimental tool for investigating the rheology of mud and granular flows under conditions closer to natural systems.

# Tephra characteristics of small-volume, lithic-rich deposits at Campi Flegrei: New insights from the Santa Maria delle Grazie explosive eruption

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Small-volume eruptions (smaller than 0.1 $km^3$) are a common feature of the post-caldera eruptive activity of Campi Flegrei. While the magnitude and intensities of these eruptions are limited and the resulting tephra distribution is often restricted to a few kilometers from the eruptive vents, they have the potential to cause severe damages in highly urbanized areas. Understanding and constraining the mechanisms governing this type of activity is fundamental to improve hazard assessments at Campi Flegrei and at other calderas worldwide.
In late 2024, fieldwork was completed by a team near Solfatara in Campi Flegrei, Italy. During the course of this campaign, samples were collected from a recently discovered outcrop of the Santa Maria delle Grazie event 300 meters from the Solfatara crater. The Santa Maria delle Grazie (SMG) event, which occurred 4382-4509 years BP in the Solfatara area, offers insights into the system just before the Solfatara eruption [Smith et al., 2011]. With the Solfatara-Pisciarelli region continuing to be the area of utmost concern (most intense fumarole activity and other hydrothermal manifestations, high probability of new vent opening in the case of future eruptions, and seismicity), this new data offers additional information for possible future scenarios for events at Campi Flegrei.
The SMG pyroclastic sequence is bracketed between the Agnano-Monte Spina deposits below and the Solfatara deposits above. Deposit characterization led to the preliminary subdivision of the SMG sequence into three distinct units: a 60-cm thick bottom Unit 1, a 300-cm thick middle Unit 2 which comprises the majority of the SMG sequence, and a 90-cm thick uppermost Unit 3. Units 1 and 2 consist of the stacking of numerous ash-dominated beds, alternating with poorly sorted ash and lapilli beds and lapilli lenses. Unit 3 consists of scoriaceous bombs and spatter that correlate with the late-stage SMG scoria/spatter cone, which formed in the vicinity of the study's section. Fourteen selected samples were retrieved from Units 1 and 2 to characterize the sedimentological and lithological properties of the pyroclastic sequence along the stratigraphy.
Samples were sieved into half phi sizes down to +1 $\phi$. In order to obtain the grain size distribution with a higher degree of certainty of the finest portion, that above 0 $\phi$, the samples then went through the particle size and shape analyzer, Retsch CamSizer X2. This gave grain size results up to about 10 $\phi$, showing a median $\phi$ range of 2.5 to 5.1 with an average median $\phi$ of 3.3. The sorting ranges from 0.7 to 1.8 with an average sorting of 1.2.
For selected samples, componentry was completed on three grain sizes each (0.5 $\phi$, 0 $\phi$, and -0.5 $\phi$) counting at least 500 clasts under a binocular microscope. Componentry analysis reveals that the SMG deposit is made of primarily lithic clasts that have been recycled. However, detailed observations display the presence of glassy fragments of likely juvenile origins. Furthermore, the trend vertically in the sequence shows an increase in the juvenile percentage moving

towards the stratigraphic top, moving from an average of 20% of the total sample towards an average of 50%. The juvenile portion can then be split into three primary categories: the vesicle-rich light grey, the dense darker grey, and the black vesicular. The vesicle-rich light grey group was the most common throughout the sequence, usually making up the majority of the juvenile portion. The dense darker grey group shows an increase moving up in the section so much so that it becomes an almost equal percentage to the vesicle-rich light grey group. The black vesicular group stays the least common juvenile throughout. Other than the lithic and juvenile clasts, free crystals compose around 6% across all of the samples. In addition, fragmentation through decompression experiments were conducted on lithic clasts from both SMG and Solfatara deposits to investigate their mechanical properties (namely porosity and permeability), fragmentation threshold and behavior.

Componentry shows a base-to-top increase in juvenile material, consistent with trends described for the Solfatara eruption, suggesting a progressive transition toward greater magma input during the SMG event. These observations, together with fragmentation experiments, suggest differences in the SMG and Solfatara events previously unknown. Future work will focus on obtaining more fragmentation data as well as on the geochemical characterization of SMG juvenile clasts to enable direct comparison with Solfatara products, ultimately improving our understanding of pre-eruptive conditions, eruption dynamics, and refining hazard scenarios for the Solfatara-Pisciarelli area.

# Triggering mechanisms for paroxysmal activity at open-conduit volcanoes: the 2019 eruption crisis at Stromboli

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Stromboli is famous for its persistent, ordinary activity that is characterised by periodic, low-intensity explosions affecting mostly the crater terrace. Over the last 25 years this ordinary activity has been interrupted by 5 more violent events in 2003, 2007, 2019 (2) and 2024 that involved higher duration, mass and energy and that in 4 cases were preceded by lava effusion of variable duration. These higher intensity explosive events are classified as paroxysms, with their ejecta having an impact well beyond the crater terrace, thus posing a threat to the island's population and tourists. While there is general consensus that potential triggering mechanisms comprise two end-member scenarios being decompression of the magmatic system due to prolonged lava effusion ("top down") or the input of $CO_2$-rich magma at depth ("bottom-up"), the most recent events have shown that the reality is often more complex. In-depth studies of the erupted ejecta are fundamental to discuss the processes (and timescales) in the magmatic system prior to paroxysms and the associated variability of the precursory phenomena. The integration of this data with both the geochemical and geophysical monitoring data adds fundamental constraints to our understanding of the underlying triggering mechanisms and the plumbing system, in turn allowing better interpretation of the detected signals for appropriate hazard and risk management decisions.

The 2019 eruption crisis has involved two paroxysms in short succession: the 3rd July event was not heralded by effusive activity, but was preceded by months of $CO_2$ excess in the degassing plume and intensified ordinary activity. Following changes in the SW crater morphology, lava effusion started and continued until the 28th August paroxysm. The variability in the eruption sequence allows discussing changes in magmatic processes and degassing over the several month-long crisis duration. Here, we provide a detailed geochemical characterisation of olivine-hosted melt inclusions, crystals and matrix glass for both paroxysms. Major element data on melt inclusions and matrix glass is combined with olivine compositions to discuss magma source and ascent dynamics, suggesting a deeper source and faster ascent for the July paroxysm, while the August paroxysm shows a more complex behaviour. Water and carbon dioxide contents in melt inclusions and embayments are combined with sulphur and chlorine compositions to discuss the degassing history and integrate this data with that from the monitoring network, confirming differences between the two events. Re-homogenisation experiments on melt inclusions from the 3rd July paroxysm provide additional insights into the degassing behaviour and melt inclusion entrapment. Maximum $CO_2$ values analysed in the re-homogenised melt inclusion glass are up to 1000 ppm higher than average compositions in non-homogenised melt inclusion glass, suggesting the presence of $CO_2$ in the co-existing

vapor bubbles. This suggests that volatile-solubility entrapment pressure estimates might be potentially underestimated if only non-homogenised melt inclusions are considered.
Overall, the integration of the geochemical-petrological dataset within the framework of both geophysical and geochemical monitoring records adds further understanding of the magmatic processes and mechanisms that triggered paroxysms at Stromboli in the last 25 years.

# Satellite-based analysis of $SO_2$ plume emissions during the 2007-2016 Mt. Etna's lava fountains sequence

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Satellite-based observation of volcanic $SO_2$ emissions is a key tool for volcanic hazard assessment and risk mitigation. In this study, we analysed the total mass of $SO_2$ released during the 54 lava fountains that occurred at Mt. Etna between March 2007 and May 2016, using multisensor satellite data from IASI and OMI. The target of the study was to investigate the relationships between $SO_2$ emissions and degassed magma, plume features, comparing the results with the daily volcanic tremor with erupted masses and column heights. Our results show that $SO_2$ masses exhibit a fluctuating trend, peaking during the 3 December 2015 paroxysm - one of the most violent eruptive episodes recorded at the volcano in the last two decades. Conversely, the lowest values were recorded during eruptions characterised by relatively low-altitude plumes (e.g., 18 February and 23 October 2011, and 28 December 2014), possibly characterised by lower energy. Fluctuations similar to those in the $SO_2$ mass have been observed in the erupted masses and column heights, indicating a strong link between these parameters. These findings underline the effectiveness of satellite data in quantifying eruptive intensity and characterizing volcanic activity.

# Rheology of Pyroclastic Density Currents of the Pollena ACE472 eruption (Vesuvius): first insights from laboratory experiments

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Geophysical granular flows, like pyroclastic density currents (PDCs), are common and destructive events in active volcanic areas. In particular, PDCs are also considered the most lethal of all volcanic hazards. Modelling these flows for hazard quantification applications is a very challenging task due to their inherent complexity since they are: unsteady, multiphase, multi-component, interacting with the topography, etc. Among the several parameters that characterize them, rheology is one of the most important since it captures how the material flows in response to an applied stress. In this presentation, we share first insights on the rheology of PDCs of the Pollena ACE472 eruption of Mount Vesuvius. We first present results of preliminary material characterization analyses, such as particle size analysis, Gas Pycnometer Density Analysis, Photogrammetry Analysis, and BET (Bruner, Emmet, and Teller) analysis by gas sorption analyzer. Then we present the shear cell experiments carried out by means of an Anton Paar MCR702e rheometer, with which we determined rheological parameters like cohesion, internal friction angle, and flowability, which quantifies the onset of movement conditions and if the material shows cohesive properties.

# From particle comminution to large-scale granular flows: experimental insights into Pyroclastic Density Currents at mafic volcanoes

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Pyroclastic density currents (PDCs) are considered one of the most hazardous phenomena related to volcanic eruptions and in recent years are increasingly observed even in mafic volcanic systems. Some of the most important examples include small-volume PDCs that occurred at Etna and Stromboli in Italy, Volcán de Fuego in Guatemala, Klyuchevskoy in Russia, Llaima and Villarrica in Chile. They represent a potential hazard to local communities placed on the volcanic slopes as well as to the large number of tourists and hikers who regularly visit these areas. Although these phenomena have been extensively investigated in more evolved volcanic systems, the physical characterization of mafic PDCs and the mechanisms controlling their initiation and propagation remain comparatively poorly constrained, despite the growing number of documented cases.
In order to address this gap of knowledge, a series of experimental investigations was conducted to explore both particle-scale processes and flow dynamics in granular volcanic systems. The experimental strategy combines controlled laboratory analyses of particle comminution with large-scale analog experiments aimed at reproducing granular flows triggered by different mechanisms. First, a quantitative morphological analysis of clasts was performed to investigate the effects of mechanical comminution and abrasion produced by particle-particle interactions during granular transport. For this purpose, mixtures of basaltic scoria and latitic material were subjected to controlled abrasion experiments for specific time intervals using a rotating drum known as the Los Angeles Abrasion Machine (LAAM), a device widely used in civil engineering to evaluate the abrasion resistance of aggregates. The resulting clast populations were analyzed through morphometric parameters in order to quantify changes in particle shape and surface texture induced by mechanical interactions. The experimental results were then compared with natural samples derived from a recent PDC that occurred at Mount Etna on June 2, 2025 that allowed the correlation between experimental abrasion patterns and those observed in natural deposits.
A series of large-scale experiments was subsequently carried out using “GRANFLOW”, an experimental flume developed at the Laboratory of Image Analysis and Analog Models (LAIMA) of the Institute of Geology at the Universidad Autónoma de San Luis Potosí (Mexico). These experiments were designed to reproduce and compare two of the main mechanisms responsible for PDC generation, using basaltic scoria and latitic clasts as representative end-members for mafic and felsic products, respectively. The collapse of lava fountain was replicated through a “Free-Fall” release configuration, whereas the gravitational failure of pyroclastic accumulations on steep slopes and the cone flank-collapse were reproduced using a “Dam-Break” experimental setup. These complementary configurations allow investigation of how bulk density, grain-size distribution and clast morphology influence propagation dynamics and depositional architectures of the resulting granular flows.
Particle-scale comminution experiments, experimental large-scale granular flows, and comparisons with natural deposits contribute to improve the understanding of these complex processes.

S11 - Oral Presentation

# Triggering of Deposit-Derived Pyroclastic Density Currents: Insights from High-Temperature Rheology of Lava and Spatter from the 1944 Vesuvio eruption

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Hot volcaniclastic deposits emplaced on steep slopes during explosive eruptions can rapidly destabilize and collapse, generating hazardous hot avalanches, known as deposit-derived pyroclastic density currents (dd-PDCs). Such processes were directly observed during the early stages of the 1944 eruption of Vesuvio. Here, we use this case study to investigate how lithology (coherent lava vs. spatter) and texture (welding degree, porosity, and crystallinity) influence high-temperature material behaviour and stability.

Our multidisciplinary approach combines field observations, microstructural analyses, and high-temperature deformation experiments on cylindrical cores, drilled from natural samples of four different deposits of the last eruption of Vesuvio. The experiments consist of uniaxial compressive deformation performed using the Volcanological In-Situ Deformation Instrument (VIDI) at the temperatures ranging from 950 to 1100°C and strain rate on the order of $10^{-4}$ to $10^{-5}$ $s^{-1}$.

Analysis of flow curves highlights the complex rheology of these multiphase materials (melt, crystals, and pores), resumed in three different deformation regimes: (i) pure brittle failure up to 1000°C, marked by a sharp stress drop, and a strain gap in the stress-strain curve; (ii) brittle-ductile (brittle dominated) behaviour at 1050°C, characterized by a stress drop discretely spaced; and (iii) brittle-ductile (ductile dominated) at 1100°C, where stress drop becomes more closely spaced. ending with a progressive weakening associated with shear band development.

Results indicate that the mechanical strength of the samples is poorly dependent on strain rate, whereas temperature has a primary control (35 MPa at 950 °C vs. 0.1 MPa at 1100 °C). Porosity, and consequently density, have a key role on mechanical behaviour: less porous samples (25-35% vs. 35-45%) exhibit higher resistance to failure, despite having similar crystallinity (20-30%).

Pre- and post-deformation microstructural analysis by scanning electron microscopy (SEM), and 3D X-ray microtomography (microCT) reveals that vesicles strongly influence the mechanical response, as they focus deformation and govern the strain localization. These findings improve our understanding of how rheology and textural heterogeneity control the onset of gravitational collapse.

# Lahars at Stromboli Island (Italy): insights from fieldwork and numerical modelling

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Stromboli Island (Italy) is characterized by persistent volcanic activity that continuously produces loose volcanoclastic deposits accumulating along steep slopes. These unconsolidated materials, in recent years, are remobilized by intense rainfall events, generating lahars that represent a new recurrent hazard for inhabited areas of the island. A specific fieldwork campaign was conducted to collect representative samples of the lahar deposits in several key areas of Stromboli occurred in last years. Grain-size analyses were performed to derive rheological parameters, which were used to define the physical properties of the material and calibrate numerical simulations. The simulations were carried out using the IMEX_Sflow2D code, a depth-averaged numerical model capable of simulating granular and debris flows over a detailed topography. This latter is generated from Pleiades satellite stereophotogrammetry by using NASA ASP, reproducing, with a spatial resolution of 0.5 m, the recent morphology of Stromboli. The simulations estimate the flow propagation, velocity distribution and deposit thickness within the main drainage basins of Stromboli. Model results were compared with field evidence of recent events in order to evaluate the reliability of the simulations.

# The 2 June 2025 pyroclastic density current at Mount Etna: dynamics and hazard of a widely observed event

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Pyroclastic density currents (PDCs) at Mt. Etna have become more frequent in recent years as a consequence of the rapid accumulation of lava and mostly tephra deposits during the numerous lava fountain episodes, leading to potential conditions of instability. Most of these granular flows were generated from the collapse of ultra-proximal volcanoclastic deposits constituting the South-East Crater (SEC). The last and very notable event occurred in the morning of 2 June 2025, when a voluminous avalanche detached from the northeast flank of the SEC during the peak of the ongoing lava fountaining. This triggered a granular flow characterized by an extreme kinetic energy, possibly enhanced by interaction with snow along the path affected by the propagation of the current, reaching a distance of ~3 km from the source. Several surveys were conducted to map the resulting deposit, study the stratigraphy, and collect representative samples.
In this study, we provide a comprehensive investigation of the 2 June 2025 PDC by adopting a multidisciplinary approach. The combination of field observations, INGV video recordings, laboratory analysis, remote sensing, and numerical modeling allows us to reconstruct the initiation and propagation dynamics of this type of phenomenon in basaltic systems.
The 2025 PDC gained exceptional media exposure since it occurred in the forenoon of 2 June with fine weather during the start of the summer tourist season, when a large number of visitors were present at high elevations. Although established protocols provide for access restrictions in the summit areas of Etna during paroxysmal activity, such phenomena remain hazardous because of their unexpected onset, limited warning time, potentially long runout, and wide dispersal of the hot, elutriated ash cloud. Our findings can improve the understanding of these hazards, providing essential data for risk mitigation in frequently active volcanic areas.

# Generation of Pyroclastic Density Currents at Mount Etna: triggering processes, related deposits and links to eruptive styles

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Repeated observations through recent decades have demonstrated that Pyroclastic Density Currents (PDCs) in mafic volcanic systems occur more frequently than previously assumed. Such phenomena have been widely documented worldwide over the past century, particularly at Mount Etna, where more than fifty PDC-forming events have been recorded during the last four decades. This contribution presents the most comprehensive and updated review of PDC occurrences at Etna since 1986, integrating field observations and published literature to evaluate the diversity of mechanisms responsible for their generation and emplacement. The compiled dataset highlights that PDCs at Etna originate from a broad spectrum of processes, which may operate independently or interact during single eruptive episodes. Identified triggering mechanisms include: (1) the instantaneous collapse of dense pyroclastic mixtures generated during lava fountain activity, (2) gravitational remobilization of freshly deposited, still-hot tephra accumulated on steep slopes, (3) partial flank failures of pyroclastic cones promoted by rapid growth, structural weakening, and shallow magma intrusion, and (4) explosive interactions between lava flows and snow-covered or water-saturated substrates. Several well-documented events illustrate the superposition of multiple triggering processes within individual episodes, emphasizing the multi-stage and non-linear nature of PDC initiation at Etna. The temporal distribution of PDCs indicates a marked increase in occurrence over recent decades, correlated with the intensification of summit paroxysmal activity and the rapid construction and repeated destabilization of the Southeast Crater, currently the most active of the summit craters. While many PDCs are characterized by limited runout distances and relatively small volumes, larger events in recent years have travelled up to 2-3 km from their source, locally affecting areas commonly accessed by hikers, tourists, and scientists in the summit area. Although PDCs at Etna have not traditionally been considered among the primary volcanic hazards, their enhanced frequency and occasional mobility highlight their increasing relevance. This review underscores the need to systematically incorporate PDC-related processes into hazard assessments at Etna and, more broadly, to reassess the role of PDCs in mafic volcanic systems worldwide.

# Multi-sensor geophysical observations constrain lahar flow dynamics at Volcan de Fuego, Guatemala

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Lahars pose a major hazard to communities living near active volcanoes, yet their evolving flow dynamics and sediment transport processes remain difficult to constrain in natural volcanic channels where direct observations are limited. To address this challenge, we integrate seismic, infrasound, and high-resolution video observations of a rainfall-triggered lahar in the Ceniza channel at Fuego volcano, Guatemala, to quantify flow dynamics in a morphodynamically active setting. Independent estimates of flow-front velocity from seismic, infrasound array, and video analyses provide consistent propagation speeds of 4.3 m/s within the confined upper reach of the channel. Using these velocities, we invert high-frequency seismic energy to estimate a proxy for the coarse (decimetre- to metre-scale) sediment fraction mobilised by the flow.

Our observations reveal a systematic downstream transformation of lahar dynamics over kilometre scales, characterised by decreasing velocity, loss of high-frequency seismic energy, and progressive fining of the transported coarse fraction. These changes coincide with a transition from a steep, confined channel to a wider, lower-gradient reach, indicating that channel morphology reorganises sediment transport and modulates the resulting seismo-acoustic signals.

Our approach provides low-latency constraints on key flow parameters, with direct implications for flow characterisation, hazard assessment, and lahar early warning.

# Atmospheric Controls on Dense Volcanic Plume Transport: Insights from Idealised LES Experiments

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The transport of dense fluids, or particle-gas mixtures that can be treated as gases, is an important process in volcanic environments. During events such as gas-rich lava fissure eruptions, the emission rate is a key parameter because it is used to initialise external dispersion models. In this study, we investigate the role of external atmospheric forcings in the transport of a dense fluid and consider strategies for estimating emission rates. As an example, we evaluate the applicability of the mass-flux approach.

