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Cover Strombolian activity of the Voragine crater at Mt. Etna taken on June 26, 2024 (photo M. Viccaro) | In copertina Attività stromboliana al cratere Voragine del Mt. Etna ripresa il 26 Giugno 2024 (foto M. Viccaro).



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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 - GEOFLUIDS FROM MANTLE TO VOLCANIC AND
GEOTHERMAL SYSTEMS: SAMPLING, ANALYTICAL
TECHNIQUES, AND INTERPRETATION OF DEEP AND
SHALLOW MAGMATIC PROCESSES

Conveners:

Franco Tassi, Francesco Maria Lo Forte, Orlando Vaselli,
Andres Libardo Sandoval-Velasquez, Sergio Calabrese, Giulia Marras

Mount Etna volcanic emissions signature on chemical and isotopic composition of rainwater

Filippo Brugnone¹ and the Atmospheric Deposition Team*

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Mt. Etna is one of the most studied active volcanoes in the world, located on the eastern coast of Sicily, Italy. It is constantly monitored due to its high level of activity and is known to release huge amounts of volcanic gases, i.e., CO₂, SO₂, halogens, and trace elements into the atmosphere. Here we present the results of the research conducted between March 2021 and April 2023, during which 219 rainwater samples were collected from 11 different sites located in eastern Sicily, at varying distances (4-75 km) from Mt. Etna's main vents. The collecting systems used for the study were bulk collectors, which remained open during the whole sampling period, thus receiving both wet and dry deposition, and in many cases also significant amounts of ash and lapilli. Rainwater samples were analysed for pH, electric conductivity (EC), major ions (Na⁺, K⁺, NH₄⁺, HCO₃⁻, NO₃⁻, Cl⁻, F⁻, Ca²⁺, Mg²⁺, and SO₄²⁻), minor/trace elements (Li, Be, B, Al, Si, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Rb, Sr, Mo, Cd, Sn, Sb, Cs, Ba, Tl, Pb, Bi, U), and Technology-Critical Elements – TCEs (Sc, Ge, Te, Y, Nb, Zr, Hf, Th, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). All the samples were analysed for their chemical characteristics at the laboratories of the University and the INGV of Palermo. The isotopic compositions of boron ($\delta^{11}\text{B}\text{‰}$) and strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) were measured in 13 of the collected rainwater samples using a mass spectrometer MC-ICP-MS (Neptune Plus™), following specific pre-concentration procedures in clean rooms (class 100 - 1000). Sample preparation and isotopic analyses were performed at the laboratories of the IGG-CNR of Pisa. In the monitoring sites most affected by the volcanic emissions, such as Cratere 2001 (4 km from the main vents of Mt. Etna), the pH of the rainwater reached values as low as 3.1 due to the interaction with acid volcanic gases. The study evidenced that the Mt. Etna area had the highest volume weighted mean concentrations of F⁻ (97.0 $\mu\text{eq L}^{-1}$), SO₄²⁻ (284 $\mu\text{eq L}^{-1}$), and Cl⁻ (618 $\mu\text{eq L}^{-1}$), up to one order of magnitude higher than the other study areas. In addition, the research shows that the Mt. Etna area had the highest concentrations of most of the minor/trace elements analysed, including Si, Ti, Al, Tl, V, Cd, Li, Br, Cs, Mo, Fe, Ba, Co, Cu, Rb, Mn, U, Sn, Se, and Pb, as well as many TCEs, including Ge, Te, and all the lanthanides. For the lanthanides, the chondrite-normalised trends presented by the Mt. Etna sampling sites seem to follow the main trend of Etna's source rock, although noticeable positive anomalies in Y and a few exceptions

of negative anomalies in Ce and Eu in the less concentrated samples. Overall, the isotopic composition of B ranged from +1.3‰ to +42.9‰. The lowest $\delta^{11}\text{B}\text{‰}$ values were measured in the site closest to the main active craters (Cratere 2001), with a median value of +11.4‰, while the highest values were measured in the sites close to the coastlines, such as Zafferana Etnea, with a median value of +38.1‰. Strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios ranged between 0.70373 ± 0.00001 and 0.71036 ± 0.00001 , with a median of 0.70854 ± 0.00001 . The lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured in the sites most affected by the contribution of the volcanic emissions, with a median value of 0.70434 ± 0.00001 , while higher ratios were measured in samples from the other study sites. For the Etna area, the highest median value was measured in samples from the site least affected by volcanic emissions, i.e., Mt. Intraleo. During the period between 2021 and 2022, Mt. Etna experienced a sequence of more than 50 paroxysms that resulted in the dispersal of volcanic products such as gases and ash over large distances. The signature of this activity was occasionally noticeable in the chemical and isotopic composition of atmospheric deposition in areas far from the volcano, such as the Priolo Gargallo (about 75 km S of Mt. Etna) and Mt. Soro (about 35 km NW of Mt. Etna). The effects of Mt. Etna's volcanic activity were evident in the concentrations of major ions, trace elements, and lanthanides. Boron and Sr isotopes have proven to be effective tracers of volcanic emissions in the atmosphere. The study emphasizes the importance of a comprehensive approach to monitoring the impact of volcanic emissions on the chemical and isotopic composition of atmospheric deposition in areas affected by active volcanoes.

Satellite and in-situ measurements of the 2022 degassing unrest at Levante bay (Vulcano island, Italy)

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This study investigates the temporal evolution of physicochemical parameters in seawater during a period of volcanic unrest in Levante Bay, Vulcano Island. The volcanic degassing initially concentrated in the central crater in September 2021 and shifted towards the bay by May 2022, resulting in increased degassing in underwater fumaroles. Combining in-situ measurements with satellite imagery from Sentinel-2, we provide comprehensive insights into the spatial and temporal dynamics of these phenomena. In-situ temperature, pH, salinity, and redox measurements were conducted at one-meter depth to characterize the marine environment's response to volcanic activity. Concurrently, Sentinel-2 satellite imagery revealed changes in seawater colour, indicative of underwater degassing. Remarkably, a distinct shift towards a light-blue colouration was observed, coinciding with increased degassing in Levante Bay. Furthermore, mapping the spatial distribution of acidity and colour changes revealed a strong correlation, highlighting the utility of satellite imagery for monitoring volcanic activity-induced alterations in seawater chemistry. Notably, a decrease in underwater volcanic degassing was inferred from the observed changes in colouration and acidity mapping, suggesting a potential decrease in volcanic unrest.

These integrated findings underscore the effectiveness of combining satellite remote sensing with in-situ measurements for monitoring and understanding dynamic processes in volcanic marine environments. The results advance our knowledge of the impacts of volcanic unrest on coastal ecosystems and underscore the importance of interdisciplinary approaches in assessing and managing volcanic hazards.

The geochemical monitoring of volatiles outgassing, soil CO₂ and plume SO₂, from Vulcano Island: 18 years of observations

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The Active cone of La Fossa caldera is a close conduit volcano affected by solphataric activity, manifested in the hot fluids released from fumaroles and the associated thermal anomalies in groundwater and exposed ground.

The evaluation of the volcanic activity changes are inferred by the near real-time monitoring of soil CO₂ fluxes diffused at the La Fossa Cone and in the peripheral areas of Palizzi and Levante Bay (VULCO2_NET) and the discontinuous monitoring of CO₂ fluxes diffused by soil in the anomalous areas. Moreover, the SO₂ fluxes released from solphataric area has been monitored by UV-scanning DOAS network (VULSO2_NET).

In particular, three main changes in degassing activity were recorded in 2009, 2021, and 2022 and allowed us to evaluate in near real-time the level and duration of the exhaling crisis affecting the Island of Vulcano, by measuring the changes in mass and energy carried by the fluid release. The strong and deep input of volatiles released, in the last decades, from the underlying magma batch strongly modified the chemical composition of the shallow plumbing system, leading the system to an increase in the level of CO₂ and SO₂ over time.

Magma degassing processes tracked from daily OP-FTIR gas survey throughout the 2021 explosive-effusive Tajogaite eruption (La Palma, Canary Islands)

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In September-December 2021, after half a century of quiescence, Cumbre Vieja volcano on La Palma (Canary Islands) produced an 85-days long mixed explosive-effusive eruption of basanitic magma, which severely impacted the island. Explosive activity persisting at the summit vents of a growing volcanic cone, Tajogaite, showed fast transitions from powerful lava fountaining, Strombolian stages and ash-rich explosive jetting, while lava spattering and lava flow effusion simultaneously occurred at lower flank vents. About $\frac{1}{4}$ of the overall magma budget ($\sim 0.25 \text{ km}^3$) was erupted explosively and $\frac{3}{4}$ effusively. From October 3, 2021, until the eruption end we daily measured the chemical composition of magmatic gases involved in both explosive and effusive activities, by operating open-path Fourier transform infrared (OP-FTIR) spectroscopy at 0.5-5 km distant sites. The molar proportions of H_2O , CO_2 , SO_2 , HCl , CO and occasionally COS were retrieved from gas absorption spectra of the radiation emitted by incandescent ejecta and flowing lava. $\text{SO}_2/\text{HCl}/\text{HF}$ ratios were also determined from solar occultation across the volcanic plume. Our results reveal a sharp compositional contrast between explosive and effusive gas emissions over the whole eruption: explosive degassing was characterized by extremely high CO_2/SO_2 (av. 34, sometimes >50) and CO_2/HCl molar ratios, whose temporal oscillations closely correlate with the intensity of seismic tremor, while effusive degassing displayed much lower CO_2/SO_2 ratios (from 10 down to 0.1) and higher proportions of H_2O , S and Cl. $\text{CO}/\text{COS}/\text{CO}_2$ ratios are consistent with petrological evidence of an oxidised magmatic system ($\text{FMQ} + 1.7 \pm 0.2$) favouring sulfur solubility and late-stage outgassing of SO_2 . Combining our results with the magma eruption rates, petrological data, and the initial abundances and solubility behaviour of volatiles in La Palma basanitic magma, we show that i) an exsolved CO_2 -rich gas phase early coexisted with the erupted basanite at great depth, ii) closed-system degassing prevailed until shallow depth owing to fast magma upraise, and iii) gas fractionation (open system degassing) started at a very shallow (ca. 400 m depth) conduit branching point beneath Tajogaite cone, leading to the compositional contrast between explosive and effusive gas emissions. Most of the pre-exsolved CO_2 -rich gas phase and a small fraction of the bulk magma were directly erupted through the sub-vertical summit conduit, while CO_2 -depleted gas and most of the magma were discharged through lateral effusive branches. An apparent increase of CO_2/SO_2 and SO_2/HCl ratios in explosive emissions

during the first half of the eruption matches the influx of gradually more mafic (deeper-derived) basanitic magma, but we cannot exclude artefacts due to more challenging measurement of the pure explosive gas in that period. A sharp drop of CO_2/SO_2 and SO_2/HCl in explosive emissions marked the eruption decline. The high CO_2/SO_2 ratio, low HCl/HF ratio and high oxidation state of Tajogaite magmatic gases are consistent with the HIMU-like OIB mantle source of alkaline magmatism in the Canarian archipelago. Our study provides the very first detailed data set for gas geochemistry during a subaerial eruption in this OIB region and further illustrates the remarkable potential of OP-FTIR spectroscopy for real time investigation of volcanic eruptions in general.

Evaluation of gas data variability from low-temperature fumaroles in the Azores archipelago, 2015 - 2023

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The Azores archipelago, located in the North Atlantic Ocean, is formed by nine volcanic islands. Present-day volcanic activity in some of the archipelago islands comprises hydrothermal manifestations, including low-temperature fumaroles, thermal and cold CO₂-rich springs, and soil diffuse degassing areas. The main fumarolic emissions are associated with the central quiescent volcanoes of São Miguel, Terceira, and Graciosa islands and have been sampled in the past two decades using the Giggenbach methodology. This work evaluates five main gas ratios (CO₂/CH₄, H₂/CH₄, He/CH₄, He/CO₂, and H₂/Ar) of fumarolic gas samples collected during a period of eight years, from July 2015 to February 2023. The ratios were chosen based on their relevance to identifying unrest periods and their lower analytical uncertainty. Additionally, equilibrium temperatures are estimated for the reservoir feeding the hydrothermal emissions using the H₂/Ar geothermometer from Árnorsson et al. (1998). As a result, the equilibrium temperatures inferred for São Miguel Island fumaroles (Fogo and Furnas volcanoes) range between 223 °C and 262 °C, whereas for Terceira emissions (Pico Alto Volcano), an average temperature of 254 °C is estimated. No significant variations over time on the gas ratios and on the equilibrium temperatures were observed for the studied period, which is consistent with the dormant state of activity of the Azorean volcanic systems. Furthermore, this work proposes an approach for assessing the analytical uncertainties of the methodologies used to analyse the gases collected through the Giggenbach sampling strategy. The results suggest that the chosen methods are adequate, with the analytical uncertainties obtained for most of the gases (Ar, N₂, CH₄, He, H₂, and CO₂) being relatively low, varying between 1% and 3%. Outside that range are the higher analytical uncertainties associated with the O₂ and the H₂S determinations, and efforts should be made to reduce them in the future. Despite the identified analytical uncertainties, the evaluation of sampling uncertainty on the results obtained is also crucial to understand the natural variations and eventually identify unrest periods in volcanic areas.

The plumbing system of Fogo volcano (Cape Verde archipelago) inferred from Carbon and Helium isotopes

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Studying magmatic volatiles (e.g., H₂O, CO₂, S, noble gases), either surface emitted as volcanic gases at active volcanoes or entrapped in minerals as fluid inclusions (FI), contributes to characterising their source and behaviour, and to our understanding of magmatic plumbing systems. Here, we use new noble gas (He-Ne-Ar) and carbon (C) isotope results for olivine- and clinopyroxene-hosted FI from enclaves, lavas, tephra, and volcanic gas samples to characterise the plumbing system of Fogo volcano (Cape Verde archipelago). The plumbing system is thought to consist of: (i) a deep magma reservoir at 27-36 km depth, (ii) a main magma storage zone between 12 and 24 km depth, (iii) and a magma stagnation zone at ~ 9-12 km depth.

The air-corrected 3He/4He ratios of both FI and fumaroles range from 7.14 to 8.44 Ra (where Ra is the same ratio in air), falling in the typical range of MORB (Mid-Ocean Ridge Basalt) mantle (8±1 Ra). The carbon isotopic compositions of CO₂ in both FI and fumaroles range between -6.04 and -4.41‰ (expressed as $\delta^{13}\text{C}$ vs. Pee Dee Belemnite). We find systematic dependency of $\delta^{13}\text{C}$ and He/Ar* ratios on FI entrapment pressures, from which we develop a model for volatile degassing in the mantle-to-crustal magma plumbing system. With this model, we predict a crustal-like signature for carbon ($\delta^{13}\text{C}$ of -0.4±1.0‰) in primary melts formed by mantle melting at ~ 2200 MPa (~ 77 km) and a He/Ar* ratio of 0.90-0.24 in the same mantle source. These values are indicative of a variably depleted mantle metasomatized by C-rich melts/fluids from a crustal component. We put our results in the context of global trends in C and He isotope compositions in Oceanic Islands Basalts (OIB) to (i) prove that carbon metasomatism in the mantle source of OIB magmatism is recurrent, although often masked by isotope fractionations during magmatic degassing, and (ii) corroborate previously established global relationships between OIB He isotopic signature, plume buoyancy flux, and overlying plate velocity.

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The relationship between the geochemistry of light hydrocarbons and the redox conditions of hydrothermal systems: new clues from fumarolic gases of Vulcano Island, Southern Italy

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Magmatic gases exsolving from a shallow magma chamber are typically characterized by high concentrations of carbon dioxide (CO₂), sulphur dioxide (SO₂) and hydrochloric acid (HCl). In contrast, hydrothermal gases originate from the interaction of groundwater with hot rock, leading to a varied composition, commonly rich in H₂O, and influenced by temperature, surrounding geology and circulating water. However, the chemical and isotopic signatures can become muddled when magmatic gases rise and interact with hydrothermal systems, altering their composition. Distinguishing between magmatic-hydrothermal and hydrothermal gases is, therefore, a complex task due to their overlapping characteristics including that, at surface, both these gases are often released by fumaroles with similar temperatures (around 100 °C). The aim of this study was to test if geochemical features of light hydrocarbons in fumarolic gases could be used as a discriminating factor. For this purpose, low-temperature (less than or equal to 100 °C) fumarolic discharges of the Baia di Levante beach from Vulcano Island (Aeolian Islands, Southern Italy) were sampled and analyzed for the carbon isotopic composition of CO₂, CH₄ and C₂-C₆ hydrocarbons, the hydrogen isotopic composition of CH₄, H₂ and H₂O, and the chemical composition of inorganic and organic gases. Our investigations revealed that fumarolic gases at Baia di Levante are characterized by: (1) CH₄ with ¹³C- and ²H-enriched isotopic compositions ($\delta^{13}\text{C}$ ranging from -10.4 to -4.7 ‰ vs. VPDB, $\delta^2\text{H}$ ranging from -102 to -78 ‰ vs. VSMOW), (2) remarkably high CH₄/(C₂H₆+C₃H₈) ratios of up to 40000 and (3) high concentrations of C2-C3 alkenes, iso-C₄H₁₀ and benzene in the gas emissions closest to the La Fossa crater. The source(s), formation conditions and controlling factors of the abundances and isotopic signatures of methane and light hydrocarbons are discussed. We argue that the geochemical characteristics of light hydrocarbons could be interpreted as the result of a series of organic reactions occurring within a hydrothermal system characterized by strongly oxidizing redox conditions, reflecting a constant intense injection of magmatic volatiles. Finally, we present two plots based on the relative abundances of C₂-C₆ hydrocarbons and we show that their use might help in distinguishing purely-hydrothermal from magmatic-hydrothermal systems. We suggest that the monitoring of organic species in an active volcanic system could provide additional information on its physico-chemical evolution and possibly trace the injection of magmatic volatiles into the overlying hydrothermal systems.

Active OP-FTIR measurements reveals water vapor and methane chloride emissions from Salinelle mud volcanoes, Paternò (Sicily, Italy)

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About 20 km Mt. Etna south of central craters, at the contact between the volcanic and sedimentary formations, three mud volcanoes (the “Salinelle”) discharge large quantities of CO₂ and CH₄ rich gases and small amounts of Na–Cl cold hypersaline waters and mud, escaping from sometimes ephemeral pools. The main site (the Salinelle “Stadium”), is located at the NW boundary of the city of Paternò: in this area, mud volcanoes activity and human factors influence each other: morphology and fluid activity is disturbed and destroyed by anthropogenic factors, but - sometimes - vice-versa. The main component of the gas phase is CO₂, followed by CH₄ and minor species. These emissions have been interpreted as the result of a mixing between hydrothermal fluids and the magmatic gases of nearby Mt. Etna.

The temporal variations in the gas fluxes and water and mud temperature, are strictly correlated to the changes in pressure of the gas/water at depth: sometimes, gas/water flow rates and temperatures have suddenly increased determining fountains of muddy water.

While in the literature there is a lot of compositional data on the gases, relative amounts of water vapor have never been measured before. Here, we report the first OP-FTIR measurements of water vapor and halogenated organic compound (CH₃Cl) in the Salinelle gas emission. The origin of the latter can be ascribed to oxidation processes of organic matter in the presence of halide ions, both conditions which occur in the Salinelle environment.

In-soil radon data collected throughout the 2015-2023 period at Mt. Etna: correlation with magma dynamics and potential use in volcano monitoring

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Volcano monitoring is crucial especially in densely populated areas such as around Mt. Etna. In this regard, new monitoring parameters able to catch subtle magma dynamics within the volcano or to predict the run-up of eruptions are really welcomed. In doing this, our research is based on the investigation of in-soil radon, a natural noble gas potentially effective in tracking magma dynamics and crustal/sub-crustal fluid movements along active volcano-tectonic structures. In this presentation, we show continuous in-soil radon data, collected throughout the period 2015 - 2023, at a station on the southeastern flank of Mt. Etna that is part of the INGV-OE monitoring network. The approach proposed in this work is unique and really innovative, even in consideration that the time series of radon data analyzed is the longest, to the date, on Mt. Etna and among the longest for active volcanoes worldwide. Choice of this period is strategic, considering the incredible record of volcanic eruptions that encompass different behavior, i.e. from wholly effusive to strikingly energetic explosive eruptions. In order to constrain the radon signal from the influence of environmental cycles and to highlight those variations possibly linked to volcanic activity, we have applied novel mathematical algorithms to this long-term data series. The filtered signal revealed variations, both long-term and short-term, that are correlated with the activity of Mt. Etna during the investigated period. Specifically, significant correlations were observed in correspondence of periods characterized by paroxysmal eruptions (i.e., the 2015-16 eruptions at the crater Voragine or the exceptional 2020-22 sequence) or in concomitance of intense seismic swarms caused by shallow magma intrusions within the volcano. To corroborate the interesting findings coming from the radon data, we have also integrated our record with important petrological dataset enlightening the major recharging phases occurred during the 2015-23 [Cannata et al., 2018 – G3; Viccaro et al., 2019 – Sci. Rep.; Borzi et al., 2020; Giuffrida et al., 2021 – JVGR; Giuffrida et al., 2023 – Earth Sci. Rev.]. Integration of these data provided crucial insights into the dynamics of magmatic storage, transfer and magma interaction within the Etnean plumbing system. Although the considerations here reported needs to be further pondered and examined in depth, this study preliminarily emphasizes the great potentiality of in-soil radon for tracking magma movements before eruptions, encouraging therefore its use as a further tool for monitoring the volcanic activity.

Spatio-temporal compositional evolution of the La Fossa fumarolic field (Vulcano, Italy)

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Direct sampling of fumaroles is the most widely used (and valuable) geochemical monitoring methodology at dormant, closed-conduit volcanoes. However, because direct sampling is operationally limited to a relatively limited number of fumaroles, a complementary and helpful exercise is to characterize the chemical fumaroles' heterogeneity by real-time sensing methods that can rapidly (and relatively inexpensively) survey the entire fumarolic field. These full field mapping methodologies are useful for quantifying how magmatic-hydrothermal reactions vary in space and time (if repeated periodically) contributing to monitoring and hazard assessment.

We report here on repeated mapping of the compositional heterogeneity of the fumarolic field at La Fossa crater on Vulcano island in a ten period (2014-2024) encompassing the recent 2021 degassing unrest [Federico et al., 2023]. Our field mapping methodology is based on chemical profiling through the near-vent fumarolic plumes using a hand-held multi-gas system comprising an infrared spectrometer for CO₂ detection, two electrochemical sensors for the determination of SO₂ and H₂S, and P-T-humidity sensors [Aiuppa et al., 2005]. As in previous studies [Aiuppa et al., 2005, 2022], the fumarolic field is totally covered in a series of walking traverses in circa 1 hour, while the instrument acquires at 1 Hz rate and position is spatially located with a GPS. Data are then post-processed using a R code that automatically calculates average ratios between magmatic volatiles (CO₂/SO₂ and H₂S/SO₂ ratios) over moving temporal windows of 60 s. Ratios are calculated at condition that two criteria are satisfied (that the correlation coefficient between volatile couples, R₂, is > 0.7, and the SO₂ concentration is higher than a 1 ppm threshold). The final output show the spatial variability of CO₂/SO₂ and H₂S/SO₂ ratios during each of the surveys (n = 15).

Our results highlight a large spatio-temporal variability of the fumarolic field. We show that, relative to background periods (DATA), when hydrothermal fumarole compositions (CO₂/SO₂ > 20 and up to 50) prevail, the fumarolic system homogenized to more magmatic values (CO₂/SO₂ 20 and exceptionally 10) during the peak of the unrest in October-November 2021. We find that, since late 2022, the fumarolic field is progressing toward a return to pre-unrest spatial diversity, with more magmatic compositions in the crater rim fumaroles (F0-F11) and more hydrothermal signatures in the inner crater fumaroles (FA). This is testified by the increasingly hydrothermal nature of the western part of the fumarolic field, which points to progressive (but still not complete) vanishing of the unrest.

Gaseous elemental mercury (GEM) in interstitial soil and free gases in a peripheral area of Mt. Etna, a preliminary study

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Mercury (Hg) is one of the most hazardous elements emitted into the atmosphere from both natural and anthropogenic sources, and it occurs in three oxidation states: gaseous elemental Hg (GEM), monovalent Hg, and divalent Hg. Volcanic emissions are an important natural source of Hg in the environment. It is important to understand the pathways of this element once released into the atmosphere, given its potential toxicity and for its long atmospheric residence time (~ 1 yr), which allows for an efficient global distribution compared to many other volcanogenic elements. This research is framed within the broader context of the HERMES project (co-founded PRIN 2022) and involves the biogeochemical study of Hg on the Mt. Etna volcano. Specific objectives include: (i) determination of the Hg concentrations in soils and interstitial gases in soils; (ii) characterisation of the microbiota associated with the mercury cycle in soils; (iii) quantification of the mercury emissions from the volcano's peripherals emissions, and (iv) quantification of the atmospheric Hg deposition fluxes.

Here, we present the preliminary data on the Hg outgassing from some degassing areas around Mt. Etna, including some of the sites of the "Etnagas" CO₂ monitoring station network (INGV). Degassing Hg from soil was collected using a Lumex® RA-915M (Zeeman atomic adsorption spectrometer) analyser over a wide concentration range (2 to 50,000 ng m⁻³). The inlet port of the instrument was equipped with a three-way valve and the gas was injected into the instrument using a 100-mL syringe.

Compared to the atmospheric background values (median value of 2.17 ng m⁻³), the Hg concentration in free gas samples reached higher values (264 - 9,913 ng m⁻³) at the Salinelle, Acqua Grassa and Fondachello sites, highlighting the important outgassing of mercury to the atmosphere. Although with higher than background values, the Hg concentration measured in the interstitial soil gas was lower compared to the free gas samples. The highest Hg concentration (~ 100 ng m⁻³) was measured close to the low-temperature fumarole located near the Cratere 2001 site, while the Hg concentration in the intermediate zone between the low-temperature fumarole and the non-degassing area ranged from 10 to 50 ng m⁻³. These preliminary results indicate that the contribution of peripheral and soil degassing respect to the crater degassing is non-negligible and requires further investigation.

Fluid inclusions trapped in ultramafic rocks and lavas reveal the existence of crustal fluids infiltrating the Polynesian upper mantle

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Polynesian OIB localities (es, Society, Samoa and the Austral-Cook Islands) have been considered a perfect natural laboratory to study the heterogeneity of the mantle. Indeed, Sr, Nd and Pb isotopes of lavas collected in the Polynesian region has allowed to infer the existence of distinct mantle reservoirs whose origin is intimately related to the local tectonics: DMM, HIMU, EM1, EM2. In this regard, we now attempt to study the isotopic composition of CO₂ ($\delta^{13}\text{C}$) (coupled to noble gas isotopic studies) in fluid inclusions trapped in xenoliths and lavas (collected from some localities such as Samoa, Tubuai and Moorea) with the aim of evaluating the role of the recycled crustal carbon and active tectonic processes on the composition of the local upper mantle. In this work, we present isotopic data from both ultramafic xenoliths and lavas: three harzburgites and a picrite from Savai'i Island (Western Samoa, Samoa hotspot), two harzburgites from Tubuai (Southern Islands, McDonald's hotspot), and a lava from Moorea (Society Islands). The most abundant volatile species found in fluid inclusions is CO₂; in the ultramafic xenoliths, CO₂ concentrations vary from 4.30.10⁻⁷ mol g⁻¹ to 5.58.10⁻⁶ mol g⁻¹ while in lavas from 3.03.10⁻⁷ mol g⁻¹ to 3.32.10⁻⁷ mol g⁻¹. Rc/Ra ratios (³He/⁴He corrected for atmospheric contamination) confirm the isotopic values already presented in the literature for the studied localities: high ³He/⁴He for Savai'i with values around ~11.32Ra, and low ratios for Moorea (6.35Ra) and Tubuai (~6.43Ra). The CO₂/³He ratios vary from 3.90.10⁹ to 6.55.10¹⁰ for the Savai'i samples, 4.49.10¹⁰ for the Tubuai Island and 7.74.10¹⁰ for the Moorea Island. Regarding $\delta^{13}\text{C}$, we found three data groups: 1) the Savai'i groups which vary from -6.83‰ to -3.82‰ (within or very close to the MORB range); 2) the Tubuai group which exhibit positive values from -1.33 ‰ to +1.00‰; 3) and an intermediate value from the Moorea sample (-3.12‰). Using a $\delta^{13}\text{C}$ -CO₂/³He plot it is possible to explain the carbon data variability through a mixing model relating two components within the local mantle: a MORB and a crustal component. In fact, the existence of a positive signatures coincides with petrological studies performed in ultramafic xenoliths from Samoa and Tubuai [Hauri et al., 1993] whose results suggest the occurrence of a metasomatized mantle infiltrated by carbonatite fluids. Considering that fluid inclusions in mantle xenoliths better preserve the isotopic composition of the local mantle, these preliminary results suggest the existence of a crustal carbon reservoir in the mantle source beneath the localities above mentioned.