The numerical simulations are performed using the Weather Research and Forecasting (WRF) model, adapted to allow the release of a dense gas, following the method described by Burton et al. 2016 (https://doi.org/10.1002/met.1603). The model has been further modified to include a surface heat source at selected locations. WRF is run in idealised large-eddy simulation (LES) mode, in which there is no orography and the simulation is initialised with prescribed vertical profiles of temperature and wind. This high-resolution configuration enables the model to function as a numerical "laboratory", allowing a large number of controlled sensitivity experiments to be conducted.

The study addresses two main questions. Firstly, how does a dense plume behave under different atmospheric and surface forcings? Secondly, is it possible to estimate the emission rate downwind of the source using a mass-flux method?

To address the first question, we examine the response of the plume to a range of background wind speeds, atmospheric stability regimes, and surface heating conditions. For the second question, we analyse the downstream structure of the plume across a control plane, enabling the mass-flux method to be applied. The estimated emission rate derived from this approach is then compared with the known emission rate specified in the model. This analysis allows us to determine the minimum number of transects that an aircraft platform—such as an uncrewed aerial vehicle (UAV)—would require to accurately estimate the emission rate under both neutral and stable atmospheric conditions.

The results are expected to be of interest to both atmospheric modellers and observational scientists involved in volcanic measurements.

# Cryptic volcanic eruptions preserved in Antarctic fumarolic ice caves: geochemical evidence from Mount Melbourne (Northern Victoria Land)

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Volcanic deposits preserved within Antarctic fumarolic ice caves (FICs) represent a rare archive of eruptive activity otherwise hidden beneath the ice cap. In glacio-volcanic environments such as Antarctica, where exposed outcrops are scarce and access to proximal volcanic deposits is limited, these sub-ice systems provide unique opportunities to investigate the eruptive history of ice-covered volcanoes and to refine regional tephrochronological frameworks.
This study presents the first integrated geochemical and statistical investigation of tephra deposits preserved within fumarolic ice caves at Mount Melbourne (Northern Victoria Land, Antarctica). During the XXXVII Italian Antarctic Expedition (2021), 21 tephra samples were collected from three summit cave systems (MC1-Aurora, MC3 and MC4).
Tephra samples were geochemically characterised through major and trace elements analyses on glass shards. The resulting dataset was integrated with previously published geochemical data from Mount Melbourne eruptive products. To explore compositional variability and identify potential correlations, we applied a multivariate statistical methods including hierarchical clustering (HC), principal component analysis (PCA), and t-distributed stochastic neighbour embedding (t-SNE). These clustering and dimensionality-reduction approaches allowed objective identification of geochemical groups within the combined dataset.
The analysis reveals eight distinct compositional clusters (C1-C8), linking fumarolic ice-cave deposits to previously recognised eruptive units. In particular, strong geochemical similarities are observed between some cave deposits and tephra layers documented in englacial sequences and marine sediment cores, providing new constraints on correlations between proximal and distal archives. Importantly, the statistical clustering also identifies a distinct compositional group (C3) that has no equivalent within the currently documented Mount Melbourne eruptive record. This cluster likely represents at least one previously unrecognised Holocene eruption, preserved exclusively within the fumarolic ice-cave system.
These results demonstrate that fumarolic ice caves can preserve eruptive products not recorded in exposed stratigraphic sequences, revealing cryptic eruptions that would otherwise remain undetected. Moreover, combining geochemical fingerprinting with multivariate statistical methods provides an effective approach for identifying subtle compositional relationships and improving correlations among different Antarctic tephra archives. More broadly, this work highlights the potential of fumarolic ice caves as valuable sub-ice volcanic archives capable of extending eruptive histories and improving tephrochronological correlations across Antarctic environmental records. The approach presented here provides a rapid and robust framework for exploring complex geochemical datasets and may contribute to improving volcanic hazard assessments in ice-covered volcanic regions where eruptive histories remain poorly constrained and outcrops are difficult to access.

# Volcanic vortex rings at Bocca Nuova, Mt. Etna (Italy): field observation with thermal, highspeed and visible cameras and experimental simulations

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Active volcanic degassing often includes puffing activity, consisting of the repeated emission of gas puffs at the vent, with inter-event durations of few seconds. This pulsatory degassing regime can generate volcanic vortex rings (VVRs), i.e., toroidal vortices of volcanic gases that propagate through the surrounding atmosphere while entraining air. Although VVRs have been reported at several mafic volcanoes worldwide (e.g., Yasur, Aso, Pacaya, Whakaari, Mt. Etna, Stromboli), their quantitative characterization and the conditions controlling their formation remain poorly constrained in the volcanological literature. Understanding the dynamics of VVRs may provide important insights into shallow conduit processes and magma degassing mechanisms. In the summer of 2023, the persistent degassing activity of a newly formed pit crater within Bocca Nuova crater at Mt. Etna (Italy) was monitored using a multiparametric system known as SKATE. The monitoring setup included synchronized thermal, visible and highspeed cameras. The acquired video sequences were analysed to investigate the formation, evolution and propagation of VVRs above the emitting vent. Image analysis was performed through a combination of manual tracking using ImageJ and automated processing in MATLAB. The automated workflow was based on the analysis of brightness temperature variations of individual pixels extracted from the thermal imagery, allowing VVRs identification and tracking with time. A total of 236 VVRs were investigated in detail in thermal imagery, with rings remaining identifiable as long as they exhibited a thermal anomaly relative to the surrounding ambient air. Based on their morphological and dynamical characteristics, including ring shape, outer radius, distance from the vent, residence time in the atmosphere, vertical rise velocity, radial expansion rate, emitting temperature, entrainment factor, and Mach number, two main classes of VVRs were identified. Class 1 rings are well-defined, coherent and stable structures, typically reaching heights greater than 50 m above the vent, with initial outer radii ranging between 6 and 12 m and initial rise velocities between 8 - 20 m/s. They are characterized by a mean Mach number of 0.027 ± 0.006 and emitting temperatures higher than 350 °C. In contrast, Class 2 vortex rings are irregular in shape, less coherent and short-lived, typically remaining within 50 m from the vent, with smaller initial radii (3 - 10 m) and lower initial rise velocities (less then 10 m/s). They exhibit a mean Mach number of 0.019 ± 0.003 and emitting temperatures below 350 °C. A comparative analysis was also conducted between phases of Etna's activity preceding and following documented occurrences of VVRs, from the early 1900s to the present day. This historical comparison aims to assess whether VVRs formation is associated with specific degassing regimes, conduit conditions, or transition to a peculiar volcanic activity. Since vortex rings are extensively studied in fluid dynamics, engineering and biological systems, where their formation mechanisms are well constrained both theoretically and experimentally, the physical conditions required for VVRs generation at volcanic vents were further investigated. Vortex rings were experimentally reproduced using a device consisting of a cylinder and a piston equipped with a spring-driven mechanism, allowing controlled generation of gas pulses. The

bursting of gas slugs with different volumes was simulated under varyingpiston accelerations to reproduce a range of impulsive gas release conditions comparable to those occurring during VVRs formation. Comparison of field and experimental results provides constraints on the source parameters controlling VVRs generation, including the L/D parameter of the gas pulse and magma depth, associated with VVRs formation. The characterization of VVRs thus represents a valuable tool for probing near-surface conduit dynamics and gas release processes. VVRs observations offer a unique opportunity to infer source conditions at the top of the magma column and to improve our understanding of degassing dynamics, gas flux and conduit processes during persistent active degassing of volcanoes.

# Mass Eruption Rate and dynamics of Etna's tephra plumes: insights from VOLDORAD-2B Doppler radar high-rate time series

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The near real-time estimation of eruptive source parameters is a major challenge for volcano monitoring. Mass Eruption rate (MER) and plume height are crucial to timely assess tephra plume hazards, these parameters being essential for initializing forecast plume models of ascent, sedimentation, and atmospheric ash dispersion (VAAC) used in crisis management.
Since 2009, the integration of the VOLDORAD-2B L-band Doppler radar of OPGC (23.5 cm) into the INGV-OE monitoring network of Etna has provided detailed time series of over 60 paroxysms. Aimed fixedly towards the summit area, the radar probes the ejecta at the base of the eruptive column, regardless of weather conditions, using range gating to discriminate among eruptive craters. The combined measurements of the radar echo power and Doppler velocities can be used to derive a proxy for the emitted mass, then calibrated into a MER using a plume rise model based on observed plume heights [Freret-Lorgeril et al., 2018]. As a follow on to this work, we computed the MER time series at high rate (down to 0.2 s) to investigate applications for both real-time monitoring and understanding of the dynamics of tephra plumes at short to long time scales.
The study of about sixty tephra plumes recorded by VOLDORAD-2B since 2011 shows MER ranging over four orders of magnitude from 102 to over 106 kg per s. These estimates combined with plume height measurements from various sensors provide a large data set from which a new statistical power law relating the height of the plume to the source MER is inferred, making it possible to estimate one from the other. Being based on direct observations and more specific to Etna eruptive conditions, this relationship improves on more widespread relationships in the continuity of [Mereu et al., 2023] and can be used as an input parameter to forecast models, including in operational context.
Furthermore, the high temporal resolution of VOLDORAD-2B allows the typology, duration and fluctuations of each paroxysm phase to be precisely identified, potentially in real-time. We show that the most intense minutes of the lava fountain phase (climax) not only release most of the total tephra mass but also provide the highest momentum necessary for the plume to rise to its maximum height. This points to the maximum sustained MER as the critical parameter for plume dynamics and height relationship, rather than the eruption average MER. The time delay from emission source to plume top can also be characterized. Another capacity stemming from our high-rate measurements is the all-weather detection of eruptive regime transitions, such as Strombolian activity turning into lava fountains that feed sustained ash emission into the atmosphere. This can contribute effectively to refining the alert thresholds and early warning system during emission phases of increased volcanic hazards, in order to limit the impacts on air traffic, human health, and infrastructures affected by the transport and sedimentation of tephra.

S11 - Poster

# Spatio-temporal distribution of ash load in volcanic plumes: insights from Doppler radar and disdrometer at Sabancaya

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We carried out unique measurements of ash plumes from Sabancaya volcano (Peru, May 2018) by combining transportable instruments from the VOLDORAD platform (OPGC, SNOV): a 3.2 mm-wavelength scanning Doppler radar and a laser disdrometer, respectively located at 4.5 km NNE and 4.5 km E from the vent. Our main objectives are to: 1) estimate the mass loading parameters (concentration, mass flux), which are critical for forecast models of plume rise, ash fallout and atmospheric dispersal, and 2) investigate links between the internal dynamics of ash plumes and ash sedimentation processes. Using disdrometer records of ash size and settling velocities and microphysical analyses of ash samples, we estimate sedimentation rates at ground level and derive an empirical relationship between radar reflectivity and ash concentration. We use the latter relationship to estimate particle concentrations inside the plume. Multiple radar sounding configurations with unprecedented space-time resolutions (down to 12.5 m and 0.25 s) reveal strong variations in the spatio-temporal distribution of ash concentration within the plume still reaching one order of magnitude at 5 km from the vent. We take advantage of fixed pointing radar configuration to track along-beam and temporal fluctuations of the emission source or farther plume regions whereas scans across various plume regions are used to constrain the relative particle mass distribution. In particular, vertical and horizontal 2D scans of eruptive columns document the spatio-temporal evolution of their ash concentration profiles and geometry while 3D sector scans extending above the disdrometer location provide stringent constrains on particle mass loss with distance. Fallout sequences measured on the ground by the disdrometer lag 1-4 km high ash plume emissions by 10-22 min and last up to 30 minutes. Interestingly, inferred sedimentation rates are characterized by minute-scale fluctuations consistent with ash sedimentation by ash fingering and sediment thermals. These sedimentation processes are proposed for weaker plumes at Stromboli [Freret-Lorgeril et al., 2020] and our results suggest they may be widespread among stronger plumes.

# Tephra characteristics: insight into fragmentation and paroxysmal dynamics

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Basaltic explosive activity produces heterogeneous juvenile population, including sideromelane, tachylite, and free crystals. A detailed characterization of clast morphology, texture and porosity with varying grain size, can therefore provide valuable constraints on both fragmentation dynamics and eruptive behaviour. In low-viscosity mafic systems, the mechanisms governing primary fragmentation remain poorly understood; however, this process is increasingly attributed to the fluid-dynamics resulting from the balance between capillary, inertial, and shear forces.

Here, we investigate the 1 December 2023 Etna eruption, performing a detailed morphological and textural analysis of basaltic juvenile material spanning various grain-size classes. We examined how clast shape, vesicularity, and groundmass crystallinity change with particle size. Previous studies suggest that the most degassed and microcrystalline juvenile component may preserve key information on ascent rate and residence time within the conduit. In our case, although this component is only a minor fraction of the deposit, its distribution across grain-size classes, when integrated with remote-sensing reconstructions of the lava fountain, provides clues to the syn-eruptive evolution of the system. By contrast, the more vesicular and less microcrystalline fraction represents the most primary magma and can record more clearly the fragmentation processes associated with capillary instabilities.

The integrated study of componentry, shape parameters, and textural data suggests that primary fragmentation was not governed by a single mechanism, but rather by the interplay of multiple fluid-dynamic processes, operating during ascent and fountain development. This multidisciplinary approach, combining laboratory analysis of erupted products with remote sensing data, offers new constraints on fragmentation in basaltic eruptions and improves our understanding of explosive mafic volcanism.

# Sensitivity retrieval in satellite remote sensing of volcanic clouds

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Explosive activities inject in the atmosphere gases and volcanic particles, the latter known as tephra, within a volcanic plume, where the smaller particles (below 2 mm in size) are distally transported within a volcanic cloud. The dispersion of volcanic clouds poses a risk to aviation safety, as small particles can damage engines turbines. For this reason, a prompt estimate of volcanic cloud properties is essential to identify areas affected by low, medium and high concentration of ash according to the International Civil Aviation Organization (ICAO) standards. Satellite observations are an important source of data for near real time monitoring and for retrieving volcanic cloud properties through inversion techniques. Radiative transfer models are used to simulate the spectral radiance in presence of different particles. In the case of volcanic clouds, these mainly consist of silicate and liquid/ice water particles. For example, at thermal-infrared wavelengths silicate particles absorb more in range 9-11 μm, while water particles absorb more in the range 12-14 μm. This different absorption behaviour is used in split window techniques to first distinguish between meteorological and volcanic clouds and later to estimate quantities of the observed clouds. In this analysis, we used a radiative transfer model algorithm to simulate the spectral radiance observed by a passive thermal infrared radiometer aboard a Geostationary satellite platform: SEVIRI instrument aboard the MSG satellite. To simulate the spectral radiance, we consider either one or two layers approximation of the atmosphere to solves the radiative transfer differential equation. The atmosphere is assumed to be homogeneous in the layer. In this work, we investigate how different assumptions on the thickness of the layer, the size distribution of the particles and the satellite viewing inclination angle affect the retrieval of volcanic cloud properties: the mean particle radius, the optical depth, the ash mass and the ash concentration. For the investigation we considered different eruptions occurred at Etna volcano in 2021. The results show that adopting a lognorm rather than a scaled-gamma particle size distribution has a limited impact on retrievals. In particular, for the ash mass and concentration quantities, slightly higher values are associated to simulations assuming a lognorm distribution compared to a scaled gamma distribution, while the mean particle radius and the optical depth remain largely unchanged. In contrast, variations in the satellite viewing angle from nadir to off-nadir produce more pronounced effects, with decreasing estimates of fine ash mass, concentration, and optical depth as the viewing angle increases, and only minor changes in the mean particle radius. A similar sensitivity is observed with respect to layer thickness. In conclusion, this analysis shows the importance of accurately accounting for satellite viewing geometry and atmospheric layer thickness in retrieval algorithms. Reliable estimates of ash mass and concentration are critical for hazard assessment and support decisions for aviation risk management, including the definition of no-fly zones.

# Toward a unified database of explosive eruptions in the Euro-Mediterranean area over the last 2,500 years

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Explosive volcanism in the Euro-Mediterranean region has generated a wide range of eruptive styles, magnitudes, and impacts throughout historical and late Holocene times. Despite the wealth of volcanological information available from catalogues, historical records, and scientific literature, these data are dispersed across heterogeneous sources. This fragmentation limits large-scale comparative analyses and hampers the integration of eruptive parameters into regional hazard and climate-oriented investigations.

Here we present the ongoing development of a unified database of volcanic eruptions that affected the Euro-Mediterranean area over the last 2,500 years. The primary objective is to construct a comprehensive chronological framework integrating key volcanological parameters, such as eruption age, location, magnitude indicators (e.g., VEI), and geochemical data, with a consistent structure. The database is designed to support systematic analyses of eruptive frequency, magnitude variability, and potential temporal clustering, with particular attention to eruptions capable of producing regional to large-scale climatic perturbations.

The construction of the database is grounded in an Exploratory Data Analysis (EDA) framework combined with structured data mining and processing.

The integration of multiple catalogues involves several critical challenges, such as inconsistencies in volcano nomenclature, differences in temporal coverage, chronological discrepancies among sources, and conflicting magnitude classifications. In addition, eruption ages are frequently associated with significant uncertainties or expressed as age ranges, requiring careful handling to preserve data integrity while enabling quantitative analysis.

Although still in progress, this database represents a necessary step toward establishing a coherent regional eruptive framework. By providing a harmonised dataset of explosive eruptions over the last 2,500 years, the project aims to facilitate multidisciplinary investigations linking field-derived eruptive parameters, statistical analyses of eruption patterns, hazard assessment, and the evaluation of possible connections between major explosive events and short-term climatic variability.

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# Paleomagnetic constraints on emplacement temperatures in phreatomagmatic deposits from the Astroni volcano (Campi Flegrei, Italy)

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Explosive volcanic eruptions encompass a broad spectrum of eruptive styles and transport-depositional processes, generating diverse deposits and volcanic hazards. Among these, phreatomagmatic eruptions are particularly hazardous due to their ability to produce highly mobile pyroclastic density currents (PDCs) capable of causing severe destruction. Magma-water interaction processes have played a major role in the evolution of Campi Flegrei (Italy), one of the largest and most densely populated active calderas worldwide. Constraining the physical parameters that control PDC generation, mobility, and emplacement under these conditions is therefore critical for reconstructing eruption dynamics and improving hazard assessment and numerical modelling of eruptive scenarios.

In this study, we use paleomagnetic methods to constrain the emplacement temperatures of the ~4 ka pyroclastic deposits from the Astroni volcano. The Astroni pyroclastic succession represents a unique and well-preserved eruptive sequence characterised by phreatomagmatic and magmatic events closely spaced in time, providing an excellent opportunity to examine fragmentation processes, transport-depositional mechanisms, and thermal conditions during PDC emplacement.

We collected and oriented in situ two hundred one lithic clasts (0.3 - 4 cm in size) from ten intra- and extra-crater sites representative of six different volcanic units. Paleomagnetic analyses indicate that the clasts experienced different thermal histories, displaying either a single (CH) or two (HT-LT) magnetic components. Clasts with a CH component were subdivided based on magnetic directions: cold (≤ 160 °C to ≤ 470 °C) clasts display randomly oriented directions, whereas hot (≥ 550 °C) ones show directions subparallel to the expected geomagnetic field. Clasts with HT-LT magnetic components record temperatures between 190 °C and 470 °C.

Lithic clasts recording lower temperatures are interpreted as fragments incorporated cold and subsequently heated by the deposit; these clasts were therefore used to constrain the emplacement temperature of the PDC. In contrast, clasts recording higher temperatures are interpreted as hot lithic fragments, derived from the upper part of the plumbing system.

Based on the lowest values identified at each locality, inferred emplacement temperatures range between 220-250 °C for Unit I, ≤160 °C for Unit II, 220-250 °C for Unit III, and 250-280 °C for Unit IV. Unit V, investigated in an ultra-proximal intra-crater area and at extra-crater localities, yields values ≤280 °C within the crater and ≤160-280 °C outside the crater. Unit VI, including an ultra-proximal intra-crater exposure and a proximal extra-crater exposure, shows temperatures of 220-250 °C and ~190 °C, respectively.

Low temperatures both within the crater and on the outer slopes of the volcano consistently characterise the products of all Astroni eruptions, indicating relatively cool PDCs even in proximal depositional settings.