Classical geochemical methods vs. Unmanned Aircraft Systems: Mapping of the gas manifestations at Pantelleria island (Italy)

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In the framework of the INGV project Pianeta Dinamico (PANTAREI), all known gas manifestations have been resampled, while during the same campaigns many other have been located thanks to the indications from colleagues involved in the geological mapping of the island and from local inhabitants. All manifestations have been located through a handheld GPS receiver and their coordinates will be uploaded in a GIS project. Temperature measurements were taken at 15 and 50 cm depth. Gas samples were taken inserting a tube at 50 cm depth and their chemical composition were analysed at INGV-Pa.

The collected gas samples can be included into two main groups. The first shows temperature between 70 °C and boiling and the chemical composition is CO₂-dominated with abundant H₂ and CH₄. The second group shows temperatures mostly 60°C and the chemical composition is air-dominated with CO₂ mostly 10 %, absence of H₂ and low CH₄.

The first group can be interpreted as fed by the deep high enthalpy geothermal system through the main deep tectonic or volcano-tectonic structures. The second group is mainly found in the area of the NW flank of Mt. Grande and its manifestations are possibly fed only by the perched low enthalpy hydrothermal aquifer.

Due to the fact that a large part of the island is very difficult to access, we took 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. The first UAS surveys were made on the south flank 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 that will be the target of gas sampling and direct temperature measurements.

S02 - INTEGRATED APPROACHES IN VOLCANIC STUDIES: FROM FIELD INVESTIGATIONS TO GEOCHRONOLOGY, STRATIGRAPHY, VOLCANO-TECTONICS AND GEOMORPHOLOGY

Conveners:

Jacopo Natale, Matteo Roverato, Arianna Beatrice Malaguti, Paola Donato, Gilda Risica, Claudia Romagnoli

$^{40}\text{Ar}/^{39}\text{Ar}$ ages of the ignimbritic units of Pantelleria Island (Italy): revision of the stratigraphic sequence of major explosive eruptions

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Pantelleria Island (Italy) is a subaerial volcanic complex located within the Sicily Strait Rift Zone. Pantelleria is renowned as the type locality of pantellerite, an iron-rich peralkaline rhyolite. Peralkaline magmatism often correlates with highly explosive volcanic activity. Therefore, accurately determining eruptive times and rates is crucial for assessing volcanic risk, particularly given the typically high population density in these regions.

Over a span of more than 300 kyrs of subaerial eruptive history, at least nine ignimbrite-forming eruptions have occurred on Pantelleria, associated with a minimum of five caldera collapses. While the last seven ignimbrite units have been well-constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ dating in the range 187-46 ka [Rotolo et al., 2013; Scaillet et al., 2013; Jordan et al., 2018], the eruptive ages of the two oldest ignimbrite formations remain poorly determined or unknown. Specifically, the Zinedi Formation has been dated at ~ 189 ka using the K/Ar method [Mahood and Hildreth, 1986], but with a rather large error and undefined internal systematics, while the undated Pozzolana Formation is bracketed between 189-128 ka based on field relationships.

We conducted radiometric analysis using the $^{40}\text{Ar}/^{39}\text{Ar}$ method to better constrain the stratigraphic sequence of the major explosive eruptions. Following meticulous hand-picking selection, alkali feldspar separates were neutron-irradiated at the Oregon State TRIGA Reactor alongside sanidine from the Fish Canyon Tuff [28.305 ± 0.036 Ma; Renne et al., 2010] serving as a flux monitor. Measurements of argon isotopic ratios have been performed using a last-generation mass spectrometer housed at the Institut des Sciences de la Terre d'Orléans (CNRS-ISTO). Monitor calibration is still underway, and data presented are subject to further refinement (but internally calibrated to better than ± 0.5 ka relative variation).

The Zinedi Formation yields a weighted mean age (WMA) of 176.2 ± 0.9 ka (mean square of weight deviations, MSWD = 1.59, 2σ), while the Pozzolana Formation exhibits WMA = 153.9 ± 1.3 ka (MSWD = 1.77, 2σ). Consequently, the Polacca Formation [~ 187 ka; Jordan et al., 2018] is now identified as the oldest ignimbrite on the island. This is also the most voluminous one with an onshore estimated dense rock equivalent (DRE) of 0.64 km^3 [Jordan et al., 2018, 2021]. Dating of the banded pantellerite lava underlying the Zinedi Formation at Cala della Pozzolana provides a WMA of 186.2 ± 1.6 ka (MSWD = 1.47, 2σ), suggesting the possibility that the pyroclastic density current from the Polacca eruption may have reached the northernmost sector of the island. Volume estimates are minima, considering that the eruption occurred during low-level stand of Marine Isotopic Stage MIS 7 (sea level up to 20 m lower than present in the western-central Mediterranean).

Considering the previously known eruptive ages, chemical analysis of the ignimbrites reveals a general decrease in peralkalinity and evolution rate of the erupted magma, as well as a decrease in the erupted magma volumes. Only the last ignimbrite unit, the Green Tuff Formation, deviates from this general trend, exhibiting a slight increase. Our new data not only refine the

stratigraphic sequence of major explosive eruptions of Pantelleria but also provide new insights into the dynamics of the island's plumbing system. Indeed, the estimated DRE and the evolution degrees of the erupted magmas exhibit some variability over time based on the new $^{40}\text{Ar}/^{39}\text{Ar}$ ages, suggesting different scenarios regarding magma productivity and residence times in magma reservoirs.

Advanced AI-based Techniques for Dating Lava Flows Using High Spatial-Resolution Satellite Imagery: A Case Study of Mount Etna

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Integrated approaches in volcanic studies, particularly in dating lava flows, are crucial for understanding volcanic processes and potential hazards. Accurate dating of lava flows improve our ability to reconstruct the history of volcanic activity, assess the frequency and scale of eruptions, and predict future volcanic behavior, which is vital for risk management and mitigation strategies in vulnerable regions. Satellite thermal infrared remote sensing measurements play a key role in observing and mapping lava flows through electromagnetic spectrum analysis. These measurements capture images across various wavelengths, enabling detailed analysis of the spectral characteristics of volcanic deposits. Thermal infrared wavelengths (TIR) are particularly valuable in detecting heat emitted by active lava flows, allowing real-time monitoring of their temperature and facilitating identification of areas with recent or ongoing volcanic activity. Meanwhile, images in the visible and near-infrared (VNIR) regions are useful for determining the mineral composition of lava flows. Given the different light reflectance properties of various chemical compositions, this method enables distinguishing between lava flows of different ages or compositions. Shortwave infrared wavelengths (SWIR) are sensitive to vegetation presence and changes in lava flow surfaces due to alteration and degradation. Older lava flows, typically more weathered and covered with vegetation, exhibit different spectral responses compared to more recent ones. The practical applications of this technology are manifold, ranging from creating detailed maps of volcanic areas and identifying active and past lava flows to determining the relative age of lava flows through spectral analysis over time. Here, we propose an AI-based approach for dating lava flows using satellite images, leveraging machine learning algorithms and high-resolution satellite data to estimate the age of volcanic deposits. In the proposed advanced dating model, detailed spectral information of volcanic surfaces is extracted from high-resolution satellite images, such as those from Sentinel-2 (ESA). The case study focuses on Mount Etna, Italy, carefully selecting areas covered by single lava flows over the last 400 years and avoiding zones with overlapping lava deposits that could compromise accurate dating. This automatic approach offers unique advantages over traditional methods for dating lava flows in terms of speed and global coverage.

Stratigraphy, chronology and landscape evolution on the Vulcano Island (Italy) during the last 1100 years of activity

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Careful study of historical eruptive events is essential for understanding volcanic systems and the hazards they pose. We present an exhaustive stratigraphic investigation, a thorough chronological reconstruction, extensive tephra mapping and a detailed analysis of the interaction between primary and secondary volcanic processes concerning the post-900 AD activity of the La Fossa caldera, encompassing the two main systems of La Fossa volcano and the Vulcanello cones (Vulcano Island, Italy). Our assessments show that recent volcanic activity within the La Fossa caldera is dominated by Vulcanian eruptions, together with effusive and Strombolian activity, sporadic sub-Plinian events, and both “impulsive and short-lived” and “long-lasting” phreatic explosions, all of which have the potential to significantly affect the entire northern sector of Vulcano Island. We record a total of 30 eruptions, 25 from the La Fossa volcano and 5 from the Vulcanello cones, with deposits ranging from ash to lapilli, as well as fields of ballistic bombs and blocks. The volcanic activity is interspersed with significant periods of erosion and volcanoclastic re-sedimentation. Extensive secondary erosion processes are manifested by the widespread deposition of fine-grained ash blankets, affecting both the active cone of La Fossa and the watersheds draining into the La Fossa caldera. The continuous rise in ground level above sea level, particularly in the western sector of the caldera depression where critical infrastructure is located, is primarily attributed to prolonged alluvial processes. We demonstrate the key role of a specific methodological approach in characterising and assessing the hazards associated with volcanic activity of varying intensity, characterised by prolonged periods of tephra emission interspersed with episodes of erosion and re-sedimentation.

The ~14.5 ka tephra record from the NDT09 core in the Marsili basin and its implications for the timing and tempo of volcanic eruptions

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Tephrochronology is widely used for dating, synchronizing, and correlating geological records, providing crucial insight into past volcanism and magmatic evolution. Through higher-resolution analyses of geological records, it became possible to obtain the greater details on the recorded events. Indeed, despite extensive prior researches, tephrochronological studies in the Tyrrhenian area continuous to offer new information on the eruptive history of peri-Tyrrhenian volcanoes and on the dynamics of depositional processes.

We present here the results of a tephrochronological study of the 5.70 m long NDT09 gravity core sampled close to the western rim of the Marsili Basin in the southern Tyrrhenian. The succession was studied within the framework of the AMUSED (A MULTidisciplinary Study of past global climatE changes from continental and marine archives in the MeDiterranean region) - INGV (Istituto Nazionale di Geofisica e Vulcanologia) project (<https://progetti.ingv.it/index.php/en/amused>), which aims to reconstruct the climatic variability in the central Mediterranean region during the middle-late Quaternary by integrating multi-proxy paleoclimate data acquired in marine and continental archives. We provide a detailed tephrostratigraphic framework based on textures, mineralogy, and single-shard major- and trace-element glass compositions. The results reveal that the tephra intercalated in the NDT09 core span from the Neapolitan Yellow Tuff to the 512 A.D. Vesuvius eruptions, and comprise deposits from the Phlaegrean Fields, Somma-Vesuvius, Ischia, and Aeolian Islands. The identified isochrons are intercalated within an epiclastic/volcaniclastic succession characterised by the recurrent occurrence of remobilised deposits by turbidite processes. The tephra record demonstrates that the explosive activity of peri-Tyrrhenian volcanoes in the last 15,000 years was very intense and provides new clues on the timing and tempo of the volcanic activity from some of the studied volcanic sources.

Lava flow field development and lava tube formation during the 1858 eruption of Mount Vesuvius

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The importance of lava tubes in active lava flows is due to their capacity to enhance lava propagation further from the eruptive vent than lava channels. Tubes insulate the molten lava from the atmosphere by forming a solid crust that increases in thickness when cooling proceeds. To understand lava flow propagation and improve hazard management during volcanic crises, it is necessary to comprehend the mechanisms that permit lava tubes formation and development in lava flow. Most of the modern scientific investigations on Vesuvius have been mainly focused on its explosive activity; but extensive periods of open conduit with Strombolian and Hawaiian eruptions took place on the stratovolcano. The last eruptive cycle of Vesuvius was a three hundred yearlong open conduit period that initiated with the 1631 eruption and ended with the 1944 eruption. Since then, Vesuvius has been in a state of quiescence. In this study, we investigate the emplacement timeline and surface characteristics of the 1858 lava flow field, describe the lava tubes found within it and analyze the characteristics of the largest one. We reconstructed the temporal and spatial evolution of the 1858 lava flow field based on historical documentation (geological maps, paintings, written description). We defined a contour corresponding to the entire lava flow field and one corresponding to the now exposed and accessible flow field using geological maps and analyzed its surface using a 1-m resolution Digital Elevation Model. We described the morphology of three lava tubes found in the 1858 lava flow field. We finely described the morphology of the largest lava tube found in the 1858 lava flow field based on a high-resolution 3D model of its interior and overlying surface.

Our results highlight the presence of surface features such as tumulus on the mostly pahoehoe surface of the 1858 lava flow field. In a flat area of the lava flow field (3°), we found the largest lava tube of the flow field. Our analysis shows that this lava tube is 30.15 meters long, 1.40 to 17.41 meters wide and has a mean inside height of 1.40 meters. The roof of the lava tube has an average thickness of 2.40 meters. This roof is fractured in the southern part of the lava tube and has collapsed in its northern part. We describe multiple internal features that can be observed inside the lava tube, such as stalactites and wall linings. We gain information on the temporal and thermo-rheological conditions and evolution of the activity within the lava tube by analyzing these internal features.

This study is the first in modern science to shed light on the presence of lava tubes at Vesuvius. Our results allowed us to understand the development and characteristics of the 1858 lava flow field. Based on our results, we proposed a formation mechanism for the described lava tube based on inflation processes and lateral capture, typical of pahoehoe lava flows.

Unveiling the ancient history of the southwestern sector of Campi Flegrei through the stratigraphy, compositional variability and physical volcanology of the pre-caldera Vitafumo and Miliscola tuff cones

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Campi Flegrei is a densely populated active volcanic field, characterized by the presence of diffuse monogenetic volcanic cones and two nested calderas associated with the Campanian Ignimbrite [39 ka; Rosi and Sbrana, 1987; Perrotta et al. 2006] and the Neapolitan Yellow Tuff [15 ka; Scarpati et al. 1993] eruptions, respectively. Due to dense urbanization and caldera collapses, the youngest products of the Campi Flegrei are well-exposed and generally better known than those of the older, pre-caldera deposits. Aiming to contribute to a better definition of the volcanic hazard produced by phreatomagmatic eruptions through the reconstruction of the ancient eruptive history of the Campi Flegrei, our research focuses on the Monte di Procida cliff, in the southwestern sector of the district. In this area thick pyroclastic sequences, separated by several paleosol horizons, are spectacularly exposed, encompassing all the volcanic activity of Campi Flegrei. A stratigraphic study was conducted on the pyroclastic sequences of two distinct monogenetic volcanoes: Vitafumo and Miliscola. Although the absolute age of these ancient volcanic edifices is unknown, they are capped by a tephra sequence erupted from the nearby island of Ischia, with an age between 74 and 55 ka [Vezzoli, 1988]. The remanent of Vitafumo is formed by three main pyroclastic sequences, overall thick up to 130 m, separated by two erosional unconformities. The lowermost sequence shows a quaquaversal structure, while the two upper successions thicken on the eastern slope of the basal sequence and strongly thin on the western slope, possibly indicating a westward shift of the source area during the eruption. The deposits consist mainly of thick, massive, pumice and lithic-rich pyroclasts alternating with stratified, coarse to fine grained ash layers. Large bombs are present producing deep impact sags. Towards the top, the sequence becomes coarser and is represented by alternating blackish and reddish stratified scoria beds. The deposits are locally lithified, both in the lower and middle sequences. The Miliscola succession, resting on the Vitafumo volcano, thins towards the west, reaching a thickness of up to 12 meters. It reveals significant vertical lithostratigraphic variations, with alternating plane-parallel, matrix supported, massive or stratified ash layers, along with thick pumice lapilli deposits containing large blocks and scattered bombs. Both volcanoes formed during explosive eruptions, during which sustained eruptive columns accumulated pumice lapilli and blocks, alternating with repeated column collapses. These resulted in the emplacement of unsteady and non-uniform pyroclastic density currents characterized by traction to granular to fluid-escape dominated flow boundary zones. Both the edifices are characterised by juvenile

clasts that are extremely homogeneous in composition throughout the entire stratigraphic sequence, both showing a typical trachytic composition with no significant difference between Vitafumo and Miliscola samples. The incoherent nature of most deposits, coupled with the high degree of vesicularity of pumice clasts and their relative abundance (up to 84 wt.% for both the Vitafumo and Miliscola sequences) compared to that of lithic fragments suggest a mainly magmatic activity for both volcanoes. The presence of lithified horizons and accretionary lapilli bearing layers, along with the abundance of fine ash and cineritic aggregates testify to periodic phreatomagmatic pulses, during which magma-water interaction occasionally occurred. The increase of the lithic content upward in the sequence (from 9.5 to 46 wt.% and from 6 to 44 wt.%, respectively in the Vitafumo and Miliscola successions) suggests that erosion or partial collapse of volcanic conduit events occurred during both the eruptions. This research provides new insights into the knowledge and risk assessment of Campi Flegrei activity. It shows that, although pre-caldera Phlegrean volcanism is represented by monogenic and scattered vents with a confined distribution [Perrotta et al. 2010], some eruptions show complex dynamics conditions that changed during the single event.

Constraining the poorly known pre-CI volcanic activity of Campi Flegrei caldera through tephrostratigraphy and tephrochronology

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The Campi Flegrei (CF) caldera, southern Italy, is the source of some of the most powerful Late Pleistocene eruptions of the central Mediterranean area (e.g., Campanian Ignimbrite, Neapolitan Yellow Tuff, Masseria del Monte Tuff eruptions). Although the volcanic history of the CF caldera has been continuously and intensively investigated, relatively little is known about its earliest activity. The present study aimed at integrating existing and new tephrostratigraphic, geochemical (EMPA + LA-ICP-MS), and geochronological (⁴⁰Ar/³⁹Ar) data, which relate to CF tephra deposits preserved in mid-proximal (Campanian Plain), distal (Tyrrhenian Sea) and ultra-distal (Lower Danube area) sedimentary archives. Our high-resolution stratigraphic and chronological investigation led to a comprehensive and updated framework for the CF volcanic activity, suggesting a more complex and intense volcanic history than previously thought. In addition, a Bayesian age-depth model, constrained by previous and new high precision ⁴⁰Ar/³⁹Ar ages, provides a reliable estimate of the ages of some undated CF eruptions. Overall, the updated framework on the stratigraphy, geochemistry and geochronology of the CF tephra consolidates the notion that the Middle-Late Pleistocene activity at CF area represents a significant stage of its volcanic evolution, characterised by intense and frequent explosive eruptions.

These new findings are pivotal for a reassessment of recurrence times of the CF explosive activity, thus allowing an improved long-term volcanic hazard assessment in the Neapolitan area.

A high-resolution tephra record from Castiglione maar reveal the timing and unveils cryptic eruptions over the most recent volcanic activity at Colli Albani, central Italy

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We present a review of the eruptive history of the most recent activity of the Colli Albani volcanic district, central Italy, based on new tephrochronological data from the lacustrine sediment sequences of the Castiglione maar, as part of the AMUSED (A MULTidisciplinary Study of past global climatE changes from continental and marine archives in the MeDiterranean region) project. Combined stratigraphic, textural, mineralogical and geochemical data on tephra layers found between 11 and 15 m of composite depth, supported by ^{40}Ar - ^{39}Ar ages determined by multi-collector noble gas mass spectrometry on leucite crystals, allowed to define in detail the number, chronology and dynamics of the most recent phase of activity at Colli Albani. Results suggest that the Castiglione maar preserves tephra layers derived from six explosive eruptions of the last eruptive sub-cycle of the Albano maar (ca- 40-36 ka), two more than those previously reconstructed. Based on the data collected, the previously unrecognised explosive eruptions were of lower intensity when compared to the Albano 4 to Albano 7 eruptions, but high enough to produce highly fragmented tephra, relatively poor in lithic components and thus feed by an important contribution of a juvenile magma. In addition, direct ^{40}Ar - ^{39}Ar ages determined on five of the six tephra and the estimated, modelled age for the sixth one would show that the eruptive activity of the last sub-cycle of the Albano maar would be ended some millennia after than previously determined. We argue that these new findings should be considered for an updated assessment of the volcanic hazard in the Rome area.

The contribution of paleomagnetism and $^{40}\text{Ar}/^{39}\text{Ar}$ dating to unravel the dynamics and PDCs emplacement of the latest caldera-forming eruptions of Latera (Vulsini Volcanic District, Central Italy)

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Identifying and correlating the different ignimbrite units at polygenic calderas is a mandatory target for the appropriate reconstruction of caldera-forming events and assessment their physical volcanology parameters such as eruption intensity and eruption volume. However, because different ignimbrites originating from the same caldera system often display similar compositional and lithological characteristics, correlation of different deposits is often not straightforward, or even impossible.

In this study, new paleomagnetic and $^{40}\text{Ar}/^{39}\text{Ar}$ data along with stratigraphic evidence were used to address the correlations among different sillar-type ignimbrites characterizing the Latera Volcanic Complex (Vulsini Volcanic District, central Italy) during the last caldera-forming eruptions. In particular, the two ignimbrite complex units of Grotte di Castro and Onano were targeted with 32 studied sites for paleomagnetism and 11 new $^{40}\text{Ar}/^{39}\text{Ar}$ dating.

Paleomagnetic directions for both Grotte di Castro and Onano Formations are characterized by well-defined ChRMs (characteristic remanent magnetization directions). The palaeomagnetic directions obtained from the matrix and scoria deposits at 18 different sites out of 32 are statistically indistinguishable, providing a correlative tool which suggests a similar age of emplacement. Dating obtained from $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine and leucite crystals extracted from both the Grotte di Castro and Onano deposits show a narrow time window suggesting that – consistently with paleomagnetic data – the Grotte di Castro and Onano deposits were emplaced in a short time interval. Taken together, these data provide the first compelling evidence that Grotte di Castro and Onano Formations do not represent separate eruptions as suggested so far, but likely belong to a single, large-scale, caldera-forming event. Accordingly, we merged and renamed both units as “Grotte di Castro-Onano”, with a very narrow emplacement interval peaking near ~214 ka. The variability of the exposed deposits observed in the field can be interpreted as the different pulses on a same caldera-forming eruption. The ~214 ka age of the Grotte di Castro-Onano eruption represents the final evolutionary phase of the Latera caldera, which thus developed in few tens of thousands of years, over a much shorter time span than previously estimated in the literature.

In addition, we estimated the emplacement temperature of Grotte di Castro-Onano deposits, using thermal demagnetization of oriented lithic clasts (7 test sites), because only 18 out of 32 sites – demagnetized by alternating field (AF) method – showed ChRMs, whereas scattered demagnetization diagrams were observed for the remaining 14 sites. The results showed that ignimbrites yielding ChRMs were emplaced between 440 and > 600 °C, whereas sites providing

scattered diagrams revealed significantly colder temperatures 200 °C. These findings suggest, on one hand, that “cold” deposits were generated either from lahars or from late, gravity-driven reworking in dry conditions, of partially cooled still unconsolidated and unstable pyroclastic deposits. They also reveal, on the other hand, that AF demagnetization of matrix samples from deposits of dubious origin provides a fast and efficient reconnaissance tool for discriminating low- from high-temperature consolidated tuffs that would otherwise appear indistinguishable both in the field and petrographically. Such a coupled approach is thus essential to discriminate emplacement mechanisms (temperatures, eruptive phase) in complex, large-scale, calderas.

Stratigraphy of the prehistoric-historical hydrothermal crater field of Nisyros volcano (Dodecanese archipelago, Greece): insights for hazard evaluation in a touristic geosite

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Nisyros is a Quaternary calc-alkaline composite volcano in the eastern Hellenic arc, last active ~15,000 years ago. A series of prehistoric-historical hydrothermal eruptions occurred within the summit caldera infilling and lava domes, in the southern Lakki plain, where a large fumarolic field is active. In the field, we recognized eight eruption units related to the hydrothermal craters of (in chronostratigraphic order) Kaminakia (unknown age), Megalos (Big) Polyvotis (unknown age), Stephanos 1-2 (older than 1414-1420), Andreas or Mikros (Small) Stephanos, Polyvotis (1871-1873), Alexander (Flegethron, 1873) and Mikros (Small) Polyvotis (1887), whereas other small craters have no clear deposits attribution. Their relative stratigraphy is established based on angular discordances, thickness and grain size variations, and the occurrence of interlayered stratified lacustrine deposits. The eruption units are m-thick, poorly sorted deposits of ash-supported lapilli and blocks (up to 1,5 m) of hydrothermally altered lavas, with no fresh juvenile material, interpreted as proximal fallout deposits with ballistic ejecta and subordinate pyroclastic density currents and water-rich mass flows, with a max runout of ~400 meters from the crater margins. Most of the craters intersect each other, with a max diameter of ~400 meters, and max depth of 20 meters. We infer that the leading mechanism for the occurrence of hydrothermal explosions is the sudden depressurization of the shallow geothermal reservoirs (250–700 m deep) induced by earthquake-related fracturing along the active NE-SW fault system. A concurrent contribution of deep-seated magmatic fluids cannot be ruled out. This study represents the basis for hazard evaluation in the caldera floor of Nisyros, which is visited by many tourists every year.

Uneven Holocene eruptive frequency of the Cumbre Vieja (La Palma, Canary Islands) volcano: evidence from paleomagnetic dating

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A detailed knowledge of the timing of past eruptions and their eruptive style is pivotal for volcanic hazard assessment. This is even more crucial for inhabited lower slopes of active basaltic volcanoes such as the Cumbre Vieja volcano (La Palma, Canary Islands), where the 2021 Tajogaite eruption caused severe destruction. We paleomagnetically investigated eight La Palma Holocene eruptions which are currently loosely dated either by few K/Ar and ¹⁴C ages or by stratigraphic and archaeological evidence. We carried out paleomagnetic dating by comparing the paleomagnetic directions gathered from 28 sites (300 oriented cores) with updated reference curves of the Paleo-Secular Variation of the geomagnetic field direction. Concerning three eruptions (Malforada–Nambroque, Montaña Quemada, and Fuego–La Fayana), we find paleomagnetic age widows consistent with (and in some case narrower than) available ¹⁴C ages. Moreover, overlapping mean paleomagnetic directions from the Fuego and La Fayana lava flows, along with geologic and geochemical evidence, implies that the two flows were likely issued during the same eruptive event dated at 2000–1727 BC. The improved chronologic framework of the pre-historic volcanic activity at La Palma shows that the past 4 ka were characterized by an early period of low eruptive frequency (three lava flows between 2000 BC and ca. 300 BC), followed by a ca. 1000 yr quiescence, and by a subsequent clustering of nine events during the last 1100 years (about one eruption per century). This work confirms the relevance of paleomagnetism as dating and correlation tool for Holocene eruptions. with an accuracy unlikely to obtain with other radiometric methods.

Eruptive dynamics of a long-lasting, hybrid eruption: the 2021 Tajogaite eruption (La Palma, Spain)

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A first classification of volcanic eruptions typically involves a distinction between effusive and explosive activity. From a risk and emergency management perspective, these two types of eruptive behaviour have distinct implications and pose different challenges. A specific category of eruption activity, known as hybrid, displays effusive and explosive behaviour occurring simultaneously or in very short succession. In long-term records, hybrid eruptions tend to be overlooked due to the challenges of identifying simultaneous activity based only on deposits. To better understand associated mechanisms and processes, recent studies that are well characterised based on both geophysical and direct observations are crucial.

The Tajogaite eruption of Cumbre Vieja volcano of La Palma (Spain) began on 19 September 2021 and lasted for about 86 days. The eruptive activity was characterised by effusive activity from the base of the newly-formed Tajogaite cone and erupted a volume of lava of approx. $1-3 \times 10^8$ m³, covering an area of 12 km² and reaching the sea. Contemporaneously, the summit vents were associated with explosive activity that varied in intensity and style through time and included ash-poor gas puffing, Strombolian, violent Strombolian, and lava fountaining. While the tephra constitutes only about 7–16% of the total erupted volume, the explosive pyroclastic material provides fundamental insights into the dynamics of this hybrid eruption.

In this contribution, we present a multi-parametric characterisation of the Tajogaite tephra sequence with the aim to discuss syn-eruptive changes in eruptive dynamics and in the conduit processes that resulted in such a variability. Integrated within the tephro-stratigraphic framework of previously published research, tephra layers representative of the different eruption phases were characterised in terms of grain-size characteristics (Md(Phi), Sigma(Phi), F1 and F2) through mechanical sieving and bulk clast density. This characterisation identifies patterns that are consistent with the three main units (Lower, Middle and Upper Units) that have been identified by Bonadonna et al. (2022), distinguishing the lapilli-dominated Lower and Upper units from the ash-dominated Middle Unit and highlights an overall increase in clast density along the eruptive sequence. Componentry analysis allowed distinction of four main groups of juvenile glass, whose proportions vary within individual layers and with eruption progression. Further, in-depth morphological and textural data were obtained through SEM imaging of selected juvenile glass shards and show a high variability in key parameters such as solidity, convexity, concavity index and vesicle volume distributions as well as vesicle number density and size, providing insights into the processes that occur in the conduit. In particular, vesiculation and late-stage crystallisation vary along the eruptive sequence, showing that the processes controlling explosive activity changed between the different eruption phases. We also combined the dataset obtained from the detailed study of tephra deposits with published data on mass eruption rates

and geophysical parameters to discuss the dynamics of this eruption in the broader framework of hybrid eruptions.