A comprehensive explanation can be obtained by comparing the paleomagnetic results with data obtained from sedimentological observations and morphological and textural studies of the products. The occurrence of juvenile pumice clasts characterised by well-developed vesicles indicates that magma fragmentation was largely driven by magmatic volatile exsolution during eruption, resulting in rapid bubble growth and expansion typical of magmatic explosive activity. The coexistence of these pumiceous juvenile fragments with deposits containing accretionary lapilli and emplaced by relatively cool PDCs suggests that the Astroni eruptions involved a complex interplay between dominantly magmatic fragmentation and subsequent interaction with external water. While vesiculated pumice records primary magmatic degassing and fragmentation, the comparatively low emplacement temperatures inferred from paleomagnetic data indicate that cooling likely occurred during the final stages of magma ascent and/or at the surface, possibly through interaction with shallow water bodies and incorporation of external water and cold material.

This scenario implies that fragmentation remained predominantly magmatic, whereas magma-water interaction occurred mainly after fragmentation, promoting cooling, ash aggregation and early deposition, and the emplacement of relatively dilute and low-temperature pyroclastic density currents.

# Deposits and eruptive products of repeated small-scale explosions during the 2014-2020 eruption cycle at Kuchinoerabujima Volcano, Japan

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Phreatic activity consists of explosive events resulting from the sudden flashing of subsurface water into steam, without the direct involvement of new magma. This type of activity remains challenging to forecast and causes abrupt disruption and ejection of pre-existing rocks, which can severely affect the areas surrounding the craters, up to a few km away. At active volcanoes, the availability of water and pressurized fluids within hydrothermal systems can increase the likelihood of frequent phreatic eruptions, either as standalone explosive events or in association with magmatic eruptions. While significant advances have been made in recent years in the study of phreatic activity worldwide, the drivers and dynamics of phreatic explosions, as well as the possible interplay between external water/fluids and magma, remain poorly understood. In this context, the slow intrusion of magma bodies at shallow depths may prime the hydrothermal systems for failure, eventually reaching the conditions for phreatic explosions triggering.
In this work, we present a preliminary study of the pyroclastic deposits emplaced during the 2014-2020 eruption cycle at Kuchinoerabujima volcano in Japan. These eruptions have been previously suggested to have resulted from phreatic explosions with, however, the possible presence of small amount of juvenile material [Geshi et al., 2016; Minami et al., 2022]. Deposit characterization and stratigraphic reconstruction of the 2014-2020 pyroclastic succession were coupled with a detailed review of the available official volcanic activity reports and monitoring camera recordings, providing a high-resolution chronology of the eruptive activity during this period.
Fieldwork and deposit analysis revealed that the 2014-2020 succession consists of multiple discrete beds of limited areal dispersal (1 to 2.5 km from the active Shindake crater). Proximal sections are dominated by meter-thick breccias and poorly sorted tuff breccias, which are locally preserved at medial sites. Medial areas commonly exhibit massive to occasionally cross-stratified, ash-dominated deposits, ranging from 10 to 75 cm in thickness and interbedded with a distinctive clast-supported lapilli layer. In contrast, distal sections are mainly characterized by thin, massive to crudely laminated ash beds. At the macroscopic scale, all beds are dominated by dense lithic clasts, showing various degrees of alteration. Based on facies variations, litho-sedimentological characteristics, and the nature of contacts between beds, six main lithostratigraphic units (A to F), are identified within the succession and are tentatively correlated to observed 2014-2020 activity.
Review of the official activity reports and available video recordings revealed similar eruptive patterns during the 2014-2020 cycle, which was characterized by discrete, short-lived explosive pulses producing pyroclastic density currents (PDCs) and associated buoyant co-PDC plumes, reaching heights of 1 to 9 km above sea level. Each pulse was typically accompanied by prolonged (hour-long) ash venting. The eruptive cycle started with a single explosive pulse in August 2014 and continued with two explosions in 2015, the latter forming the most widely

dispersed PDCs of this recent activity. After a two-year break, activity resumed in October 2018 with a series of repeated small-scale pulses lasting over a month and culminating in a larger explosion in December. Activity continued through January 2019 with intermittent explosions and two larger explosions in late January. Notably, during the December 2018 event, a very short-lived (30 seconds) lava fountain was recorded by monitoring cameras, reaching altitudes of ca. 200 m above the crater. In 2020, two explosions occurred in January and February and were followed by intermittent small-scale pulses.

Petrographic and scanning electron microscopy analyses of the eruptive products are currently underway to characterize componentry and its variability throughout the eruption cycle. Two grain size fractions (-1 to 0 $\phi$ and +2 $\phi$) were used. Preliminary results indicate that each unit in the studied succession is largely dominated by lithic clasts that display various hydrothermal alterations and secondary mineralization (e.g., alunite, pyrite, clay minerals, as well as tridymite). Minor amounts of unaltered to poorly altered glass fragments, generally characterized by a highly crystalline rhyolitic groundmass, were observed in the finer grained portions (+2 $\phi$ fraction) of all units.

These observations raise new questions about the origin (s) of the deposits and the nature of the eruptive dynamics, making the 2014-2020 explosions at Kuchinoerabujima a particularly valuable case study for investigating eruptive processes occurring at the boundary between phreatic and magmatic activity.

# On the use of unconformity surfaces as stratigraphic markers for identifying and correlating eruptive units in the Astroni pyroclastic sequence (Campi Flegrei, Italy)

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Understanding eruptive behavior, eruption frequency and associated hazards represent major challenges in the volcanological community. Establishing a robust stratigraphical framework is the fundamental step for reconstructing the eruptive history of a volcano, whether characterized by single or multiple eruptive events. Unconformity surfaces (e.g. angular discordances, erosive surfaces, disconformities) are common features in all volcanic settings and record hiatuses in the stratigraphical succession associated with periods of quiescence in the eruptive activity. In the field, they are typically identified as irregular or truncated surfaces, often associated with erosive contacts, paleosols and/or interbedded reworked or weathered materials between primary tephra deposits. In this study, we present new field evidence of numerous unconformity surfaces within the ultra-proximal, proximal and medial sequences of the Astroni volcano, a multistage tuff ring edifice (4.1-3.8 ka) formed during the most recent eruptive epoch of Campi Flegrei. Previous studies have shown that Astroni was the source of seven relatively short-lived explosive events, separated by variably long repose intervals [Isaia et al., 2004]. Our analysis identifies five major unconformity surfaces throughout the Astroni sequence, which serve as key stratigraphic markers for correlating eruptive units from ultra-proximal, intra-crater to medial areas. These unconformity surfaces range from (i) irregular to smooth erosional surfaces, locally forming well-developed, U-shaped channels up to 2.20 m deep and 4.5 m wide, (ii) steeply sloping (46° dip), planar, surfaces, extending for over 5 meters in width, to (iii) gently undulated erosional surfaces with diffuse, low-amplitude, mm-to cm-sized scours. Thin paleosols and/or variably humified horizons are found locally at top of these surfaces, subsequently buried by pyroclastic density current and/or fall deposits of the following eruptive event. These features record multiple hiatuses of variable duration, possibly from hours to days or longer, suggesting an episodic nature of the Astroni eruptive activity. During these time breaks, secondary processes such as weathering, extensive erosion, reworking and crater wall collapses occurred, marking quiescent periods between successive Astroni eruptions. Our results show that reconstructing volcanic stratigraphy and constraining eruption frequency in complex multi-vents environment requires not only the analysis of primary deposits, but also the identification and interpretation of quiescent intervals recorded by unconformities. Finally, our study emphasizes the need to explicitly incorporate subaerial processes, including crater wall collapse and extensive erosion, into stratigraphic reconstructions and volcanic hazard assessments.

# Textural characterization of tephra of Mt Etna from eruptive episodes from 2007 to 2024: Insights into the porosity-sphericity correlation in lapilli particles

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One of the central goals of volcanic hazards assessment is to understand what factors control the eruptive style of a volcano, its evolution through time, and how to promptly evaluate these controls in the field. Eruptive styles arise from interrelated magmatic properties, such as viscosity, volatile content, and gas loss, and external factors such as conduit geometry. These parameters control magma ascent rates, degassing, and decompression. Given that these processes occur inside the volcano, hidden from people's view, predicting the type, intensity, and magnitude of an eruption remains challenging. To address this, we examine textural characteristics of tephra particles of lapilli size (bigger than 3mm), such as vesicularity/porosity, shape, and sphericity. The inspected lapilli belong to several explosive eruptions (spanning from Strombolian to paroxysmal activity) occurring from 2007 to 2024 at Mt. Etna. We integrated samples from two activity cycles of 2007-2009 and 2011-2012, retrieved from the rock repository of INGV through Geo-INQUIRE Transactional Access, with samples from the most recent eruptions of Etna (2022-2024), derived from field campaigns sponsored by the University of Georgia and NSF grants. To ensure temporal continuity, these samples were supplemented by an additional set of tephra collected during research activities across the entire 17-year study period. The inclusion of such samples allowed for expanding the database related to the most recent eruptive episodes, which is needed to quantitatively correlate tephra shape and size with porosity. Samples were characterized for grain-size distribution and particle shape using a CAMSIZER (Retsch) particle analyzer in the Laboratory of Sedimentology of Osservatorio Etneo of the INGV and funded by ILGE/TNA access grant. The most representative grain-sizes of each sample were selected for density and volume measurements using both helium pycnometry and Archimedes' method. Integrating these characterizations enables the calculation of isolated and connected porosity contained in the analyzed tephra. Furthermore, exploring the relationship between rock porosity and its geometrical characteristics provides a statistical basis for developing a new scientific protocol that better constrain the volume of gas stored in magma at depth beneath Mt. Etna.

Based on preliminary data, the sphericity of lapilli is roughly indicative of the porosity level. Specifically, an elongation of the lapilli correlates with poor sphericity, suggesting a higher connected porosity. This work expects to contribute to monitoring techniques by proposing a method of sample collection and rapid analysis during ongoing-eruptions. Such methodology could provide timely information on magmatic properties, such as magma porosity, and thus how much gas is charged in the magma at depth during an eruptive episode.

# Textural and morphological characterization of the ca. 4 ka Astroni eruptive products (Campi Flegrei, Italy)

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In the last 15 ky, Campi Flegrei caldera was characterized by numerous phreatomagmatic and magmatic eruptions from several intra-caldera vents. Understanding the eruption dynamics and fragmentations styles is fundamental to constrain the impact related to ash depositions over densely populated areas. The Astroni volcano is located in the central-eastern sector of Campi Flegrei and grew during at least seven eruptions, which occurred in a relatively short time interval (4.1-3.8 ka). The Astroni eruptive activity was dominated by explosive eruptions, characterized by the deposition of pyroclastic density currents (PDCs) and subordinate fallout deposits. In this context, the Astroni deposits offer a valuable case study to gain insights into the role played by magma-water interaction during typical eruptions of Campi Flegrei.
To provide a better understanding of conduit dynamics and fragmentation styles, we present a characterization of the Astroni eruptive products via density measurements and morphological and textural analyses of juvenile clasts from two selected units of the Astroni sequence (Units 3 and 5). Samples from Units 3 and 5 are retrieved from key sections both inside and outside the crater. Density of juvenile fragments was measured for seven layers from Unit 3 and two layers from Unit 5, on subsamples of 50 clasts in the -4 $\phi$ to -3 $\phi$ range; density variation with grain-size (from -4 $\phi$ to +1 $\phi$) was also measured on selected samples. Vesicle textures were studied through image analysis for five pumice clasts (-3 $\phi$ and -2 $\phi$ in size) of different samples along the stratigraphic sequence of Units 3 and 5. Finally, the ash fraction (below 0.250 mm) of Unit 3 and 5, retrieved from inner and extra crater samples, was analyzed using the static particle analyzer Malvern Morphologi G3SE to quantify the whole particles' morphology. Juvenile clast densities show mostly unimodal trends with similar modes across both units (around 700 kg/m$^3$ and 600 kg/m$^3$ for Units 3 and 5). Density variations with grain-size reveal the classical sigmoidal variation, reflecting the presence of vesicles with homogeneous size distributions and the scarcity of large (over 1mm) vesicles.
Scanning electron microscopy observations reveal heterogeneous vesicle textures in both units, with clasts displaying both circular and elongated vesicle shapes, including highly stretched, tube-like vesicles. In samples from Unit 3, vesicularity clusters between 53 and 73%, with few clasts having lower vesicularity (39-47%). Samples from Unit 5 show vesicularity values consistent with those of Unit 3, varying between 55 and 71%. Vesicle size distribution and vesicle volume distribution plots suggest for both Unit 3 and Unit 5 processes of multiple nucleation and growth events, however possibly dominated by a final event of delayed vesiculation.
The external surfaces of the ash fragments was observed at SEM. 3D ash shape was quantified using elongation, circularity, convexity and solidity as descriptors. Particles between 30 and 70 microns show two different trends which mainly reflect differences in vesicle shape and size. Inner-crater samples follow one trend, while extra-crater samples follow a different trend. In Unit 5, differences in ash morphology can also be noted between fallout and PDC deposits.
The collected textural, morphological and density data are interpreted as related to the

fragmentation of moderate to highly vesicular magma during the Astroni eruptions, with only limited interactions with external water. Although the Astroni deposits are generally considered as the result of phreatomagmatic activity, the data collected in this work raises some questions on the nature and extent of the role of magma-water interaction on the dynamics of the Astroni and other Campi Flegrei eruptions.

# Thermo-rheological controls on ductile-brittle transitions in high-grade ignimbrites

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The thermal evolution of pyroclastic deposits exerts a primary control on their rheology during and after emplacement, governing the timing and style of welding and rheomorphic deformation. We compare two high-grade ignimbrites emplaced under contrasting thermo-rheological conditions: the Kencherra Ignimbrite (Main Ethiopian Rift) and the Green Tuff of Pantelleria (Italy). Field observations are integrated with Differential Scanning Calorimetry (DSC)-derived viscosity and cooling rates to reconstruct the temperature-time-viscosity evolution of the deposits.
The Green Tuff records persistently high-temperature conditions and low effective viscosity, maintaining a dominantly ductile regime throughout emplacement and post-depositional evolution. In contrast, the Kencherra Ignimbrite preserves evidence of repeated transitions across the ductile-brittle boundary during syn-depositional aggradation, recorded by the coexistence of eutaxitic fabrics, localized brecciation, and fracture development within welded facies.
A Weissenberg number framework shows that these contrasting behaviours arise from the dynamic interplay between relaxation and deformation timescales. Variations in strain rate, sedimentation rate, shear zone geometry, and cooling-driven viscosity can rapidly shift the system across the ductile-brittle threshold.
These results highlight that deformation regimes in ignimbrites are governed by the evolving balance between temperature-dependent viscosity and deformation timescales, which may either stabilize ductile flow or promote transient brittle-ductile oscillations during emplacement.

# S12 - RECONSTRUCTING SUBAERIAL AND SUBMARINE VOLCANIC SYSTEM EVOLUTION AND CHANGING LANDSCAPES THROUGH GEOLOGICAL MAPPING, STRATIGRAPHY, GEOCHRONOLOGY, VOLCANO-TECTONICS AND ADVANCED TECHNOLOGIES

Conveners:
Jacopo Natale, Arianna Beatrice Malaguti,
Alessandra Cinquegrani, Eugenio Nicotra

# A new catalogue of eruptive events at Vulcano Island, Italy, reveals decades-long macro-cycles of open-conduit activity

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A reliable reconstruction of eruptive activity is fundamental for understanding volcanic behaviour and for improving hazard assessment at volcanoes. Vulcano Island (Aeolian Islands, Italy) is characterized by recurrent Vulcanian activity and long repose periods, last eruption being a cycle of Vulcanian explosions in 1888-90. Eruptive activity can be reconstructed by multiple historical accounts and by field geology analyses. Despite its importance, existing catalogues are fragmented, heterogeneous, and mix eruptive phases, cycles, and individual episodes within cycles, often lacking systematic integration of geological and historical records. Here we present a revised and harmonized eruption catalogue for Vulcano Island, spanning from ~3500 BC to present, obtained through the critical revision of historical sources and their integration with volcanic deposits. Historical accounts were systematically analysed to distinguish eruptive activity from fumarolic unrest, to find potential false events (eruptions reported as such without any significant support), and were cross-correlated with stratigraphic, sedimentological, and geochronological data available in the literature. This approach strengthens the geochronological reconstruction of the island's eruptive activity, reducing previous uncertainties and reinforcing the potential correlations between field deposits and historically reconstructed activity. The resulting catalogue includes 60 eruptive events (53 of La Fossa and 7 of Vulcanello), classified by standardized eruptive style following a standardized scheme and supported by explicit historical and geological evidence. Completeness analysis suggests that the catalogue is reliable for all eruptive styles only after ~1700 AD, while earlier periods are likely biased toward longer-lasting and higher-impact events. Using hierarchical cluster analysis, we show that Vulcano's eruptive history is organized into macro-cycles, consisting of multi-phase sequences that include a complex sequence of effusive and Strombolian activity, as well as single Vulcanian explosions or long cycles of explosions. These macro-cycles may last decades and are interpreted as potential prolonged open-conduit phases. The track of macro-cycles is recognizable at least in the last 1100 years of activity. This result provides a robust framework for reinterpreting the concept of Vulcanian cycles commonly adopted for Vulcano, and for linking eruptive styles within coherent dynamic units, and for comprehending long-lasting repose periods like the present one.

# Central Mediterranean tephrochronology and explosive volcanism over the 240-190 ka interval: a highly-detailed record from Castiglione Maar, central Italy

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A comprehensive tephrochronological study was carried out on the lacustrine sedimentary sequence of the Castiglione Maar, located in the Colli Albani volcanic district (Lazio, Italy), and focused on the Marine Isotope Stage 7 (MIS 7; approximately 243-190 ka). Identified tephra layers were characterised for texture, mineral content, glass chemistry (major, minor, and trace elements), and dated by the $^{40}Ar/^{39}Ar$ method. The volcanic sources of the investigated tephra have been identified in the Sabatini Volcanic District and the Latera Volcanic Complex in the Vulsini District, with a smaller contribution from the Campanian province (Ischia) and Colli Albani District. Specifically, we identified tephra from the Vigna di Valle eruption ($^{40}Ar/^{39}Ar$ age 199.54 ± 0.43 ka, ±2σ), along with four tephra from presently unknown eruptions of the Sabatini Volcanic District. Particularly well-expressed and represented is the activity of the Latera Volcanic Complex, with tephra layers deriving from the eruption of Upper Grotte di Castro (modelled age 216.30 +1.24/-1.88 ka), Sorano (modelled age 220.8 ka +1.7/-2.0 ka), Farnese (modelled age 234.8 ka +1.3/-2.1 ka and 234.4 +1.5/-2.2 ka), and Stenzano (modelled 240.5 +2.1/-2.0 ka). Six additional unknown eruptions from the Latera activity were found together with the above-listed well-defined ones, one of which was directly dated by $^{40}Ar/^{39}Ar$ at 219.98 ± 0.44 ka (±2σ). This highlights a more complex history of the Later caldera. In particular, many of the identified well-known eruptive units were not single explosive events (i.e., single tephra). Instead, they represent a sequence of highly energetic events, separated by hundreds to thousands of years (multiple stacked tephra beds), sharing similar, yet geochemically barely distinguishable glass composition and mineralogical assemblage. Results allow a more complete reconstruction of the explosive history of Italian volcanoes during the MIS 7 and integrate the regional tephra lattice by introducing several new chronostratigraphic markers. These geochronological constraints are crucial to establishing a robust age model for the Castiglione maar sequence and refining the history of Latera caldera.

# Investigating volcaniclastic turbidites from Stromboli: implications for landslide frequency and tsunami generation in the last 10,000 years

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Active volcanoes are morphologically unstable environments that are constantly evolving under the influence of both constructive and destructive processes. Among these, one of the most significant hazards is volcanic landslides, including debris avalanches, lahars, and sector collapses, which can occur during or independently of eruptive activity. On volcanic islands, flank collapses are particularly critical because they can generate tsunamis that can cause serious damage to nearby coasts and propagate hundreds of kilometers. Understanding the timing, frequency, and magnitude of these events is therefore essential for an accurate assessment of hazards and risks. A typical example is Stromboli volcano (Aeolian Islands, southern Tyrrhenian Sea), known for its predominantly mild, intermittent and explosive Strombolian activity. The volcano is affected by recurrent volcanic flank collapses, that reflect the structural instability of the edifice and have played a major role in shaping its current morphology. To reconstruct volcano instability, marine sedimentary sequences are valuable long-term archives, as they can preserve both the turbidite sequences produced by past volcanic flank collapses as well as tephra deposits from nearby volcanoes, which provide important chronological constraints. In this study, we present sedimentological and geochemical analysis of volcaniclastic deposits from three marine sediment cores collected offshore Stromboli, at distances of ~30 and ~43 km northwest of the volcano. The cores consist of hemipelagic muds intercalated with volcaniclastic deposits that can be classified into three main types: (a) primary tephra layers and cryptotephra horizons produced by direct fallout from explosive eruptions; (b) mono-magmatic volcaniclastic turbidites linked to collapse events from the north flank of Stromboli; (c) multi-magmatic volcaniclastic turbidites resulting from the mixing of materials—including contributions from the Calabrian Arc—and from multiple volcanic sources during transport through the Stromboli canyon.

Our analysis focuses on the upper 2 m of the cores, representing the Holocene period. Sedimentological observations combined with geochemical fingerprinting allowed the identification of three primary tephra layers that can be correlated with well-known eruptions on land. These include the Vallone del Gabellotto rhyolitic tephra (dated 8.9-8.7 ka BP, Lipari), a high-K trachyandesitic tephra related to Neostromboli explosive activity (~8.7-6 ka, Stromboli), and the Monte Pilato rhyolitic tephra sequence (~776 CE, Lipari) near the top of the cores. Within this stratigraphic framework, we identified 18 distinct mono-magmatic volcaniclastic layers linked to the main eruptive periods of Stromboli (Neostromboli ~13-6 ka BP, Lower Sequence ~6-1.5 ka BP, Present-day ~1.7-1.3 ka BP-present). Stratigraphic correlations indicate that these deposits record at least 10 large-scale landslide events at Stromboli over the last ~10 kyr. Compared with the 2002 tsunamigenic landslide (~30·10$^6$ m$^3$), the landslide

volumes estimated from the turbidite thicknesses (~40·$10^6$ $m^3$ to ~500·$10^6$ $m^3$) suggest that most of these events were potentially tsunamigenic.
This study provides a detailed reconstruction of Holocene flank-collapse events at Stromboli and highlights the associated tsunami hazard, offering new constraints that are essential for hazard assessment and risk mitigation in the southern Tyrrhenian Sea.

# 160 years of Etna Summit Craters through a photogrammetry-based time machine

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This study presents a quantitative, multi-temporal assessment of Etna's summit morpho-structural evolution, spanning an unprecedented 160-year period (1865-2024). We successfully integrated historical topographic maps with modern, high-resolution remote sensing data, including Uncrewed Aerial System surveys. Rigorous validation confirms the reliability of all datasets, with accuracies improving from decametric scales in 1865 to metric precision for post-2020 datasets. Our topographic time series are cross-correlated with geological observations and geodetic data. The results document a profound structural shift from a monocentric system to today's highly dynamic polycentric system characterized by four craters with different behaviour. This morphological evolution is strictly dictated by individual role and location of each crater with respect to the structural framework, the feeding system, and the volcanic activity type. The divergent evolution of the four craters underscores a profound volcano-tectonic control due to the rift areas. In addition, the seaward sliding of the eastern flank generates a regional extensional regime that maintains the North-East and South rift zones, where repeated magma intrusions occurred. The South-East Crater's massive topographic growth, over the Valle del Bove hanging-wall, acts as a stress multiplier, exacerbating the hazard of flank instability and lateral collapses. Etna's evolution represents a complex, coupled system where intense magmatic flux interacts dynamically with gravitational spreading and structural failure, resulting in a continuously evolving and asymmetric volcanic structure. The presented workflow can be applied globally to other dynamic stratovolcanoes to better anticipate structural failures and vent migrations, ultimately improving volcanic hazard assessment and risk mitigation.

# Geological mapping of the Eocene Lessini Mountains volcanic district (Veneto, Italy) within the CARG project

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A new geological map is being produced for the Lessini Mountains in the Italian Southern Alps, (Veneto Region) as part of the National Geological Mapping CARG Project (Sheet 124 - Verona Est). The study area comprises Meso-Cenozoic sedimentary rocks, Tertiary volcanic products belonging to the Lessini Mountains volcanic district and Quaternary deposits, all affected by compressional to extensional tectonics linked to the Alpine orogenesis.
Mapping of volcanic rocks is performed at the 1:10.000 scale. Based on lithological and petrographic features, basaltic hyaloclastites and basaltic submarine to subaerial lava flows are recognized as the main volcanic lithofacies. To support geological mapping, morphological analyses have carried out using Red Relief Image Maps (RRIM) obtained from high resolution Lidar-derived DTMs. This technique is particularly useful for highlighting volcanic landforms such as lava flows and eruptive centers in highly vegetated and cultivated areas. Stratigraphic and geomorphological evidence allow us to distinguish two lithostratigraphic units. The older "Lavas and Hyaloclastites of Vandinei" are a succession of basaltic hyaloclastites and associated submarine lavas related to NNW-SSE fissural activity, intercalated with Eocene calcareous layers (Calcare Nummulitico). The overlying "Lavas of Monte Calvarina" mostly comprise a sequence of subaerial lava flows forming a low-angle shield volcano with some lateral vents. The two units are separated by the "Volcanoclastites of Cortivo", a laterally extended stratigraphic marker consisting of volcaniclastic sedimentary reworked deposits that record a quiescence phase of the Lessini Mountains volcanic activity. New $^{40}Ar/^{39}Ar$ ages obtained from samples selected along the entire volcanic succession, ranging from 43.60 ± 0.64 Ma to 41.09 ± 0.54 Ma moving to the top, confirm the stratigraphy and an Eocene age for the Lessinian eruptive activity.
Field observations, morphological analyses, stratigraphic constraints and radiometric evidence suggest that volcanism started with submarine basaltic fissural eruptions and later evolved into subaerial shield volcanoes, migrating progressively southward.

# Constraining the Youngest Volcanic Phase in Saudi Arabia: Eruption Distribution and Mantle Petrogenesis

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Saudi Arabia hosts 13 intraplate volcanic fields (Harrats) covering ~ 90,000 km$^2$ along the western continental margin, distributed at varying distances from the Red Sea spreading axis and the Afar mantle plume. Volcanism in the region spans from ~ 30 Ma to historical times, ranging from mafic to felsic compositions and from effusive to explosive eruptive styles [Coleman et al.,1983]. The last confirmed eruption occurred in 1256 AD near Madinah city, but seismic swarms in 1999 and 2009 linked to dyke intrusions confirm that the system remains active [Downs et al., 2018; Nobile et al., 2020]. Several additional historical eruptions, including a possible 1800 AD event in the southern Harrats, remain poorly documented and largely unconfirmed [Moufti & Németh, 2016], underscoring the lack of constrain on the present volcanic phase. The origin and source of the Harrats remains debated, with hypotheses invoking Afar plume upwelling [Civiero et al., 2022; Lim et al., 2020; Camp & Roobol, 1992] or involving decompression melting of a metasomatized Arabian lithospheric mantle [Bowden et al., 2023; Sanfilippo et al., 2021, 2024]. However, existing studies have relied on samples spanning broad age ranges, limiting their relevance to the current state of the system.

In this study, we focus on the youngest volcanic phase (< 100 ka) across all Harrats. We constrained the spatial extent and timing of recent activity through integration of geological maps, satellite imagery, and field observations, identifying ~ 50 eruptions dominated by mafic alkalic products emplaced as lava flows and scoria cones. We present whole-rock major and trace element geochemistry and radiogenic isotope data (Sr-Nd-Pb-Hf), along with mineral chemistry of these youngest volcanic products to better understand the composition of the mantle and the physicochemical conditions of partial melting. Our results reveal geochemical variability across and within the different Harrats, suggesting source heterogeneity and variable melting regimes rather than a uniform mantle source across the volcanic provinces. This variability persists even between volcanic fields along the same tectonic lineament. By targeting the youngest eruptive products, these data enable a direct comparison with geophysical observations of asthenospheric flow extending from the Afar plume, allowing an integrated assessment of mantle dynamics and petrogenesis across the region. This work provides the first systematic geochemical characterization of the < 100 ka volcanic phase across the entire Harrat province, improving our understanding of active mantle dynamics beneath the Arabian plate. Moreover, characterizing this youngest volcanic phase is critical for hazard assessment and risk mitigation in the region.

# Persistent dual source magmatic system beneath Campi Flegrei (Italy) inferred from 5,000 years of deformation

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Campi Flegrei caldera (Italy) has experienced repeated unrest episodes and eruptions over the past five milennia, including the 1538 Monte Nuovo eruption and the ongoing unrest since 2005. However, it remains unclear whether the shallow sources invoked to explain modern deformation represent transient features or long lived elements of the plumbing system. To adress this, we reconstruct a 5,000 year vertical deformation field from 32 paleoelevation markers, corrected for Holocene sea level change and integrated with historical and modern deformation, documenting up to 38.8 m of uplift near the La Starza terrace and subsidence toward the caldera margins. We model the vertical deformation using rectangular Okata type dislocations in an elastic half space. The lowest misfit configuration comprises four sources: two sill like magmatic bodies undergoing tensile opening and two steep dip slip faults. A shallow east dipping inflating sill (top at 4 km) reproduces the uplift peak in the Pozzuoli sector, whereas a deeper horizontal deflating sill (top at 8 km) explains the far field subsidence. Fault slip to the east and west adds localized vertical offsets that sharpen spatial gradients. We then evaluate whether the inferred deep shallow volume changes can be matched by realistic magma volatile mass balances, using petrologically constrained mass volume bookkeeping for magma transfer and open system degassing. Together, the deformation and petrological constraints suggest that a shallow magmatic storage region at 4 km depth has persisted and been repeatedly reactivated over the last 5 ka. These results support a persistent, vertically connected plumbing system operating over 5 ka that links Holocene resurgence to modern unrest.

# Assessing flank instability and lateral collapse stories in volcanoes from the Southern Volcanic Zone of the Andes

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The southern volcanic zone of the Andes (SVZ) offers excellent conditions for studying volcano flank instability and collapse. It comprises an almost continuous chain of active, structurally controlled volcanoes, some of which have large volumes (i.e., greater than 100 $km^3$), complex eruptive records, and historical eruptive activity. In these areas, tectonic stresses deform the substratum, and earthquakes impose significant seismic loads on the flanks of volcanoes. In addition, active geothermal systems produce extensive hydrothermal alteration, while climate factors enhance rapid weathering, sediment erosion, and transport. All those factors combine to set up flank instability and ultimately collapse, driving catastrophic volcanic debris avalanches (DADs). In this arc segment, human settlements around active volcanoes have almost permanent economic activities (e.g., tourism, energy production, international routes), as well as rich natural and cultural resources. Therefore, DADs can inflict a severe impact on these Andean communities. In this contribution, we highlight the concepts, challenges, and findings of the Fondecyt 11241126 grant (2024-2027), which aims to determine the distribution and geometry of slope instability and its controlling factors at volcanoes in the Chilean SVZ. We carried out in-situ geotechnical surveys and geomechanical investigations at San Jose, Planchon-Peteroa, Nevados de Chillan, Antuco, Lonquimay, and Osorno volcanoes. In addition, the DADs of Tinguiririca, San Pedro, and Calbuco volcanoes were studied in this project, as well as the newly recognized DADs at Nevados de Chillan and Osorno volcanoes. The results show that, despite hydrothermal alteration being an important factor in the debris avalanche transportation mode and the resulting deposit facies, it is not a fundamental condition for flank instability. In fact, some volcanoes with prominent collapses show marginal hydrothermally altered components within their DADs (e.g., Planchon-Peteroa, Antuco, and San Pedro), which grew over tectonically active, strike-slip fault systems. Also, volcanoes with low to intermediate silica content (i.e., basaltic to andesitic) have a high number of collapses, probably because of their high eruptive fluxes, which foster rapid edifice building approaching the critical angle of repose. Finally, complementing field-based observations, such as the Geological Strength Index and Schmidt Hammer rebound tests, with rock-mechanical characterization in the lab and numerical modelling of slope stability seems to be a suitable approach to delineate unstable portions of volcanic flanks.

# Fluid-Induced Fault Reactivations in Strike-Slip Regimes: Geodetic and Seismic Evidence from the Peloritani-Aeolian Sector

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Fluids can significantly modify the mechanical properties of rocks by lubricating faults, reducing friction, and altering strain behavior. In this study, we combine continuous GNSS position-time series, GNSS velocity field and relocated earthquake hypocenters to investigate fault kinematics and seismic strain release across the Peloritani Mountains (northeastern Sicily) and the adjacent Aeolian Archipelago. Our analysis highlights a complex crustal deformation zone along the Aeolian-Tindari-Letojanni Fault System (ATLFS), a crustal-scale right-lateral transtensional zone, alongside WNW-ESE to NW-SE right-lateral transfer zones in the western and central Aeolian sectors. Focusing on the 2021 deformation episode, GNSS data reveal a sharp kinematic velocity increase in the eastern block of the ATLFS compared to its fixed western counterpart, shifting from a pre-2021 baseline of 1.6 mm/y to 3.3 mm/y. This kinematic anomaly was strictly synchronous with a peak in seismic strain release and a significant unrest phase at Vulcano Island, characterized by rapid ground inflation and intense degassing. The temporal correlation of these phenomena, combined with evidence of gas discharges in the Peloritani area, suggests that enhanced fluid pressure effectively lubricated the fault surfaces, facilitating sustained slip and low-magnitude microseismicity over a 9-month period. These findings provide critical constraints on the timing and mechanics of fluid-induced fault reactivation in active strike-slip tectonic settings.

# Spatio-temporal geodynamic evolution related to the February 2025 subterminal eruption at Mt. Etna

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Mt. Etna is one of the most active and monitored volcano in the world proving to be an open laboratory to understand volcanic eruptions and seismotectonic processes. In this context the 2025 subterminal Mt. Etna eruption clearly represent a very good example of how seismicity, tectonics and flank instability play a crucial role in driving the magmatic activity.
In this work, we provide an accurate description of the February 2025 subterminal eruption using a multidisciplinary approach. Specifically, we describe the seismicity and the surface deformation, particularly along active faults, preceding and accompanying the eruption. We also compared faulting along the eastern flank with the subsequent changes of the volcanic activity in the subterminal eruptive fissure.
The eruption started on 8 February 2025 with the opening of an eruptive fissure in the saddle between Bocca Nuova and South East Craters at 3070 m a.s.l., marking the onset of effusive activity. The eruption has been preceded and accompanied by relatively moderate seismicity affecting the entire volcanic edifice with some clusters located in specific sectors. From September 2024, seismic activity increased on all flanks of the volcano, mainly at depths greater than 5 km. At the end of January 2025, a seismic cluster near Ragalna, in the south-western flank of the volcano, was followed by increased shallow seismicity (less than 2 km) and a slight rise in volcanic tremor. On February 10, a shallow seismic swarm (maximum local magnitude 3.7) along the Pernicana Fault, in the north-eastern sector of Mt. Etna, coincided with a rapid increase in volcanic tremor and lava effusion at the subterminal fissure. During the eruption, some shallow earthquakes affected the SE flank around the Trecastagni Fault on February 19, 23, 24 and 27, reaching a maximum local magnitude of 2.8. Notably, these earthquakes along the Trecastagni Fault immediately preceded the decrease of the volcanic tremor. The day after the 19, 23-24 and 27 February earthquakes respectively, we observed surface faulting along the Trecastagni Fault, characterized by offset up to 1.2 cm and a spatio-temporal evolution of the rupture from the SE toward NW. The evolution toward the NW of the rupture along the Trecastagni Fault has been detected also by InSAR LoS displacement, clearly showing deformations also along the Pernicana, Aci Catena and Aci Trezza Fault. where no clear evidence of surface faulting has been observed. The eruption ended on 2 March 2025, experiencing a drastic reduction in activity following the 27 February earthquakes.
The trend of the February 2025 eruption appears to be driven by deep tectonic structures prior to its onset, and subsequently strongly controlled by the flank instability process. This behaviour is uncommon during subterminal eruptions which are usually not accompanied by seismicity or the activation of the flank faults. Conversely, the flank eruptions may be accompanied by seismicity affecting the faults marking the distribution of the deformation along the sliding eastern flank. In fact, the Pernicana and the Trecastagni faults bound the unstable flank to the N and SE respectively. In this context, the February 2025 Etna eruption clearly shows, for the first time, that feedback processes between flank instability and magmatic intrusions

may be observed also during subterminal activity. Furthermore, this eruption demonstrates how volcano monitoring, also in terms of field surveys, during volcanic and seismic events, can improve forecasting and thus reduce volcanic risk in densely populated areas.

# Tracking the growth and deformation of fissure phreatomagmatic eruptions: Insights from the ca. 3.9 ka Nisida eruption at Campi Flegrei caldera, southern Italy

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Monogenetic eruptions characterize volcanic activity in caldera volcanic fields. One remarkable example is Campi Flegrei (southern Italy), which has experienced over 70 moderate-sized explosive eruptions in the past 15 k.y. Among these, only a few had a lateral propagation of the vent along an eruptive fissure. In this work, we explore the ca. 3.9 ka phreatomagmatic eruption of Nisida that occurred in the southeastern caldera ring fault zone. Combining field and uncrewed aerial vehicle (UAV)-based structural analysis with the available seismic reflection data, we traced the different stages of growth of a tuff cone complex along a 1.4-km-long eruptive fissure. The eruption started within the ring fault zone and propagated first toward the northeast, and then toward the north-northeast, producing a dike-induced graben. We have evidence of multiple gravitational collapse events throughout the eruption, mainly accommodated by approximately west-northwest, south-dipping normal faults, and outward-dipping slip surfaces. An energetic maar-forming eruptive phase produced inward-dipping circumferential normal to transtensive faults accommodating the vertical collapse. Post-lithification northeast-southwest and west-northwest normal-to-left-lateral faulting may indicate reactivation of the buried caldera rim in historical times. Features of fissure explosive eruptions, such as those observed here, are rarely reported in the literature. This case study thus offers an exceptional opportunity to examine syneruptive volcano-tectonic processes. Furthermore, we reassessed the eruption volume, including the dismantled morphology, yielding an unprecedented value of 0.17 $km^3$ of dense rock equivalent (DRE), with the subaerial extent now mostly eroded. Our results suggest that most of the eruptions of the last eruptive epoch (5.5-3.7 ka) had similar sizes (Volcanic Explosivity Index of 4), considering the single eruptive episodes. This work could prove useful for improving volcanic hazard assessment at the active Campi Flegrei, which represents the world's highest-risk volcanic area.

# Field and InSAR ground deformation evidence in the southern sector of Catania: active tectonic thrust or Etna's lateral spreading?

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Starting in early 2026, the urban area south of Catania has been affected by impressive evidence of ground deformation. Numerous and extended ruptures, exhibiting from compressive to extensional kinematics, were detected along a narrow strip. These features have caused damage to local roads and buildings, with field-measured displacements on the order of 4-5 cm. Notably, the formation of these surface fractures occurred aseismically. To constrain the spatial extent and magnitude of this significant deformative event, we analysed the Sentinel-1 SAR data acquired in ascending and descending geometries.
The observed displacement field is characterized by ~5 cm of horizontal shortening and ~3 cm of vertical uplift, indicating ongoing contractional deformation. The shortening-to-uplift ratio suggests that deformation is accommodated primarily by slip along an inclined thrust ramp, rather than by purely distributed folding.
The preliminary results of the kinematic analysis suggest a ~30° dipping plane, consistent with the geometry of the Catania Thrust Ramp proposed in the literature.
Furthermore, the detected ground deformation pattern highlights the coexistence of multiple deformation mechanisms. These may range from deeper detachment processes and localized ramp-related thrusting to effects induced by the lateral spreading of Mt. Etna's southern sector.
Finally, the identification of active shortening beneath or adjacent the Catania urban area has important implications for seismic hazard assessment, since part of the deformation may be also accommodated by seismogenic structures at depth.