Characteristics, Morphometry, Facies, and Emplacement Dynamics of the Debris Avalanche Deposits from the Ollagüe Volcano, Central Volcanic Zone of the Andes

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Flank collapses are one of the most prominent destructive and hazardous processes that can occur during the evolution of long-lived volcanoes. These events can drastically change the morphology of the volcano and the landscape of the surrounding area and can modify the eruptive behavior of the volcano following flank collapse. Debris avalanche deposits (DADs) represent the fingerprint of these natural catastrophic phenomena and comprise pieces of the pre-collapse edifice and material incorporated during transport. Thus, the description and interpretation of the DADs facies, structures, and morphologies, together with morphometric features of hummocks, can provide insights into the size, mechanisms, physical characteristics, and internal processes of the volcanic landslide and their interaction with the substrate. This work focuses on the DADs of the Ollagüe volcano, a long-lived and mainly effusive andesitic to dacitic volcano in the Central Volcanic Zone of the Andes. The volcano is developed along a NW-striking extensional fault and is surrounded by widespread salt flats (Carcote and Ollagüe basins). The study provides a detailed characterization through a multidisciplinary approach combining fieldwork and remote sensing morphometric analysis of the different identified DADs of the Ollagüe volcano, constraining the destabilization and triggering factors of the flank collapse and the effect of substrate on the emplacement (run out) of the debris avalanche. We identified three main DADs with the classical hummocky topography and hummocks decreasing in size, volume, and competence with distance. The size-distance relationship of hummocks reveals the magnitude and mobility of the debris avalanche, with a low rate of hummocks size decrease being mainly related to the effusive nature of the volcano, that retards blocks fragmentation and to more surficial collapses. This low rate of size decrease and the large runout (despite their relatively small volumes) of the three identified DADs suggest initial high mobility within the proximal parts (suggested by the absence of hummocks in a proximal belt) and rapid deceleration of the avalanche. The rapid deceleration of the debris avalanches may be directly attributable to the combined effects of topography and substrate's nature during transport and emplacement, with a passage from a shallow paleolake to a dry and non-competent evaporitic substrate (salt flat) in the salt flat area. The two collapses identified in the Carcote Basin were possibly triggered by small and shallow magma intrusions or cryptodomes, favored by a pre-destabilized volcanic edifice product of the reactivation of substrate faults along the volcano. Remote morphology-based assessments of DADs integrated with fieldwork provide further insights to the understanding of the effects of weak ductile substrates in the mechanisms of transport and emplacement of debris avalanches. The study of the DADs from the Ollagüe volcano reveals a complex dynamic interplay between the evolution of the volcano and the landscape, as reflected by fluctuations in the level of the Carcote paleolake.

S02 - Oral Presentation

3D fault geometry of a giant landslide on a volcanic island (Kilauea, Hawaii)

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The Kilauea volcano, together with the Mauna Loa, are the most active and the largest volcanoes on Earth. They also represent a giant landslide zone, with different detachment structures rooted several kilometers below the surface, able to generate large earthquakes and tsunamis. The Kilauea is made of a central caldera, two rift zones, and by two normal fault systems called Koa'e and Hilina Pali. The south flank, defined by the Hilina Pali fault system, is unstable and free to move in the seaward direction accommodating the long-term volcano flank motion. At around 10 km depth, the flank lies above a major gentle north dipping basal detachment, which was the locus of several large earthquakes in the last century. Transient deformations were of up to 8 meters during the M7.7 Kalapana earthquake in 1975. This event was related to a magmatic intrusion and slip on a deep detachment surface inducing transient flank acceleration. The above statements and the rapid deforming south flank suggest that large-scale slumping or landslide failures are likely future events and thus critical to study.

There have been several studies of fault mapping, ground deformation and magma intrusions over time in the Kilauea volcano and Koa'e fault system areas. However, an integrated multi-temporal analysis (decades, centuries) focusing on the Kilauea fault system, the Hilina fault and the offshore landslide area using field observations, remote sensing (e.g., air photos, lidar imagery) and bathymetric data, as well as an identification and detailed mapping of the active fractures and faults is still lacking, despite being key for volcano-tectonic hazard assessment in the area. Here, we built a high-resolution Digital Elevation Model (DEM) of the Hilina Pali fault system using optical images acquired by helicopter survey during our 2023 mission. 3D point cloud and mesh analysis highlight the outcrops geometries and rockfalls located over the Hilina Pali fault system. The integration of onshore morphology analysis with offshore measurements and bathymetric data will possibly validate our results of fault-normal extension and right-lateral strike-slip motion over the western part of Hilina Pali fault system. This will also provide new insight about the geometry and aim to better understand the gravitational and landslide processes that, together with magmatic intrusions along the rift zones, control the evolution of flank instability at Kilauea volcano. Future investigations concerning the link between shallow faults and the basal detachment are required to better define the flank instability geometry of the Kilauea volcano.

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

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Etna is one of the most active volcanoes in the world, with almost continuous eruptive activity from its four summit craters resulting in frequent morphological variation of its upper area. The summit area is frequently site of effusive and explosive activity, but also of local flank collapses of the summit cones and pyroclastic flows with different triggering mechanisms. Such a dynamic environment requires a thorough understanding of its temporal evolution in order to properly assess the state of the volcano over time, and infer further insight into its potential hazard. Voragine (VOR), formerly called the Central Crater, is the oldest and has been depicted on topographic maps since at least 1865; the NE-Crater (NEC) cone was born in 1911; the Bocca Nuova started as a pit crater next to Voragine in 1968, and the SE-Crater (SEC) cone started in 1971. Since 2011, a new cone grew on the SEC eastern lower flank during a series of paroxysmal episodes and it progressively coalesced with the SEC cone. To properly model the temporal changes of the summit area, we exploited archival topographic maps and aerial photogrammetric stereo-pairs. This reconstruction started from the digitising and processing of topographic maps that were produced on 1897, 1932, and 1985. We also processed aerial stereo-images acquired since 1954. From these datasets we extracted Digital Elevation Models (DEMs) with 5-10 m pixel size. We integrated historical data with already available DEMs: the 1998 and 2001, interpolated from vector maps; the 2005, obtained from aerial photogrammetry; and the 2012, 2014 and 2015 derived from helicopter-acquired data. Finally, between 2017 and 2023 we performed UAS (unoccupied aerial systems) surveys to derive high-resolution DEMs and orthomosaics with sub-meter pixel size. This new multi-temporal Digital Elevation Models (DEMs), from ancient topographic maps and aerial photo as well as from recent and current UAS data, have been analysed through the ESRI ArcGIS software to reconstruct the topography and quantify the main morphological changes of Etna summit area. Our modelling increases the knowledge about the evolution and the behaviour of a frequently active volcano, thus enabling to mitigate the associated risks.

Development of a global database of deposit-derived pyroclastic density current occurrences

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The gravitational instability of glowing volcanoclastic deposits, whether it is the collapse of the crater rim or the failure of hot deposits on the flanks of volcanic cones, can give rise to so-called deposit-derived pyroclastic density currents (PDCs). These flows can remobilise volumes of 10^3 to 10^7 m³ and travel several kilometres from the source area. They are deposited at extremely high temperatures, posing a potential threat to nearby communities, scientists and tourists in the vicinity of volcanoes.

Deposit-derived PDCs are much more widespread than originally thought, and two distinct phenomena have been documented: i) those induced by magma thrust; ii) those resulting from the accumulation of hot materials on the slopes of the volcano. In the latter scenario, loose volcanoclastic material can collapse due to factors such as exceeding the angle of friction or other mechanisms such as undercutting or overloading by volcanoclastic or lava flows. Deposit-derived PDCs have been documented at several sites, e.g. Stromboli, Etna and Vesuvius (Italy), Fuego (Guatemala), Fuji (Japan), Ngauruhoe (NZ), Tungurahua (Ecuador). In all these events, glowing avalanches are reported to have formed from the remobilisation of poorly welded volcanoclastic agglomerates.

Here we present a database, currently under construction, focusing on deposit-derived PDCs observed worldwide. The database is designed to collect information on the geographical distribution of occurrences, event dates, collapse mechanisms, remobilised volumes, flow types, deposit characteristics and bibliographic references. This effort is part of a larger project to elucidate the formation mechanisms and potential impacts of deposit-derived PDCs. Such knowledge will help to mitigate short- and long-term risks associated with these flows, by contributing to the interpretation of monitoring data from active volcanoes, and informing appropriate land-use planning in their vicinity.

Preliminary $^{40}\text{Ar}/^{39}\text{Ar}$ ages for Cala delle Giache centre (Pantelleria Island, Italy)

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Pantelleria Island (Sicily Strait, Italy) is a volcanic complex with a subaerial eruptive history spanning 300 kyrs. Variations in depositional facies and lithology indicate significant variability in eruptive styles, ranging from highly explosive ignimbrite-forming eruptions to effusive ones, largely driven by peralkaline magmatism. In this work, we use the $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric method to provide highly accurate eruptive ages, with a focus on an eruptive centre located at Cala delle Giache, in the southeastern sector of Pantelleria. This site is iconic for reconstructing the volcanic history of the island and for enhancing our understanding of eruptive trigger mechanisms.

The Cala delle Giache centre consists of (i) the unique phreatomagmatic deposit recorded on the island (pre-Giache centre), underlying a weathering horizon (paleosol) underneath (ii) a gradually welded deposit (Giache centre). The stratigraphic sequence is crosscut by a dyke, probably feeding lava flows outcropping more to the west.

Pumices from Giache volcanic complex plot in the comenditic trachyte field of the diagram for peralkaline rocks, with a peralkaline index P.I. (mol Na+K/Al) ranging from 1.2 and 1.4. The dominant phenocryst (~ 10 vol. %) is anorthoclase (Or_{33}), with subordinated low sodium clinopyroxene (augite) and iron-rich olivine. Ilmenite and magnetite are present as traces and yield a temperature of 788 °C and $f\text{O}_2$ of -16.4 log [Romano et al., 2022].

Single crystals of anorthoclase were irradiated with fast neutrons at the Oregon State TRIGA Reactor along a flux monitor [Fish Canyon Tuff, 28.305 ± 0.036 Ma; Renne et al., 2010]. Single crystal laser fusion was performed at the Institut des Sciences de la Terre d'Orléans (CNRS-ISTO). Ages are here expressed as Weighted Mean Ages (WMA) with a Mean Square of Weight Deviations (MWSD) remaining within the fiducial interval (uncertainties at 2σ). Monitor calibration is still underway, and data presented are subject to further refinement (but internally calibrated to better than ± 0.5 ka relative variation).

Two similar eruptive ages have been obtained for the pre-Giache eruptive centre, that is 106.3 ± 0.7 ka (MWSD = 1.49) for feldspars from pumices and 104.9 ± 0.9 ka (MWSD = 1.53) for a loose feldspars level collected within the deposit. Giache centre has an eruptive age of 100.7 ± 0.7 ka (MWSD = 1.2), which may exclude the presence of Acqua Formation [$^{40}\text{Ar}/^{39}\text{Ar}$ age of ~ 107 ka; Rotolo et al., 2013] overlying the unit. In addition, the dyke is significantly younger at 95.6 ± 1.9 ka (MWSD = 1.08).

The obtained ages show that the eruptive activity at Cala delle Giache began around 104-107 ka, with a pause between pre-Giache and Giache eruptions consistent with the development of a weathering horizon. The Ar/Ar data place the eruptive activity during Marine Isotopic Stage MIS 5.1-5.3, coinciding with various sea level oscillations that resulted in a general decline of up to 20 meters lower than present levels in the western-central Mediterranean. Hence, sea level oscillations may have contributed to rapid pressure buildup or pressure-release oscillations of the plumbing system, locally and temporally modulating the explosive volcanic activity.

New insights on the submarine morphology and evolution of Pantelleria volcanic complex from marine geology studies

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The submarine flanks of Pantelleria volcano were the subject of recent marine geological surveys acquiring geophysical data (multibeam data integrated by seismic reflections profiles) and seabed sampling. Pantelleria Island is the upper part (about 18%) of a large submarine volcanic edifice, ~36 km long and ~15 km wide, encompassing a surface of approximately 310 km². The volcanic complex is markedly elongated along a NW-SE direction, and its base can be morphologically traced down to a maximum depth of 1300 m on the SE flank, to less than 700 m wd on its NW flank. The morpho-bathymetric analysis of the submarine flanks allowed us to map and characterize the main primary volcanic and erosive-depositional features. In detail, volcanic features include lava flows, volcanic cones and elongated ridges. Lava flows are mainly recognized in shallow-water, while volcanic cones and ridges are mostly concentrated along the steep submarine flanks, especially along the wider SE and NW ones. Their preferential elongation or alignment along the (main) NW-SE and (secondary) SW-NE directions, controlling the evolution of the volcanic edifice, supports a marked volcano-tectonic interaction on their formation.

Erosive-depositional features mainly include small-scale landslide scars, gullies and larger channels. In shallow water (100-200 m of depth), insular shelves (remnants of previous sea-level fluctuations) are characterized by different extension, appearing narrower on the NE and SW submarine flanks, and larger on the NW and SE ones. Moreover, the different depths of the insular shelf edge (considered a marker of paleo sea-levels) around the island have been related to differential vertical deformations that affected Pantelleria volcano during the Late-Quaternary. Overall, the distribution of the mapped features suggests the interplay between volcanic, tectonic and erosive-depositional processes, modulated by sea-level fluctuations, in shaping the volcano, and give hints on its overall spatial and temporal morpho-structural evolution [Casalbore et al., 2024]. Based on the marked morphological differences between the flanks of the volcano, in fact, an overall migration of the volcanic activity from SE to NW over time is inferred, implying a multi-

stage model of growth and emergence of the volcanic edifice, with the last known eruption (1891) recorded in the offshore NW sector [Conte et al., 2014].

Evidence related to the occurrence of eruptive events are also recognized in the submarine area, both as erosive-depositional features on the seabed (probably generated by co-eruptive gravity-driven flows) and tephra layers, sampled in the sedimentary sequence on the northern flank of the Pantelleria Basin, in the framework of the Eurofleets2-funded PANTHER (PANTelleria High-Energy ERuptions from marine studies) project [Romagnoli et al., 2024]. In particular, a coarse-grained (lapilli-size) pumiceous deposit (partially sampled through coring) is considered to represent the near-vent, marine equivalent of the Y-6 tephra layer. The latter is widely found throughout the Central and Eastern Mediterranean and has been interpreted as the co-ignimbrite primary (fallout) deposit of the Green Tuff violent eruption (about 45 ka BP) [Keller et al., 1978; Mahood and Hildreth, 1986; Paterne et al., 1988; Narcisi and Vezzoli, 1999; Margari et al., 2007; Vogel et al., 2010; Sulpizio et al., 2010; Scaillet et al., 2013; Tamburrino et al., 2012; Zanchetta et al., 2018; Rotolo et al., 2021]. The geochemical characterization of pumice and glass shards from the deposit sampled north of Pantelleria Basin, mostly rhyolitic and partly trachytic, supports (and slightly enlarge) the bimodal composition reported in literature for the distal tephra Y-6, highlighting the potential of near-vent primary volcanic deposits in providing additional information on the record of eruptive processes.

Crystallization and eruption age estimations using U-Th disequilibrium dating: Torfajökull volcano, South Iceland

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Improving the chronology of volcanic eruptions is crucial for studying the evolution of any volcanic system, especially if the lateral extent of the outcrops and their lithofacies do not allow for relative stratigraphic distinction between the units. In such cases, there are several geochronological methods at our disposal. A system especially applicable to date young volcanics, erupted in the past ~250-300 ky, is the U-Th disequilibrium method. Mainly used on zircons, this technique allows us to date the crystallization age of minerals and subsequently estimate the age of the eruption. However, the method of calculating the individual crystal ages depends on how the isotopic ratio of the rock or groundmass glass is determined and treated. Likewise, estimating eruption ages is not straightforward and depends on different assumptions. The global isochron and global weighted mean ages are prone to overestimate the eruption ages in cases of extended crystallization over 10s to 100s of thousands of years. The Bayesian approach aims to find the most probable eruption ages based on an assumed prior age distribution between saturation and eruption, which is difficult to determine. When assuming that the eruption ages are best described by the weighted mean of the youngest zircon population, the iterative MSWD approach can be used to identify the different zircon age populations, but such populations are sometimes difficult to distinguish for the younger crystals.

We aim to improve the method of better determining the crystallization and eruption ages of young volcanic units, based on a large dataset of U-Th isotopic ratios in zircons from rhyolitic units of the Torfajökull volcanic system in Iceland. We are using known ages of the youngest units, relative stratigraphic relationships, and timing of the last glacial period as constraints to validate the different approaches. Furthermore, for volcanic units falling short of producing statistically significant zircon populations, we use the U-Th disequilibrium dating method on ilmenite to complement our geochronological study. On the latter, preliminary results suggest that the abundance of U and Th, as well as the type of mineral inclusions, influence how well ilmenite can be dated.

Anatomy of a volcanic vent: new insights into the intra-crateric pyroclastic deposits of the Astroni volcano (Campi Flegrei)

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Spatter and scoria cones, as well as tuff ring and tuff cones, are characteristic products of single or multiple small-volume eruptions ($<1\text{km}^3$) [e.g. Nemeth et al. 2015] that typically exhibit a great variety of depositional features. These volcanic edifices form from the accumulation of erupted products proximal to their vent. In this scenario, the Astroni volcano (Campi Flegrei, Italy) represents the only documented example of well-preserved multistage vent in the most recent epoch of activity (4.8–3.8 ka) of Campi Flegrei caldera, reactivated by seven, relatively short-lived explosive eruptions [Isaia et al. 2004]. It represents a case study as a complex and highly dynamic depositional environment in which a wide spectrum of volcanic processes operated simultaneously or sequentially, not only during the active lifetime of the volcano but also during its periods of quiescence. The volcano and its deposits have been extensively studied and multiple interpretations were reported in the scientific literature [e.g. De Lorenzo and Riva, 1902; Rittmann, 1950; Scherillo, 1954; Rosi and Sbrana, 1987; Di Filippo et al. 1991; Di Vito et al. 1999; Isaia et al. 2004, 2022; Tonarini et al. 2009] with a general reconstruction of the volcanic and magmatic history [Isaia et al. 2004]. Most interpretative models are based on medial to distal outcrops, where the Astroni sequences are more readily observable. Here, we present a sedimentological analysis of ultra-proximal lithofacies combined with grain size, component and petrochemical data for the well-exposed intra-crateric Astroni pyroclastic deposits. Our aim is to reconstruct the architecture of the edifice and investigate the overall processes at play within the crater. We used a very detailed stratigraphic approach to identify several lithostratigraphic units separated by either thin paleosols or irregular to steep, erosive unconformities. The sequences are composed of matrix-supported, massive to diffuse bedded, lithic brecciae and coarse-grained pumice-rich deposits alternating with well-stratified, laterally persistent, fine to coarse ash layers and fine to coarse lapilli deposits. Undulating to cross-bedded, low-angle truncations, laminae and few centimeters thick lenses of pumice clasts are common in the stratified ash layers. Plane-parallel, stratified accretionary lapilli bearing deposits and lithified units are also observed. Laterally impersistent, clast-supported and well-sorted layers of dominant grey lapilli to block, pumice clasts are locally interbedded in the sequences at several stratigraphic heights. Outsized lava and pumice ballistic bombs, up to 40 cm in diameter, are also very common forming deep, mostly symmetric impact sags. The systematic survey, conducted through 10 measured sections only few tens of meters apart, allowed us to study the vertical and lateral facies variations of the different lithostratigraphic units. This investigation revealed a wide range of predominant pyroclastic density currents (PDCs) and minor fallout transport regimes and emplacement mechanisms in the vent setting. They include: ballistic impacts associated with short-lived to sustained, unstable to buoyant eruption column phases and contemporaneous fountaining activity. Unsteady, channelized to unconfined PDCs varying from dilute, turbulent

suspensions with tractional bedload flow boundary zone to high-concentrated fluid-modified granular flows developed. The presence of several unconformities of variable time-duration and nature, suggests that weathering, erosion and/or crater wall collapse events also occurred during the periods of quiescence between the different Astroni eruptions, allowing a complex stratigraphy and intra-crateric history to be reconstructed. Our research provides a very close up view of the extremely complex, multiphase and multiscale phenomena and unpredictable dynamics occurring at a volcanic vent that might be considered in future hazard and risk assessments, especially in calderas with uncertain vent opening locations. The work in progress also emphasizes the importance of considering external, non-eruptive subaerial processes (such as erosion, collapse and remobilization events) that may occur at any time and are highly common at the vent, in terms of potential hazards.

Application of paleomagnetic methods on two variably welded peralkaline fallout deposits from Pantelleria Island (Sicily Strait): inferences on emplacement temperature and welding

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One of the major volcanological issues is to outline the eruptive and depositional mechanisms of explosive eruptions and to constrain the emplacement temperature (Temp) of the associated pyroclastic deposits for the inferences on the thermal evolution, welding and rheomorphism, before cooling to the glass transition temperature (T_g).

Emplacement temperature of pyroclastic deposits, in particular ignimbrites, can be constrained using paleomagnetic methods on lithic clasts entrained during eruptive climax. At Pantelleria island, a paleomagnetic study was carried out on the Green Tuff welded and rheomorphic ignimbrite [Scarani et al., 2023], but there is limited understanding of less explosive inter-ignimbritic eruptions.

Here we provide paleomagnetic data of two variably welded fallout deposits belonging to the old local centres of Cala dell'Altura (pantelleritic) and Cala delle Giache (comenditic), in the attempt to ascertain any possible relationship of welding degree of peralkaline airfalls with the emplacement temperature recorded by lithic clasts.

Thermal demagnetization of lithic clasts does not show evident relationships with welding in the Cala dell'Altura fallout, indicating that unwelded and welded layers were emplaced at the same temperature range between the T_{Curie} of magnetite (580 °C) and T pre-eruptive (700°C for pantelleritic magma, 800 °C for comenditic), thus suggesting poorly efficient cooling (low column height or high deposition rate). On the contrary the Cala delle Giache fallout, characterized by some initial phreatomagmatic episodes, shows an evident bimodality, with lithics in the welded layers emplaced at high temperature (580-800°C) and those in the unwelded layers at lower temperature, pointing out to a more efficient cooling, possibly due to early magma-water interaction and/or lower deposition rate.

Post-depositional magnetic disturbance occurred in proximity of some large (30 cm in length) lithics, deforming very local (cm-scale) geomagnetic field and affecting the magnetic orientation of smaller lithics nearby. Secondarily, we detected post-depositional tilting of few lithics due to sliding along the unconsolidated matrix of the unwelded fallouts.

Tree-ring anomalies in temperate forests of central and southern Mexico associated with large historical volcanic eruptions worldwide: preliminary results.

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Large volcanic eruptions inject huge amounts of sulfur dioxide (SO₂) into the stratosphere, where they are transformed into sulfate aerosols. The sulfate aerosols are then dispersed over long distances by winds, remaining suspended for several months, or even years, causing a short-term cooling effect on the planet. However, the effects of volcanic aerosols on low-latitude temperate forests, and their environmental implications, are not well known. Dendrochronological approach is an excellent tool to identify growth ring anomalies associated with volcanic forcing and reconstruct climatological variability caused by cold and/or dry periods after strong volcanic events. In this work, based on dendrogeomorphological methods and dendrochronological techniques, we present evidence of disturbances in tree-rings from forests in central and southern Mexico related to large historical volcanic eruptions around the world. Series of tree rings from the last ~150 years of *Abies religiosa* Kunth Schltdl. et Cham, *Pinus hartwegii* Lindl., *Pinus pseudostrobus* Lindl., *Pinus rudis* Endl. and *Pinus oocarpa* Shiede were used. We identified abrupt tree ring growth suppressions in 19th, 20th and 21st centuries in both geographic regions associated with possible volcanic signals such as Krakatau (1883), El Chichón (1982), Pinatubo (1991) and Eyjafjallajökull (2010). Interesting to note that the growth suppression occurred between one to three years after the main volcanic event. These results can be a starting point to identify possible effects on the climate in our study areas and thus better understand their socio-environmental implications.

An updated stratigraphy of the Sabatini Volcanic District

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The Sabatini Volcanic District (SVD) experienced multiple eruptive events, producing over 40 km³ (DRE) of K-Alkaline magma. These volcanic products extend over an area of 1500 km², forming a volcanic plateau around Bracciano Lake and bordering the northern part of Rome. The volcanic sequence alternates between effusive and explosive episodes, two of which contributed to the formation of the caldera depression where Bracciano Lake is located. The most recent eruption occurred less than 50 ky in the Sacrofano area. Although classified as an extinct volcano, the SVD exhibits high heat flow values comparable to other active volcanic fields. Therefore, a better characterization of the volcanic sequence is necessary. This work, part of the CARG project (sheet 364, Bracciano), aims to present a new, revised stratigraphy of the Sabatini District volcanic sequence, supported by fieldwork, geochemistry, and isotopic data.

Precursory phreatic activity of the 1888-90 eruption of La Fossa of Vulcano (Eolian Islands, Italy)

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Explosive phreatic eruptions result from the sudden decompression of pressurized shallow hydrothermal aquifers hosted in a volcanic system. Pressurization is mainly related to transfer of magmatic heat and fluids to the hydrothermal systems, in some cases associated with magma ascent toward the surface. Extrusion of magma plugs or domes, typical of vulcanian eruptions, has also been commonly observed in association with phreatic activity, suggesting that the progressive degassing of slowly ascending, viscous magma represent an important (although not strictly necessary) condition for an efficient fluid and heat transfer to the surface anticipating magma arrival.

The 1888-90 eruption of La Fossa of Vulcano (Eolian Islands, Italy) is the prototype of vulcanian activity during which the slow, continuous growth of a rhyolitic magma plug in the conduit established the conditions for frequent, variably energetic, vulcanian explosions. Observations and studies of this activity were accurately reported in two volumes and several memoirs by Profs. G. Mercalli., O. Silvestri and O. De Fiore, where these authors also collected the direct observations of other eyewitnesses of the eruption. The authors well describe the activity and the erupted products which characterized the years immediately before the 1888-90 eruption, evidencing several crises, starting from 1873, formed by repeated small explosions dominated by vapor and ballistics emission concentrated in periods of days to weeks (1873, 1876, 1878-79, 1886). All these products, as well as those erupted during the first three days of activity of the 1888-90 eruption are clearly described as very similar one to the other and lacking a clear magmatic component.

In the framework of the PRIN 2022 “Heated” project, we performed a detailed stratigraphic study of the products immediately preceding the 1888-90 sequence, recognizing a major deposit of a clearly phreatic eruption, mainly dispersed along the northwestern slopes of the cone, which we attribute to the 1873 crisis. Other distinct beds rich in hydrothermally altered material have been also recognized and sampled below the 1888-90 deposits along the western and southern slopes of the La Fossa cone, as well as in the basal deposits of the 1888-90 eruption. The sedimentological features, grain size, and componentry of the different beds allows to highlight the characteristics of the hydrothermal system and the role of ascending magma at different times, up to the definitive onset of magmatic activity.

DTMs using drone-based LiDAR for morpho-structural analysis of active calderas: the case of Ischia Island, Italy

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Light Detection and Ranging (LiDAR) technology has been a tool for collecting thousands of georeferenced geographic positioning points per second to produce high resolution Digital Elevation Models (DEMs). During the last couple of years, LiDAR sensors transported by drones have emerged as an innovative and useful tool for active tectonic studies as they offered a very high resolution topographic data [e. g. Resop et al., 2019; Arora et al., 2022; Finley et al., 2022]. A significant advantage of the LiDAR systems is the capacity of the laser beam to penetrate densely vegetated areas and accurately measure distances to the ground beneath [Shan et al., 2018], whereas, for example, with the photogrammetry techniques, the vegetation is deleted by estimating the height, potentially impacting the accuracy of the resulting topography [Baltsavias et al., 1999]

The main objective of our study is to propose a reproducible methodology for deriving DEMs from drone-based LiDAR with the aim to assess the applicability of this tool in enhancing the geomorpho-structural analysis by extracting landform features from very high-resolution topographic data. This is help full in analysing ground deformation and ground ruptures [Fleming et al, 2022; Valkanou, et al. 2021] caused by volcano-tectonic structures with rapid fault slip rates and high rates of Holocene deformation (e.g., Mt. Etna, Italy [Barreca et al., 2018], Campi Flegrei, Italy [Vitale et al., 2014]; Los Humeros Caldera, Mexico [Norini et al., 2021; Norini et al., 2019]; Galeras Volcano, Colombia [Tibaldi et al., 2000].

We tested the method in the volcanic Ischia Island where a moderate, (Md=4.0 and I=VII ESI scale [Nappi et al., 2018, Nappi et al., 2021] shallow earthquake (1.5 kmdepth) hit the Casamicciola Terme on the 21 August 2017, causing severe damage, two casualties and many coseismic surface ruptures.

We assessed the quality of our acquired DTM by comparing it with existing elevation datasets for the same area. We evidenced the advantages and limitations of each DTM product in relation to our results, particularly applying to fault mapping. We analysed derivative DTM products for identified the fault scarps within the Casamicciola Holocene Graben and mapped its structural geometry in detail [Silva Fragoso et al., 2024]. The analysis of both linear and areal geomorphic features allowed us to identify the primary factors shaping the current morphological arrangement of the Casamicciola Holocene Graben area. Our detailed map depicts a nested graben formed by two main structures (Maio and Sentinella faults) and minor internal faults (Purgatorio and Nizzola faults). High-resolution DEMs acquired using drone-based LiDAR facilitate detailed studies of geomorphology and fault activity. A similar approach can be applied in regions where the evidence of rapid deformation rates is challenging due to thick vegetation and difficult access areas.

An updated catalogue of the past 10 ka eruptions at Ischia (Italy), based on stratigraphical, archaeological and geochronological data

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The completeness of the catalogue of occurred eruptions, the reliability of the reconstruction of stratigraphic relationships among the recognized units, and the precision of the age determination of each eruption event, are of fundamental importance in the assessment of volcanic hazard.

In order to perform this assessment at Ischia, we have taken into consideration only the volcanic history subsequent to the last significant change in the behaviour of the plumbing magmatic system. According to the most recent researches, such a change occurred during the 8 ka long quiescence preceding the outburst of the last period of activity, at about 10 ka. Starting from 10 ka repose times alternated with very intense volcanic activity, likely resulting from discontinuous refilling of a shallow magmatic system by poorly evolved magma batches arising from depth.

The catalogue of eruptions and related Lithostratigraphic Units of the past 10 ka has been revised through a detailed comparative analysis among all published stratigraphical and geochronological data and new data from field surveys. In order to minimize the uncertainty related to the age of some units, for which absolute determinations are lacking or the error was too large, some new ⁴⁰Ar/³⁹Ar dates were commissioned and performed at the Berkeley Geochronology Center (California, U.S.A.) and new palaeomagnetic dating has been carried out at the INGV paleomagnetic laboratory, Roma.

The revised catalogue includes currently 50 volcanic eruptions, occurred in the past 10 ka. On the basis of this new revision, it was possible to identify three clusters of events: the first one, between 13-10 ka and 8.5 ka, includes four effusive eruptions; the second one, between 6.6 ka and 4.3 ka, includes ten effusive and explosive (both magmatic and phreatomagmatic) events; the third one, between 3.0 and 1302 CE, includes 36 effusive and explosive (both magmatic and phreatomagmatic) events.

Hydromagmatism at Stromboli volcano revealed by ash morphology in the Scari Formation (PaleoStromboli III, 41-34 kyrs)

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Stromboli is one of the most known volcanoes, famous for its persistent low-to-mid energetic eruptive activity, giving place to alternating emission of tephra and lava flows mainly from its summit area. However, if the attention is moved to its ancient activity, some more energetic and anomalous events are recorded. For this reason, it becomes of paramount interest the use of a multi-disciplinary approach, based on the investigation of stratigraphy, eruptive dynamics, and petrological features, with the purpose of defining the possible eruptive scenarios and volcanic hazard.

Here we present some preliminary results about the pyroclastic deposits of the Scari Formation [Francalanci et al., 2013], located in the northeastern part of Stromboli. This consists of a basal, poorly sorted, lithic-rich tuff-breccia followed upwards by a succession of thin to medium beds of coherent, planar to cross stratified lapilli-tuffs with accretionary lapilli and some impact sags as a result of multiple dilute pyroclastic density currents (PDCs) associated with ballistic fallout. This unit crops out at the top of the upper portion of the Paleostromboli III epoch products, dated at between 41 and 34 kyrs, which is truncated by the major SE-dipping lateral collapse of Le Schiccirole-Rina Grande [sc2 in Francalanci et al., 2013], developed between 34 and 26 kyrs. This study particularly investigates the role of hydromagmatism in the eruptive dynamics of the Scari Formation, which was suggested by the lithofacies analysis, through a combination of petrographic microscopy, electron microprobe analysis, and Scanning Electron Microscope SEM observations on the morphology of ash particles (between 250 and 63 μm) from selected samples along the whole succession. Most of the fragments show key features revealing the interaction between magma and external water, like adhering particles on the surface, mudcrack-like texture of altered glass skin, blocky shapes and numerous of them have chemical pitting on the surface and step-like cleavage. Moreover, preliminary petrographic results highlight the presence of not common (at least for Stromboli) hydrous phases, such as amphibole, in equilibrium with the surrounding melt.

Based on these features and the field evidence of coherent ash-rich deposits with accretionary lapilli, we outline a clear hydromagmatic signature for the Scari Formation, which is fairly atypical with respect to the dominant Strombolian/effusive eruptive behaviour of Stromboli during most of its eruptive history. Moreover, this unit can be related to an eccentric eruptive source located to the SW and not far from the outcrop area, as revealed by the occurrence of proximal lithic-rich deposits at the base, thickness variations and impact sags. We thus suggest that the Scari hydromagmatic eruption is linked with the major lateral collapse of Le Schiccirole-Rina Grande (34-26 kyrs), which is still well exposed to the SW of the outcrop site, by assuming that this collapse have induced unloading of the magmatic and hydrothermal system and

enabled magma-water interaction and explosive decompression of a (shallow) magma reservoir. Further studies will be aimed to better understand and constrain structural and magmatic conditions during the Scari activity. A similar collapse-eruption link have been proposed in literature [Lucchi et al., 2019] to explain the occurrence of different pyroclastic successions throughout the Holocene volcanic succession of Neostromboli, thus highlighting a previously underestimated source of volcanic hazard at Stromboli.

A Messinian tephra layer in the marine deposits of the Squillace area (CZ, eastern Calabria): a preliminary study

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Inside the Messinian deposits in central Calabrian Arc, more specifically near the town of Squillace, located in the eastern portion of the Catanzaro Trough, a tephra level, was found, little or no documented in literature. This volcanic ash deposit has been observed exclusively in the above area: it is not present either in the Crotone and Rossano Basins or in other areas of the Catanzaro Trough. Stratigraphically, it is intercalated within an alternation of decimetric layers of clays and sands. The volcanoclastic level is about 20 cm thick, well sorted and is mainly made up of volcanic fragments, with a subordinate non-volcanic fraction. Microscopic observation shows that the volcanic fraction, is mainly represented by glass fragments occurring both as shards and as small vesiculated pumices. Preliminary microanalyses of the glass fragments showed that their composition is rhyolitic, with SiO₂ between 74.95 and 79.32 wt.%, and total alkalis between 3% and 8 wt.%. The shards have generally a cuspidate or platy shape, while pumices are shards. The volcanic fraction also includes crystalline phases represented by plagioclases, orthopyroxenes and clinopyroxenes, the latter in a subordinate quantity compared to the seconds, both having an elongated prismatic shape. Plagioclase ranges in composition from Andesine to Bytownite, and sometimes shows a slight normal zoning. They occur as geminated individuals of the order of millimeter size and as tabular euhedral crystals. Most of the crystals observed in thin section have rounded edges, indicating that the single particles have suffered reciprocal impacts given by the transport within a medium. Along with this, the presence of a sedimentary component, mainly consisting of lithic fragments, is also an indication of re-sedimentation. As a whole, therefore, the layer represents the product of an explosive eruption transported and deposited in the marine environment.

Volcanoclastic levels intercalated in Messinian successions, of similar composition and comparable age (about 5.5 Ma), have been identified and analysed in the northern Apennines by several authors [Trua et al., 2010; Potere et al., 2023] and have been attributed either to a calcaline magmatism related to the early stages of the opening of the Tyrrhenian Sea or to highly explosive eruptions that occurred in the Carpathian volcanic district. However, similar levels have never been found in southern Italy. Therefore, if further analyses will confirm a correlation between the Squillace and the Apennines tephra levels, they would represent an occurrence of capital importance to understand the origin and distribution of the products of what seems to be one a very violent eruption in the Mediterranean area and of which few traces remain.

Paleomagnetic correlation and dating of Montaña Goteras and La Cucaracha volcanic units from Cumbre Vieja (La Palma, Canary Islands) volcano

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The Montaña Goteras and La Cucaracha scoria cones (from Cumbre Vieja volcano, La Palma, Canary Islands) were paleomagnetically investigated at two sites (30 oriented cores). The question of whether the two volcanoes were produced by a single phreato-magmatic eruption or by two distinct events is still debated. We found that the mean paleomagnetic directions of the two scoria cones are similar, proving, along with petrographic/geochemical evidence, that they belong to the same eruption. Moreover, our paleomagnetic age (AD 967–1068) is in fully agreement with the ¹⁴C age previously obtained from human bones embedded into a spatter block discovered, not in situ, within the La Cucaracha archaeological site. This datum confirms that the spatter was emitted during the Montaña Goteras–La Cucaracha eruption, providing additional elements which enhance the comprehension of the relationships between the Cumbre Vieja eruptive activity and La Palma pre-historic human settlements.

The Solfatara eruption of Campi Flegrei (Italy): phreatic to phreatomagmatic dynamics at active calderas through deposits and products characterization

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Active hydrothermal systems are common in many caldera volcanoes worldwide. The interaction between magma and/or magmatic fluids with the hydrothermal system adds further complexities to the types of eruption scenarios. In these volcanic settings, phreatic and hydrothermal explosions, often associated with none to limited precursory signals, can occur as single event and/or precede purely magmatic to phreatomagmatic activity. This type of eruption dynamics is particularly crucial during post-caldera volcanism, which is typically characterized by frequent, small-to-moderate eruptions (VEI 1 to 4). These eruptions, although smaller than the caldera-forming events, can potentially impact the communities living in and around the caldera. Understanding the dynamics of past eruptive events, the interactions among magmatic and hydrothermal systems, and the potential future scenarios of such smaller eruptions is pivotal to volcanic hazard assessment.

The 4.3 ka Solfatara eruption of Campi Flegrei (Italy) represents an excellent case study to better understand phreatic to phreatomagmatic eruption dynamics. In this study, we present results from the stratigraphic analysis of the deposits emplaced during the Solfatara eruption and an in-depth characterization of the textural and chemical features of the erupted products. The combined findings of this study provide new insights into the eruptive and emplacement mechanisms, and the origins of the erupted materials.

The results of the field survey show that the Solfatara deposit can be subdivided into two main stratigraphic units representing two main phases of the eruption. Unit 1 comprises predominantly massive to plane-parallel ash beds, typically showing signs of hydrothermal alteration. Furthermore, within the proximal area, Unit 1 is characterized by a few cm thick basal cohesive coarse ash layer containing many leaf imprints. Conversely, Unit 2 is characterized by the alternation of fine and coarse ash beds, massive to cross-stratified, with pumice-bearing, juvenile lapilli layers. Additionally, Unit 2 contains common accretionary lapilli clasts. Unit 1 is thinner compared to Unit 2 in the mid-proximal area with Units 1 and 2 being about 2 and 4 m thick, respectively, at a key section located 500 m from the Solfatara crater. Outcrops within 700 m from the crater include ballistic blocks mainly composed by hydrothermally altered clasts, with the larger blocks measured in Unit 2. Notably, the contact between the two units consists of a breccia deposit in proximal sites. The Solfatara ash deposit extends mainly to the NNE up to about 10 km from the crater. Pyroclastic density currents (PDCs) deposits are confined around the volcano and a lobe is observed to the S, where the deposit thins rapidly towards the sea. The total volume of the deposits, comprising both Unit 1 and Unit 2, was estimated at 0.06 km³.

Juvenile material cannot be unambiguously distinguished in Unit 1 where the erupted products are commonly altered. However, componentry and textural analysis indicate the presence of 10–20 wt.% of dense to moderately vesicular clasts that could be derived from the magma involved

in the Solfatara eruption. In Unit 2, juvenile material is more clearly identifiable and varies from 30 to >50 wt.%, consisting of pumice clasts of trachytic composition.

Overall, field characteristics, grain-size, and textural analyses suggest that Unit 1 was emplaced during explosions producing predominantly small-volume PDCs, with dispersal typically limited to proximal areas. This opening phase was likely phreatic. An explosion breccia-like event characterized the second phase of the eruption during which PDCs and low-level eruptive columns producing tephra fallout resulted in the emplacement of stratified, pumice-bearing deposits, which laid down the deposit sequence of Unit 2. This eruption phase was characterized by a clear involvement of magma from depth.

Spatial distribution and morphometric analysis of the monogenetic edifices of Etna volcano

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Mount Etna volcano is characterized by intense explosive and effusive activity in its summit craters but hundreds of monogenetic cones are also spread across all over its flanks and the most of them are scoria cones. These cones were formed during strombolian lateral eruptions mainly from ballistically-ejected pyroclastic fragments build up and lava flows. The eruptive dynamics, fracture length, and explosivity index control their growth and morphology. In this work, more than 200 cones, distributed at different altitudes between 500 and 3000 meters a.s.l., have been identified and analysed. Not all these landforms have a well-formed edifice: they are often characterized by complex morphologies and sometimes are not easily recognizable because partially or totally buried from latest volcanic products and lava flows.

The spatial distribution of the flank cones is often constrained by the orientation of the tectonic structures and the cones appear clustered, showing preferential alignments (NE, NNW, N). Even if several investigations in the last years have been performed on Etnean cones, the literature is lacking of a complete and robust morphometric analysis, and a detailed map of all cones does not exist. The aim of this work is to realize a mapping of all Etnean scoria cones, to investigate their spatial and volumetric distribution, to analyse morphometric parameters and their relationships. The proposed methodology consists of a detailed morphologic analysis of the different shapes edifices and their spatial distribution using GIS technique. In addition, an automated analysis accurately obtains all required morphometric parameters.

Most of cones are located at low to intermediate altitudes, especially in the southern and western sectors of the volcano, following a NW-SE trend. These zones are also the most densely populated areas of the volcano. In fact, the knowledge of location, morphometric characteristics, growth evolution, spatial distribution and classification of cones and their morphologies associated, are essential in order to estimate the volcanological hazards and risks.

Moreover, a careful morphometric and morphological analysis of some cones studied could lead to effective actions for the monitoring of possible instability of cones in anthropic areas. Considering that the most of cones are located in the low-intermediate altitudes, a study of these volcanic structures and the realization of a specific map will be useful for a proper planning of the territory.

S03 - OBSERVATION AND MODELLING OF THE ATMOSPHERIC DISPERSION AND FALLOUT OF VOLCANIC PRODUCTS

Conveners:

Fabio Dioguardi, Federica Pardini, Simona Scollo, Matteo Cerminara

Combining visible- and infrared-wavelength observations with numerical modelling to describe Vulcanian eruption plumes at Sabancaya, Peru

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Sabancaya volcano (Peru), is a stratovolcano in the Central Volcanic Zone of the Andes. Since November 2016, it has been in constant activity, marked by daily multiple Vulcanian explosions. In this contribution, we first characterise the plumes generated by the explosions using visible- and infrared-wavelength imagery, describing plume morphologies and quantifying rise rates. Secondly, we use a numerical model to invert our observations for eruptive source conditions, including the initial temperature, gas mass fraction and bulk density, as well as the air entrainment coefficient. Our results show that two main types of plumes occur at Sabancaya. Class A plumes are characterised by an amorphous head containing multiple vortices which may combine to form a vortex ring. These plumes have high initial velocities (>10 m/s) which monotonically decrease as the plume rises. Conversely, class B plumes have narrow, conical morphologies and lack large vortical structures in the head. They have smaller initial velocities (5-10 m/s) and, after an initially slow rise, undergo a short acceleration in rise velocity before slowing down again. From our numerical inversions, we find that class A plumes have entrainment coefficients between 0.03-0.11, whilst corresponding values for class B plumes are ~ 0.05 . Based on our results, we characterise class A plumes as starting plumes or rooted thermals, whilst class B plumes more closely resemble short-lived and unsteady jets. This work provides insight into the dynamics of transient plumes and highlights the need for better models to describe their dynamics.

Fine tuning eruption source parameters to improve ash dispersion simulations: an example of Eyjafjallajökull 2010

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Numerical simulations of the atmospheric dispersion of volcanic ash are routinely used for operational purposes and hazard quantification studies. To run these simulations, it is necessary to accurately model the emission of ash in the atmosphere, which in the case of explosive volcanic eruptions often occurs via volcanic plumes. Particularly for the operational applications, fast and reliable plume simulation tools are necessary, which is why several simplified plume models have been developed over the last few decades. These models are generally designed to link the top plume height (H) to the mass flow rate of ash, also known in volcanology as Mass Eruption Rate (MER), via a single equation that often includes parametrizations of some of the key physical processes characterizing a volcanic plume. For atmospheric dispersion applications, these models are used to estimate MER as a function of H, since H is the parameter that can be measured during an eruption via various monitoring techniques. Some of these models take into account the effect of wind, which: 1) enhances the entrainment of external air into the plume, which, by decreasing the bulk density of the plume, contributes to enhancing its buoyancy; 2) bends the plume, hence limiting its ascent to a height lower than the theoretical H it would reach without the wind at the same MER. The wind affected plume models take the former process by means of an entrainment coefficient, whose value is still a matter of debate in the community, yet significantly affects the MER estimates. Concerning the distortion effect, it has been often suggested that in case of bent-over plumes it is better to correct H by decreasing it by subtracting the plume radius, if available.

Recently, by comparing observations with measured data and using REFIR, a tool that allows obtaining time series of MER by using a combination of simplified plume models, we suggested a new estimate of the wind entrainment coefficient and a new H centreline correction for the Eyjafjallajökull 2010 eruption. In this presentation we introduce the results of these corrections and their application to atmospheric dispersion simulations carried out by using the simulation tool FALL3D. Specifically, we reproduced the volcanic ash cloud and compared the eruption source parameters obtained with REFIR using the originally suggested parameters for the wind-affected plume models with those obtained with the new parameters. We show how the simulation outputs, in particular the extent of the volcanic ash cloud and the ash concentration, are significantly affected by the chosen parametrization. Finally, by comparing simulations outputs with actual satellite retrievals of the ash cloud, we found that the corrected eruption source parameters provide a significantly better agreement between simulated and observed ash mass loadings.

In-situ volcanic ash sampling and aerosol-gas analysis based on UAS-embedded technologies: insights into airborne ash aggregation

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Volcanic degassing and explosive eruptions inject significant amounts of gas and ash in the atmosphere, impacting the local environment and atmospheric dynamics on regional to global scales. While ground- and satellite-based measurements are keys to the description of explosive volcanism and to the assessment of associated hazards, they cannot provide direct observation of clouds and atmospheric settings. This study presents an innovative approach using an unmanned aircraft system (UAS) and embedded instruments for (i) airborne ash sampling and (ii) measurements of aerosol and gas concentrations. Commercial instruments (DJI Matrice 30 UAS, Alphasense N3 Optical Particle Counter, Soarability Sniffer4D Mini2 multigas) were combined with dedicated home-made ash samplers to optimize the analysis of volcanic plumes and clouds. We use the example of Sakurajima volcano (Japan), known for its frequent explosive and degassing activity, to show how this approach enables in-situ and high-resolution sample and data collection within challenging environments. In parallel, plumes were characterized thanks to high-resolution videos taken from distant sites. Ash fallout samples and atmospheric parameters were collected in more proximal locations directly below the clouds, combining ground sampling and drone-embedded instruments. This multi-disciplinary approach first reveals that ash aggregation occurs even in low-intensity events. Characteristics between the samples collected at ground level and the ones collected 500 m above, evidence that ash aggregation is also developing during the ash sedimentation. We interpret this dynamic process as the result of the formation of discrete areas of highly concentrated volcanic aerosols and gas (i.e., PM₁, PM_{2.5}, PM₁₀, and SO₂) within some sedimentation streaks.

Measuring the electrical charge and the settling velocity of volcanic ash particles

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The electrical charge carried by volcanic ash particles is known to play a crucial role in the formation of aggregates, which modulate the atmospheric transport and deposition rate of volcanic ash. However, direct field measurements of these charges remain rare, and more investigations are required to better comprehend both charge generation and aggregation mechanisms. This study aimed at building and testing low-cost portable devices to quantify the charge of individual volcanic ash particles and aggregates using a Through-Type Faraday Cage (TTFC) connected to a charge amplifier circuit capable of detecting the very small voltages induced by charged particles entering the TTFC.

Laboratory tests were first performed, using different quantities and types of particles, in order to validate measurements against an independent analytical method. Beside the charge, results revealed that the device can be used to obtain the particle settling velocity, based on the duration of the voltage signal. An autonomous version of the device was then tested during a field campaign conducted in November 2023 at Sakurajima volcano (Japan). Charges between 0.1 and 100 pC were detected, associated with velocities ranging from 0.5 to 5 m s⁻¹. It demonstrates the potential of this device for continuous charge and velocity measurements of volcanic ash particles over durations of several hours.

Volcanic cloud monitoring by thermal-infrared and micro-millimetre waves radiometry

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Volcanic clouds represent one of the most dangerous natural hazard during volcanic explosive activities. During these events, a huge amount of volcanic particles, named tephra, are ejected into the atmosphere where remain suspended even for long time. The residence time increases with the decrease of the particle size. Volcanic particles represent a natural threat for humans, and tracking the dispersal of the volcanic cloud is essential to mitigate the associated hazard. Low Earth Orbit (LEO) satellites are a fundamental asset to monitor volcanoes, in particular for those where the ground-based monitoring sector is not implemented. LEO satellites carry different payloads, included thermal-infrared (TIR) and Micro (MW) - Millimetre Waves (MMW) passive radiometers. The acquisition delay between the two sensors is about 1 minute. Satellite TIR radiometry represents the classic approach to study the dispersal of fine ashes due to the presence of two channels sensitive to ash (8-11 μm) and water/ice (12-14 μm) particles. In presence of bigger particles, such as coarse ashes and lapilli, the TIR signal may saturate while the MW-MMW does not.

In this work we couple the two spectral signatures to study different explosive eruptions, with a Volcanic Explosive Index (VEI) = 3, in terms of volcanic cloud height and instantaneous total mass (ITM) retrieval. For the height retrieval we use different meteorological information, as the temperature gradient and wind intensities and directions. For the ITM retrieval, we use our radiative transfer model algorithm, that is based on the inversion of the forward model to simulate the Brightness Temperature (BT) detected by a passive radiometer. It is implemented under the simplified assumption of considering the atmosphere as a single layer to solve the radiative transfer differential equation.

In conclusion, this work shows how the combined use of the TIR and MW-MMW observations provide a more accurate characterization of the volcanic cloud, in particular during the first hours of the eruptive event.

Evaluating the Performance of Volcanic Ash Dispersion Models Using Remote Sensing and in-situ instruments from Mount Etna Eruptions

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The injection of volcanic ash into the atmosphere during an explosive eruption significantly impacts air traffic by causing severe damage to airplanes, especially to their engines, compelling air traffic controllers to redirect or cancel flights. Additionally, the dispersal of tephra material in the atmosphere results in its fallout to the ground, affecting areas both near the erupting volcano (with coarser particles) and far away (with finer particles), potentially disrupting ground traffic and general mobility in cities.

Accurate forecasting of volcanic ash dispersion plays a crucial role in hazard management, providing critical lead time for institutions responsible for public safety. Numerical models are employed for such predictions, and their accuracy depends on the quality of the initialization parameters. Equally important is validating these predictions through feedback from the synergy between remote sensing and in-situ instruments strategically placed around the affected areas. This work evaluated the performance of a numerical prediction model for volcanic ash dispersion by collecting and analysing data from remote sensing and in situ instruments.

The numerical model used for prediction in this study is the WRF-Chem, which will be assessed for its predictive accuracy and reliability based on the data collected from these instruments. WRF-Chem is defined as a fully coupled “on line” chemistry model. This means the air quality component of the model is fully consistent with the meteorological component. When compared with the other models used by the scientific community, the WRF-Chem is the only one in which both components use the same transport scheme, the same horizontal and vertical grid size, and the same physics schemes for sub-grid scale transport. Moreover, because the components use the same time-step, no temporal interpolation is necessary. All these features make the model unique, very simple to use and inexpensive in terms of computing resource. In this work, the simulation of the eruption has been performed using a high-resolution grid size of 3000 and 1000 meters. The dimension of nested domain is 100 x 100 and it is centred on the vent of Etna volcano. To initialize the model a set of ECMWF GRIB Data was used.

For two recent eruptions of Mount Etna, we used data coming from i) automated lidar ceilometers (ALC) with depolarization capability installed around the Mount Etna area, managed by the Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania (INGV-OE) and the Istituto di Scienze dell'Atmosfera e del Clima (CNR-ISAC), which are part of the Automated Lidar-Ceilometer network (ALICEnet), ii) an optical-disdrometer located in Nicolosi, a town near Mount Etna, operated by INGV-OE and CNR-ISAC, and integrated into the disdrometric network managed by Gruppo Italiano Disdrometria (GID), to validate the results of the chosen numerical model and enhance the predictions of the volcanic ashes dispersal and air-space contamination.

The inland reconstruction to explain the complex dispersion of the Neapolitan Yellow Tuff eruption, Campi Flegrei, Italy

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Large explosive eruptions are among the most extreme geological events that can occur in our planet, although infrequent, and their eruptive dynamics is mostly reconstructed by examining the corresponding pyroclastic deposits. The Neapolitan Yellow Tuff (NYT) is well known as latest large eruption of the Campi Flegrei Caldera, Italy (14.0 ± 0.2 ka), and its deposits are mostly composed by pyroclastic density currents (PDCs) and a minor fallout component, with distal ash layers found in marine cores in the Adriatic Sea.

Our stratigraphic reconstruction divided the eruption in two members (Lower and Upper) and subdivided it in seven eruptive units. Despite the homogeneous appearance of the eruption, key parameters made possible the reconstruction, such as: angular unconformities, variation in the grain size matrix of the PDCs, correlation of the fallout considering the grain size distribution and their component variations and the chemical glass composition through the stratigraphy.

The NYT eruption showed pulsatory long-lasting eruptions (vulcanian style), with unstable fallout that reached 30 km height and dispersive in variable directions. This deposit represent 1 km^3 , which correspond with the 5% of the total volume of the eruption.

Thanks to the unique variation of the components and the occurrence from one to four magma clusters compositions going upwards in the stratigraphical sequence, three main axes of dispersion (D1, D2 and D3) of the distal deposits could be defined. D1 shows two magma cluster composition (Magma A and B) and is dispersed to the NE covering an area of ($\sim 6,000 \text{ km}^2$). D2, the largest dispersion, is composed by the Magma C cluster composition accompanied with the two previous magma cluster, which covered $>200,000 \text{ km}^2$. D3 is mainly spreaded to the NE to E in an area of $\sim 150,000 \text{ km}^2$, with the chemical composition of the four magma clusters.

In this presentation, we reproduced using the inverse model, the eruptive source parameter of every dispersion axes and compared them with the empirical model obtained from the isopachs and isopleths data. The modelling showed robust similarities with the empirical model and the single fallout used to simulate the dispersions. However, we are not able to reproduce all the area covered by the NYT, which is probable due to the role of the coignimbrite dispersion, formed by the large volume of the PDCs, which corresponds with the 95 % of the total volume (24 km^3).

This research shows how a detailed stratigraphical reconstruction can give insight of the dispersion of the distal deposits and thus understanding the complete history of a determinate eruption.

Probabilistic Volcanic Hazard Assessment for tephra fallout from Etna summit eruptions

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Between 1986 and 2022 Etna has produced about 260 lava fountains, also known as paroxysms, which usually occur clustered in time. Each of these paroxysms generated a tephra plume that was drifted by the winds and deposited on the surroundings of the volcanic flanks, sometimes impacting local traffic and requiring clean-up measures on roofs and roads.

In this study we have evaluated the probabilistic volcanic hazard for the tephra accumulated at the ground due to this summit activity. These hazard evaluations are necessary for quantitative risk assessment and to plan risk and multi-risk mitigation actions.

In order to evaluate the probabilistic hazard, we first updated the existing catalogue of paroxysms (in terms of date and time of the event, top of the column height and duration of the tephra emission), adding new data from the 2020-2022 cluster and including, where possible, a quantification of the eruption source parameters (ESPs) retrieved by remote sensing systems, either from the X-band weather radar located in Fontanarossa airport, or by analysing thermal and visible calibrated cameras and SEVIRI images. In particular, with the radar and/or cameras, we tried to constrain the Mass Eruption Rate and the effective duration of the tephra-emission phase, which are crucial to correctly evaluate the tephra mass erupted in the paroxysm.

On the one hand, the updated catalogue allowed defining suitable probability density functions (pdfs) for the paroxysms' ESPs. On the other hand, it allowed us to statistically model the temporal occurrence of Etna paroxysms.

Then, by means of the temporal model, we generated 8000 synthetic catalogues of paroxysm onset times in the next 25 years (2024 to 2048), that mimic the tendency of Etna real paroxysms to occur in clusters.