# Why Marsili Seamount? An example of unexpected super-inflated seamount along a bounded Back-Arc Ridge

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This provocative title intends to draw attention to the distinctive and peculiar morphological features of Marsili Seamount, a ~70 km long and ~30 km wide volcanic complex emplaced about 1.0 Ma in the Southern Tyrrhenian Sea. Its size and location within the homonymous basin represent exceptional characteristics in the broader Mediterranean region.
Investigations of this seamount began in the 1980s with the first bathymetric surveys and continued in the 1990s with the acquisition of first magnetic data and rock sampling. Thanks to these pioneering studies, together with more recent investigations, significant insights into its geological and volcanological evolution have been achieved. Nevertheless, several key questions remain unresolved: Is Marsili truly an inflated ridge? If so, which is the mechanism(s) controlling the inflation?
Integration of magnetic anomaly patterns of the edifice and surrounding basins with detailed morphological analysis suggests that Marsili Seamount was emplaced above the former ridge of a back-arc basin that began its opening at ~2.0 Ma. Seafloor spreading in this sector appears to have been discontinuous and characterized by an initial phase of high spreading rates at the onset of basin opening followed by a progressive decrease, possibly culminating to its cessation around 780 ka.
During this time span, at approximately 1.0 Ma, the magmatic regime of the basin changed significantly being marked by an increase in magma supply. This renewed magmatic upwelling led to the construction of a large volcanic complex. The key open questions concern the evolutionary history of the seamount and the mechanisms responsible for its pronounced vertical growth.
Here, we propose a novel model for the inflation of Marsili Seamount based on 3D thermal models constrained by data on its internal structure derived from magnetic inversion results. We present a quantitative reconstruction of the thermal evolution of Marsili from its initial formation to its most recent phase of activity. Our results suggest that the seamount represents an inflated segment of a back-arc spreading ridge displaying structural and geophysical features analogous to those observed at other spreading centers.
These findings indicate that ridge inflation in back-arc settings may be more common than previously recognized.

# Assessment of the tsunamigenic potential of seamounts in the Tyrrhenian sea

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While consolidated methodologies exist for tsunami hazard quantification related to seismic sources, hazard studies for other tsunamigenic sources remain rare and are usually based on the analysis of specific scenarios. In fact, the generation and propagation of tsunamis produced by submarine landslides are complex processes that require specific knowledge about potential sources and sophisticated modeling of both the source and the tsunami generation and propagation. Given the scarcity of direct data for most submarine structures and the high computational cost of advanced models, systematic studies capable of quantifying the tsunamigenic potential of non-seismic sources over an entire basin, while accounting for full source variability, are still lacking. However, such sources may be significant and may even dominate in regions at low seismicity, such as the Tyrrhenian Sea, a geologically complex region hosting numerous submerged volcanic edifices in the central Mediterranean. Here, an innovative approach is developed to identify the most relevant tsunamigenic sources in terms of their potential impact on surrounding coasts. A simplified modeling approach for the tsunamigenic source is developed and coupled with a nonlinear model for the subsequent tsunami propagation (Tsunami-HySEA). This model is tested and calibrated using well-known sources at Marsili volcano, simulated with a more complex model (Landslide-HySEA), which allows fully coupled modeling of the landslide and the water body. The simplified model can be applied homogeneously to all existing potential sources within large source areas in order to quantify their tsunamigenic potential in terms of the maximum impact at the coast. The results consist of non-trivial prioritization maps for each target area, enabling the identification of sources that deserve specific attention, as they may potentially dominate the hazard at the target. Such prioritization maps may constitute a fundamental first step toward hazard quantification for this type of source.

# Constraints on magma ascent dynamics beneath Marsili Seamount (Tyrrhenian Sea) from plagioclase textures and geochemical records

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The potential of plagioclase as archive of magmatic processes was used to constrain the processes governing magma dynamics at the Marsili Seamount (Tyrrhenian Sea, Italy). As a low-pressure mineral phase that crystallizes over a wide temperature range, plagioclase is ubiquitous in the lava rocks forming the volcanic edifice. Here, we present an extensive morphological and compositional dataset obtained through optical and BSE images, together with in situ SEM-EDS/WDS and LA-ICP-MS analyses of plagioclase crystals from basaltic and andesitic lavas collected at different locations across the seamount.

Textural analysis reveals a plagioclase cargo dominated by clear oscillatory zoning in both basaltic and andesitic melts. Disequilibrium textures, ranging from dissolution features to sieve-textures, occur almost exclusively in plagioclase cores, suggesting complex early crystallization histories within the lower crustal plumbing system, possibly involving decompression occurring at various rates and/or magma mixing events. In contrast, the clear and euhedral oscillatory-zoned rims indicate more uniform late-stage crystallization under relatively stable physical and chemical conditions.

Variations in anorthite content along core-to-rim transects were evaluated against Sr/Ba and Li concentrations in plagioclase phenocrysts representative of near-equilibrium crystallization. At similar anorthite contents, Sr/Ba ratios vary significantly within both plagioclase suites, indicating local variations in the melt geochemical signature rather than changes in element partition coefficients. In situ Li systematics were used to infer shallow conduit dynamics associated with magma ascent and degassing that may have triggered volcanic activity at Marsili. A remarkably consistent Li distribution pattern is observed across all lavas, with plagioclase phenocrysts showing rimward Li enrichment. These Li enrichments are not correlated with variations in anorthite content and are therefore interpreted as the result of gas flushing in shallow reservoirs, which in turn triggered rapid magma ascent. Diffusion modeling of Li concentration gradients yields ascent timescales on the order of minutes to hours. Combining these results with constraints on magma storage depths allows us to estimate mean magma ascent velocities of 1.4-10.4 m/s for basalts and 0.6-9.2 m/s for andesites.

# A catalogue of data from the MAR98 and TIR2000 oceanographic campaigns (ISMAR-CNR): the "Marsili" section of the "Tyrrhenian Rocks" website

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Seafloor exploration of the Tyrrhenian Sea was carried out in the late 90s by the Istituto di Geologia Marina of Bologna (now ISMAR-CNR), during oceanographic campaigns. During two of these campaigns, i.e., the MAR98 and TIR2000 ISMAR-CNR cruises, several submarine volcanic edifices and structures of the Tyrrhenian Sea were mapped and sampled. The "Tyrrhenian Rocks" website (https://tyrrhenian-rocks.ismar.cnr.it/) aims to offer a catalogue of the data (bathymetric maps, metadata, and visual documentation of the rock samples) retrieved by the two campaigns and archived at ISMAR-CNR. The website was created by a team of researchers from ISMAR-CNR (M. Marani, F. Gamberi, V. Ferrante) and the University of Parma (C. Cavozzi, T. Trua), and is organized into the following sections: Home; Oceanographic surveys and maps; Samples; Bibliography; Collaboration network; Team. It reports published or public data that may be freely downloaded. The "Samples" sub-sections of the website refer to the samples collected in the following areas of the Tyrrhenian Sea: the Marsili, Vavilov, Palinuro, Eolo, Enarete, Sisifo, and Glabro volcanoes; the Prometeo lava field; the Basiluzzo area; and the southern margin of the Marsili Basin.
Currently, only the Marsili sub-section is complete thanks to a cataloguing work carried out within the framework of the PRIN2022-AWARE project. The Marsili seamount is the largest volcano in the Tyrrhenian Sea, formed over the last 0.7 million years along the active back-arc spreading center of the Tyrrhenian Sea. During the MAR98 and TIR2000 campaigns, a large set of volcanic and sedimentary samples was recovered from different parts of the volcanic edifice. The "Marsili" sub-section of the "Tyrrhenian Rocks" website provides a virtual view of a comprehensive inventory of volcanic and sedimentary rock samples collected from the volcano, including images, 360 degree photography, and thin-section photomicrographs. All the samples are georeferenced, but only a few of them have been studied in detail so far. An overview of the references referred to the results obtained from these studies, carried out within the framework of a scientific collaboration network, is reported in the "Bibliography" section of the "Tyrrhenian Rocks" website. The "Bibliography" section will be updated with the results obtained from the units involved in the PRIN2022-AWARE project.
The "Marsili" sub-section is a pilot section. It will guide the creation of sample sub-sections for the other Tyrrhenian Sea submarine areas sampled during the MAR98 and TIR2000 campaigns. The "Tyrrhenian Rocks" website will serve a wide community, including researchers, students, and amateur users. It provides closer contact with the collected rocks from the Tyrrhenian Sea

and highlights the limitations of the current sample studies. The site may also suggest future directions for new research collaborations and multidisciplinary investigations. It helps advance the comprehensive understanding of geodynamics, geo-resources, and natural hazards in the Tyrrhenian Sea region.

# Lava Mineralogy on Venus: Experimental and Thermodynamic Constraints

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Venusian lava flows display surface morphologies and inferred chemical characteristics that contrast markedly with those observed in terrestrial volcanic systems, yet the mineralogical makeup of these lavas remains only loosely constrained. This limitation hampers interpretations of radar observations and geochemical data returned by past and future missions. To address this gap, we investigate the liquidus temperature of Venus analog basalts with high temperature petrological experiments, followed by thermodynamic modeling using RhyoliteMELTS.
A basalt from the Krafla volcanic system in Iceland was selected as a compositional analog for Venusian lava. Experimental runs conducted under simulated Venus conditions yield a liquidus temperature of 1214.26 °C. This experimentally derived value was used as a reference for modeling crystallization sequences across a range of oxygen fugacity conditions, pressures representative of the Venusian crust and surface, in anhydrous conditions. The models indicate that feldspar is the predominant crystallizing phase across all tested conditions, whereas the appearance and stability of olivine, pyroxenes, and oxide minerals are strongly modulated by redox state and volatile availability. In particular, more oxidizing conditions promote the formation of ilmenite.
Normative mineral assemblages were compared with normative mineralogies derived from geochemical data collected during Soviet-era Venus missions. While the predicted abundance of feldspar broadly agrees with these datasets, notable differences emerge in the proportions of mafic phases, suggesting sensitivity to local redox and volatile conditions not fully captured by normative calculations alone. Overall, our initial results imply that Venusian magmatism operates under distinct redox and volatile regimes relative to Earth, influencing lava mineralogy and, by extension, surface spectral properties. This combined experimental and modeling framework offers new constraints for interpreting Venusian volcanic terrains and provides a useful reference for upcoming orbital and in situ investigations of the planet surface.

# Pulsed dike emplacement and lava tube formation during the 1971 Etna eruption

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The Serracozzo cave, formed during Mount Etna's 1971 flank eruption, offers a rare insight into feeder dike dynamics and lava transport. This bipartite cavity comprises an upper section within an eruptive fissure and a lower portion developed in a confined arterial aa lava flow. Here we combined historical imagery, geological field surveys and high-resolution digital modeling via terrestrial laser scanning and drone photogrammetry to reconstruct the cave's morphological evolution. Our analysis reveals a pulsating dike emplacement characterized by alternating cycles of magmatic pressure buildup and release, driving both upward and downslope propagation. The morphology of the fissure exhibits distinctive pinch-and-swell geometry, while surface vents acted as pressure-release valves, producing localized pahoehoe overflows and skylights. We have estimated the volume of the whole cavity at about 1270 $m^3$, which compared to that of the proximal host lava, makes the cavity just 3.6% of the flow. These findings enhance understanding of fissure-fed lava systems and provide valuable constraints on the timing and processes of lava tube formation, contributing to improved volcanic hazard assessments and mitigation at Etna and analogous basaltic volcanoes worldwide.

# Field and petrological studies on the last remnants of an explosive eruption at Yali (Greece) to understand the feeding system architecture

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Understanding the structure and evolution of volcanic feeding systems is essential to interpret the eruptive history of volcanoes and to contribute to volcanic risk assessment.
The island of Yali is a volcanic complex of the South Aegean Active Volcanic Arc (Greece), located within a highly tectonically active area and characterized by relatively recent explosive acidic volcanism that is still poorly studied. The present-day volcanic edifice consists of two distinct sectors with complex stratigraphic relations. The SW sector is dominated by a thick sequence of pyroclastic deposits, including the submarine Lower Pumice (YLP), the subaerial Upper Pumice (YUP), and overlying reworked pumice layers (YRL) separated by a thin Neolithic paleosoil. The NE sector, on the other hand, is formed by extensive perlitic lava flows and obsidian lava domes, associated with an explosive episode that created the Kamara tuff cone.
We have focussed on the fallout deposits of the Yali Upper Pumice (YUP - 31 ka) plinian eruption, which are rapidly disappearing due to intense quarrying activity and they may soon be completely lost. These deposits also crop out on Nisyros and other neighbouring areas. Rhyolitic pumices constitute the main volume of the erupted products, associated to variable proportions of dense, crystal-rich mafic clasts. The coexistence of these different magma types indicate possible interactions between compositionally distinct magmas within the feeding reservoirs. Through a detailed petrological approach, we have reconstructed the architecture of the feeding system of this eruption and investigated the genetic relationships between the different involved magmas, by the application of several analytical methods: detailed petrographic investigations, mineral chemistry analyses providing geothermobarometric constraints, and geochemical analyses of major and trace elements together with radiogenic isotope ratios.
The obtained results suggest a complex and dynamic system characterized by a shallow rhyolitic chamber fed by mafic pulses of different composition that interacted with the acidic magma through mingling processes and crystal recycling. The integration of petrological and geochemical data allows the definition of a coherent model of the YUP feeding system, highlighting the presence of multiple reservoirs and different levels of magma storage, and emphasizing the role of mafic inputs as a common mechanism in triggering explosive eruptions.

# Rheology of Lunar Basalt Analogues

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The morphology of the lunar surface records widespread volcanic activity dominated by low-viscosity basaltic lava flows emplaced under reduced gravity and vacuum conditions (up to $10^{-15}$ bar; [Johnson et al., 1972]). Understanding the rheological behavior of lunar magmas is therefore essential to constrain the emplacement dynamics of mare basalts, volcanic domes, and the erosive processes responsible for the formation of channel-like structures such as lunar sinuous rilles.

In this work we investigate the rheological properties of laboratory-produced lunar basalt analogues representative of four compositions: Apollo 11 high-Ti mare basalt (MB), Apollo 15 low-Ti basalt (LTB), Apollo 15 KREEP basalt (KB), and Apollo 15 Green Glass (GG). These compositions were selected among those presented by [Taylor (1982)] to reproduce a range of lunar basaltic melts with variable Ti, Fe, and incompatible element contents. Synthetic glasses were prepared by mixing reagent-grade oxides, melting them at 1400 °C in a high-temperature furnace, and rapidly quenching the melts to obtain homogeneous amorphous samples. XRPD analyses confirmed the predominantly glassy nature of the products, although minor crystallization of ilmenite and Fe-Ti spinels was detected in the high-Ti MB composition, likely related to its relatively high Ti content, which may enhance the nucleation kinetics of Fe-Ti oxide phases during cooling.

Rheological measurements were performed on remelted samples using a high-temperature rotational rheometer (concentric cylinder geometry) over a range of shear rates between 1 and 10 $s^{-1}$. The measured viscosities fall between ~10 and $10^2$ Pa s, significantly lower than those typically observed for terrestrial basalts and consistent with the high fluidity inferred for lunar lava flows. Experimental values are systematically higher than viscosities predicted by the [Giordano et al., 2008] model, suggesting that current compositional parameterizations may underestimate viscosity for these Ti-rich lunar melts. No significant shear-rate dependence was observed, indicating near-Newtonian behavior under the explored conditions.

Complementary spectral measurements in the VNIR and MIR ranges were carried out on different grain-size fractions of the glasses to build a reference dataset for lunar materials. The spectra show clear grain-size-dependent reflectance variations and typical silicate features, including Reststrahlen bands near ~1100 nm and a Christiansen feature near ~8000 nm.

The combination of experimental rheology and compositional control provides new constraints on the physical properties of lunar basaltic melts. Ongoing work includes viscosity measurements under controlled atmospheric conditions, expansion of the compositional dataset, and numerical modelling of lava flow dynamics and thermal erosion under lunar environmental parameters.

# Coupled paleomagnetism and $^{40}Ar/^{39}Ar$ dating of Latera ignimbrites (Vulsini volcanic district, Italy) unravel processes associated to piston-collapse calderas

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Ignimbrites are highly explosive volcanic products typically spread over wide areas around calderas. Many calderas are polygenic implying that they formed as a result of repeated ignimbrite events whose mineralogical and geochemical features can be similar. The complexity of these caldera-forming eruptions commonly produces ignimbrite deposits displaying significant internal variability, including facies changes and sectorial zoning related to emplacement dynamics. Furthermore, ignimbrites erupted at different times from the same caldera may have similar lithological and compositional characteristics, making it difficult to establish correlations between different caldera structures. Taken together, these factors can hamper correlation and clearcut identification of key eruptions in the sequence. Establishing correlations between ignimbrite units in such contexts is therefore essential for reconstructing the events that led to the formation of calderas and understanding eruptive dynamics.
In this study, we focus on the Quaternary Latera caldera (Vulsini Volcanic District, Italy), known as a world-class area for studying caldera-forming processes. We are going to deal with the correlation of two major units (the Grotte di Castro and the Onano Formations) through a systematic paleomagnetic and $^{40}Ar/^{39}Ar$ investigation on several key sites distributed across the caldera structure. Paleomagnetic sampling was carried out at 32 sites, while eleven sites were sampled for $^{40}Ar/^{39}Ar$ dating, encompassing proximal and distal facies.
The findings show that two major depositional units previously identified as two separate eruptive events (Grotte di Castro and Onano Formations) are shown to represent a single, major caldera-forming event, here renamed the "Grotte di Castro-Onano" eruption. This is supported by independent and consistent paleomagnetic directions and a common emplacement age near 205 ka identified both on sanidine and leucite juvenile crystals from proximal and distal facies. The "Grotte di Castro-Onano" eruption represents the largest and latest (with the exception of some younger/minor pyroclastic formations) caldera-forming stage of the Latera system. The eruption started with a high-intensity Plinian eruption gradually evolving from locally distributed PDC's into widely dispersed ignimbrite sheets when piston-collapse occurred and the mass discharge peaked. The sectorial preservation of pre-eruptive $^{40}Ar/^{39}Ar$ ages across the depositional sequence is interpreted to reflect the extraction processes with selective (re)mobilization of magma batches associated with piston collapse dynamics. Coupling paleomagnetism with $^{40}Ar/^{39}Ar$ dating is shown to be a key step in such cases for successful resolution of individual caldera-forming events at the millennial scale.

# Tephrostratigraphic Record and Chronostratigraphic Evolution of the Quaternary Bojano Basin (Southern Apennines): Insights from the BJ1 Deep Core

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The Bojano basin, located in the axial sector of the Southern Apennines, represents a strategic intramontane tectonic depression whose sedimentary infill constitutes an exceptional high-resolution archive of the dynamic interplay between regional crustal subsidence and distal volcanic activity. Within the framework of the MOSAICMO Project (Molise SAnnio Integrated Crustal MOdel), a 175 m deep borehole, Core BJ1, was successfully drilled in June 2024 to reconstruct the long-term evolution of the basin and establish a high-resolution chronostratigraphic framework. The BJ1 core recovered a continuous 139 m thick Quaternary succession, characterized by a complex alternation of fine-grained clayey-sandy silts and coarse-grained alluvial deposits, which unconformably overlie the Late Miocene Molise Flysch bedrock. A major highlight of this stratigraphic sequence is the identification of eight primary tephra layers, preserved within a dominant alluvial-palustrine facies, which have been thoroughly characterized through integrated textural, geochemical, and geochronological analyses. These primary pyroclastic deposits represent fundamental synchronous markers for correlating the basin infill with the major explosive activity of the Roman and Campanian Magmatic Provinces. The geochemical signatures of the identified tephra reveal a distinct stratigraphic evolution of the volcanic contributions: the two uppermost layers exhibit trachytic compositions, likely related to the Late Quaternary activity of the Campanian volcanic complexes; the four intermediate layers show a clear phonolitic affinity, providing a potential link to major regional marker tephra associated with large-scale explosive eruptions; finally, the two lowermost layers are characterized by phonolitic to tephri-phonolitic compositions, marking the onset of volcanic input during the early stages of basin formation.
To constrain the timing of sedimentation and evaluate the long-term variability of fault slip rates, four of these primary tephra samples were selected for high-precision geochronology. These absolute dates, integrated with tephrostratigraphic correlations and paleomagnetic analysis, allow for the construction of a robust, multiscale age model for the Bojano basin. The lack of significant pedogenesis and of deep lacustrine features points to a long-term dominance of stable alluvial-palustrine environments suggesting a persistent balance between tectonic subsidence and sedimentation rates throughout the Quaternary.
This study highlights the importance of the Bojano basin as a crucial distal tephrostratigraphic site, offering high-quality data to refine the Mediterranean tephra framework and providing essential constraints for the seismic hazard assessment of the active fault systems characterizing the Molise-Sannio region.