Tephra fallout from each synthetic paroxysm was then simulated with TEPHRA2 model. To run the model, we associated each synthetic paroxysm to a set of ESP values sampled from their pdfs. We also associated a wind field retrieved from the ERA5 dataset over the period 2007-2019. Since the years of occurrence of the synthetic paroxysms are in the range of 2024-2048, we associated each synthetic paroxysm with a wind field stored in ERA5 for the same month and day, and (approximately) hour, but for a year in the range 2007-2019.

Finally, we post-processed the TEPHRA2 simulations, analysing the runs relative to each synthetic catalogue separately, in order to have statistics for the next 25 years of paroxysms. This allowed assessing tephra fallout hazard from Etna summit eruptions during (i) a paroxysm, (ii) a cluster of paroxysms, and (iii) within a given exposure time window of 1, 3 and 5 years.

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Characterization of volcanic ash from the Campanian Ignimbrite super-eruption: new insights into dispersion mechanisms and health hazard

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Volcanic ash from large explosive eruptions is extremely impactful for both the environment and humans due to the wide areas that can be affected [Blong, 1996]. Indeed, the dispersion and deposition of volcanic ash, especially when wide areas are involved such as in the case of super-eruptions, can affect global-scale climate, ecosystems, and atmospheric processes [Jones et al., 2007; Langmann, 2014; Mather et al., 2003]. Volcanic ash can also impact aviation infrastructures [Prata and Rose, 2015] and represents a source of water contamination [Stewart et al., 2006] and a potential health hazard by inhalation [Horwell and Baxter, 2006]. The effects of volcanic ash can persist for decades consequently to their remobilization in the environment by wind or anthropogenic activities [Jarvis et al., 2020]. The fractionation and transport of ash particles are strongly controlled by their modal composition, grain size, shape, and aerodynamic properties [Bagheri and Bonadonna, 2016; Dioguardi et al., 2018]. Despite the importance of determining these characteristics, studies on dispersion and deposition of volcanic ashes in distal areas from super-eruptions are rare in the literature [Costa et al., 2012; Matthews et al., 2012]; also, atmospheric dispersion models consider a single composition and density for all the ash particles, thus ignoring the effects of different components and aerodynamics properties. In this context, the characterization of volcanic ashes and the determination of their aerodynamic characteristics are fundamental to investigate the dispersal areas of explosive eruptions. In the present work, the Campanian Ignimbrite (CI) super-eruption was selected as a study case. The CI is a super-eruption from the Campi Flegrei volcanic field (Southern Italy) that occurred at 39.8 ka [Giaccio et al., 2017] with a DRE > 200 km³ [Silleni et al., 2020]. It was the largest known eruption that took place in the Mediterranean during the Quaternary [Barberi et al., 1978] and it dispersed material over extremely wide areas, therefore it represents an ideal candidate for this study. We determined componentry and shape of fine ash from the CI, also including breathable fraction (<4 µm). Specifically, we investigated fine ash particles from the CI from proximal, mid-distal, and ultra-distal (i.e., up to 930 km from the source) areas by considering different depositional environments through various analytical techniques. Samples were separated into five particle size fractions (i.e., < 4µm, 5-8 µm, 9-16 µm, 16-63 µm, > 63 µm). XRPD analysis allowed the identification of minerals of primary paragenesis and secondary mineral phases. Componentry analysis by SEM-EDS observations through grain counting pointed out significant changes in the abundance of mineral phases within the different size fractions as a function of the distance from the source. The shape of particles was also analysed using secondary electron SEM images processed with the image analysis software ImageJ [<https://imagej.net/ij/>]. For each

particle, we measured the three form dimensions (longest, intermediate, and shortest length) and flatness and elongation shape descriptors. The morphological parameters were used to determine the drag coefficient and terminal fall velocity of ash particles. The obtained values were compared to theoretical velocities of ash grains under a spherical particle approximation; the results show that the terminal fall velocity of the sphere-approximated particles is generally overestimated. This work also highlights the key role played by fractionation and transport mechanisms in the dispersion of volcanic fine ash, with implications on health hazard assessment of super-eruptions.

Understanding the impact of atmospheric conditions and turbulence on settling-driven gravitational instabilities (SDGIs) forming ash fingers

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Settling-driven gravitational instabilities (SDGIs) occur at the base of the volcanic clouds due to density differences created by settling particles. These instabilities develop downward-moving plumes at the base of the cloud, known as ash fingers, characterised by higher terminal fall velocities than individual particles and may cause premature deposition of tephra that would normally be transported for longer distances. Turbulence in the cloud further influences the distribution and settling behavior of particles, interacting with the atmospheric conditions (e.g., wind, temperature, humidity) to create complex dynamics.

To better understand this phenomenon and its impact, we use numerical modelling to propose a parametrization for SDGIs, which considers the amount of fine ash removed from the cloud as a function of volume fraction, wind speed, and turbulence in the cloud. This approach integrates data from both field observations and laboratory experiments, providing a comprehensive view of the processes involved. By combining these methodologies, our study aims to enhance the accuracy of models predicting ash dispersion and sedimentation, ultimately improving hazard assessments related to volcanic eruptions.

Characterisation of the eruption magnitude distribution during the last three Epochs of activity (~14 ky) of Campi Flegrei caldera (Italy)

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The eruption magnitude is one of the most important parameters for the characterization of volcanic events. It depends on the mass of erupted material and is very crucial for hazard assessment. In this regard, estimating tephra fallout volumes erupted during explosive eruptions has been the focus of several volcanological studies, which greatly depend on the quality and quantity of available field data. However, for very old eruptions, proximal data can be absent, and sometimes what is found in distal areas (such as tephra layers in lacustrine and marine settings) is not always satisfactory. In this work, a novel simplified statistical method is applied to assess the volume of tephra deposits for which at least two locations with thickness data are known. We systematically apply such new method to the existing database of explosive eruptions from Campi Flegrei caldera (Italy) that occurred within the last 14 ky and were commonly subdivided into three distinct Epochs. As a result, we obtain the distribution of the volumes of tephra fallout deposits with the related uncertainties for each Epoch. Based on the published estimates of the density of tephra fallout deposits, we convert the evaluations of erupted volumes into erupted masses. In addition to this, from the few published data of erupted volumes which also account for the deposit generated from PDC, we propose a statistical distribution of the erupted mass partition allowing us to estimate the eruption magnitude's probability density function.

Model calibration and validation of carbon dioxide dispersion in the Atmospheric Surface Layer using data from La Solfatara crater (Campi Flegrei, Italy)

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The development of efficient methods to monitor gas concentrations in volcanic areas and to evaluate the related hazard is pivotal for developing strategies for risk mitigation. Numerical models are commonly used nowadays together with gas concentration measurements in order to quantify local emission sources. However, large uncertainties can derive from approximations associated with the physics and formulation used to reproduce the natural phenomena. In this study, we present the validation of a passive gas transport atmospheric model using local CO₂ concentration and wind measurements acquired at La Solfatara crater (Campi Flegrei Italy), during an ad hoc campaign from 4 to 10 May 2023. We simulated gas dispersion using the DIGAS v.2.5.1 model and calibrated it against the observations. Our results indicate that in order to avoid systematic overestimations of the gas concentrations during stable atmospheric conditions, a minimum value of the eddy diffusivity coefficient has to be set between 1.5 and 2.0 m² s⁻¹. Such a correction drastically improved the agreement between model results and observations. The performance of the corrected model allows us to use it in an integrated way with the periodic measurements in order to retrieve the gas source conditions.

Proximal deposition from Etna paroxysmal eruptions: implications for TGSD assessment

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This study examines proximal deposits associated with 17 lava fountains occurred at the South-East Crater (hereinafter referred to as SEC) between 16/02 and 1/04, 2021. This eruptive crisis gave rise to some of the most intense eruptions of the last decade. We performed a field study to correlate and sample the tephra layers preserved within the snowpack in the summit area. Samples were taken from 1 up to 3.2 km from the SEC. We constrained the granulometric distribution of these multimodal proximal and ultra-proximal deposits (empirical parameter range between MdPhi -2.79 and -1.84, and Sigma 1.34 and 1.80). Finally, our refined data (50% of the main population range between MdPhi -2.63 and -1.63, and Sigma 1.01 and 1.41) were used in a comparative study with existing datasets for selected eruptions with medial and distal samples. After deconvolution of the GSDs, the MdPhi parameters related to the main population (linked to the plume fall-out sedimentation) are likely representative of the proximal trend of Etna's high-intensity paroxysms occurred in the last decade. Our data demonstrate that the analysis of proximal tephra fall deposit is fundamental for a proper assessment of the TGSD. The lack of sampling from proximal zones can cause a shifting towards fine sizes in the reconstructed distribution of up to

S04 - APPLICATIONS OF REMOTE SENSING TECHNOLOGY IN VOLCANO HAZARD MONITORING

Conveners:

Emanuela De Beni, Gaetana Ganci, Cristina Proietti, Christian Bignami, Stefano Corradini, Alessandro Pignatelli

A new algorithm for the global-scale quantification of volcanic SO₂ exploiting Sentinel-5P TROPOMI and Google Earth Engine platform

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Sulfur dioxide (SO₂) is sourced by degassing magma in the shallow crust, hence its monitoring provides information on the rates of magma ascent in the feeding conduit and the style and intensity of eruption, ultimately contributing to volcano monitoring and hazard assessment.

Here, we present a new algorithm to extract SO₂ data from TROPOMI Level-3 imaging spectrometer, onboard the Sentinel-5 Precursor satellite, which provides atmospheric column measurements of sulfur dioxide and other gases with an unprecedented spatial (pixel) resolution. A common SO₂ detection method is based on the consideration of the pixels above a certain threshold, which however doesn't always allow to best distinguish the pixels contaminated by SO₂ from the noise ones.

Specifically, we exploited Offline imagery, and applied the Simple Non-Iterative Clustering segmentation method, which is an object-based image analysis approach. In this way, we assembled clusters from neighboring pixels based on parameters of compactness, connectivity, and neighborhood size, allowing us to segment images into regions with similar characteristics. The K-means unsupervised Machine Learning technique was then applied to the segmented images, identifying 10 different classes and allowing a further and better clustering to distinguish the SO₂. For sulfur dioxide quantification, only the classes with a high density were considered. We implemented this algorithm in the open-source Google Earth Engine computing platform, which provides collections of images adjusted in terms of Quality Assurance for several quality parameters and factors.

Here we show the time series related to total SO₂ Vertical Column Density data from 2018 to date on Mount Etna, one of the most active volcanoes in the world, typically emitting 500 to 5000 tons of sulfur dioxide/daily. We compared our results with the data available in the literature, finding a general good agreement. This work could have important implications regarding the calculation time, to have a rapid response in terms of volcanic SO₂ fluxes and it could be potentially applicable to other volcanoes worldwide.

Dispersion modelling of the 2021 eruptive plumes at Mt. Etna by coupling WRF-Chem model with ground-based and satellite remote sensing observations

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From 20 December 2020 to 22 February 2022, 66 paroxysmal events occurred at Mt. Etna volcano by the South East Crater. Among these, the events occurred on 4 and 12 March are studied by coupling plume dispersion modelling with ground-based and satellite remote sensing observations. Both events produced ash-SO₂ rich plumes that spread up to a height of 11.8 and 10.8 kilometres asl respectively. In this work, we investigated the spatial dispersion of the volcanic ash and sulfur dioxide plume by using the Weather Research and Forecasting Chemistry (WRF-Chem) model. The adopted modelling system was specially configured and equipped with additional computational routines to read and process, at each model integration timestep, the Eruption Source Parameters (ESPs) time series obtained from the observed data. The bulk SO₂ flux time series was measured from the ground by the FLAME (FLux Automatic MEasurement) DOAS scanning spectrometers network while the ash Mass Eruption Rate (MER) was inverted from the plume injection height estimated from MGS-SEVIRI satellite for each paroxysm.

In order to assess the predictive performance of the model in simulating volcanic plume transport, the dispersion maps obtained from the simulations were compared with those retrieved from SEVIRI and TROPOMI sensors onboard the geostationary MSG and polar Sentinel-5p satellites respectively. Comparisons highlight that the simulated spatial dispersion patterns for both ash and SO₂ closely agree with those observed by the satellites. Furthermore, the plume transport was well reproduced by the model on the Mediterranean scale, as in both cases the simulated volcanic cloud crossed the Ionian Sea, reaching Greece about 10 hours after the paroxysm, consistently with satellite observations. In addition, the simulation of the 4 March paroxysm was also validated by the online available data from in situ observation performed by the LIDAR belonging to the ALICENet (Automated Lidar-Ceilometer network) and the AERONET (Aerosol Robotic Network) located in Messina (Northeastern Sicily, Italy).

Results achieved in this study, underline the capability of WRF-Chem in reproducing the dynamic of volcanic plume clouds at both temporal, spatial and magnitude scale over the Mediterranean region. The predictive performance of the model, represented a powerful tool for assessing air quality, aviation safety and potential hazard scenarios connected to the paroxysmal activity of Mt. Etna and worldwide.

Machine Learning-Based approach for volcanic cloud detection during the 2020-2022 Etna activity using MSG-SEVIRI data

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During a volcanic eruption large quantities of particles and gases are emitted into the atmosphere. The detection and retrievals of volcanic constituents are crucial to support aviation safety and to quantify their impact on human health, environment and climate. In particular, the volcanic cloud detection represents the key input for retrieval algorithms as VPR (Volcanic Plume Retrieval) and LUT (Look-Up Tables), which are applied to get information on particles total mass, optical depth and effective radius and gas mass. Clearly, high-quality quantitative information requires accurate volcanic cloud detection.

Volcanic cloud detection using satellite data is challenging, particularly in the presence of high quantities of water vapor. This latter, in combination with ash particles, form water droplets that, under particular conditions of pressure and temperature, can turn into ice. This physical phenomenon supposes a limitation for volcanic cloud detection because it masks the reverse absorption signal when using the traditional brightness temperature difference (BTD) methodology considering 11 and 12 μm bands.

Mount Etna (Sicily-Italy) is one of the most active volcanoes in the world, and between 2020 and 2022, has produced 66 lava fountain events. These events have generated volcanic clouds mixed with ash, ice and SO_2 , with a top height ranging between 4 and 13 km.

In this work a Machine Learning-Based approach to analyze and explore the volcanic cloud detection during the Etna's lava fountain events, occurred between 2020 and 2022, is carried out. The models exploit a large dataset covering all of the 66 lava fountains observed by the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument, on board of Meteosat Second Generation (MSG) geostationary satellite, aiming to get insights for discrimination of ash, ice, and SO_2 in the volcanic clouds. This Machine Learning-Based approach using satellite images can help build an automated volcanic cloud detection procedure to improve the workflow for the VPR real-time algorithm.

Keywords

Volcanic clouds, Remote sensing, Satellite data, Machine Learning

Applying Artificial Intelligence to Satellite Data for Predicting Volcanic Eruptions: A Case Study of Etna Volcano

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Identifying the observable signals that warn against volcanic unrest and impending eruptions is one of the greatest challenges in the management of natural disasters. In this regard, satellite data has become a strong focus of global interest, offering abundant datasets from multiple missions and valuable tools to study Earth and improve physical models. Our purpose is to explore artificial intelligence techniques applied to volcanic data collected by satellites in order to check if there is any connection between such signals and volcanic states. A first attempt was made to classify the eruptive states of Etna volcano using several supervised machine learning techniques, considering the following input data: radiance, day/night surface temperature, gravitational anomaly, SO₂ gas concentration, and ground displacements computed using Interferometric SAR. More specifically, almost all supervised machine learning classification methods have been applied in our analysis, namely Decision Tree, Random Forest, Multiclass Support Vector Machine, Naïve Bayes classifier, K-Nearest Neighbour (KNN), Discriminant Analysis, and a 3-layer fully connected Neural Network. Our preliminary results show high accuracy in terms of state prediction, especially using the Random Forest method. Additionally, further analysis has been conducted to analyse the impact of specific variables related to prediction capability.

A hidden eruption: the 21 May 2023 paroxysm of Etna volcano (Italy)

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On 21 May 2023, a hidden eruption occurred from the South East Crater (SEC) of Etna (Italy), indeed bad weather prevented its direct and remote observation. Tephra fell toward the southwest, and two lava flows propagated on SEC's south and east flanks. The monitoring system of Istituto Nazionale di Geofisica e Vulcanologia, testified to its occurrence. We analyzed the seismic and infrasound signals to constrain the temporal evolution of the fountain, which lasted about 5 hours. We finally reached Etna's summit two weeks later and found an unexpected pyroclastic density current (PDC) deposit covering the south lava flow on its middle portion. We performed Unoccupied Aerial System and field surveys to reconstruct in 3D the SEC, lava flows, and PDC deposits and to collect some samples. The data allowed for detailed mapping, quantification, and characterization of the products. Lava flows and PDC deposit volumes result in $(1.54 \pm 0.47) \times 10^6 \text{ m}^3$ and $(1.30 \pm 0.26) \times 10^5 \text{ m}^3$, respectively. We also analyzed ground-radar and satellite data to evaluate that the plume was about 15 km high. This work is a comprehensive analysis of the fieldwork, UAS, volcanic tremor, infrasound, radar, and satellite data. Our results increase awareness of volcanic activities and the potential dangers for visitors of the Etna's summit area.

10 Years of Sentinel-1 data to monitor the Italian volcanoes through DInSAR techniques

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Since 2014, the Sentinel-1 satellite constellation has provided a massive amount of Synthetic Aperture Radar (SAR) data across the Earth with an unprecedented continuous and high acquisition rate. This aspect, together with the free and open access data policy of Copernicus program, has fostered the development of services to monitor the Earth surface. In particular, at the Institute for the Electromagnetic Sensing of the Environment of National Research Council of Italy (IREA-CNR), an operational service has been developed with the aim of detecting the displacements of Earth surface, with centimeter to millimeter accuracy, via the Differential Synthetic Aperture Radar Interferometry (DInSAR) technique.

The implemented service is constantly used to support the Italian Department of Civil Protection (DPC) for the ground displacement monitoring of Italian volcanic areas. In this regard, every time a new Sentinel-1 SAR acquisition is available over a selected volcano, the monitoring service, based on the Parallel Small BAseline Subset (P-SBAS) approach, is automatically triggered and allows updating the ground displacement time series for both the ascending and descending passes. The so-retrieved radar Line of Sight (LOS) measurements are then properly combined to compute the Vertical and East-West components of the displacements, which are straightforwardly interpretable and usable by most of the end users.

The service is currently running for Campi Flegrei caldera, Mt. Vesuvius, Ischia, Mt. Etna, Stromboli and Vulcano, providing us and the DPC team with the temporal evolution of the ground displacement (since 2015) for the main active Italian volcanoes. Approximately, in the last 10 years, the monitoring service has processed more than 2,500 Sentinel-1 acquisitions of the Italian volcanoes and has allowed us to investigate their deformation behaviors during unrest periods and seismic crisis. For instance, it was possible to detect: the ground displacements associated to the 2017 Ischia earthquake; the ground movements due to the 2018 Etna eruption; the Sciara del Fuoco (Stromboli) displacements following the 2019 paroxysmal events; the 2021 uplift of La Fossa caldera (Vulcano); the long term Campi Flegrei uplift, characterized by different rates along time. This work is supported by: the CNR-IREA and Italian DPC 2022-2024 agreement; the EPOS-RI, including the one obtained through the EPOS-Italia JRU; the European Union - NextGenerationEU through the projects: MEET - PNRR - IR0000025; ICSC - CN-HPC - PNRR

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A Deep Learning Model for Classifying Ground Deformations from Multi-Temporal SAR Interferometry

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Multi-temporal InSAR (MT-InSAR) has become a prominent technique for studying and monitoring ground movements across extensive regions and for different geodynamic settings. Advances in the technology of SAR sensors have enabled the collection of dense spatial data, providing vast amounts of information on regional and national scales. Despite this progress, the interpretation and classification of such large data remains challenging. MT-InSAR results are typically presented as mean ground velocity or acceleration. These representations often fail to capture the full complexity of surface displacement changes over time, which is critical when dealing with nonlinear processes, periodic behaviours, or combinations of steady states and sudden accelerations. InSAR analysts often need to manually inspect the InSAR time series from Persistent Scatterers Interferometry to model the complexity of the geological and tectonic phenomena. This task is time-consuming and impractical for wide area monitoring. Leveraging artificial intelligence (AI) for the identification and classification of deformation processes offers a promising solution. AI can automate the spatially clustering of crustal deformations, thereby aiding in identifying different geological or geodynamic processes. In this work, vertical ground deformation time series of the North-eastern part of Italy have been downloaded from the European Ground Motion Service (EGMS) and categorized by experts into deformation classes. Convolution Neural Networks (CNNs) have been trained and tested on the labelled numerical time series and on the images of the trends. The results confirm the ability of the CNNs to recognize regions belonging to distinct geodynamic processes ongoing in the North-eastern Alps sector.

Monitoring low-temperature volcanic features from space with TIRVolcH: applications to crater lakes

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Crater lakes are established at more than 15% of the potentially active Holocene volcanoes on Earth. Despite only ~3.5% of recorded eruptions occurring through volcanic lakes, studies suggest that these account for ~15% of the overall death toll related to volcanic eruptions. Crater lakes are typically sited at remote, barely accessible, locations, and the difficulties associated with installation and maintenance of monitoring equipment in highly toxic, low-pH, corrosive, and potentially explosive environments, result in a lack of continuous data.

Satellite-retrieved thermal information (i.e., radiative heat flux), has long been used as (i) a monitoring tool to assess variations at volcanic systems, (ii) to mitigate the lack of ground-based information, and (iii) ensure data collection in a risk-free manner. In this regard, several satellite-based volcano monitoring systems have been developed. Nevertheless, these systems either target high-temperature (active lava/vent) features (i.e., Mid-Infrared, MIR, -based systems), thus excluding crater lakes from their detection range, or provide information with a temporal frequency (typically 10s of days) inadequate for daily monitoring (i.e., Thermal InfraRed, TIR, -based systems), precluding the assessment of rapidly escalating volcanic phenomena, especially in areas prone to high-frequency of cloud cover.

TIR-equipped platforms, however, like the Visible Infrared Imaging Radiometer Suite (VIIRS), offer an unprecedented trade-off between spatial (375 m) and temporal (multiple acquisitions per day) resolution, having the potential to provide heat flux measurements of low-temperature volcanic features at a relatively high (daily) frequency.

To exploit the capabilities of these sensors, a new TIR-based algorithm, namely TIRVolcH, was developed. Here we present results from applying TIRVolcH to selected crater lakes around the world, revealing the effectiveness of the algorithm in detecting subtle thermal anomalies and quantifying the radiative heat flux from these low-temperature volcanic systems.

We envisage that TIRVolcH will prove instrumental for timely detection, and tracking the evolution, of thermal emissions at crater lakes worldwide. Such a compilation of statistically robust multidecadal TIR datasets will provide a new capability for volcano monitoring and insights into processes driving activity at crater lakes, offering a useful tool for hazard management and risk reduction, as well as scientific applications.

Long-term analysis of satellite-retrieved effusion rate: insights into 24 years of activity at Piton de la Fournaise

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The use of remote sensing has improved the monitoring of volcanic activity, especially through satellite-retrieved thermal measures. Focusing on effusive activity, a parameter such as the effusion rate reflects the pressure conditions within a magma reservoir, and controls the length, areal expansion and emplacement style of lava flows. This parameter is thereby fundamental for assessing the hazard associated with effusive eruptions, but its measurement remains challenging to estimate from the ground. Satellite-based approaches using thermal infrared imagery have enhanced the capability to determine effusion rates in terms of Time Averaged Discharge Rate (TADR) both in near-real-time and for retrospective studies.

In this study, we analyze 24 years of effusive activity at the Piton de la Fournaise (PdF) volcano (La Réunion, France). We used thermal satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) instruments and employed the Middle Infrared Observation of Volcanic Activity (MIROVA) system's algorithm to track the thermal activity of 37 effusive eruptions between 2000 and 2023. We computed the TADRs and volumes using a satellite-based approach that considers the relationship between erupted volumes and thermal energy radiated during an eruption.

The reconstruction and analysis of eruptive attributes such as final lava volumes, duration, TADR peaks and trends reveal the occurrence of 4 distinct groups of eruptions characterized by: (1) medium to high volumes ($7 \pm 4 \text{ Mm}^3$), long durations (~ 1 month on average), exponential decreasing trend; (2) low volumes ($\leq 1 \text{ Mm}^3$), variable durations (from weeks to months), steady trend; (3) medium to high volumes ($11 \pm 3 \text{ Mm}^3$), long durations (~ 1 month), waning-waxing trend; (4) low volumes ($< 1 \text{ Mm}^3$), very short durations (< 3 days), single pulsation of thermal activity. We also recognised a fifth group, defined by a mixed TADR trend, high volume involved ($> 15 \text{ Mm}_3$) and longer durations (> 1 month), which does not belong to any of those described above.

The recognition of different eruptive groups reveals a complex behaviour of PdF eruptions not always compatible with the “pressure-cooker” model commonly invoked to explain basaltic volcanism in closed-vent volcanoes. We suggest that long-term analysis of satellite-retrieved effusion rate may provide new insights into the eruptive dynamics of basaltic volcanoes and can enhance a more comprehensive risk assessment of future eruptions of PdF and a better prediction of their end.

Seamounts of the Mediterranean in comparison to worldwide occurrences and detectability through future gravity missions

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We pose the problem to estimate the detectability of seamounts of the Mediterranean sea which have appeared and vanished spuriously, as the Ferdinandea island, through remote sensing techniques. In particular we consider the observation of the gravity field from satellites. We estimate the mass of the Marsili seamount and Ferdinandea seamount and set them in relation to a collection of seamounts worldwide, considering also the possibility of mass changes of the seamounts, which could lead due to seamount growth. The mass estimate is made based on the bathymetry and realistic density values, which must take into account the composition and the porosity of rocks. Mass changes during magmatic unrests add mass at the top of the seamount, which is not compensated in the case that the magma source is refilled from below, probable in the case that the volcanic eruption is not accompanied by a summit subsidence. Up to present the greatest mass change occurred during the Hunga Tonga Hunga Ha'apai eruption of 2022, followed in size by the silent eruption of the Fany Maorè seamount, offshore Madagascar in 2018-2021. We consider the future MAGIC NGGM satellite constellation of 2 couples of satellites, which greatly enhance the sensitivity to mass changes compared to the presently acquiring polar orbit GRACE-Follow On satellite couple.

Volcanic activity classification through Semi-Supervised Learning applied to satellite radiance time series

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Automated early warning systems for volcanoes, capable of early recognition of any signs of impending eruption, as well as to track the evolution of different kinds of eruptive activity in near real time, are essential to assess the volcanic hazards and mitigate the associated risk. Satellite imagery offers a systematic, synoptic framework for monitoring active volcanoes in even the most isolated corners of the Earth.

A machine learning technique is applied here to automatically classify pixels in SEVIRI images over Etna volcano, in order to detect and characterize its eruptive activity. In particular, four main classes have been taken into account: clear sky (class 0), cloud-contaminated (class 1), thermal anomalies (class 2) and ash-contaminated (class 3).

Due to the enormous amount of data and the difficulty in labeling it, Semi-Supervised learning (with a Semi-Supervised GAN architecture) has been used to study the data acquired since 2005. A 5x5 pixel area around Etna Summit has been selected to analyze the spectral radiance variation of each pixel in the 11 bands available.

Additionally, from single pixel classification results, we classify the entire SEVIRI scene at a time instant, from the percentages of the four classes in the grid as output.

The permanent Thermal Infrared Surveillance ground Network of INGV-Osservatorio Vesuviano at Campi Flegrei caldera (Italy): two decades of observations

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The analysis of time-series of thermal infrared (TIR) images from diffuse degassing volcanic areas, acquired by ground proximal TIR stations, allows the opportunity to study the evolution of the surface temperatures field of studied areas. TIR images acquired daily at night-time by six ground stations of the permanent Thermal Infrared Surveillance Network of INGV-Osservatorio Vesuviano (TIRNet) at Campi Flegrei are processed by the automated Matlab software ASIRA developed by the TIRLab (www.ov.ingv.it/ov/thermolab/index_eng.html) of INGV-Osservatorio Vesuviano. The current infrared sensors installed in the TIR ground stations are FLIR SC655 cameras (resolution 648x480) which acquire scenes from the diffuse degassing areas of Solfatara, Mt. Olibano, Pisciarelli and Antiniana in the surroundings of the town of Pozzuoli since year 2004. The procedures used to analyse IR images acquired by TIRNet ground stations are the result of more than a decade of constant evolution both in laboratory and in the field. The main processing steps performed by ASIRA can be listed in: a) conversion of FLIR radiometric Jpeg raw file into temperature matrix files; b) quality control of temperature matrix files; c) correction of the pixels alignment between all frames in respect of a reference one; d) estimation of continuous apparent temperature time-series inside Regions of Anomaly (RoA) in TIR frames; e) removal of seasonal component of the temperatures time-series by applying statistic STL algorithm ("Seasonal and Trend decomposition using Loess"); f) computation of radiative heat flux; g) spatial distribution of thermal anomaly.

The main final products of ASIRA are continuous apparent maximum temperature time-series (TmaxTS) from RoA inside TIR frames, time-series of radiative Heat-Flux (HFluxTS), maps of spatial distribution of thermal anomaly inside the TIR frames and time-series of variations in the extent of the anomaly area (AreaAnomalyTS). TmaxTS plots are regularly included in monthly Surveillance Reports of INGV-Osservatorio Vesuviano to Civil Protection.

The preliminary comparison of the maximum de-seasoned temperature plots from all the TIRNet stations in the period October 2004-February 2024 and the seismicity occurred at Pisciarelli – Solfatara area in the same period, can offer an interesting contribute to open points of discussion about the behaviour of the surface geothermal system. What is the connection between the sudden variations of surface temperatures from different TIRNet stations in correspondence of periods characterized by intense seismicity at Campi Flegrei volcano? In which way the recent bradyseismic dynamics of Campi Flegrei volcanic area, characterized by increasing rates of ground uplift and intense seismicity, can drive the variations of surface temperature values of some TIRNet stations? Does the seismic activity really increase the efficiency of heat-flux transfer between the magmatic system and the surface or in some cases opposes it?

The investigation of these open points can be improved by comparing TIRNet and other multidisciplinary data from observables with the aim to build a model useful also for volcanic surveillance purpose.

Using remote sensing data to detect and map fires induced by volcanic activity: the case study of Stromboli during the 2019 summer

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In active volcanic environment, the explosive activity can affect vegetation causing fires due to the fallout of incandescent material thus create serious danger in populated volcanic areas. This is the case of Stromboli island, an active volcano of the Aeolian archipelago (Sicily, Italy) characterized by continuous mild explosive activity, interrupted by effusive eruptions, major explosions and paroxysms [Rosi et al. 2003]. In particular, in the period between 2nd July and 5th September 2019, two paroxysms and an intense explosive activity generated many fires all around the island, hitting not only the vegetation but also the inhabited area of Ginostra village. In order to map and distinguish the multiple fires, in this work three temporal period were analysed, in relation to the different volcanic activity. The first period is referred to the 3rd July paroxysm (2nd – 7th July 2019), the second period, between 7th July and 1st August, was characterized by a moderate to high intensity explosive activity, and the last period (1st August 2019 – 5th September) dominated by the 28th August paroxysm. Due to the fact that the first paroxysm affected an inhabited area of Ginostra and caused the loss of a human life due to exposure to smoke and heat generated by bush fires [Giordano and De Astis 2021], the Ginostra village was selected as test area. In this area, an accurate mapping and quantification of the burnt areas has been obtained by selecting the best spectral index and the most suitable satellite data to produce such maps. For this purpose, the spectral indexes NDVI and NBR, derived from Landsat-8, Sentinel-2 and Pléiades data, and the respective maps of difference between pre and post the 3rd July paroxysm, were created and compared with the burnt areas map obtained by a very high spatial resolution drone imagery (8cm). Such imagery, acquired a few days after the paroxysm, was considered in this work the most reliable reference data to map the burnt areas, thanks to its high spatial resolution. The comparison between satellite and drone maps highlighted that the Sentinel-2 NDVI provides the best result, matching the 98.2 % of the drone imagery burnt map. For the first time, through Sentinel-2 NDVI, the areas burned in each period of the 2019 summer were distinguished, mapped and quantified, allowing to define a total burnt area of 5.47 km² that results mostly generated by the 3rd July paroxysm and the explosive activity related to the period 7th July - 1st August 2019. In addition, analyses on the fire vegetation resilience and hazard evaluations on touristic pathways were presented providing useful indications to the management and mitigation of fires induced to the volcanic activity at Stromboli island.

High resolution topographies from satellite data to reproduce secondary volcanic hazards at Stromboli: the case of Gravity Induced Flows related to the 3rd July 2019 paroxysm

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Stromboli island (Aeolian archipelago) is one of the most active volcanoes in Italy. Its peculiar activity, consisting of mild strombolian explosions with a frequency from 5 to 30 explosions per hour is sometimes interrupted by paroxysm or explosive events at high intensity capable to generate secondary volcanic hazards. Frequent examples are the Gravity Induced Flows (GIF), occurred during the 3rd July 2019 paroxysm. Because such flows involved touristic pathways, simulating such phenomena can be useful to better understand their impact on the territory. To reach this purpose, two requirements are fundamental: i) use a code that better reproduces the rheological behavior of the flow; ii) have an updated topography at high spatial resolution which represents the main input data for every simulation code. In this study we show how the 3d topography, reconstructed with a stereo photogrammetry applied on satellite data with NASA's Ames Stereo Pipeline platform well satisfies the second requirement. We also present the first results obtained simulating the GIFs occurred at Stromboli during the paroxysm of 3 July 2019 through dedicated numerical codes.

High-Rate Real Time GNSS monitoring of active Italian volcanoes

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Since 2000 high rate GNSS geodetic monitoring of active Italian volcanoes has been carried on by the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (Catania). An intense development of remote stations, transmission devices, software for data processing and tools for time series analysis was carried out. From the first case study, during the 2001 Mt. Etna flank eruption, to the July 3rd and August 28th 2019 paroxysms of Stromboli volcano, many observations were analyzed that led to increase experience. In this work we describe the evolution of the high rate real time GNSS geodetic monitoring at INGV and the most important results collected in these years on Italian active volcanoes (Etna, Stromboli) to track rapidly developing deformation patterns associated to different volcanic processes, as dike intrusions or explosive activity. Moreover, we describe the improvements of the high rate real time GNSS monitoring network realized in the densely populated area of the Campi Flegrei Caldera (Naples, Italy). Finally, we show a web application for high rate real time signals visualization from permanent GNSS remote stations developed and managed by INGV-OE based on the Grafana open source platform and InfluxDB open source database. This web interface is applied to different active Italian volcanoes as Etna (Sicily), Stromboli (Aeolian Islands) and Campi Flegrei (Naples). We tested the performance of this software using as a case study the 24th December 2018 dike intrusion on the Etna volcano.

Recent updates of the lava flows of Mt Etna, Italy: the 1999–June 2019 and July 2019–December 2023 maps

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Integration of multi-sensor, multi-platform remotely sensed data is an effective methodology for monitoring active volcanoes, as it ensures a constant data flow, which is needed for repeated eruptive events in brief intervals. For example, UASs have become a useful and increasingly used tool. This comprehensive analysis allows broad observation of the eruptive scenario and quantification of the erupted products, i.e., measurement of the length, area, thickness, and volume of lava flows and the minimum front elevation. We used a GIS (Geographic Information System) software to map the lava flows of Etna, one of the most active volcanoes in the world. Our analysis resulted in two maps representing different updates of recent lava flows. Nine flank eruptions and dozens of summit eruptions occurred from 1999 to 2019, they are shown in the first map and are grouped by year for graphic simplicity. Between July 2019 and December 2023, seventy-five eruptive events emplaced one hundred lava flows, mainly from the summit craters. These are shown in the second map where, for graphic simplicity, summit flows are grouped by year or eruptive cycle, while flank flows are distinguished by date.

A new TIR ground based system for Volcanic cloud monitoring

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Monitoring of volcanic activity can be realized with both ground- and space-based instruments, with advantages and drawbacks. The ground-based systems generally provide a high spatial and temporal resolution, good accuracy, but generally insufficient density and limited coverage. Conversely, satellite systems ensure global spatial density of measurements and a synoptic view of the investigated area, but generally with a low spatial resolution and accuracy.

In this work a novel TIR ground based systems (named "VIRSO2") have been developed for the detection of volcanic clouds and the retrievals of SO₂ columnar abundance and plume height. It ensures data acquisition at high frequency with two broadband TIR cameras (7.8-14 micron) able to acquire data simultaneously. To obtain quantitative estimates of the SO₂ inside the volcanic cloud, an 8.7 micron filter is installed in front of one of the TIR cameras.

Until now the VIRSO2 camera has been tested during some field campaigns carried out on Etna (March-April 2021), Stromboli (July 2021, May 2022, May 2023), Sabancaya-Perù (November 2022) and Popocatepetl-Mexico (February 2024). In this work, these latter measurements are presented, which are particularly significant for the strong emission with the simultaneous presence of SO₂, ash particles and water droplets. To obtain reliable SO₂ results a correction, due to the particles presence, is also presented. Finally, an optical flow algorithm was applied to obtain the plume speed, needed for the SO₂ flux computation. The products obtained have been cross-compared with those obtained by using satellite (TROPOMI).

S05 - VOLCANOLOGY AND ARCHAEOLOGY: BRINGING THE WORLD OF PHYSICAL SCIENCES CLOSER TO THE HUMANITIES

Conveners:

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

“On volcanoes, or ignivomous mountains” of Giovanni Targioni Tozzetti (1779)

Paolo Sammuri

Libero Ricercatore

In this work Targioni recalls that his master, the great Florentine naturalist Pier Antonio Micheli, recognized as ancient volcanoes in 1722 the Mount of Radicofani and in 1734 the Mount of S. Fiora (M. Amiata). The recognition was possible by analogy, observing the similarity of the rocks in these localities with certain lavas of Vesuvius, observed by him in 1710. This method of observation and comparison of rocks led to the recognition of volcanic characteristics in various locations in the upper Lazio (Montefiascone, Acquapendente, Viterbo) that were identified as the site of extinct volcanoes. Moreover, the observation of the diversity of the lavas (melted, vitrified, cooked or decomposed) also leads to the evaluation of the different degrees of fire, which is considered very strong and much higher than the fires produced by man. The study of the extension of the ancient deposits also led to hypothesize vents or secondary openings, also ignivomous, in analogy with the descriptions of the most recent eruptions observed of Vesuvius and Etna. There is also the collection and study of samples and the observation with the microscope, for example of Pitigliano pozzolana powders defined as similar to the ash thrown by Vesuvius on Naples in 1767 with the description of rounded crystals and well-defined crystalline shapes. In conclusion we can say that it is a real treatise on volcanology “ante litteram”, which shows us the knowledge, limits and methods of study of volcanoes in the eighteenth century.

Science and iconography in *Der Aetna* by Sartorius von Waltershausen

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Sartorius' work is the most important product of the geological studies (in particular the stratigraphic and mineralogical ones) on Etna in the 19th century, and all this is well demonstrated by the fact that these researches culminated in the first geological map of a volcano at world. Unfortunately, the sudden death of Sartorius prevented him from completing the work which represents the sum of forty years of research on Etna carried out during long stays in Sicily. The work of *Der Aetna* was published posthumously in 1880 based on the manuscripts of Sartorius, profoundly revised and integrated by Arnold von Lasaulx. Therefore, if it is true that Sartorius' *Der Aetna* represents a watershed compared to the scientific production that preceded it, it is equally true that its impact on the studies of the time was very limited by the language in which the work was written. Nonetheless, it fits fully into the great eighteenth-nineteenth century debate on the genesis of volcanoes which saw the contrast between the supporters of the theory of uplift craters and those of external accumulation and does so by examining one of the most active volcanoes in 'Europe. On the whole, the data presented in this work they were absolutely original for the time, as regards the complex structure of the volcanic edifice and its evolution, the development in time and space of the individual eruptive manifestations, the characterization of the various products, both on the basis of field observations and analytical data in the laboratory. This contribution, starting from the first Italian translation of the second volume of *Der Aetna*, therefore intends to analyze the most salient scientific aspects of the work, exposed above all in this part of the work, and its iconographic apparatus, starting from the *Atlas des Aetna*, 1845–1861, placing it in the context of the time and highlighting its innovative character compared to the previous iconography of earth sciences, as well as its contribution to the development of a new iconography dedicated to volcanology and, specifically, to the Sicilian volcano.

Pompeii before the “Pompeii” eruption: insights into the pre-79 CE volcanic chrono-stratigraphy for geo-archaeological studies in one of the world’s most famous archaeological sites

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The ancient city of Pompeii is inextricably linked to the 79 CE Plinian eruption of Vesuvius, also known as “Pompeii” eruption. The city met its fate having been buried under a thick pyroclastic blanket consisting of fall and pyroclastic current deposits. The 79 CE eruption is the most studied eruptive event of Vesuvius and Pompeii is an outstanding site that keeps providing information on many aspects of this eruption. However, the intertwining of volcanic activity and human occupation of the site dates back to the Late Neolithic and Bronze Age. This is testified by the finding of pottery fragments belonging to the Early Bronze Age Palma Campania culture [Nilsson, 2008; Boman and Nilsson, 2008], in association with a tephra layer speculatively attributed to the 3.9 ka Avellino Plinian eruption, and material fragments of the Diana culture, dated to the IV millennium BCE [Varone 2008], incorporated in the paleosol developed on the deposits of the 8.9 ka Mercato Plinian eruption. The pre-79 CE volcanic stratigraphy at Pompeii includes several tephra layers whose attribution to specific eruptions has often been made without any robust volcanological constrain. This contribution provides useful insights, for future geo-archaeological studies of pre-Roman layers, into the pre-79 CE “Pompeian” volcanic chrono-stratigraphy. The study is based on the stratigraphic survey, coupled with a geochemical characterization, of tephra layers recognized in twenty trenches dug below the 79 CE street level in different parts of the city.

Ancient Pompeii was built on a hill that represents the remnant of a local volcanic vent(s), whose activity is not thought to be directly related to that of Somma-Vesuvius [Cinque and Irollo, 2004], from which lavas and welded pyroclastic deposits were deposited (hereafter referred to as the “lava bedrock”). The lava bedrock is covered by a sequence of loose to compacted sediments consisting of primary tephra layers, reworked volcanoclastic deposits, paleosols and anthropogenic deposits. The total thickness of sediments is variable, ranging from absent (outcropping bedrock) to a few meters [Amato et al., 2022].

The macroscopic textural features of some of the lava bedrock have been investigated under the Insula Meridionalis, the only area of the archaeological site of Pompeii where there are extensive outcrops of these volcanic rocks, which form a scarp up to 13-15 m high. At this site, the lava bedrock consists predominantly of clastic deposits, locally reddened, made up of lapilli- to block-sized, leucite-bearing scoriaceous to spatter clasts, showing a variable degree of welding. Overall, the degree of welding decreases upwards, varying from strongly welded/coalesced to unwelded deposits from lava fountain episodes.

Results of the field survey and geochemical characterization of the sediments overlying the lava bedrock show that the pre-79 CE composite volcanic stratigraphy at Pompeii consists of at least eight, Late Pleistocene to Holocene, tephra layers. Of these, six have been attributed to explosive eruptions of Somma-Vesuvius (Pomici di Base, Mercato and AP1 to AP4) and two have been

sourced to the Campi Flegrei caldera (Neapolitan Yellow Tuff eruption and possibly Soccavo 4 eruption). The oldest of these tephra layers, attributed to the 22 ka Pomici di Base Plinian eruption, rests directly on the lava bedrock via interposition of a thin, reworked and weakly humified layer. This conclusion allows the products forming the lava bedrock, possibly erupted from multiple coalesced vents, to be definitively dated to >22 ka. Although such local volcanic activity is thought to be unrelated to that of Somma-Vesuvius, the lava bedrock is coeval with several lateral vents >22 ka, forming parasitic cones on the Mt. Somma flanks and mantled by the Pomici di Base deposits with thin paleosols/humified layers in between [Sparice et al., 2017]. Similarly, the presence of a weakly humified volcaniclastic layer, between the Pomici di Base tephra and the underlying deposits at Pompeii would indicate that the Pomici di Base eruption may shortly postdate the deposition of the upper part of the lava bedrock. The recognition of the AP1-AP4 eruptions provides new chrono-stratigraphic data for geo-archaeological studies of the occupation levels predating the foundation of the city. Finally, the most interesting geo-archaeological result, in all the trenches investigated, is the lack of a tephra layer consistent with the Avellino eruption, unlike what is reported in the archaeological literature of Pompeii. Nonetheless, we cannot completely exclude that ashfalls could have affected the Pompeii area depositing a thin ash layer, later rapidly erased by reworking and human occupation, or an indistinct tephra in the form of glass shards incorporated into the soil. This suggests more caution in the attribution of Bronze Age tephra layers to specific eruptions during future archaeological investigations in Pompeii.

The impact of the eruptive phases during the 79 AD Vesuvian eruption on Pompeii: insights from the recent excavations in Regio IX, insula 10

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The catastrophic eruption of Vesuvius in 79 AD resulted in the destruction of the city of Pompeii and the death of many of its inhabitants. Analyzing the eruption's products within the archaeological sites yields essential and unparalleled insights into understanding how the various eruptive phases affected Roman cities and their residents. The systematic observation, carried out during the recent excavation works in Regio IX, Insula 10 of Pompeii involved analyzing the stratigraphic relationships between the products of the different phases of the Vesuvian eruption of 79 AD, and the structural components of the edifice, including both preserved and collapsed elements such as walls and roofs. This analysis has enabled the reconstruction of the sequence of destructive events that led to the ruin and burial of this large roman building.

The excavation area comprises the main building and the two adjacent aisles, covering more than 3000 m². The planimetric organization of the Aulo Rustio Vero complex, is the result of a series of restructuring of two housing units facing Via di Nola, one of the main roads in the centre of Pompeii, converted into residential workshops. The southern half of the block develops a large domus with rooms overlooking a large peristyle. At the time of the eruption, significant renovation works were underway, clearly evident in the piles of demolished building material stacked in every area investigated so far [Zuchtriegel et al., 2024]. The house is divided into over 75 rooms, both covered and uncovered, on the ground floor. The remnants of an upper floor, frequently severely affected by the eruption, are standing only partially. The deposits observed in the excavation area, as well as in the other Pompeian Regiones [Amoretti et al., 2021] are predominantly of two types: primary pyroclastic deposits, accumulated during the course of the 79 AD explosive eruption, and reworked pyroclastic deposits of anthropogenic origin. The latter are the result of intensive excavation work carried out in previous centuries, which investigated the site through the creation of trenches or, more often, galleries. The pyroclastic sequence observed is similar to that reconstructed by Scarpati et al. [2020] whose stratigraphic nomenclature we adopt. The Plinian pumice lapilli fall, consisting of white pumice clasts in unit A overlaid by grey pumice clasts in unit B, exhibits significant thickness variation, contrasting with the typically uniform thickness observed in open areas. Pumice lapilli rest upon the floor in nearly all ground-floor rooms. Their thickness ranges from few centimeters to over 5 meters, creating locally mounds with slopes exceeding 30 degrees. The lapilli penetrated the rooms through openings in the ceiling (impluvium), through doors and windows that face gardens filled with this material, or through openings that occur in the roof due to the increasing overload of the lapilli themselves. Two intraPlinian pyroclastic density currents (PDCs) flowed southward without producing relevant damage leaving in the house a faint trace formed by discontinuous layers of ash (units C1 and C2). During the Plinian phase, the collapse of roofs occurred progressively, as indicated by the presence of tiles at various stratigraphic heights within the pumice lapilli deposit. The successive pyroclastic currents were able to penetrate into all the rooms, resulting in the deposition of ash both on the lapilli, in areas where they had already accumulated, and directly on the floors where the lapilli are absent. Furthermore, the strong impact of the pyroclastic

currents on the structures caused erosion, collapses, and the dragging of wall fragments. The main damages are due to the PDC associated with unit E. Large wall blocks and numerous roof tiles were observed within this unit. The masonry blocks, some overturned or dragged for several metres, were found in the rooms southward (undercurrent) their original position. The impact of this pyroclastic current proceeded undiminished throughout the building, knocking down columns and the overhanging canopy in the peristyle south of the main body of the building. The upper part of the sequence, related to the final phreatomagmatic phase of the eruption, consists of very fine ash deposits containing accretionary lapilli of PDC origin, interspersed with four thin, lithic-rich, lapilli fall layers. The presence of bricks and tiles in this part of the sequence indicates a renewed destructive capacity in the latter stages of the eruption. The results obtained allow us to reconstruct how the building's articulated structure influenced the impact of the different eruptive phases, either favoring or preventing the destruction of various rooms. These observations can be extremely useful in assessing the hazard to cities surrounding Vesuvius.

An updated multidisciplinary review of the manner of death in Pompeii during the 79 CE eruption of Vesuvius.

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The 79 CE “Pompeii” eruption of Vesuvius is one of the most iconic volcanic catastrophes as well as the quintessential example of the relationship between archaeological sciences and volcanology. The volcanological literature concerning the damage to the city is very rich, and equally rich is that concerning the causes of death of the inhabitants of the destroyed Roman cities [e.g. Luongo et al., 2003; Mastrolorenzo et al., 2010; Mastrolorenzo 2021].

This contribution aims to thoroughly review the literature about the causes of death in order to debunk a number of scientific clichés and enrich the record of findings, and related interpretation, with evidence that has not been reported in the past, thanks in part to recent and ongoing excavations within the ancient city of Pompeii.

This reappraisal is enhanced by interdisciplinary fieldwork, involving archaeologists, anthropologists, volcanologists, and earthquake geologists, as well as two agreements with scientific institutes dedicated to volcanology. This synergistic work leads to an ‘integrated’ stratigraphy that merges archaeological and volcanological layers and allows an almost forensic reconstruction of what happened to human beings during the eruption.

Traditionally two means of death have been identified during the 79 CE eruption in Pompeii and both are linked to the main phases of the eruption: 1) deaths from crushing trauma resulting from the collapse of roofs due to the accumulation of pumice deposited during the Plinian phase; 2) death caused by the arrival of the pyroclastic currents. Regarding the latter, authors are divided between those who claim that death was caused by thermal shock due to extreme temperatures, detected in the limb contraction and in the “pugilistic pose” resulting from a shortening of the tendons, and those who claim by asphyxiation as a result of the exposure time in an ash-rich environment [Petrone 2021, Dellino 2021].

Recently, the same “pugilistic pose” has been found in two individuals recovered directly under a structural collapse in an excavation in the north-eastern part of the Insula dei Casti Amanti. However, neither of the bodies were buried in the ash deposited by the pyroclastic currents, as, by the time of their arrival, the corpses were lying under collapsed walls and pumice. These observations lead to an important consideration: the position of the flexed limbs is not necessarily an effect of the exposure to extreme temperatures. The same context also provides information about the triggering mechanism that caused the walls to collapse, overwhelming the two individuals, and the timing of this event during the eruption: the individuals met their fate as a result of earthquake-induced structural failures, stratigraphically consistent with the beginning of the caldera-forming phase of the eruption [Amoretti et al., 2023], revealing a greater complexity in the reconstruction of the damage inflicted during the catastrophe.

Similarly, the discovery of two more bodies in a room in the western part of the same insula has highlighted how death during the Plinian phase could have occurred even in the absence of a roof collapse. In fact, the field investigation suggests that the two victims were trapped between the

inner and outer doors of a hallway, where they probably sought refuge, and that the pumice, accumulating with considerable thickness in the adjacent alley, broke down the outer wooden door and fell back on the individuals, who were found engulfed by grey pumice and probably died of asphyxiation due to their confinement.

Regarding the deaths caused by pyroclastic currents, although further analyses are currently underway to integrate additional data on temperatures, the latest (May 2024) victim found in Pompeii, in the ongoing excavations in Regio IX, 10, lies in a crouched position, probably due to an attempt to shelter under an object whose traces remained in the ash deposit. The body shows no traces of alterations due to high temperatures, and no hypercontraction of the limbs. This evidence brings us back to what has already been demonstrated above: the complexity of the archaeological contexts in which victims of the eruption are recovered can only be unraveled by an in-depth multidisciplinary analysis, where each clue (be it archaeological, stratigraphic, or volcanological) is put in place like the pieces of a jigsaw puzzle. The result is an integrated and updated view of the syn-eruptive manner of death in Pompeii that entails a more comprehensive understanding of the effects on humans in one of the most famous eruptions in history.

The casts of the victims of Pompeii

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Of the over one thousand victims recovered in Pompeii, plaster casts were made for 104. While the discovery of skeletons is more common inside buildings, the casts almost always refer to bodies that were found in open places.

Of only three groups (Orto dei Fuggiaschi, Casa Stabiano and Casa del Criptoportico) are there photographs which testify to the position of the casts in the stratigraphy of the volcanic products and which allow us to temporally place the escape attempt which occurred during the eruption. The other casts, after execution, were moved and placed in various museum contexts.

From the set of observations made on the few casts remaining in the original position on the site and through the images published in various archaeological works, as well as, above all, from the reports drawn up at the time of the excavation, we reached the conclusion that the execution of a cast requires constraints in the type of volcanic material placed above and below the victim.

The bodies leave their imprint, which can be filled with fluid plaster, when they gradually decompose and when the material that covers them is able to adhere perfectly to the shape of the limbs and clothes. For slow decomposition, the body must not be on the ground, but above the pumice layer; to have a perfect negative reproduction of the victim, it must be covered with fine ash, which creates a sort of shell around the body.

The casts whose stratigraphic position is known are not placed directly on the pumice, but are located above a thin level of ash that covers the layer of pumice. During the eruption, this may have facilitated the walking of individuals, who otherwise would have sunk in the freshly fallen and uncompacted pumice; during the making of the cast, it prevented the fluid plaster poured into the cavity from slipping and dispersing into the layer of pumice underneath.

Therefore, if to obtain the cast, the victim must be above the thin layer of ash that covers the pumice, this means that after many hours from the beginning of the eruption (the duration of the pumice falling phase is estimated between 12 and 20 hours) there were people in the city still alive and able to walk in difficult conditions. The number of these fugitives may include all the casts and not just only the approximately thirty individuals of the photographed groups.

The choice of many to flee at the same time also supports the hypothesis that the collapse of the eruptive column and the formation of pyroclastic flows was accompanied by strong earthquake shocks which pushed those who had sought refuge outside their homes.

The position, the symptoms of nervous contraction, the presence of perishable materials, such as fabrics and hair, also provide estimates of the temperature of the volcanic products and its variability from one point to another, even over a short distance.

From the description of the bodies we also tried to distinguish between how many may have perished due to the temperature, how many due to mechanical trauma and how many due to inhalation of ash to the point of suffocation.

New geophysical and archaeological investigations at the “Nunziatella” site in Mascali, Mount Etna (Italy)

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The archaeological site known as “Nunziatella” of Mascali is located in the lower east flank of Etna volcano at 230 m of elevation. This site is characterised by the presence of a mediaeval church of the XII century AD, with the remains of a painting of Christ Pantocrator which adorns the apse basin, and by a small Early Christian basilica with three naves which has a floor with polychrome and figured mosaics well preserved. In addition, two burials were recently discovered during excavations carried out for the laying of fiber optic cables. From a geological point of view, the Nunziatella archaeological site is located in a sector of the volcano edifice characterised by the presence of old lava flows, ranging in age between 180 ka and 130 ka ago, resting on the clays of the sedimentary basement. This geological setting allows the presence in this area of small springs that feed a limited drainage network.

In order to develop knowledge on this important archaeological site of Etna region, an interdisciplinary study was performed through new geophysical and archaeological investigations and ¹⁴C dating. In particular, ground penetrating radar (GPR) surveys were realised in the external area of the mediaeval church. Through this non-destructive geophysical technique, it was possible to obtain high resolution images of buried structures preparatory to carrying out archaeological excavation tests. In particular, the GPR investigations, carried out using IDS Hi-Mod ground penetrating radar system equipped with a bi-frequency antenna 400-900 MHz, highlighted a series of reflections and anomalies in the signal in an area adjacent to the southern wall of the church, as observed in the vertical two-dimensional sections and the horizontal tomographies parallel to the surface and at variable depths (time slice). Based on the results of the GPR investigations, a new archaeological excavation was started which brought to light the remains of a wall that runs parallel to the southern wall of the church for over nine metres. The wall has a thick layer of plaster on the internal facade and a “cocciopesto” floor at the base. The connection with the mediaeval building and, above all, with the nearby early Christian basilica remains to be defined for this structure. The excavation has, in fact, revealed numerous fragments of ceramics, tiles and pottery, dating back to between the 6th and 9th centuries AD, together with bone fragments. These findings testify to the uninterrupted attendance of this area of the monumental complex of the “Nunziatella” of Mascali, rich in water sources and therefore suitable for human settlement, since ancient times.

New age determinations of the prehistoric human presence on Mount Etna

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New ¹⁴C dating from main excavations were performed with the aim of validating the chronology of the sequence of the different phases of the prehistoric human presence on Mount Etna. The sampling involved numerous sites dated between the end of the Neolithic and the Early Bronze Age and allowed us to define interesting questions relating to: settlement continuity on the different slopes of the volcano; the lack of sites after the mid-15th century BC; the particular concentration of ages around certain periods, such as the end of the 5th millennium, the second half and the end of the 3rd millennium. This study intends to individuate lines of development of the settlements on Mount Etna slopes in the different phases of prehistory and to try to understand the main factors that influenced the population of the Etna region in relation to the eruptive activity.

A Multidisciplinary Study in the Archaeological Park of Valle dell'Aci: Exploring Ancient Settlements, Hot Springs, and Fluid Emissions to Reconstruct its Geological-Structural Framework

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The archaeological park of Valle dell'Aci represents a suitable open-air laboratory favourable to multidisciplinary studies aimed at integrating historical, archaeological and geological data to gain a comprehensive understanding of the area's history and geology. This work seeks to analyze and connect historical and archaeological remains, focusing mainly on the ruins of Greek-Roman thermal baths, volcanological observations, structural data, and their correlation with geothermal fluids emissions.