# Assessing EarthDEM and ASTER-DEM products for volcano monitoring: effusion volumes and crater morphology at Mount Etna

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Volcanic eruptions are dynamic events capable of rapidly and significantly altering the appearance of the Earth's surface. Measuring changes in topography caused by volcanic activity is an essential tool for understanding and monitoring volcanism and its associated hazards. Satellite-derived topography has been used for several decades to study eruptions, albeit with limitations in spatial and/or temporal resolution of the data [Pritchard et al., 2022]. Here we explore the suitability of two separate datasets with different spatial and temporal coverage for use in quantitative determination of lava effusion volumes and crater morphology changes during eruptions of relatively small magnitude, with an example at Mount Etna in Sicily, Italy. The ASTER captures nadir/off-nadir stereo image pairs at 15 m/pixel resolution (Bands 3N and 3B) that can be used to create a single-scene digital elevation model (DEM) at 30 m/pixel. Although the primary use of these DEMs is to contribute to the ASTER Global DEM dataset [Abrams et al., 2022], single-scene DEMs can also be used to identify topographic change over time when averaging single-scene DEMs from before and after an eruption to decrease vertical errors [Flynn et al., 2024]. The EarthDEM dataset, which uses stereo images from high-resolution optical imaging satellites to generate DEMs, provides topographic data at 2 m/pixel with a repeat observation interval as low as a few days [Porter et al., 2024]. This spatial and temporal resolution is similar to that of airborne survey datasets [Carr et al., 2023; Lundgren et al., 2019; Pedersen et al., 2022], which are considerably more resource-intensive to obtain. Recent studies have shown EarthDEM is capable of measuring eruptive volumes and generating detailed maps of eruption deposits [Dai et al., 2024; Galetto et al., 2024]. Here we demonstrate this potential for recent eruptions of Mount Etna, where we identified ~25 EarthDEM scenes spanning the period 2011-2023. We compare EarthDEM analysis of topographic change with that obtained using a similar processing pipeline and scenes from the ASTER-DEM dataset, quantify the precision and errors associate with each dataset, and compare results with independent measurements of topographic change that occurred at Etna during the 2011-2023 time period [Acocella et al., 2016; Ganci et al., 2018, 2022].

# Stratigraphic reconstruction methods for the geological map of Pantelleria Island

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In the framework of the CARG Program, aimed at the reconstruction of the complete stratigraphic succession of Pantelleria Island and the publication of the Geological Sheet 626 of the Geological Map of Italy (1:25,000 and 1:50,000 scales), multiple approaches were adopted, due to the peculiar characteristics of the island and its complex eruptive and volcano-tectonic history.
In fact, in a context with over one hundred eruptive centres often overlapping in time and space, with deposits frequently interdigitated and similar in composition (mostly pantellerites, to a lesser extent basalts), geochemical analyses (whole-rock major and trace elements) and a significant number of $^{40}Ar/^{39}Ar$ ages proved fundamental to successfully differentiate or correlate the stratigraphic units. Furthermore, the widespread welding and rheomorphism in ignimbrites and fluid-textured lavas obscure some mesoscopic aspects (e.g., internal architecture), making the petrographic approach (microscopic characterisation) mandatory.
To overcome these challenges, modern digital and remote acquisition technologies have complemented classic geological mapping and analytical methods.
High-resolution remote geological observations by mosaicking georeferenced images taken by drone, allowed visual access to inaccessible areas, while video acquisitions for 3D digital photogrammetric modelling supported the reconstruction of geometric relationships between different eruptive centres, often obliterated by the extensive deposition of the last main pyroclastic flow (i.e., Green Tuff Fm., $^{40}Ar/^{39}Ar$ age ca. 46 ka in [Scaillet et al., 2013]).
Moreover, the Digital Elevation Model at 2 m and the Red Relief Image Map [Chiba et al., 2008] allowed an improvement in the delimitation of deposits and individual volcanic structures, highlighting, through the image analysis, small details and also morphological structures otherwise hidden by vegetation. In particular, it was possible to establish how the spatial distribution of emission points emphasises the overlapping of regional tectonic directions (NW-SE like the Rift of the Strait of Sicily) to volcano-tectonic structures.
Furthermore, in order to give a useful interpretation key to the stratigraphic reconstruction of the island, we adopted Unconformity-Bounded Stratigraphic Units (UBSU) together with lithostratigraphic criteria, as required by the CARG guidelines. The elements used for the identification of the discontinuities necessary for the definition of the UBSU were paleosols, epiclastites and collapse scarps. This allowed the correlation among the identified discontinuities and how these are connected to the main phases of evolution of the island, in particular, eruptive stasis and volcano-tectonic movements.
All these methodologies allowed the refinement of some aspects of the volcanological record of the island.
From a structural point of view, at least two episodes of caldera collapse are morphologically evident, linked to high-energy eruptions, which in part reactivated pre-existing lines of weakness, but, in agreement with [Jordan et al., 2018], other caldera collapse episodes probably occurred, as witnessed by at least three welded pyroclastic breccias at different stratigraphic horizons.
Broadly speaking, the evolution of a great part of this complex system was guided by rejuvenated

volcano-tectonic structures, with tens of volcanic centres distributed in pericalderic areas or, to a lesser extent, in resurgent intracalderic zones.
The most paradigmatic example of resurgence, after the paroxysmal Green Tuff eruption and related caldera collapse, is represented by the Montagna Grande - Monte Gibele trachyte lava complex, whose rapid asymmetric uplift post-22 ka ($^{40}Ar/^{39}Ar$ rock age from [White et al., 2024]) originated the present-day relief of the central part of the island.
Outside the caldera or in pericalderic areas, both acidic and basic volcanic activity is observed, primarily along NW-SE trends, with ages confirmed at 14 ka for the pantellerites outcropping south of the island and between approximately 44 ka and 15 ka for the basalts in the northern sector (original CARG data).

# Tephra and cryptotephra records from the Marsili Basin: A 40,000-year archive of southern Tyrrhenian volcanism

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Over the last twenty years, tephrochronology has become a fundamental tool for high-resolution stratigraphy, providing robust chronological markers for dating, correlation, and synchronization across different Earth science disciplines. In this context, marine sedimentary sequences are particularly valuable because deep marine environments accumulate sediments continuously, with minimal erosion, preserving both visible and crypto (not directly visible) tephra layers and providing high-resolution chronological records.
In this study, we applied an integrated tephrochronological, sedimentological, and geochemical approach to a marine sediment core (POS522-48) recovered from the eastern part of the Marsili Basin, ~43 km NW from Stromboli volcano. From a tephrostratigraphic point of view, the Marsili Basin represents a strategic archive due to its proximity to several volcanic sources in the Tyrrhenian Sea, including the volcanoes of the Aeolian Islands (such as Stromboli, Lipari, Salina, Vulcano), the Phlegraean Fields, and Vesuvius. The sedimentary core was sampled for both visible tephra layers and cryptotephra horizons. Cryptotephra deposits were identified through X-ray fluorescence (XRF) analysis. All samples were subsequently characterized through lithological, sedimentological, and geochemical analyses. The texture and morphology of volcanic particles were investigated using scanning electron microscopy (SEM), while the glass compositions and trace element concentrations were analyzed by electron microprobe analysis (EMPA) and LA-ICP-MS, respectively. The core consists mainly of hemipelagic mud interbedded with two main types of volcaniclastic deposits: (i) primary tephra layers, representing direct fallout from explosive eruptions, and (ii) reworked tephra layers, formed by the remobilization and redeposition of previously erupted volcanic material by sedimentary processes. Compositional data identified tephra layers from several volcanic centers surrounding the southern Tyrrhenian Sea, including Phlegraean Fields, Somma-Vesuvius, and the Aeolian Islands. Preliminary results have identified well-known eruptions, including those of Monte Pilato, Vallone del Gabellotto, and Monte Guardia from Lipari; Avellino - Pompeii from Vesuvius; Soccavo and the Campanian Ignimbrite from the Phlegraean Fields; and Upper Pollara from Salina. Furthermore, a tephra sequence identified in the core could be tentatively linked to a submarine eruption of the Marsili volcano around 20 kyr ago, potentially extending the known explosive history of Marsili beyond the already known Holocene events. Analyses also included radiocarbon ($^{14}C$) dating on planktonic foraminifera that provided additional chronological constraints and precise age estimates for the tephra layers. Based on the analyses conducted so far, a preliminary age model indicates that the 684 cm long POS522-48 core covers approximately the last 40 kyr of volcanic activity.
This study further expands the tephrochronostratigraphic framework of the southern Tyrrhenian Sea, yielding fundamental insights into the timing and variability of volcanic activity during this period.

# High-Resolution Mapping of Geomorphological Changes at the Vesuvius Crater through Multi-temporal TLS data

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An accurate reconstruction of the geomorphological evolution at Vesuvius Crater has been performed through Multi-temporal Terrestrial Laser Scanning. Field surveys conducted in 2005, 2015 and 2024 allowed to reconstruct the evolution of landscapes for the purposes the monitoring on span of twenty years. The TLS survey was executed in May 2005, by Optech ILRIS 3D, in October 2015 by Reigl VZ1000 and lastly in July 2024 by a Reigl VZ2000.
Over time, the data have been acquired using different instruments, making comparisons challenging due to issues related to dataset alignment and differences in resolution and noise characteristics. The datasets were found comparable, and therefore it was possible to create difference maps (DoD/cloud-to-cloud); volumetric analysis of collapsed materials; and identification of the most active areas over the long term.
Multitemporal comparison of 3D data with high resolution obtained from each survey allowed to identify a morphological evolution especially due to collapse phenomena inside to Vesuvius crater. This allowed us to define a progressive trend of landslides, estimating the stability of the slope, i.e. the accelerations over time, but above all to better isolate the volumes mobilised over time.
Finally, Digital Terrain Models (DTMs), obtained from filtered datasets for each survey period were compared to assess the relationships between observed deformation patterns and the geological-structural framework, also considering the distribution of fumarolic activity within the crater area, in order to identify the principal predisposing factors for slope instability.

# CARG-based (Sheet 416 and 364) volume reassessment for the caldera-forming, VEI 6/7 ignimbrites along the Roman Magmatic Province

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The renewed implementation and funding of the CARG project in volcanic areas have enabled new surveys and major refinements in the assessment of ignimbrite volumes and areal extents across the Roman Magmatic Province (RMP). Recent work has produced robust quantitative constraints for the Bracciano caldera (Sheet 364 Bracciano) and preliminary qualitative evaluations for the Roccamonfina volcano (Sheets 416 Sessa Aurunca), with the potential to expand this dataset to additional ignimbrites throughout the RMP.
New quantitative analyses indicate that ignimbrite volumes are approximately one order of magnitude larger than previously reported. Similarly, qualitative field observations reveal a marked discrepancy between earlier estimates and the actual areal distribution of the deposits. Here, we present updated quantitative constraints on the volume of the Tufo di Bracciano ignimbrite, produced by the latest caldera-forming event of the Sabatini Volcanic District (SVD, north of Rome). These estimates are derived from integrated field data and a critical reassessment of the existing literature. The revised volume is substantially larger than previously published values. Taken together, the new and literature-based datasets highlight the need for a comprehensive re-evaluation of ignimbrite volumes across the RMP.

# Morphological changes at Mt. Etna: two decades of volcanic activity (2005-2023) revealed by Airborne LiDAR surveys

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The topography of Mt. Etna, the largest and most active volcano in Europe, is frequently modified by eruptions of varying intensity and magnitude that occur at its summit and along its flanks. The reconstruction of detailed and accurate topographies of the volcano, especially over significant time intervals, is essential to better define the spatiotemporal evolution of the volcanic edifice. Surface modifications can be investigated and provide useful information to improve our understanding of the volcanic processes. Thanks to two distinct Airborne Lidar surveys, the first conducted in September 2005 and the second in August 2023, it was possible to generate Digital Elevation Models at high spatial resolution that reproduce the morphologies of Mt. Etna in two distinct points in time, separated by 18 years. The comparison between these two models and specific elaborations allowed us to map and quantify, in terms of area and volume, the morphological changes generated by volcanic activity over nearly two decades. The most significant and interesting results will be presented and discussed.

# Slope instability mapping and ground deformation at Colli Albani Hills volcanic area

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Colli Albani Hills is a quiescent volcanic complex located 20 km SE of Roma (Italy), it is represented by a dormant calderic system whose activity originated 600 ky and was characterized by the occurrence of pyroclastic flows, lahars, lava fields and ash falls. Its last eruption is dated back about 20 ky but the area is still subjected to seismic swarms, gaseous emissions and ground deformations; due to the high population density, it is included among the Italian areas exposed to volcanic risk.
The whole volcanic complex is affected by different typologies of landslides, in the past the most frequent were debris flows. In this study, for the first time, the debris flows susceptibility of the volcanic complex is mapped through a heuristic approach that combines parameters recognized in literature as the main predisposing factors to slope instability. Such parameters are morphometry elements, lithology and land cover. The resulting map, validated through the study of historical landslides, classifies the entire complex according to five degrees of susceptibility, identifying Tuscolano-Artemisio caldera edge, Mt. Faete, and steep slopes of Nemi and Albano lakes at high and very high susceptibility. The instability of the entire complex is further investigated measuring the ground deformations observed by using InSAR data in the period 2016-2023. InSAR results, validated through GNSS data, show the overall stability of the complex, except a few areas. In detail, an ongoing uplift of about 1.5 mm/yr is recorded in Genzano di Roma municipality. The InSAR results combined with the debris flows susceptibility map and historical landslides highlight the steep slopes of Albano and Nemi lakes and Giulianello locality, outside the caldera, as the areas potentially most predisposed to trigger debris flows as classified at very high susceptibility and affected by both ground deformations and historical debris flows. This work highlights the importance of studying volcanic areas combining different approaches and datasets in order to better understand volcanic surfaces dynamics and their involvement in hazard assessment, especially in highly populated areas.

# Mineral chemistry investigations of the quaternary alkaline basalts erupted at Dilo-Dukana and Mega volcanic fields (Southern Ethiopian Rift)

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Continental rifting is often characterised by complex interactions between volcanic activity and tectonics. The southernmost termination of the Ethiopian Rift, in East Africa, exemplifies this complexity. The area is indeed characterized by a complex tectonic evolution, with rapid episodes of rift propagation, abandonment and migration, and is associated to an anomalous volcanic activity spatially and temporally unrelated to rifting. This volcanism, focused on the Late Pleistocene-Holocene Dilo-Dukana and Mega volcanic fields, formed long after the tectonic activity ceased. It is characterized by several NE-SW aligned vents, cutting the rift-related features, suggesting emplacement disconnected from the main rift structures and likely exploiting inherited deep lithospheric fabrics [Corti et al., 2019, Nat. Commun., doi.org/10.1038/s41467-019-09335-2]. Dilo-Dukana and Mega volcanic fields formed through monogenetic eruptions of alkaline basalts, rich in mantle and crustal xenoliths, postdating the emplacement of the voluminous Pliocene subalkaline basaltic lavas related to the main rifting phase.
Alkaline lavas are dominated by olivines and pyroxenes phenocrysts, with minor Fe-Ti oxides. Feldspars are present in the groundmass, together with clinopyroxenes, olivines and oxides. Occurrence of interstitial feldspathoids in the groundmass is also observed in some samples. Olivine is the most abundant phase with frequent dendritic habit or jagged rims. Four different olivine populations can be recognized according to their composition and zoning. The most common type includes directly zoned olivines, with Fe-enriched rims. Minor reversed zoned crystals or complex banding zoning are also found. CaO contents in olivines increase from core to rim, regardless of the zoning pattern, suggesting either heating due to recharge events or decompression during ascent. Orthopyroxenes are always in disequilibrium, featuring olivine coronas or clinopyroxene armored-rims testifying for silica under saturation conditions in the host melt. Clinopyroxenes show complex sector zoning, especially in the microlites of the groundmass, indicating rapid crystallization rates. Some phenocrysts and micro-phenocrysts show resorbed cores with Ti, Al, Fe enriched (coupled with Si, Cr, Mg Na depleted) rims suggesting cooling and/or decompression during magma ascent, or an increase of the oxidation conditions. We performed new detailed petrological and mineral chemistry data (major and trace elements) on these products aiming to investigate the ascent pathways and plumbing system architecture of the related magmas, as well as their magmatic evolution. A key role is played by kinetic processes during magma crystallization suggesting rapid decompression related to magma ascent. The occurrence of xenoliths agrees with this hypothesis, testifying the high "fragmentation capacity" of these magmas. However, the presence of complex zoning or discordant trace elements behavior suggests the possibility of more complex processes in the feeding system. Pliocene products were also investigated and compared with the Quaternary

volcanics indicating a change in the magmatic system, especially in the upward melt transfer mode (ascent rate, storage levels) related to variations of the thermal and rheological state of the extensional lithosphere associated with the transitions from the main rift phase (Pliocene) to the later rift deactivation (Quaternary).

# A newly recognised late Holocene landslide deposit from Cordillera El Mocho Pleistocene volcano, Southern Andes of Chile

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Within Chile over the last decade, southward transmigration has led to accelerated land clearance, parcelization and infrastructural development in areas increasingly proximal to stratovolcanoes of the Southern Andean Volcanic Zone (SVZ). While these areas for the time being, remain sparsely populated, entirely new volcaniclastic successions are being steadily recognised that provide more detailed insights into eruptive histories of these adjacent volcanoes, as well as the hazards they pose. In this contribution, we describe a previously unrecognised landslide deposit (informally name Palguín) that likely originated from a horseshoe-shaped scar at northern side of Cordillera El Mocho Pleistocene small stratocone (Moreno and Lara, 2008; 39°29'S - 71°48'W; 1750 m). The deposit itself consists of a valley-infill extending ~12 km northwest and west along the Río Palguín, forming a terraced geomorphology, covering ~9 km$^2$ with an estimated volume of 18·10$^6$ m$^3$. We interpret this deposit as being a valley-entrained megaclast-bearing cohesive mass flow with its longitudinal transformation into a debris flow (df) deposit. The internal architecture at proximal localities consists of brecciated and plastically deformed mega-clasts with interclast matrix forming a hummocky topography (mixed block-and-matrix facies of Glicken, 1986, 1998). Towards the distal margin the deposit forms a ~2.20 m thick massive structured df deposit (mixed facies) with suspended fragmental rock clasts (FRC's). Petrographically, the FRC's dominantly consist of porphyritic andesites and basalts. Palguín deposit is interpreted as late Holocene in age based on overlying products likely sourced from nearby Volcán Villarica dated at 3,510 ± 60 $^{14}$C years BP [Silva-Parejas et al., 2010; Moreno and Toloza, 2015]. These results indicate a relatively recent but previously unreported landslide event in the Villarrica-Lanin volcanic chain, with characteristics suggestive of a non-volcanic origin (i.e., debris stream deposit; Ui, 1983). At present, it is unknown whether climate warming with significant glacier ice loss (debutressing) and associated hydrological changes, regional megathrust earthquakes and/or seismo-volcanic events led to heightened edifice instability resulting in the triggering of the landslide [e.g., Watt et al., 2009; Guzmán-Marin et al., 2015]. However, the parallel direction of the landslide to major local structure (Liquiñe-Ofqui Fault Zone) and the perpendicular position of the source area to the Mocha-Villarrica structure, strongly suggest such type of control. The Río Palguín valley continues to be a source of modern landslides as during the 1575 and 1960 earthquakes, whose deposits overly that of the Palguín landslide. Ongoing research work will hopefully shed some light on causative factors, timing and the hazard posed for such dramatic events on fast-growing Andean communities.