The site of Santa Venera al Pozzo, located within the municipality of Aci Catena (Catania, eastern Sicily), holds a particular significance due to its millennia-history and unique proximity to Mt. Etna, the largest active volcano in Europe. The thermal baths date back to the Greek period and have given rise to myths, including that of Akis, transformed into a river whose springs sometimes take on a reddish colour due to the sulphureous nature of thermal waters. These legends, besides being an integral part of the area's cultural heritage, provide valuable clues about geology and hydrothermal dynamics of the surrounding environment.

Our research approach began with a meticulous analysis of historical sources to identify the hydrothermal fluid presence, known since ancient times. Three additional sites were identified, in addition to Santa Venera al Pozzo, where buildings attributable to ancient thermal structures were found. Subsequent fieldwork involved the identification of anomalous gaseous emissions, in particular CO₂, with the aim of discerning deep geological structures.

The resultant CO₂ map not only confirmed the presence of flow anomalies in proximity to archaeological sites with hot springs, but also facilitated its correlation. By integrating this evidence with existing geological data, such as documented faults and subsurface ruptures caused by seismic events (251 AD and 2018), alongside an analysis of the region's geomorphological features, we are able to identify structural weakness conducive to the ascent of geothermal fluids. This study therefore lays the basis for identifying new buried volcano-tectonic structures thus enhancing our knowledge of the seismotectonic model of the area.

The advancements in the studies on Serracozzo Cave I (1971 Etna eruption)

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1971 eruption presented a complex eruptive phenomenology that, from a volcanological point of view, signified the beginning of a new phase for the volcano and the way to study Mt. Etna volcanic activity. The birth of the South-East Crater, the current summit of the volcano (3348 m s.l.m.) and the protagonist of most of the activity in recent decades, and the early indications of the change in magma chemistry of Mt. Etna were the main signals of the change of the pattern in the volcanic activity that we observe even today. This eruption, therefore, represented the most important event of this period, and for this very reason has engaged the energies of many Italian and foreign researchers that carried out intense field observations and concentrated deployment of instruments during the event [Guest and Skelhorn, 1973]. Volcanospeleology is among the many relevant aspects of the study of the 1971 eruption. The study of the caves formed during this eruption has had an important impact on the history of speleology on Etna because of the ideas regarding the formation of lava tunnels that have been stimulated by the study of this eruption. It is noteworthy the fallout of the studies on the rheology of 1971 lava flows in modelling the cave formation. This contribution summarises the salient aspects of the 1971 eruption in the Serracozzo area, the observations made by volcanologists and speleologists at the effusive mouths and in the portions of the flows immediately downstream of these. Emphasis is placed on the interpretations of the processes and the model proposed by Alfred Rittmann [1977] to explain the formation of the lava tunnels in aa lava field. Finally, an interpretation of the formation mechanism of the entrance to the Serracozzo Cave I is also proposed according to Puglisi [2023] whose morphology is absolutely unique in the panorama of Etna's caves.

Geochemical and petrochemical characterization of the Breccia Museo obsidian fragments for archaeometrics purposes

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We present the first results of a study dealing with the geochemical and petrochemical characterization of obsidians from the deposits of the Breccia Museo (BM), in the Campi Flegrei area and nearby surroundings for archaeometric investigations.

The stimulus for this research was offered to us by the recent discovery, made by a group of archaeologists on the island of Procida which attests to the use of minute obsidian fragments of the local BM as an abrasive to smooth the boat hulls.

Hence our study aims to compare the geochemical fingerprint of the BM obsidians with that of the four main sources of Central Mediterranean obsidians exploited in prehistory: namely Lipari, Pantelleria, Monte Arci, and Palmarola, for discriminating the provenance of raw material in the archaeological context.

Our geochemical analyses on samples collected in Procida, and other data from the literature, indicate that the BM obsidians are clearly distinguishable from the other Central Mediterranean obsidians based on major elements composition and Chlorine content, as they are Chlorine-rich trachy-phonolites, not rhyolites, characterized by high Calcium content. These peculiarities allow clear discrimination of BM obsidians for archaeometric purposes if they are found in archaeological contexts mixed with obsidian fragments from multiple sources.

The obsidian prehistoric tools of the anthropic occupation in Tulul al Baqarat (Iraq - IV Millennium): a machine learning approach on microanalytical non-invasive geochemical data

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The geochemical characterization of 9 obsidian blades belonging to a group of lithic tools, from the anthropic settlement of Tulul al Baqarat in Iraq is performed and the provenance of source material is suggested. The anthropic occupation of Tulul al Baqarat, extensively excavated from 2008, is composed by several archaeological hills (tulul in Arabic) of different size and chronology: the area of Baqarat, was settled from the beginning of the IV millennium up to the Islamic era and once was closer to the ancient course of the Tigris river or connected to it through canals.

Since 2013, this archaeological area have been investigated by archaeological expeditions from the University of Turin who collected the 9 obsidian blades from the anthropic settlement hill dated to IV Millennium. To identify the origin of archaeological obsidians and the volcanic complexes which produced the blocks from which they were knapped, a geochemical study, from the Turkish volcano obsidian sources to the artefact samples, was carried out introducing the use of the machine learning approach, as more exhaustive approach, after the well-known geochemical comparisons and Principal component analysis.

First off, a non-invasive and no destructive investigation has been developed for the study of the nine obsidian tools. It includes the set-up of a micro-analytic methodology which avoid the studied object sampling or manipulating. Indeed, the obsidians tools have been chemically analysed by a JEOL Low Vacuum SEM-EDS for determining the major and minor elements and by a bench-to-top EDAX-Eagle micro-XRF for trace elements. They show a rather homogeneous comendite and peraluminous rhyolite composition. The paramount high content in Zr (1000-1500 ppm) in addition to high Rb, Y, Nb, and Zn and to the significant low content in Sr (below detection limit: i.e. < 20 ppm) are distinctive features.

Comparing this data set with obsidian sources in Turkey and Armenia, first selecting element pairs such as Zr-Rb and Zr-Zn, applying a Principal Component Analysis, and finally using a machine learning approach to major, minor and trace elements, the obsidian tools result geochemically comparable to Nemrut Dag mild alkaline rhyolitic obsidians from pre-caldera eruptions, and now outcropping inside the caldera as well as in Sikarcsu outcrop.

This source provenance from Nemrut Dag stratovolcano in South-eastern Turkey, located near the Turkish route of the Tigris River, supports that Obsidians from South-Eastern Anatolia were diffused through the basins of the Tigris and Euphrates to the shores of the Persian Gulf, enhancing the importance of the historical role and spatial position of the Tigris River during these periods and, finally, supporting the evidence of a network of trade and broad exchange since 4th Millennium from Turkey and the South Near Est, presumably by river transportation.

Finally, this archaeometric study of obsidian sourcing for Tulul al Baqarat tools provides also interesting volcanological inferences, for Nemrut Dag volcano, supporting volcanic correlation among outcrops and definite grouping of obsidian clusters, possibly related to different eruption episodes with rhyolitic flows.

Puteoli and the ripa Puteolana: archaeological and geological insights on a Roman submerged waterfront

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The submerged Roman districts of the ripa Puteolana, along a coastline of almost 2 km between the center of the port of Puteoli (now, Pozzuoli, Italy) and the Portus Julius, constitute an underwater archaeological area of extraordinary importance.

The headquarters of merchants and peregrini from every corner of the Mediterranean in the vicus Lartidianus, the endless rows of horrea at the service of the fleets of Rome in the vicus Annianus have been only scarcely explored in the past, due to the heavy and impactful presence of the industries that for most of the twentieth century characterized the west coast of modern Pozzuoli.

With the project *Tra terra e mare. Studi e ricerche nelle aree costiere dei Campi Flegrei / Between land and sea. Studies and research in the coastal areas of the Campi Flegrei*, born in 2021 from an agreement between the SABAP for the metropolitan area of Naples and the University of Campania Luigi Vanvitelli, with the collaboration, for the submerged areas, of the Scuola Superiore Meridionale, a systematic documentation program of the ripa Puteolana has finally been launched.

The underwater research carried on in 2021, 2022 and 2023 led to the reconstruction of the entire ancient waterfront, on the basis of an aerial photogrammetric survey calibrated with direct dives, to the identification of submerged horrea (warehouses), granaria (granaries) and quays in the vicus Lartidianus and vicus Annianus, to the localization of a previously unknown peninsula, destined to administrative duties in the harbour, and above all to the discovery of the submerged temple of the Nabataeans in Puteoli, the unique outside of Nabataea.

Together with these archaeological results, the collaboration established with the INGV made possible the collection of new important data on the relative sea level change in the bradyseismic area of Puteoli, in a period between the I and the IV century AD, when an impressive effort in the reconstruction of the breakwaters is performed, as a response to the growing level of the sea.

Chronicles of announcements eruptions in Poás volcano, Costa Rica

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On march 30th, 2024, Poás volcano began to erupt. That day, the ashes reached up to 12 km of the SW flank of the vent, affecting the local communities. Health centers located in this sector reported an increment of 22% in medical attention by respiratory problems, compared with the previous months.

In april 2017, after a month of volcanic unrest, as the increment in the temperature (up to 10° C) and level (1.5 m) of the “Laguna Caliente” lake, and the appearance of black spherules sulfur and new hot water fountains around the lake, a phreatic eruption marked the beginning of strong hydromagmatic to vulcanian explosions. These eruptions destroyed the dome structure formed in 1953-1955 eruption, throwing decimetric ballistic rocks as far a 1 km from the vent, reaching the looking point.

On april 6th 2022, a landslide triggered a new phreatic eruption in the East side of the “Laguna Caliente” lake. A month before, a new fumarolic field with a strong degassing was formed, accompanied by dozens of hot springs (90 °C, pH=2) in the zone where the eruption occurred. Since November, 2023, the Laguna Caliente lake decreased its level and new sulphur spherules and sulfur pools were visible in the surface of Laguna Caliente. On January, 2024 continuous explosions occurred, every 8 min, which sometimes reached 300 m above the lake level, accompanied by a strong decrease in the lake level. The lake was almost evaporated on the third week of march.

On March 30th, 2024, the local communities began to collect the erupted ashes, following a new and simple protocol to gather the samples. Eruptions occurred every day until april 5. The local communities sampled every eruption, day by day. Thanks to unprecedented citizen participation, we analysed the ashes and we found a large variability of the components day by day, revealing how complex the feeding system of these small eruptions is, usually underestimated by the scientific community.

Catalogue of the Etna eruptive activity from the 6th century BC to present

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The eruptive activity of Etna has been largely documented since the beginning of the recorded history, giving volcanologists a uniquely long record for an active volcano. Here we present the catalogue of the eruptive activity of Etna from the 6th century BC to present as reconstructed through a detailed review of previous catalogues, monitoring bulletins, reports and scientific literature.

The catalogue is divided in two parts: from 6th century BC to 1600 AD and from AD 1600 to present because the types and the quality of information available for the compilation of the datasets in these periods are different. In particular, the catalogue of the eruptions in the period 6th century BC-1600 AD is based on a re-examination of the original chronicles and previously published catalogues, within the context of the 2011 geological map and updated ages obtained with various geochronological methods. The catalogue of the eruptions in the period AD 1600 to present has been compiled through a detailed review of the scientific literature and a multidisciplinary approach that includes geological and historiographical studies.

The catalogue includes date, vent location, type of eruption, description of the deposits and references and will be available at INGV-OE web site. It unites in a single source the information thus far distributed in different scientific publications, not all of which are readily accessible to a broad public. Therefore, in order to make this catalogue more complete and robust, it will be open to contributions from other sources and information on the past and ongoing eruptive activity of Etna, and thus continuously updated.

The prehistoric obsidian of Lipari, Gabelotto and the so-called Pomiciazzo lava flow (Lipari, Aeolian Islands)

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This contribution intends to clarify the terminology used over time to indicate the volcanic phase of the island of Lipari which had greater recognition among prehistoric human communities, and which is at the origin of the population of the Aeolian Islands, commonly understood as the eruption of Gabelotto and the so-called Pomiciazzo lava flow. Gabelotto takes its name from the gorge located northwest of the town of Canneto, whose southern slope is largely made up of the thick deposits of this ancient eruption. The name Pomiciazzo is known in literature under various aspects: geological, topographical and historical-anthropological. Today it is a locality in the village of Lami perched on the SE slope of Monte Pelato (MP), located at an altitude between 200 and 300 m above sea level, whose soil is characterized by a high concentration of pumice. In addition to the typically white ones produced by the main crater of MP during the medieval eruptions, there are grey and filamentous pumices that were expelled from the adjacent crater of Lami in the second half of the 13th century. In geology, the toponym Pomiciazzo was adopted for the first time by Buchner [1949] to name the obsidian-rich lava flow which, starting from the village of the same name, descends along the northern margin of the Gabelotto stream, helping to form Punta Sparanello. The name assigned by Bergeat in 1899 to this formation was Ossidiane di Cannetello from the ancient toponym of the stream. In the last century, Keller [1970] defined its extension from the initial point of Gabelotto to the sea, calling it the Lami-Pomiciazzo lava flow. On the back of the casting, during the excavations which involved the construction of the Calandra road which connects Canneto to Lami, at an altitude between 100 and 130 m above sea level, numerous obsidian processing waste and coal remains pertaining to burning activities were unearthed. The latter, taken by Keller in 1969 and recently dated to the C14, returned a calibrated age of 5320-5217 BC [Martinelli et al., 2020]. Dating confirmed that the Pomiciazzo lava flow was the main source of obsidian supply in the Neolithic. The site is also of fundamental importance from a geological point of view as it constitutes a terminus ad quem of the coulée that flows along the Gabelotto torrent. Obsidian tools and processing waste were found by the archaeologist Buchner in another site south of Campo Bianco on a stretch approximately 200 m long, cited by the author as the Papesca locality, which coincides with Capo Rosso. The archaeologist specifies that the anthropic layer was interposed between the underlying pumice deposits dating back to an ancient eruption and the more recent ones of MP. The layer was characterized by stones and rusty-brown sandy detrital soil, about 1.50 m thick and composed of four horizontal levels filled with chipped obsidian alternating with sterile levels. Its formation has been attributed to a Neolithic frequentation as attested by a ceramic fragment from the Diana culture (4300-3700 BC) collected by Bernabò Brea. Such a complex stratification, in which tephritic pumices are interposed between the lava base and the paleosoil, is found only in Capo Rosso and would seem to demonstrate the greater age of this lava formation compared to the other lavas in the sector, on which instead the paleosoil is found and the deposits remain of MP. Furthermore, Buchner, during the reconnaissance, observed another lava “which extends along the entire Campo Bianco of which it forms the base”; the corresponding stretch is the one

between Spiaggia dell'Arena and Pietra Liscia. Cortese et al. [1986] consider the entire lava formation in the sector to be the effusive product of a single prehistoric eruption which they called Gabellotto-Fiume Bianco, whose eruptive centre was presumably positioned between Colle Sant'Eremo, Monte Chirica and Monte Pelato. From this moment on, the term Pomiciazzo includes all the lavas on the southern and eastern sides of MP that flow to the coastal level between Calandra and Pietra Liscia with the exception of Capo Rosso, classified by Forni et al. [2013], as an older endogenous dome. According to a different scheme previously proposed by Pichler [1976, 1980] which recognizes the occurrence of two main prehistoric eruptions in the NE of the island (Lower and Upper Pumice Series), the older obsidian lavas in the sector were essentially defined as the Monte Pelato lava dome; the most recent pumice cone is placed on them. The term Gabellotto flow used by Bigazzi and Bonadonna [1973], appears to be the most relevant of all to the only eruptive phase of prehistory currently recognized in the literature: Vallone del Gabellotto. The dating of the obsidians involved, obtained with the fission track method, returned the following dates: 11.4 ± 1.8 ka, 8.6 ± 1.5 ka and 7.17 ± 0.72 ka BP. The latter marks the arrival of the first inhabitants on the island.

Toponyms dataset of Stromboli volcano

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We present a dataset of toponyms of Stromboli volcano realized from the revision of the scientific literature that we analyzed for the compilation of the major explosions and paroxysms catalogue of the last ca. 150 years. We have collected a significant number of toponyms that, in the most of cases, have remained the same until the present day, and in few cases changed into modern names. These names are recurrent in the description of the eruptive activity because have been affected by different types of products, e.g. ballistic projectiles, fallout, lava flows, pyroclastic flows and tsunamis. The dataset contains the original toponym, the current name (if it changed), the coordinates of the location and the references. Therefore, their precise localization is important for the reconstruction of the eruptive history of Stromboli, especially for hazard assessment-related studies.

A multidisciplinary study for the recognition of fault-induced instability conditions on urban structures: the case of the 16th century AD St. Barbara's Church in Paternò (Sicily, Italy)

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The 16th century AD St. Barbara's Church in Paternò, located at the SW foot of Mt. Etna volcano (Sicily, Italy), since 2009 showed evident signs of structural instability and collapse, with great concern of the local population and growing hazard for the attendees to the masses. After the precautionary closure of the Church, we carried out geological, seismic, geophysical and geochemical surveys in order to shed some light on the possible causes of the phenomenon. From the results of all surveys above, the presence of a hidden fault was hypothesized. The fault would cross the west side of the Church, parallel to its front portal, and would continue both to the north and to the south of the edifice. It would be part of a more complex system of faults that crosses the whole town of Paternò and is likely a result of the complex dynamics of Mt. Etna. This fault seemingly is also the pathway for the upward flow of saline hydrothermal fluids, similar in composition to those already emitted in nearby areas and whose corrosive action possibly concurred to the weakening of the rocks beneath the Church. Temporal monitoring of several hydrological parameters (water temperature, water level and CO₂ content) in some sites into and around the Church allowed a better understanding both of the fault dynamics and of the extent of hydrothermal influence in the studied area.

The Mazzola archaeological site of Ischia, (Southern Italy): evidence of close relationships between humans and volcanism, on the border between hazard and resource

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Living in active volcanic areas is a challenge that humans have always accepted, despite the hazards posed by volcanoes. This was mainly due to high soil fertility, particularly in good climate conditions, or for the presence of ore deposits and the abundance of volcanic rocks that are good building materials.

The history of this kind of interaction is under investigations at Ischia, in the Neapolitan volcanic area (Italy), thanks to the close collaboration between archaeologists and volcanologists. Although volcanism was very intense on the island during the period in which civilization began to gain ground, Ischia was almost continuously inhabited since Neolithic times being humans alternately beneficiaries and victims of the island's nature.

Here we present the preliminary results of the resumed excavation activities in the archaeological area of Mazzola (Lacco Ameno, Ischia). This site, previously investigated between 1969 and 1971 by J. Klein, is occupied by a series of residential and artisanal structures referable to a Greek settlement, covering a wide chronological span that, with some significant caesuras, goes from the Middle Bronze Age 1B-3 (16th-early 14th century BC) to the archaic age (first half of the 6th century BC). The archaeological site of Mazzola constitutes a case study of particular interest which allows us to reflect, from an ecological point of view, on the close relationship existing between ancient communities and environment. It is highlighted, in fact, how the volcanic nature of the island of Ischia has constantly influenced the methods of occupation of the territory, sometimes negatively, causing the abandonment of inhabited areas following eruptive phenomena, but also positively, offering important resources that can be exploited. The archaeological stratigraphy brought to light by the recent excavations conducted in Mazzola allow us to reflect on both aspects. In the second half of the 8th century BC the Greek settlement was characterized by the co-presence of residential structures and open or semi-open areas dedicated to the artisanal processing of metals, especially iron and bronze. Among the various operations connected to this process it was possible to document pyrotechnological activities which involved the use of fragmented volcanic rocks, which, peculiarly, had a strong magnetic charge. A macroscopic examination of the rock fragments found in pits dug in the artisanal area, allowed them to be attributed to the lava formations widely exposed in the neighborhood. In order to verify the hypothesis that these rocks could be used in some way for the iron industry, some fragments were taken to perform mineralogical, petrographic and isotope analyses, by using XRD, SEM-EDS and TIMS methods. The analyses are still in course or planned (bulk rock geochemistry) and their results will be available soon.

The activities in the settlement continued over time until the beginning of the 7th century BC, when there was an abrupt break in the occupation of the site. This interruption is evidenced by a thin volcanic deposit composed of ash and millimeter-size pumice clasts, which seals the underlying stratigraphy. As evidenced by the archaeological stratigraphy placed immediately above the volcanic deposit, this caesura lasted until the beginning of the 6th century BC, when the site was reoccupied and it was possible to recognize a new building phase, which involved the construction of a rectangular building made with Mt. Epomeo Green Tuff blocks. The stratigraphic position of the volcanic deposit and its sedimentological characteristics allowed us to hypothesize the correlation with a similar pyroclastic deposit (the Punta Chiarito Tephra) exposed in the south-western corner of the island, which marks also in that case, the abandonment of a Greek settlement at the beginning of the 7th century BC and its later reoccupation. Detailed compositional and isotopic analyses are still in progress also for this volcanic deposit.

S06 - STROMBOLI VOLCANO AND ITS VARIABILITY IN ERUPTIVE INTENSITY: ADVANCES IN UNDERSTANDING ORIGINS AND IMPLICATIONS

Conveners:

Federico Di Traglia, Marco Pistolesi, Giuseppe Salerno, Alessandro Aiuppa

Sudden changes in pre-eruptive dynamics controlled the highly explosive ancient eruptive cycle of Petrazza (77-75 ka, Paleostromboli I) at Stromboli

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The interaction between regional tectonics, volcano-tectonic activity, and the amount of magma input from depth is the main factor that influences the trigger and explosivity of a volcanic eruption. At mainly constant magma input rates, the opening or closure of conduits, along with shallow dynamic events like sector collapses, landslides, caldera-forming eruptions, and the opening or closing of conduits, can regulate eruptive mechanisms, resulting in increased eruption explosivity. The source's variable magma input rate can control eruptive dynamics by promoting extreme differentiation processes (low input rate), gas flushing and/or magma mixing/mingling in the shallow portion of the magma feeding system, which ultimately leads to a rise in explosivity and energy of eruptions.

Stromboli's ancient volcanic-stratigraphic succession records a period of unusually high-energy explosive eruptions that is likely linked to partially or totally closed conduit dynamics. Our research focuses on the products of the Petrazza eruptive cycle (77-75 ka), which is part of the Paleostromboli I eruptive epoch (85-75 ka), along the Stromboli southeast flanks. Using a multi-disciplinary approach that includes whole rock, mineral compositional and textural studies, as well as geobarometry, we confirm the conditions of a closed conduit system, allowing extensive magma differentiation and amphibole crystallization. The transition from closed to open-conduit conditions caused decompression in the plumbing system. The input of hotter, more mafic magma triggered high-intensity explosions that gradually replaced the residing magma in the intermediate/shallow portions of the feeding system, leading to open-conduit eruptive dynamics. Under water-undersaturated conditions, a rapid magma ascent was caused by an extreme decompression event in the magma feeding system that occurred near the end of the eruption, probably caused by a structural collapse of the volcanic edifice. This resulted in a high-energy explosive eruption, considered the largest in the Stromboli volcanic system.

Evolution of the eruptive activity at Stromboli (Aeolian Islands - Italy) during the last 4 millennia. A tephrostratigraphic investigation on the early-phase of Recent Stromboli Eruptive Epoch

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Stromboli is known for its persistent activity and for the steadiness of its feeding system over the time. Although extensive research has been conducted on the various facets of the recent centuries volcanic activity, there is a paucity information regarding the early-phase of the Recent Stromboli Epoch (4 ka - present day), specifically spanning the period between the end of the Neostromboli Epoch and the onset of the present-day activity. In this study, we present a thorough tephrostratigraphic investigation combining field observations and sedimentological characteristics of the tephra layers with detailed textural, petrographic and geochemical analyses of juvenile clasts, along with radiometric ¹⁴C dating. This comprehensive approach allowed us to reconstruct the eruptive history, the changes in magma composition and the associated eruptive style during the past four millennia.

Specifically, during the last 4000 years and preceding the onset of the present-day activity, we document at least thirteen large eruptions characterized by a sequence of up to 50-cm thick, well-sorted beds of fine to coarse scoriaceous lapilli, alternating with massive epiclastic deposits showing faint stratification and/or mature paleosols. Such lithology likely reflects an eruptive style of repeated episodes of fire fountains, separated by periods of quiescence or weaker strombolian explosive activity.

Noteworthy is the change in magma composition with the seven oldest eruptions, occurring between 3200 and 1780 years BP, having High-K Calcalkaline (HKCA) affinity, whereas the following six belong to the Shoshonite (SHO) series. Additionally, this study unveils the first-time evidence of coexistence between low-porphyricity (LP) and high-porphyricity (HP) magmatic end-members in both HKCA and SHO series, suggesting the significant role of pre- or syn-eruptive interactions between two magmas in triggering explosive eruptions over the past 3200 years and in present-day activity.

Furthermore, we report that over the last 3200 years, except for the San Bartolo lava, there has been a progressive increase in the content and size of phenocrysts within the HP magmas. In particular, early products of the SHO series (older than 820 yrs cal BP) are less crystalline and more evolved (in both HP and LP terms) than those erupted during present-day activity. Therefore, we infer that the shift in eruptive style observed during Recent Stromboli Epoch, from the early lava fountains to the late persistent Strombolian explosions punctuated by paroxysms characterising the present-day activity, may be associated with the progressive increase in phenocryst size and content, thereby modifying the rheological properties of the HP magma in the shallow portion of the volcano's plumbing system.

These findings contribute to a holistic comprehension of Stromboli's volcanic history and hold practical significance for anticipating and mitigating potential future volcanic events.

Morphological evolution of the subaerial and submarine Sciara del Fuoco slope in response to eruptive and reworking processes

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The Sciara del Fuoco (SdF) scree slope is a partially-filled collapse scar, formed through the accumulation of volcanoclastic deposits and lava flows, and their subsequent reworking by mass flows and exogenous phenomena. Besides collecting the products of eruptive activity, it is the seat of persistent small-scale instability phenomena such as rockfalls and debris flows and, occasionally, of larger landslides of rock and volcanoclastic debris, such as the landslide occurred on December 30, 2002. Since then, Stromboli experienced flank eruptions (2002-03; 2007, 2014, 2019) and periods characterized by more intense eruptive activity, with frequent explosions, lava overflows from the crater and collapses of the crater rim. These processes lead to significant accumulation of volcanogenic material on the SdF subaerial and submarine slope but also to seafloor erosion and slope instability (2012-13, 2021, 2022). Conversely, during periods of reduced explosion frequency, the dominant processes on the slope are subaerial erosion and marine-driven reworking. Overall, the SdF slope (both subaerial and submarine) is continuously changing in response to different processes inducing erosion and deposition; significant geomorphological changes occur in short periods of time (days to months) and often obliterate preexisting morphologies.

To investigate the geomorphological evolution and dynamics of the SdF slope in response to eruptive events and reworking processes, comprehensive multi-platform and multi-temporal topo-bathymetric surveys, complemented by remote sensing data, have been carried out over the past decades. This dataset encompasses a range of topographic data sources, including multi-temporal digital elevation models (DEMs) generated by Light Detection and Ranging (LiDAR) technology and photogrammetric methods (satellite images and unmanned aerial vehicles). Offshore data were collected by repeated multibeam bathymetric surveys integrated by side scan sonar and video records (ROV), providing ground truth information of the submarine flank. These observations, acquired before, during and after main events, also allowed to estimate the erupted/remobilized volumes with a high level of detail.

The reconstructed morphological evolution of the SdF slope evidenced the correspondence (also in volumetric terms) between subaerial-submarine erosional and depositional morphologies

(such as chutes or debris fans, respectively) as well as the morphological continuity of main lava flows reaching the sea and constructing short-lived deltas. These features are rapidly changing in time, being generally scarcely preserved, especially at the foot of the slope, where wave erosion is effective in dismantling lava deltas and volcanoclastic deposits. However, the remnants of previous morphological features still play an important role in controlling the distribution and path of products involved in successive (eruptive and/or mass transport) events, for instance through the shifting of depocenters and mechanisms of morphological compensation. This clearly appears in the morphological response of SdF to the eruptive activity observed during and after the 2014, 2019-21 and 2022-23 eruptive phases]. The observed relationship between eruptive dynamics and slope instability (that can be promoted by the former one) may contribute to a better understanding of triggering phenomena and mechanisms leading to the remobilization of volcanoclastic deposits along the SdF slope, as recently observed for pyroclastic density currents entering the sea and triggering submarine slope failure.

Stromboli represents a peculiar case study for observing the geomorphological response of a volcano's flank under active dynamics. On the other side, due to the fast evolution, the low preservation potential of morphological features on the SdF slope may reduce the record of past events, and this has to be considered in the assessment of recurrence times of main eruptive and slope instability phenomena.

Can Vulcanian eruptions occur at open conduit Basaltic Volcanoes?