# Modern technologies to decode historical eruptions: a multidisciplinary approach for understanding the 1947 and 1981 dyke intrusions at Mt. Etna

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Investigating events that occurred in the past can pose significant challenges, as further back in time we look, the more fragmented and imprecise the available data often becomes, especially in highly dynamic environments such as volcanoes.
Here we reconstruct the 1947 and 1981 dyke intrusions at Mt. Etna through a multidisciplinary approach combining different kinds of imagery with advanced processing techniques.
Starting from historical aerial photographs obtained from the IGM (Istituto Geografico Militare - Regio Aeronautica Italiana and Italian Aviation) we defined the geological-structural framework before and after the investigated events. In addition, an extensive field activity was carried out, including the acquisition of high-resolution UAV images and detailed geological-structural measurements, in order to quantitatively characterize the main parameters (e.g. strike and opening) of the structures preserved despite subsequent eruptions. Photogrammetric processing in Agisoft Metashape allowed the generation of high-resolution models, enabling detailed mapping and classification of volcano-tectonic structures (e.g. faults, open fractures and eruptive fissures).
To complement the historical surface observations and constrain the deep mechanics of these intrusions, we analyzed InSAR data from recent, analogous dyke emplacements. These modern deformation patterns provided a baseline for implementing different numerical model setups in COMSOL Multiphysics. By integrating the field-derived structural parameters of the 1947 and 1981 dykes with the geophysical insights from recent events, our models focused on the role of pre-existing fractures during dyke propagation and the stress-field changes induced by magmatic intrusions.
This multidisciplinary approach allowed us to identify the conditions that favor dyke propagation versus arrest, and to define the mechanism controlling lateral versus vertical propagation, with possible implications for hazard assessment and the resilience of communities living around Mt. Etna, as well as for volcanic edifices stability more broadly [Luppino et al., 2025a, b; Tibaldi et al., 2025].

# Pressure fluctuations reveal episodic and seismic-like dynamics during caldera collapse

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Caldera collapse is a major volcano-tectonic process associated with intense seismicity, rapid ground deformation, and significant volcanic hazards. Despite extensive structural studies, the transient mechanical processes governing collapse dynamics - and their relationship with geophysical signals - remain poorly constrained.
Here we investigate caldera collapse and resurgence dynamics through laboratory analogue experiments simulating magma chamber deflation beneath a brittle crust. The experimental setup consists of a cylindrical reservoir filled with a high-viscosity analogue fluid (polyglycerine-3), overlain by a layered granular medium representing the crust and collapse is induced by controlled fluid withdrawal. A pressure sensor located at the reservoir-granular interface continuously records internal pressure variations, while photogrammetry and structural mapping document the evolution of surface deformation and faulting.
The experiments reveal a well-defined structural and mechanical evolution. Initial collapse is characterized by the nucleation of outward-dipping reverse faults at the reservoir margins, associated with transient pressure increases reflecting compressive loading. These are followed by inward-dipping normal faults accommodating subsidence, marking a transition to a dilational regime. This mechanical shift is recorded by a change from positive to negative pressure fluctuations, indicating internal stress redistribution and granular reorganization.
Notably, the pressure signal exhibits cyclic loading-release patterns consistent with stick-slip-like behavior, suggesting that caldera collapse proceeds through episodic mechanical adjustments rather than continuous subsidence. These fluctuations provide a mechanical analogue for seismic activity, linking fault kinematics with geophysical signals.
These findings provide a multiscale framework linking fault evolution, granular processes, and geophysical signals, offering new insights into the episodic nature of caldera collapse and its associated seismicity in active volcanic systems.

# Spatio-temporal distribution of the Mt. Etna eruptive fissures: relationships between regional stress field and flank instability

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Mt. Etna is one of the most active basaltic stratovolcanoes globally. Its location in the center of the Mediterranean Sea, allowed observations and descriptions of its activity since the time of the Ancient Greeks and Romans. The regional geological setting is also peculiar, in fact, the volcano is located on top of the Apennine-Maghrebian chain within the convergence between Africa and Eurasia plates under a NNW-SSE compression. In this context, the eruptive activity is mainly located on the four summit craters, but dyke intrusions also affect the volcano's flanks producing lateral eruptions. These lateral eruptions are fed by dykes diverging from the main conduits, but sometimes by eccentric dykes rising directly from the magma chamber. The volcanic activity is manifested on the surface along eruptive fissures, mostly located along the S, NE and W rifts. Furthermore, these lateral eruptions are often accompanied by the formation of several dry fissures that mark the underground dyke intrusions.
We mapped 441 eruptive fissures, mainly of the last 15 ka, dry fissures from 1669 and dykes outcropping in the Valle del Bove. The fissure's data have been obtained from: detailed DTM, satellite images, historical aerial photos, scientific literature, geological maps (e.g., Belotti et al., 2010; Branca et al., 2011; Romano et al., 1979), field survey, UAV photos for the latest events. This approach allowed us to recognise or redrawn at least 55 eruptive fissures than in previous studies [Neri et al., 2011; Sandri et al., 2024]. Furthermore, our work takes into account also eruptive fissures older than 4 ka. The fissures marked by scoria cones have been traced using the following parameters a) alignment of craters on the same monogenic edifice; b) line connecting the deepest parts of the craters; c) direction of the cone base elongation; d) direction of the crater axis elongation; d) alignment of cones with the same age [Tibaldi, 1995; Corazzato & Tibaldi, 2006; Bonali et al., 2011].
The data analysis showed that the S rift is the most active rift of the volcano, its kinematic is strongly related with the WSW-ENE regional extension, but also to the sliding of the southern flank toward S and SSE. The opening of fissures along the W rift is not favoured by the regional stress. The W Rift eruptions are related mainly to eccentric dykes, also showing an important reduction of the activity in the last century with only one event occurring in 1974. The NE rift showed an increase of the eruptions in the last three centuries accompanied also by an apparent growth of the volcanic activity along the ENE sector of the volcano in the Valle del Bove. The eruptions in these two sectors of the volcano are not favoured by the regional stress field, except for the N-S fissures along the summit part of the NE rift. The magmatic intrusions along the NE and ENE flank are probably favoured by the flank instability driving the magma in the unstable sectors of the volcano. The NE rift is in fact strongly linked to the flank sliding because of its connection with the Pernicana Fault which bounds the unstable sector to the NE. This behaviour appears to be confirmed by the orientation of the outcropping dykes that do not show the same mean strike direction of the eruptive fissures in the same area. The

prevalent strike direction of the dykes is NW-SE and NNW-SSE in accordance with the regional extension, conversely the recent eruptive fissures show ENE-WSW striking on average.
This structural analysis may suggest a change in the volcanic behaviour that could reflect an increase of the flank instability that is currently governing the shallow processes affecting the volcano's flanks. Nonetheless, also an increase of the volcanic activity related to deep geodynamic processes may contributes to the growth of the volcanic edifice, triggering the consequent flank sliding.

# Geochemical and UAS Thermal-Remote-Sensing Characterization of the Alalobad Fault-Controlled Hydrothermal System (Afar, Ethiopia): Reservoir Constraints and Planetary Analogue Implications

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The Alalobad geothermal field (Tendaho Graben, northern Afar Rift, Ethiopia) hosts a water-dominated, fault-controlled hydrothermal system sustained by deep magmatic heat sources associated with the East African Rift and Afar mantle plume. Dozens of thermal lakes (area 10-2600 m2; T above 80 °C) make Alalobad an outstanding terrestrial analogue for ancient Martian hydrothermal environments, directly supporting the objectives of the HELENA Project. Thermal waters exhibit a dominant Na-Cl composition, neutral-to-slightly-alkaline pH, and chemical homogeneity consistent with mature fluids equilibrated with basaltic host rocks. Multi-geothermometer analysis yields concordant reservoir temperatures: silica geothermometry indicates 215-222 °C, while quartz and Na-K geothermometers converge on 220-250 °C. Noble gas data provide unambiguous evidence for a mantle volatile contribution: dissolved He in pool waters shows Rc/Ra = 4.6-4.8, while bubbling gases yield Rc/Ra = 8.06-8.99, consistent with mantle-plume-influenced fluids of the Ethiopian Rift accompanied by high $CO_2$ concentrations and He above 100 ppm, reflecting deep gas-water interaction and ongoing magmatic degassing. High-resolution UAS surveys produced co-registered Digital Surface Models and thermal orthomosaics, resolving NE-SW fault-parallel degassing corridors reaching up to 92 °C, spatially coincident with hydrothermal alteration zones. The integrated geochemical and remote- sensing evidence supports a vapor-cored reservoir with rapid, enthalpy-preserving fluid upflow along rift-border faults to near-boiling surface discharge. This study was carried out as part of the HELENA Project (ASI, Contratto N. 2023-9-U.0).

# Quantitative X-ray map analysis reveals plagioclase populations in submarine lavas from Marsili Seamount

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Quantitative elaboration of chemical maps is a powerful tool for investigating volcanic rocks, mineral populations and their textural-chemical variability. In this study, we used the Quantitative X-ray Map Analyzer (Q-XRMA) software for characterizing a suite of submarine lavas from Marsili Seamount (Tyrrhenian Sea, Italy), with the specific aim of disentangling plagioclase populations based on their sizes, textures and compositions. The processing strategy uses the sequential application of Principal Component Analysis (PCA) and the supervised Maximum Likelihood Classification (MLC) algorithms for the multivariate statistical treatment of bidimensional X-ray elemental maps in two analytical cycles. In the first cycle, image analysis enables the identification of the main rock constituents and the calculation of their modal abundances. The second cycle permits to reiterate the PCA to the pixels of a selected phase (plagioclase in this case) in order to detect potential chemical heterogeneity. This approach allows compositional variations to be recognized more effectively in the case of solid-solution minerals, where the relative abundances of endmembers are tightly coupled.

This workflow was applied to basaltic and andesitic lava samples collected from five different sites across the volcanic edifice. Basalts display higher crystallinity, greater abundances of mafic phases, and a broader range of plagioclase compositions and textures, including more complex zoning patterns and a higher abundance of disequilibrium textures compared to andesites. However, our quantitative analysis reveals substantial compositional and textural variability also within each rock suite, suggesting heterogeneous crystallization conditions even among magmas that reached comparable evolutionary degree within the Marsili volcanic system.

The combination of quantitative compositional and morphological information allowed the distribution of plagioclase population to be quantified for different dimensional classes. More than 5500 plagioclase grains have been identified and classified according to their textures and chemical zoning. The textural classification of plagioclase has identified five different textural types, with a dominance of clear, oscillatory zoning crystals throughout the two suites of products. Zoning segmentation shows a decrease in plagioclase chemical complexity from basalts to andesites, along with an increase in homogeneous and high-anorthite populations in andesites. This textural and compositional variability testifies plagioclase growth histories under a variety of magmatic conditions, and when combined with in-situ geochemical investigations, may provide valuable insights into the evolution of the magmatic system.

# New insights into geochemical and isotopic compositions of bulk-rocks, crystals, and glasses from the Marsili Volcano

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Marsili is an active, NNE-SSW-elongated seamount (70 x 20 km) that rises from a depth of ~3500 m to 500 m below the sea level in the southern Tyrrhenian Sea. The volcanic complex formed entirely over the last ~0.7 My as a consequence of back-arc extension associated with the southeastward rollback of the Ionian Plate subducting beneath the Calabrian Arc.

Throughout its history, Marsili has predominantly erupted arc-like lavas ranging in composition from basalts to andesites. However, some basaltic lavas from the axial zone exhibit a more alkaline, intraplate affinity, reflecting the influence of asthenospheric mantle flow into the mantle wedge. Although occurrence of different mantle sources has been documented in previous studies [e.g., Trua et al., 2011], the genetic relationship between the various types of basaltic and andesitic magmas has been so far poorly constrained.

Here we present new major and trace element data, together with Sr, Nd, Pb, and Hf isotopic compositions of bulk rocks, glasses and mineral phases from a suite of basaltic to andesitic lavas collected from the northern summit and lower northern flank of the Marsili volcano.

Based on trace element and isotopic compositions of bulk-rock and glasses, we distinguish at least four different types of basalts derived from MORB-like to OIB-type mantle sources. Wide ranges of geochemical and Sr isotopic compositions within plagioclase crystals indicate that basaltic magmas evolve to andesitic compositions through fractional crystallization processes coupled with variable degrees of crustal assimilation. Isotopic disequilibrium is commonly observed between plagioclase and clinopyroxene crystals in andesitic lavas, suggesting that recycling of antecrysts from crystal-mush zones is a common process within the Marsili plumbing system.

These findings provide new constraints on the complex interplay between mantle heterogeneity and magma evolutionary processes in controlling the dynamics of a young back-arc spreading centre.

# Insights into the early magma differentiation at an active back-arc spreading centre: the glomerocrysts record from the Marsili Volcano (Tyrrhenian Sea)

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Marsili Volcano (MV) is a young back-arc spreading centre located in the southern Tyrrhenian Sea, where two types of subduction-related basalts with distinct phenocryst assemblages and whole-rock geochemical signatures have been erupted. Both magma types, here termed low-Ca and high-Ca basalts, derive from partial melting of a heterogeneous mantle source; however, while high-Ca basalts occur widespread along the edifice, low-Ca basalts were sampled exclusively at the northern sector. To investigate the processes controlling the evolution of these two magma types, we carried out a detailed petrological and geochemical study of glomerocrysts from a representative set of MV basalts. Interpreted as crystal aggregates formed from parental melts of the host lavas, these glomerocrysts are composed of early-formed mineral phases including olivine, clinopyroxene, and plagioclase. Their minerals record crystallization over a pressure range spanning the approximately 12 km thick oceanic crust, temperatures of 1020 to 1220 °C, low to moderate melt $H_2O$ contents (0.5 to 3.5 wt percent) increasing from northern to lateral sectors, and moderately to highly oxidizing conditions (plus 1 to plus 2.9 ΔQFM), particularly in high-Ca basalts. The glomerocryst assemblages and compositions define two distinct liquid lines of descent: one dominated by olivine and then plagioclase fractionation in low-Ca basalts, and one by olivine followed by clinopyroxene and then plagioclase fractionation in high-Ca basalts. Major and trace element systematics of these mineral phases confirm that low-Ca and high-Ca basalts erupted at the northern sector experienced limited differentiation and preserve the signatures of two separate primary melts. In contrast, olivine in glomerocrysts from high-Ca basalts erupted at the axial and lateral sectors records mixing between low-Ca- and high-Ca-derived melts, indicating a hybrid origin for these magmas. Regardless of host basalt type, clinopyroxene and plagioclase in glomerocrysts display complex major- and trace-element zoning patterns consistent with crystallization in multi-level, sill-like mush bodies. These findings imply that crustal transport and differentiation of MV basalts occur within a vertically distributed sill complex rather than in a single shallow magma chamber, supporting the hypothesis of oceanic crustal accretion by stacked sill emplacement beneath back-arc spreading centres.

# A crystal-chemical window on pulsed basaltic magmatism during early back-arc basin evolution: the case of the ODP Leg 107-site 655 (Tyrrhenian Sea)

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Textures and compositions of the igneous minerals carried in basaltic lavas can provide important insights into the sub-volcanic pre-eruptive processes, which are obscured by the relatively uniform bulk chemistry of the erupted basalts. In this study, we present textural information and chemical analyses for minerals from 11 samples spanning a 116 m-thick sequence of basaltic pillow lava flows drilled during the Ocean Drilling Program (ODP) Expedition 107, Site 655. The site is located in the central portion of the Tyrrhenian Sea back-arc basin, whose opening is linked to extensional movements within the framework of the Eurasia-Africa convergence. The drilled sequence consists of geochemically well-characterized basalts with a monotonous mid-oceanic ridge chemical affinity, emplaced during magmatic activity associated with the initial seafloor-spreading stage (4-3 Ma) of the Tyrrhenian back-arc basin. The crystal-scale investigation documents that the basaltic lava samples are weakly porphyritic, with olivine-plagioclase and olivine-plagioclase-clinopyroxene phyric types found alternating along the sequence. The groundmass in all the samples consists of microlites of the phenocryst phases, opaques, and altered interstitial glass. The co-crystallized plagioclase and clinopyroxene microlites exhibit a range of textures comparable to those observed in the groundmass of mid-oceanic ridge basalts, reflecting variable cooling rates within the hosted pillow basalt. Olivine is partially to completely replaced by Fe-hydroxides and clays in most of the basaltic lava samples, whereas clinopyroxene phenocrysts with resorbed features are restricted to the lower portion of the drilled sequence. The variability observed in crystal habit, zoning patterns, and resorption features, both within individual crystals and among basaltic lava samples, documents the role of processes other than fractional crystallization in the formation of the ultimately erupted crystal cargo. This is confirmed by mineral-melt equilibrium modelling, which identifies several plagioclase and clinopyroxene compositions that are in chemical disequilibrium with the host melt. The in-equilibrium crystal-melt pairs constrain crystallization temperatures of 1050-1150 °C and pressures consistent with the local 6 km-thick oceanic crust, as geophysically detected beneath this portion of the Tyrrhenian Sea. The compositional distribution of plagioclase, which is ubiquitous among the basaltic lava samples, documents temporal changes in the crystal population and suggests that the basaltic lavas derived from magma pulses that locally interacted with regions of an already-formed transcrustal magmatic plumbing system. Results of geospeedometric investigation, in progress on the plagioclase phenocrysts, are necessary to provide constrains on the timescales of the feeding magma pulses. The results of this study document that the chemical and textural variations exhibited by the crystals hosted in the basaltic pillow lava sequence drilled at Site 655 represent a precious archive, not yet fully exploited, of magmatic processes that occurred during the initial seafloor-spreading stage of the Tyrrhenian back-arc basin.

S12 - Poster

# S13 - VOLCANO SEISMOLOGY AND ACOUSTIC: DYNAMICS, IMAGING AND NUMERICAL SIMULATIONS OF VOLCANIC PROCESSES

Conveners:
Laura Spina, Francesco Rappisi, Mariangela Sciotto, Rosalia Lo Bue

# Seismic anisotropy reveals deep magmatic pressurization beneath the Campi Flegrei caldera

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The Campi Flegrei caldera is currently experiencing significant ground deformation and bradyseismic unrest, yet the processes driving this activity remain debated. Competing interpretations invoke magmatic intrusion, hydrothermal circulation, or regional tectonic stress, and the role of magma at depth remains uncertain.
Here we present results from a new probabilistic high-resolution seismic tomography of the Campi Flegrei caldera, imaging both isotropic velocity structure and seismic anisotropy using P-wave arrival times from a recently published machine-learning-derived earthquake catalog. The model reveals a pronounced low-velocity body extending from the surface to ~7 km depth. Within this volume, strong seismic anisotropy (20-30%) is characterized by vertically oriented P-wave fast planes arranged radially around the caldera center, consistent with aligned vertical cracks and dike-like structures.
The spatial coherence and magnitude of the observed anisotropy, together with the low seismic velocities, are difficult to reconcile with purely hydrothermal or tectonic processes. Instead, they suggest a stress regime compatible with upward pressurization from depth, likely associated with magmatic intrusion. To further test this interpretation, we performed numerical forward models exploring alternative subsurface configurations, including magma reservoirs with different geometries and pressure conditions.
While alternative mechanisms cannot be entirely excluded, our results provide geophysical evidence that magma at depth plays an active role in pressurizing the upper crust and driving ongoing deformation at Campi Flegrei. These findings provide new constraints on the physical processes underlying caldera unrest and have important implications for hazard assessment in one of the most densely populated volcanic regions in the world.

# Crustal stress state of Tenerife (Canary Islands) from P-wave anisotropic seismic tomography and geodynamic modelling

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Tenerife, the largest and most densely populated island of the Canary archipelago, hosts active volcanism characterized by explosive phonolitic eruptions in the central part of the island and basaltic fissure eruptions occurring along three radial rift zones. This volcanic activity poses a serious threat to the local population and is accompanied by intense, although generally low-magnitude, local seismicity monitored by a dense seismic network.

Here we present preliminary results from the first P-wave anisotropic seismic tomography study of the island. The model is obtained using the probabilistic rjMCMC method introduced by [Del Piccolo et al., 2025] and the seismic dataset published by [Koulakov et al., 2023]. P-wave velocity is parameterized assuming a transversely isotropic medium, which is representative of a fractured upper crust responding to regional and local stress fields.

The interpretation of the tomographic results is complemented by geodynamic modelling, which allows us to test the relative contributions of the different stress sources controlling the crustal stress state beneath Tenerife.

# Deep Seismic Imaging of Mount Etna: Architecture of a Stratovolcano

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Mt. Etna is a prominent stratovolcano located at the convergent plate boundary between the African and Eurasian plates, uniquely situated in the transition zone between the active Ionian oceanic subduction and the Hyblean continental lithosphere.
Leveraging more than three decades of seismic datasets, Mount Etna represents an exceptional natural laboratory for investigating the internal architecture and plumbing system of a stratovolcano through seismic imaging. However, identifying magma storage volumes, whether ephemeral or long-lived, from the deep mantle source poses considerable challenges. The deep crust (below 15 km depth) remains poorly defined, while most tomographic studies illuminate the uppermost 15 km; these studies converge on the presence of a central, broadly rooted, high-velocity body (HVB) interpreted as a massive complex of solidified mafic cumulates and fossilized intrusions. Seismic and deformation data suggest that magmas preferentially ascend along the western margin of the HVB and stagnate within or above it, following lithological boundaries in the crust.
Here, we review the main constraints derived from seismic tomography to date and present a new, enhanced velocity model obtained using a modern nonlinear Bayesian approach. This study utilizes the most comprehensive dataset to date, consisting of 159,207 P-wave and 47,130 S-wave arrival times from 13,498 earthquakes recorded between 2005 and 2023.
Our results, synthesized with insights from previous 3D and 4D tomographic studies, allow for a comprehensive reconstruction of the Etnean plumbing system within its regional tectonic framework, consistent with deformation and petrological data. Furthermore, the new velocity model identifies a potential detachment surface involved in the seaward sliding of Etna's eastern flank.

# Constraining Vp/Vs ratios beneath Mt. Etna with probabilistic imaging - insights from anisotropic S-wave tomography and remaining challenges

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The Vp/Vs ratio is an important parameter in tomographic imaging of the crust beneath volcanoes, as it provides insights on rock fluid properties. Most common deterministic imaging methods are limited by the underdetermination of the inverse problem, and rely on damping and smoothing constraints to find a unique solution. This problem is exacerbated in the case of anisotropic imaging, due to the increased complexity of the model. Probabilistic imaging provides a solution for this. Transdimensional Bayesian Monte Carlo sampling of model parameters allows for robust uncertainty estimation, without the need for damping and smoothing parameters. Building on the P-wave imaging efforts of Del Piccolo et al. [2025], we present the results of joint P- and S-wave probabilistic tomography of the crust beneath Mt. Etna.
The main challenge lies in the processing of S-wave data. High quality S-wave arrival time observations are often more scarce than P-wave observations, since S-waves are generally noisier, have ray-orthogonal particle motion, and exhibit splitting in the presence of anisotropy. This stresses the importance of uncertainty estimation for inferred isotropic Vp/Vs anomalies: a large advantage of the probabilistic method. Previous studies [Nardone et al., 2020; Lo Bue et al., 2024; Del Piccolo et al., 2025] have shown strong evidence for anisotropy beneath Mt. Etna, commonly attributed to the preferential alignment of eruptive fissures, dikes, sills, and (fluid-filled) microcracks with the local stress field. Therefore, probabilistic anisotropic joint P- and S-wave tomography has the potential to reveal the connection between stress state (orientation and magnitude of anisotropy) and rock fluid properties (directionally invariant Vp/Vs ratio), while providing robust uncertainty quantification. In this contribution we show imaging results for Mt. Etna, while highlighting challenges introduced by the processing of S-wave data (such as the robust measurement of polarization angles).

# Tracking stress and fluid changes at Mount Etna with 4-D transdimensional anisotropic seismic imaging

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Crustal stress at volcanoes results from the interplay of multiple forces, some of which evolve in response to the dynamics of magmatic systems. In this framework, the history of volcanic activity, stress, and crustal structure are interconnected, each providing insight into the others. However, while surface manifestations of volcanic activity (e.g., eruptions) are observable, the subsurface architecture and processes that lead to volcanic episodes remain today largely uncertain, hampering forecasts of volcanic activity with potential impact on the population.
To map the heterogeneous subsurface architecture and physical state of volcanoes, seismology represents a powerful monitoring tool. Volcanic structure and dynamics influence seismic wave velocities, making seismic wave travel times sensitive observables. In particular, fluid-filled fractures tend to open along the least compressive stress directions, producing direction-dependent seismic wave velocities (seismic anisotropy). Therefore, anisotropic seismic imaging - by exploiting wave travel times to infer the heterogeneous anisotropic seismic velocities - is the main tool for reconstructing the distribution of fluids, fractures, and for characterizing stress beneath volcanoes.
Traditional seismic imaging is based on the inversion of travel-time data grouped over discrete time windows, typically before and after major volcanic events. However, the resulting images can be discontinuous and potentially affected by artificial differences arising from uneven earthquake distributions in space and time. In this study, we implement a four-dimensional (4-D) anisotropic seismic imaging algorithm based on a transdimensional probabilistic approach to: (1) provide time-continuous mapping of the subsurface structure and stress beneath volcanoes; (2) account for heterogeneous data coverage using self-adaptive parameterizations of the reconstructed 4-D seismic velocities; and (3) robustly assess uncertainties by probabilistically exploring families of seismic velocity models consistent with the data. The method is applied to a dataset of P-wave travel times collected over the last twenty years by INGV-OE at Mount Etna, one of the most active and monitored volcanoes in the world.

# Constraining magmatic pressurization at Mt. Etna through thermomechanical modeling of transient deformation

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Magmatic pressurization significantly influences short-term deformation at active volcanoes, although its precise mechanical impact and temporal dynamics remain challenging to quantify. This difficulty arises from the complex interplay of rock rheology, magmatic processes, and volcano structural heterogeneity. The 2018 event at Mt. Etna volcano exemplifies this complexity, where magma intrusion through a dike led to local stress increase and triggered surface deformation. This process involved a dynamic interplay between magma ascent, stress changes, and structural instability of the southeastern volcanic flank [Giampiccolo et al., 2020]. Similarly, displacement and seismic observations during the same 2018 eruptive cycle showed continuous inflation driven by pressurization in a deep magma reservoir, which caused intense deformation of the volcanic edifice, illustrating the challenges in capturing the evolving mechanical impact over time [Mattia et al., 2020].

In this study, we investigate the response of Mt. Etna's southeastern flank to magma inflow using 3D thermomechanical simulations. Building on a geodynamically consistent structural framework, we implement an inflow boundary condition to simulate magma pressurization associated with the 2018 volcanic episode. The models incorporate realistic fault geometries and weakened zones representing dike pathways, while systematically varying inflow velocities to explore the relationship between pressurization rate and surface deformation. Results show that increasing magma inflow leads to a proportional increase in horizontal displacement rates, confirming pressurization as an efficient driver of transient flank motion. However, deformation exhibits a consistent temporal decay across all simulations, indicating progressive mechanical relaxation of the system even under sustained magma supply. Spatial analysis reveals that early-stage pressurization produces widespread deformation, with strong uplift and outward motion concentrated above the central intrusion zone. Over time, deformation becomes increasingly localized and decreases in magnitude, suggesting that, under constant pressurization conditions, magma-induced stresses alone may not sustain long-term displacement without renewed or increasing pressure input. Importantly, while pressurization controls deformation intensity, the spatial pattern remains governed by the pre-existing structural framework, highlighting the dominant role of edifice structure in shaping magma-driven deformation.

# The role of particle-loading on seismo-acoustic signals and volcanic jets dynamic: an experimental investigation

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Linking the characteristics of geophysical observables and the fundamental properties of explosive volcanic activity—such as the content and nature of the pyroclastic fraction—is a primary challenge for scientific and monitoring purposes. However, defining quantitative relationships between the dynamic evolution of the explosive process and its resulting elastic field remains complex, as direct observation of physicochemical properties is often unfeasible in natural systems.

To address this, we present an extensive experimental dataset of 120 analog subsonic to supersonic jets, generated using a shock-tube. The experiments were monitored through a comprehensive sensor network including three microphones, three mono-axial accelerometers placed along the conduit, and a pressure sensor at the vent. For a subset of 60 experiments, jet dynamics were visualized using dual-mirror Schlieren optical technology coupled with two high-speed cameras. We investigated two key variables: the driver section pressure (2-9 bar) and the particle load (glass microspheres, 0.5-1 mm diameter, ranging from 1 to 10 g).

Preliminary analyses highlight the influence of particles in modulating both jet dynamics and the characteristics of the recorded signal. Analysis of kymographs, obtained from Schlieren videos, reveals that the presence of particles decreases shock-cell spacing, consequently indicating a reduction in Mach number. Furthermore, spectral analysis of accelerometric data show a direct connection between the high-frequency content of the recorded transients and the passage of particles within the conduit.

Overall, our findings demonstrate the critical role of the solid phase in shaping the elastic response of volcanic jets, providing a quantitative framework to bridge the gap between experimental analog models and the real-time characterization of explosive volcanic activity.

# Expanding the observational spectrum of open-conduit volcanoes: the implementation of a VBB seismic station on Stromboli Island

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Over the past decades, seismology has provided fundamental analytical frameworks for characterizing high-frequency signals in both volcanic and non-volcanic settings. More recently, advancements in digital technology have enabled the implementation of high-performance seismic networks, replacing legacy short-period sensors with broadband instrumentation. Standard monitoring systems now primarily employ triaxial sensors with a natural period of 40 seconds, or less frequently 120 seconds, ensuring coverage across the entire conventional seismic band, from short-period (SP) to very-long-period (VLP) waves. The evolution of digitizers, which currently achieve an Effective Number of Bits (ENOB) of 25-26 and a dynamic range near 160 dB, allows for the effective management of high-magnitude events by reducing conversion system saturation, while simultaneously enabling the detection of increasingly subtle seismic phenomena.

Despite these advancements, volcanological research requires further expansion into the frequency domain, specifically targeting the Ultra-Long Period (ULP) band. This study details the installation of an experimental "infraseismic station" on Stromboli volcano, equipped with a Guralp CMG-3T 360s Very Broad Band (VBB) sensor. This instrumentation allows for high-fidelity recording of low-frequency signals down to 0.0027 Hz, maintaining noise levels below the New Low Noise Model (NLNM) for periods exceeding 200 seconds.

While Very Broadband (VBB) sensors are standard in tectonic and global seismology, their deployment in active volcanic environments represents an innovative methodological approach and a significant technical challenge.

The pilot installation at the IST3 site (San Vincenzo, 250 m a.s.l.) leverages existing infrastructure, utilizing a semi-buried, thermally insulated vault to ensure signal stability. Although traditional instruments and the new infraseismic station share power and transmission systems, they employ separate digitizers (24-bit and 31-bit, respectively) to optimize the signal-to-noise (S/N) ratio across their respective frequency bands. Low-pass signal conditioning, aimed at detecting strain transients, seeks an analytical synthesis in that frequency range that lies between standard seismology and dynamic geodesy.

This configuration is essential for isolating subtle ULP precursors that might otherwise be masked by high-magnitude events typical of volcanic and island settings, such as explosive earthquakes, volcanic tremor, secondary microseisms, or anthropogenic noise, which continue to be captured by standard seismic instrumentation. By bridging the instrumental gap between classical seismology and geodesy, VBB sensors provide nanometric sensitivity that complements existing tiltmetric data especially through the introduction of the vertical component. This scalable approach offers a cost-effective solution for enhancing multi-parametric monitoring, aimed at improving potential early warning capabilities and gaining a deeper understanding of the Stromboli magmatic system dynamics.

# Contribution of the local seismic network 'Fiumenet' to study microseismicity of the Provenzana-Pernicana fault system (Mt. Etna, Italy) during 2016-2017

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The Provenzana-Pernicana Fault system (P-PF), accommodating the seaward sliding Mt. Etna's eastern flank, is characterized by shallow microseismicity difficult to locate. Previous studies [Neri et al., 2004; Alparone et al., 2013] describe a heterogeneous seismic behaviour: the western and central segments show high activity, while the eastern segment is aseismic. To improve the monitoring capability of the Permanent Seismic Network (P.S.N.) managed by Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Etneo (INGV-OE) and investigate P-PF microseismicity, a temporary network called "Fiumenet" was deployed (2015-2018) near the easternmost portion of the structure. This work assesses the P.S.N. geometry influence and quantifies the Fiumenet contribution to improving hypocentral parameter quality. The integration of the Fiumenet mobile network allowed the relocation of two events that occurred in 2016, increasing the number of pickings, reducing the azimuthal gap, and improving epicentral accuracy. The first occurred on 4 July and the second on 6 July; in both cases, the new solutions showed a shift of the epicenters towards the P-PF trace and the cluster of events recorded by the P.S.N. during the same period, which thereby strengthening the spatial coherence of the dataset. The analysis of the considered time intervals highlights several issues related to the geometric coverage of the P.S.N. In particular, several events recorded by the permanent stations were catalogued as "imploc", as they were detected by an insufficient number of stations to allow reliable location: 11 earthquakes during the July 2016 sequence and 8 during the January 2017 sequence, corresponding to more than 46% of the total seismic events detected in the Mt. Etna area during those periods. The integration of the temporary network made possible the location of 11 "imploc" events: 7 in 2016 and 4 in 2017, reducing the percentage of non-located events to less than 20% of the earthquakes listed in the INGV-OE catalog. In the two analyzed windows, the Fiumenet network also recorded and located four additional events not reported in the INGV-OE catalog nor classified as "imploc": three events on 04/07/2016 and one on 18/01/2017. In other words, approximately 9% of the events recorded by the P.S.N. in the Mt. Etna area would have remained undetected without the contribution of the Fiumenet network. Considering all the events located in this study, from both 2016 and 2017, a classification was proposed to assign epicenters to specific categories based on spatial distribution. The analysis allowed the distinction of four main groups, each with peculiar characteristics. Although useful from an interpretative standpoint and providing a more complete representation of the microseismicity along the P-PF, this classification must be considered in light of the previously discussed limitations related to location quality. The study confirms that the P.S.N. alone cannot adequately capture the full microseismicity of the P-PF, particularly in its central sector, highlighting the need for additional stations in the central-eastern P-PF to improve the detection and understanding of its seismic behaviour and dynamics. The methodology can be applied to future sequences, supporting analysis of shallow seismicity along P-PF and other active tectonic structures of Mt. Etna.

# Atmospheric dynamics effects on seismic and infrasonic records

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Popocatépetl volcano is one of the most active volcanoes in Mexico, with millions of people living within a radius of about 60 km. Its activity is dominated by hydrothermal processes, magmatic degassing, periodic gas and ash emissions, occasional volcanic explosions, lava effusions, and construction and destruction of domes. Popocatepetl's continuous activity, altitude (5393 m asl) and location make it one of the most attractive volcanoes to monitor and investigate the interaction between seismic, infrasonic and atmospheric wavefields.

Some infrasonic and seismic records appear very noisy. Frequently such noise is associated with the atmosphere behavior, which generates compressional waves, and ground vibrations that are also recorded by infrasonic and seismic sensors. In this work we investigate the atmosphere dynamics related to such noise to distinguish and characterize its effects on seismic and infrasonic wavefields.

We report the results of the correlation analysis of meteorological (pressure, wind direction and speed, humidity, and temperature), seismic and infrasonic data. To support the analysis and visualize the atmospheric dynamics, we divided the observation records in time windows according to the weather seasons, from september 2024 to march 2026. Videos of the volcano taken by a camera at ca. 11 km N were correlated with the daily variations of wind speed versus wind direction. Based on the intensity of atmospheric activity, calm days and turbulent days were selected. For this we used wind speeds ranging from 0 to 10 km/h for calm days and from 20 km/h to 50 km/h for turbulent days. Dates with and without volcanic activity were also selected, based on the volcanic activity reported in the CENAPRED (Centro Nacional de Prevención de Desastres), SSN (Servicio Sismológico Nacional), Altzomoni Station, and USGS (U. S. Geological Service) catalogs.

The infrasonic and seismic records were analyzed considering the selected dates correlating with the atmosphere data. This information was organized into graphs synchronized with videos of the atmosphere dynamics to identify the differences and interactions between wavefields according to their dynamics. It was found that the more intense the atmospheric dynamics, the lower the signal-to-noise ratio in the seismic and infrasonic records. This does not depend only on the wind direction and speed but also on the atmosphere motion interacting with volcanic emissions. This becomes more complicated when volcanic activity presents low amplitude signals. For example, tremor can be masked and/or easily misinterpreted due to the wide range of frequencies that the atmosphere wavefield generates.

Our observations show that characterizing the influence of the atmospheric dynamics in the seismic and infrasonic records help to identify the ground-coupled airwaves and the intensity range of volcanic eruptions specially when the atmosphere presents intense activity avoiding misinterpretations of volcanic signals.

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# Temporal variations of ambient noise polarization on Vulcano Island, Italy

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We investigate directional amplification and ambient noise polarization on Vulcano Island (Italy) during the most recent volcanic unrest episode, which began in June 2021. During this period, fumarole temperatures rose anomalously, and significant increases in gas emissions, ground deformation, and seismicity were observed.
Continuous data from 10 broadband seismic stations of the Italian Seismic Network, spanning from 2020 to 2024, are analyzed. We examine temporal variations in directional amplification by calculating Horizontal-to-Vertical Spectral Ratios (HVSR), rotating the horizontal components of motion. Additionally, ambient noise polarization is assessed in the time domain using covariance matrix analysis, allowing us to characterize the shape of the polarization ellipsoid as a function of time. Variations in polarization parameters are further analyzed using continuous wavelet transforms.
Our results reveal an annual cycle at all stations, which is strongly correlated with the air temperature trend. Several subordinate cycles with different durations are also detected, but these show no significant relation to the peaks in volcanic emissions observed in October 2021 and June 2024. This suggests that the observed cycles in directional amplification and ambient noise polarization are likely not linked to volcanic activity, although we cannot completely rule out a potential volcano-related origin.

# Ambient noise surface wave tomography of Etna volcano deep structure within the geodynamic context of Eastern Sicily during 2020-2021

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Mount Etna is a stratovolcano situated in a collisional geodynamic context, at the top of the Apenninic-Maghrebian accretionary wedge and the external part of the Hyblean foreland carbonate units. The deep crustal structure and the relationships with the magmatic plumbing system are actively debated.
To image Mt. Etna Volcano deep structure and unravel the presence of seismic anisotropy, we here employ an Ambient Noise Tomography approach crossing the whole Eastern Sicily. Surface-wave dispersion curves between station pairs are derived from the cross-spectra of continuous seismic recordings.
We analyzed two years (2020-2021) of continuous three-component waveforms from 12 INGV seismic (HH) stations located in Eastern Sicily. A seasonally balanced dataset ensured uniform time illumination and excluded the seismicity related to the 2018-2019 eruptions. The station configurations maximized inter-station paths beneath Mt. Etna while minimizing volcanic tremor interferences. The waveforms were pre-processed and filtered in the 0.05-0.60 Hz range, which isolates the ambient noise generated by the sea-lithosphere interactions and avoids the ~0.70 Hz frequency characteristic of the volcanic tremor.
Following [Magrini et al. 2022], the dispersion curves are obtained through cross-spectra analysis. The cross-spectra were computed using Welch's method. The velocity-based time-domain windowing (1.2-4.0 km/s) isolates coherent fundamental-mode surface waves. These steps enhance the robustness and improve the validity of the main assumptions. Each station pair dispersion curve is extracted from the cross spectrum zero crossings. Frequency-dependent phase velocity models were then derived by inverting Rayleigh- and Love-wave dispersion via a regularized least squares scheme. Synthetic spike tests were subsequently conducted to assess the resolving power and reliability of the tomographic inversion.
Here, we present preliminary results based on Rayleigh- and Love-wave velocity models, which sample different depth ranges. A more quantitative interpretation is therefore deferred to future Vs modeling, including the anisotropy implementation.
Within the investigated 2-35 km depth range, our models reveal a prominent low-velocity anomaly west of Mt. Etna, consistent with previous regional structural models. At intermediate depths (~5-10 km), a low-velocity anomaly beneath the Nebrodi Chain is consistent with the anisotropic deep crustal shortening. In the northern Hyblean Plateau, high seismic velocities observed across all retrieved models are consistent with a mechanically rigid and thermally cooler crust.
Current research is expanding the number of stations to 30 and utilizing the depth sensitivity of different frequencies through the joint inversion of Rayleigh and Love dispersion curves combined with sensitivity kernels. The synthetic dispersion curves will be calculated using a layered medium formulation. Following [Magrini et al. 2025], a trans-dimensional MCMC

algorithm will be employed, wherein the subsurface self-organizes through adapted Voronoi tessellation. As the layer number and thickness adapt to the data, the model circumvents stratigraphic assumptions and minimizes subjective bias. Pair-dependent uncertainties and weights will be evaluated as a function of ambient noise anisotropy. The resulting model will provide a regional 3D characterization of Vs, Vp/Vs, and radial anisotropy, offering enhanced constraints on structural models of Eastern Sicily.



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