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Stromboli is an active, open conduit mafic volcano, whose persistent mild Strombolian activity erupts highly crystalline dark scoria (HP), associated with degassing of magma residing in the volcanic conduit at shallow levels. This ordinary activity is occasionally punctuated by much stronger explosions, known as paroxysms, which also erupt low-porphyritic golden pumice (LP) associated with the eruption of deeper, volatile-rich magma.

Here, we investigate the eruption style of the July 3rd, 2019 paroxysmal event at Stromboli volcano through textural analyses of the LP pyroclasts. This eruption produced an eruptive column ~8.4 km high above the volcano summit, severe fallout, and pyroclastic density currents down to the Sciara del Fuoco. All these features can be reconciled with those generally observed during Vulcanian eruptions. However, Vulcanian eruptions worldwide typically occur at closed conduits and intermediate to felsic volcanoes, where the accepted conceptual model is a top-down sudden decompression-driven fragmentation due to the failure of the shallow viscous magma plug or dome.

We present new qualitative and quantitative 2D and 3D data on LP pyroclast textures. These data show that the external shape, as well as bubble shape and size distributions of these pyroclasts, were formed in response to sudden vesiculation rapidly followed by brittle fragmentation and quenching. We propose that this vesiculation style is better explained by a top-down decompression of ponding LP magma due to the sudden pressurization and failure of the shallow, weak HP plug, rather than the widely accepted model involving the rapid ascent of batches of volatile-rich LP magma from 8-10 km depth. Our working hypothesis is that gas accumulation at depth within the plumbing system leads to the upward movement of the magma column, lava effusion and the resulting decompression triggers the explosion of the HP plug.

Constraints on magma source, pre-eruptive dynamics and timescales of the 2009 major explosions at Stromboli volcano (Italy)

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Stromboli is one of the best studied and monitored open-vent volcanoes worldwide, but still our understanding of the magma source, triggering mechanisms and ascent timescales of larger explosive events than the normal Strombolian activity remains incomplete. Within this variability, major explosions are relatively frequent (1-4 events/year) explosive eruptions of intermediate intensity between the recurrent (10 events/hour) and low-intensity regular Strombolian eruption and the more violent and rarer eruptive paroxysms (with the most recent occurred in 2003, 2007 and 2019). While regular explosions are fed by a crystal-rich (HP, high porphyricity) magma residing in a degassed shallow reservoir (less than 3 km), and paroxysms by volatile-rich (LP, low porphyricity) magma rapidly ascending from the deep portions of the plumbing system (6-9 km b.s.l. down to the crust-mantle interface), much less is known about the magma source of major explosions.

Here we present a comprehensive dataset on dissolved volatile contents (H₂O, CO₂, S and Cl) in olivine-hosted melt inclusions (MI), embayments and glassy matrix, coupled to major element compositions and Fe-Mg diffusion profiles in olivine phenocrysts from three major explosions which occurred on 3 May, 8 November and 24 November 2009. Each of these events consisted of a brief explosive sequence that erupted coarser and more widely dispersed tephra than ordinary eruptive activity, with the 24 November 2009 event being the most energetic one.

Olivine-hosted melt inclusions from the 24 November 2009 event have dissolved H₂O ranging from ca. 0.22 to 2.37 wt% and CO₂ generally below the detection limit, with a maximum of 576 ppm. Major elements composition of melt inclusions varies from the compositional field of HP products toward the LP compositional field. Two distinct compositional clusters (one overlapping with the HP compositional field and one overlapping the LP one) are observed in the glass wetting the phenocrysts, with no intermediate compositions. Excluding the rare occurrence of homogeneous evolved olivines (Fo70), the majority are variably reversely zoned, with Mg-richer (Fo77-83) reaction rims (50-100 µm thick). Melt inclusions from the 8 November 2009 event have H₂O ranging from ca. 0.15 to 0.55 wt% and CO₂ always below the detection limit. Melt inclusions from the 3 May 2009 event have H₂O ranging from ca. 0.15 to 0.75 wt% and CO₂ below the detection limit, major elements composition overlaps the HP compositional field. The host olivines are compositionally homogeneous and evolved (Fo70-72).

Volatile contents of MI (EMPA and FTIR) suggest that these explosions are fed by more degassed, shallow stored magma if compared to paroxysms. Preliminary data suggest a positive correlation between eruption magnitude and volatile content. Volatile elements are higher in

the most energetic major explosion of 24 November 2009, which erupted larger volumes of coarser pyroclasts of both HP and LP magma that eventually reached the coast of the island. In contrast, the 8 November and 3 May events ejected a smaller volume of pyroclasts (mostly confined to the summit area of the volcano) with a minor LP component, suggesting a shallower source origin.

The monitoring of the submarine portion of Sciara del Fuoco (Stromboli) by using a USV (Unmanned Surface Vehicle)

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Stromboli Island is the emerged portion of a 3000 m-high volcano of the Aeolian archipelago located in the Southern Tyrrhenian Sea. Its northwestern sector is carved by a very steep horseshoe-shaped scar called Sciara del Fuoco (SdF), along which the pyroclastic rocks erupted during the explosive activity of the volcano, as well as the lava flows generated by the summit craters or by lateral vents during effusive activities, flow down before to reach the sea.

Thus, both the subaerial and submarine portions of SdF are characterized by rapid geomorphological changes and are prone to gravitational instability induced by the combination of volcanic and depositional processes like: i) deformation triggered by dikes intrusions and ii) accumulation of volcanic products (pyroclastic rocks and lava flows) forming weak aprons and lava deltas in the nearshore. This gravitational instability could led to mass failures, such as the December 30th, 2002 landslide. The slide was triggered by the instability of the submarine portion of SdF and involved an overall volume of 24 Mm³ of rocks [Baldi et al., 2008; Chiocci et al., 2008], which generated a tsunami propagating around Stromboli and onto nearby islands. Occasionally, SdF is also affected by pyroclastic flows, which are produced by more energetic explosions (paroxysm and major explosions) or by overflows at the summit craters. Since 2019, six pyroclastic flows have been observed along SdF; some of them advanced up to 1 km offshore the shoreline.

Consequently, navigation within the first 2 miles offshore SdF is forbidden.

In order to study the stability of the submarine portion of SdF in correlation with the subaerial morphological modifications and with changes in the volcanic activity we are setting a monitor system by using a USV (Unmanned Surface Vehicle), equipped with a Multibeam EcoSounder, aimed at identifying eventually morphological changes along SdF through difference maps obtained by comparing multibeam data acquired during different surveys.

The Otter USV (Unmanned Surface Vehicle) by Maritime Robotics is the ultimate hydrographic tool for high-resolution bathymetric surveys in sheltered waters. It can be easily transported being a catamaran with reduced dimensions: 200 (length) x 108 (width) x 106 (height) cm. Moreover, it can be dismantled into smaller components. The Otter is equipped with electric thrusters that are powered by four easily interchangeable batteries, providing an endurance of up to 9 hours at 3 kn. Ideal for frequent and repeated surveys, the Otter USV is equipped with an HR Multibeam EcoSounder Kongsberg EM2040P, operating with an innovative multi-frequency mode (up to 5 frequencies in a single pass) within a frequency range of 200-700 kHz, that allows acquiring bathymetric data with a depth range of 0 – 550 m.

The Otter is also equipped with an AML 3 Hydro Sound Velocity Profiler, which could be lowered down to 100 m of depth by using the USV winch. The Otter can be controlled through a Vehicle Control Station or a mobile phone app. The operator can easily plan missions consisting of individual waypoints, or use templates for creating common patterns. Live monitoring and visualization of sensor data parameters (e.g. multi-beam quality data, swath width, coverage area) are provided in Vehicle Control Station. The Otter USV represents the best compromise between cost, transportability and data quality, and the best solution to acquire HR multibeam

data without the employment of acquisition teams and vessels in such a potentially dangerous area like the nearshore sector of SdF.

Additional scientific goals and applications for using the Otter USV are i) the monitoring of submarine hydrothermal vents by identifying gas emissions, being the EcoSounder Kongsberg EM2040P able to display and storage of water column backscatter data; ii) the nearshore seafloor mapping for modeling of tsunami scenarios offshore Italian coasts.

Joint exploitation of multi-frequency and multi-platform DInSAR data to monitor ground displacements in volcanic areas: the Stromboli case study

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Differential Synthetic Aperture Radar Interferometry (DInSAR) is a well-known technique that allows measuring the displacements affecting the Earth's surface, in both natural and anthropic hazard scenarios, with rather limited costs and a centimeter to millimeter accuracy. Moreover, thanks to the availability of long SAR data time series, it is also possible to investigate, and in some cases monitoring, the temporal evolution of the detected surface deformations through the so-called advanced (also referred to as multi-temporal) DInSAR techniques.

In the last three decades the effectiveness of the satellite DInSAR technology for ground deformation analysis, and its crucial role in emergency scenarios, have been largely demonstrated and applied in many scientific and operational contexts. In particular, starting from the 90s, thanks to the continuative C-band (~5.5 cm wavelength) SAR data availability of the ERS-1/2 and ENVISAT sensors, developed by ESA, Europe become an international reference in the DInSAR technology field. Nowadays, the real game changer in the DInSAR Earth Observation (EO) activities, is represented by the C-band Sentinel-1 satellite constellation of the Copernicus program. Indeed, since 2014 Sentinel-1 has been providing a huge amount of SAR data across the Earth with an unprecedented continuous and high acquisition rate. These characteristics, together with the free and open access Copernicus data policy, have boosted the deployment of operational DInSAR services aimed at monitoring the Earth's surface displacements, with key applications represented by volcanic and seismic phenomena investigations.

Moreover, several investments have been made in the past, in particular by the Italian (COSMO-SkyMed of First and Second Generation) and German (TERRASAR-X and TANDEM-X) space agencies, on the development of X-band (~3.1 cm wavelength) SAR sensors, and very significant are those carried out, in the last years, by ESA and several national space agencies, in the development of new L-band (~23.5 cm wavelength) satellite SAR missions. Specifically, we refer to the forthcoming ROSE-L (ESA), ALOS-4 (JAXA) and NISAR (NASA-ISRO) missions, as well as to the already operating SAOCOM-1 (CONAE) and ALOS-2 (JAXA) systems. This clearly shows the growing relevance that is nowadays attributed to L-band systems, particularly, for what attains their DInSAR applications. Indeed, it is worth noting that the L-band is effective in maintaining coherence for a long period over vegetated areas and in various cases of snow/ice-covered zones, thus allowing to overcome the typical limitations of high-frequency systems, operating at C- and/or X-band. Accordingly, we envisage that the capability of the L-band DInSAR

measurements, combined with an expected lower ambiguity to (unwrapping) errors, will be highly beneficial for the detection, monitoring and post-event assessment of rapid deformations characterizing several geohazards, such as landslides, earthquakes and ground motions in volcanic areas.

Finally, it is worth remarking that, despite the above-mentioned capabilities, the satellite SAR technologies may also have several limitations, thus pushing the joint use of data and measurements derived from different geodetic sources. In particular, the Ground Based SAR systems have proved to be powerful sensors for monitoring active landslides, glacier movements and volcanic deformations, due to its flexibility in observation direction and very high acquisition sampling.

Accordingly, in this work, we present a multi-frequency and multi-platform advanced DInSAR analysis (displacement time series, mean deformation velocity maps and/or single displacement maps) to retrieve the deformation field and the gravitational instability of material deposited during eruptive activities, related to the Stromboli volcano. In particular, we exploit Sentinel-1, SAOCOM-1 and GB-SAR data to investigate the volcano dynamics dating back to 2015. We remark that Stromboli is one of the best-known volcanos in the world, and its persistent activity consists of frequent, small-scale explosions interleaved by major or paroxysmal events. The most hazardous phenomena at Stromboli Island are the mass-flows induced tsunamis, likely generated by both intrusion-related landslides from the Sciara del Fuoco and the entry into the sea of pyroclastic currents produced during high-intensity explosions.

The presented results highlight the significant complementarity of different SAR sensing systems and clearly demonstrate the effectiveness of a joint approach to map, monitor and possibly interpret the deformation phenomena affecting volcanic areas.

Monitoring and modelling of repeated crater-rim failures of the Stromboli volcano (Italy)

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At Stromboli, effusive phases, whether from overflow on the crater terrace or from ephemeral vents in Sciara del Fuoco, are associated with small instability events (in the range of 104-106 m³). Often involving incandescent material, these phases manifest as debris slides transitioning into glowing rock avalanches, known as deposit-derived pyroclastic density currents (PDCs). To improve short-term hazard assessment, it is necessary to understand the precursor signals derived from monitoring these events. Here, we re-evaluate ground deformation data to assess the effectiveness of current warning procedure for the occurrence of 'deposit-derived' glowing avalanches. The ground deformation analysis is focused on the study of line-of-sight displacements recorded by two Ground-Based Synthetic Aperture Radar (GB-SAR) instruments using Interferometric SAR technology (GBInSAR) deployed on Stromboli to monitor Sciara del Fuoco and the crater terrace. One GBInSAR (NE400) was in operation from February 2003 to August 2022, while the other (NE190) has been in operation since December 2014. Operating in the Ku-band (17.0-17.1 mm), GBInSAR at Stromboli offers a revisit time of 6-7 minutes and an image averaging time of 30 minutes to improve the signal-to-noise ratio. Stromboli presents an ideal case for investigating these phenomena due to their frequent occurrence, the extensive dataset continuously gathered by GBInSAR deformation monitoring systems, and the presence of comprehensive multi-parametric volcanological and geophysical monitoring networks. Moreover, detailed descriptions and quantifications of geomorphological variations resulting from eruptive activity have been provided for each episode, offering crucial constraints for radar monitoring. Detection of topographic changes was achieved through the comparison of digital elevation models (DEMs) generated from surveys using uncrewed aircraft systems (UAS) at different time points. The integration of GBInSAR analysis with topographic change measurements served to constrain and validate 3D limit equilibrium and 2D finite element analyses of slope stability, shedding light on the nature of failure mechanisms potentially triggered by volcanic activity along the Sciara del Fuoco. Over the course of two decades of research, these findings have facilitated the development of operational strategies for managing the volcano's eruptive activity and associated slope instability, which could potentially lead to tsunami generation.

The transport behaviour of the Stromboli's volcanic plume inferred from combined scanning-DOAS and UV Camera observations

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The volcanic SO₂ flux has long been known as an especially useful tracer of the rate of magma supply into the shallower portions of volcano plumbing systems, and as such is central to volcano monitoring. SO₂ fluxes from active volcanos are widely measured globally with networks of scanning spectrometers coupled with the DOAS technique and UV camera systems. However, observations have traditionally been challenged by a variety of technical and methodological caveats and limitations, to overcome which an intercomparison between, and eventually integration of, different observational techniques are required. The ability of scanning-DOAS spectrometers to scan the plume from distance and from different viewing directions, allows to fully capture the “bulk” gas plume, utilising the robustness of DOAS technique to significantly reduce radiative transfer and light dilution issues. Disadvantages exist, however, especially arising from assumptions that must be made on geometry and height of the plume and, most importantly, using wind speed as a proxy for the real plume velocity. UV Cameras, in contrast to scanning spectrometers, are typically deployed near the active vents and measure the two-dimensional SO₂ distribution in the plume with a greater spatial and temporal resolution, applying optical flow algorithms to the acquired images and estimating the plume vertical velocity profile at source. However, the proximity to the active vents often causes the plume to be only partially imaged by UV Cameras, due to morphological complexity of volcano summits or unfavourable wind directions causing underestimation of the measured SO₂ flux. Furthermore, targeting the proximal and most optical opaque portion of volcanic plumes cause UV Cameras measurements to be more prone to errors related to radiative transfer issues.

All remote sensing techniques aimed to measure SO₂ fluxes can effectively ‘measure’ only gas concentrations and retrieve a gas flux by combining these measurements with estimates of the gas movement speed. To measure a gas flux away from the source (as scanning-DOAS networks do), a conservative flux model is traditionally assumed, which considers a continuous and stationary-type source. Based on this assumption, it is possible to measure a flux in distal analysis sections, by relating it to the distal-measured gas concentration, as the flux is retrieved as the product of the gas concentration with its velocity. Furthermore, in order to maintain a gas flux equal to that at source, it is assumed that gas concentrations are linearly scaled with speed, an aspect that has been little considered in the past.

Here, we compare ~9 years (2014 to 2022) of SO₂ flux records at Stromboli obtained through (i) a near-vent UV Camera system and (ii) a network of DOAS spectrometers scanning the distal bulk plume. Our combined near-vent and distal observations offer a unique opportunity to test models of gas plume dilution in the atmosphere and the local emissive source behaviour. We find a large (133 t/d on average) systematic offset between the SO₂ flux time-series streamed by the two observational techniques. Using empirical evidence, we propose this SO₂ flux mismatch to be dominantly caused by the non-continuous emission behaviour of the Stromboli's volcanic plume. If gas at Stromboli is emitted from source in discrete parcels ("puffs") rather than continuously, then the extent of plume dilution upon downwind atmospheric transport does not scale linearly with wind speed. Hence the SO₂ flux cannot be accurately retrieved from combination of wind velocity and SO₂ integrated column densities. If our hypothesis of non-continuous plume behaviour is not unique to Stromboli, but generally valid, then SO₂ fluxes can have been overestimated at volcanoes globally.

Our work suggests that a combined approach, integrating (a) gas velocities derived from optical flow algorithms implemented into UV Cameras system with (b) SO₂ column amounts obtained by DOAS processing of spectra delivered by scanning spectrometers (one properly back-calculated at near-vent conditions), may offers a sound solution for more robust SO₂ flux records, mitigating against the effects of caveats/limitations associated with each individual technique. We expect this combined SO₂ flux to be less affected by external factors (meteorological, illumination and volcano topography conditions), and hence a better proxy of volcano behaviour, with obvious benefits for volcano monitoring and volcanic hazard assessment. We recommend testing of this integrated method at other volcanoes to explore its utility for improved volcanic degassing characterization.

Joint Analysis of Distributed Acoustic Sensing (DAS), Seismic, and Infrasonic Observations of Volcanic Tremor, Explosions, and Pyroclastic Density Currents at Stromboli Volcano (Italy)

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Investigating geophysical signatures of volcanic phenomena is crucial for eruption forecasting and monitoring. In seismo-volcanic applications, Distributed Acoustic Sensing (DAS) presents new opportunities for long-term surveys at very high temporal and spatial resolutions using fibre-optic cables. We analyzed DAS strain rate signals generated by volcanic tremor, explosions, and pyroclastic density currents at Stromboli volcano (Italy), jointly with conventional seismic and infrasonic measurements. We recorded DAS data along a 4 km optical fibre deployed between 2020 and 2022. Additionally, we installed several arrays of nodal seismometers along the cable to validate and calibrate DAS strain-rate measurements. We also compared the DAS recordings with data from the monitoring network of the University of Firenze (Italy), comprising broadband seismometers, infrasonic sensors, and monitoring cameras. The inversion of time delays between DAS strain rate waveforms yields back-azimuths that indicate a dominant seismic source near the active craters during volcanic explosions and tremor. These results match those obtained with seismic and infrasonic arrays. Furthermore, we analyzed two pyroclastic density currents that occurred in 2022. These flows travelled downslope from the craters to the shore, generating centimetre-scale tsunami waves upon reaching the sea. The back-azimuths estimated with the DAS array allowed us to track the downslope movement of the seismic source, consistent with the results obtained via seismo-acoustic data and with the images recorded by the monitoring cameras. These findings demonstrate the potential of this new technology in monitoring volcanic areas.

Thermal emissions of active craters at Stromboli volcano: spatio-temporal insights from ten years of satellite observations

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Open-vent volcanoes continuously emit magmatic products and frequently feature multiple adjacent craters, in which volcanic activity shifts from one to another. Temporal records and shifts of thermal emissions are especially detectable by InfraRed satellites. Here, SENTINEL-2 and LANDSAT-8/9 Short Wave InfraRed (SWIR) high-spatial resolution satellite data, are combined to investigate ten years (2013-2023) of thermal activity at Stromboli volcano (Italy). The correlation between Volcanic Radiative Power (VRP) and Volcanic Radiative Energy (VRE), retrieved by moderate MODIS and VIIRS Middle InfraRed (MIR) data, with the Thermal Index SWIR data, allows us to quantify long-term series of heat fluxes (VRPSWIR) and energy (VRESWIR). This approach allows to measure thermal activity sourced by single craters during Strombolian activity. Long-term results highlight that thermal emissions are clustered in two sectors, located in the northern and southern parts of the crater terrace, with a total energy emitted ($\sim 12 \times 10^{14}$ J) equally distributed. The thermal increase observed since April 2017 marked a progressive reactivation of shallow magma transportation and a gradual intensification of the activity, after the 2014 eruption. Distinct thermal behaviors are shown by the NE, C and SW craters, related to different mechanisms of explosions. We identify shorter-term thermal variations that match well those resolved by ground-based signals, and the NE crater as the most sensitive to the transition to higher-intensity activity. Our multispatial/multisensory investigation allow, for the first time, the long-term quantification of heat flux from Stromboli's craters, with an improved understanding of open-vent dynamics and a new approach to monitor multi-craters volcanic context.

Effusive events at Stromboli volcano and their correlations with major explosions and paroxysms with uncertainty quantification

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Stromboli volcano (Aeolian islands, Italy) is known for its almost persistent activity since the VIII century CE, where ordinary explosive activity of small energy is punctuated by larger explosive events (major explosions and paroxysms) and lava effusion events. The latter can be of different types and scales, from short-lasting or intermittent overflows, often limited to the upper part of the volcano, up to prolonged periods of quasi-continuous lava effusion that could reach the coastline, and last for weeks/months.

The episodic occurrence of effusive events before or after large explosive events has been observed in the last decades, but only limited quantitative statistical analysis of the correlations and inter-event times among these types of activities have been done.

By relying on the large amount of information contained in monitoring and surveillance bulletins and scientific reports and articles, we first carried out a comparative review of effusive events at Stromboli over the last 50 years. Then, by critically reviewing tens of historical scientific articles and taking advantage of the existing catalogs, the analysis was extended up to the last 150 years. We counted 231 confirmed events and 19 uncertain events for a total of 250 events. They were divided into three categories based on a statistical analysis of their duration, herein assumed as a proxy of the potential erupted volume. Location of products and other characteristics of the phenomenon were used to constraint the uncertainty affecting their duration. An additional category named “Intermittent Effusive Period” (IEP) was also considered to account for events which were composed by a series of discrete effusions closely located in time. The study also included the identification and characterization of uncertain events as well as the quantification of their uncertain durations.

Collected data were used to produce an open database and to analyze mean recurrence times between events, annual rates, as well as their temporal correlations with major explosions and paroxysms. Results allowed quantifying the chance of cascading phenomena and particularly the relative increase of probability of occurrence of explosive events conditional to the occurrence of effusive events and its variation in time. Results based on preliminary versions of the catalogs indicate that effusive and explosive activities show oscillating rates, with intensification and waning trends at annual/decennial scale. Moreover, ca. 25% of effusive events contained a major explosion/paroxysm and 35% of major explosions/paroxysms occurred during an effusive event.

Toward a real-time analysis of Stromboli explosive activity using Artificial intelligence methods on thermal images from monitoring camera

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Stromboli volcano is part of the Aeolian Islands archipelago (Italy) and is well known for being 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, which often produce 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”, which eject 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, affecting the lower slopes of the island, including densely (in summertime) inhabited areas, and form pyroclastic flows along the Sciara del Fuoco.

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 pattern that can lead to deviations from ordinary activity. Here we present an automatic system based on Artificial Intelligence (AI) for computer vision techniques, applied to the SPT thermal camera mounted on Pizzo sopra La Fossa (900 m a.s.l.), aimed at characterizing the explosions of Stromboli volcano. SPT is equipped with a FLIR device featuring an uncooled microbolometer FPA (Focal Plane Array) sensor, with a resolution of 320x240 pixels; it is in a strategic position, providing a full view of the crater terrace.

As the first step of the analysis, raw data were collected through the “Camera Viewer Software”, developed by INGV-OE, and then the images were assembled. These data need to be of the quality and quantity required for effective training of AI models. The software extracts sequences of frames in JPEG format from the downloaded videos (in AVI format) each containing 5 minutes of footage.

Next, data cleaning and preprocessing was performed. Initially, data cleaning involved manually checking each video, selecting frames where an explosion is visible, frames where explosions do not occur, and frames with no signal. In this way, data were distributed into different folders, corresponding to the following classes: i) Explosion; ii) No explosion; iii) Spattering; iv) No signal. Subsequently, a labeled dataset containing images and corresponding annotations was prepared. To train the real-time detector, it was also necessary to generate a bounding box, which essentially comprises the coordinates of a rectangular outline drawn around the area of hot materials (explosion) within an image.

After all, two models based on Convolutional Neural Networks were built. The first one is a Vgg16 model for classification [arxiv.org/abs/1409.1556], which focuses on categorizing frames where an explosion is present; the training accuracy was of 99.9 %, and test accuracy: 99.9 %. The second model was RetinaNet [arxiv.org/abs/1708.02002], aimed at localizing explosion from North or Central-South, within images. The training accuracy was 96.6 %, and the test accuracy: 95.0 %.

Finally, to calculate the volume and dispersal of an explosion, a third model is needed. For this task, a segmentation model using U-Net architecture [arxiv.org/abs/1505.04597] was built. This requires labeling image at a pixel level, meaning each RGB image needs its own grayscale mask with pixel values between 0 and 255. This generated three classes: i) white, with assigned a value of 0, ii) orange, with a value of 1 iii) and red with a value of 2. White pixels represent the volume, while orange and red represent dispersal area. The output is a prediction mask image.

The trained models were tested using an imagery dataset from SPT thermal camera from 15-09-2023 to 20-09-2023; during this period, the models detected 1602 explosions. For deeper validation, the results from 15 and 20 September were manually controlled and compared with the results of the trained models. These initial experimental results showed a high correlation, demonstrating the effectiveness of the proposed method. This indicates that AI-based methods can be very powerful for characterizing and analyzing explosive activity, improving quality and analysis time compared to manual control.

The variability of Stromboli activity is extensive. Therefore, future work will involve analyzing much longer periods to understand how AI-based models can help forecast the transition from ordinary activity to non-ordinary activity. We will focus the next analyses in the mounts preceding the 6-08-2014 lava flow eruption and the 3-07-2019 paroxysm, and in the weeks preceding several major explosions occurred in the last years.

Anomalies detection in Stromboli's pre-paroxysm activity during November 2018 - September 2019

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Stromboli (Italy) is an open-vent volcano known for its persistent explosive activity, generating up to five hundred mild explosions daily. The intensity of these explosions can fluctuate significantly, sometimes varying by orders of magnitude in terms of emitted volume, and can have abrupt impacts on the surrounding areas. Consequently, predicting larger eruptive events, particularly the more intense (paroxysmal) explosions, remains a significant challenge. Recent research has focused on identifying volcanological, geophysical, and geochemical anomalies that preceded the explosive events of 2019.

These studies have shown that while changes in the intensity of ordinary Strombolian activity were not detected prior to the paroxysmal phase, some changes in Stromboli's eruptive style were observed at least a month before the paroxysm of 3 July 2019. To search for anomalies in the pre-paroxysm activity related to the summer 2019 eruption, we applied a hybrid method for the automatic analysis of geophysical and geochemical time series. This approach integrates two techniques: 1. Empirical Mode Decomposition (EMD) and 2. Support Vector Regression (SVR). The combination of these methods enabled the identification of anomalies in the geophysical and geochemical parameters measured at Stromboli over a ten-month period, encompassing the July-August 2019 eruption.

Our findings indicate that parameters such as SO₂ flux, the VLP size parameter, the fractal dimension of the seismic signal, and seismo-acoustic clusters were particularly sensitive to variations in the eruptive style of ordinary Strombolian activity preceding the 3 July 2019 paroxysm. We detected numerous early anomalies in these parameters before the paroxysm, whereas anomalies were less evident in December 2018, a period characterized by increased ordinary Strombolian activity without significant changes in eruptive style.

The proposed hybrid method, when applied to seismic, geodetic, and geochemical data, has proven effective in detecting precursory anomalies both in intensity and eruptive style of the ordinary Strombolian explosive activity, prior to hazardous volcanic events such as powerful paroxysmal explosions. This suggests that the hybrid method could enhance the monitoring of Stromboli,

addressing challenges common to other persistently active volcanoes (e.g., Etna, Italy; Volcán de Fuego, Guatemala; Sakurajima, Japan; etc.). Therefore, this method could contribute to the safety of communities in volcanic regions and improve our understanding of volcanic processes.

Airborne Single-Pass SAR Interferometry for Stromboli Volcano Monitoring

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Synthetic Aperture Radar (SAR) is an active imaging sensor, typically mounted onboard spaceborne platforms or airborne ones, such as airplanes, helicopters or unmanned aerial vehicles.

Airborne sensors have great operational flexibility, in particular they are not subject to the satellite orbital constraints and have very tight revisit times, even of the order of a few minutes. Due to the limited flight altitudes, the airborne sensors illuminate smaller swaths compared to satellite sensors but the final products have comparable geometric resolutions. All these features make airborne sensors particularly suitable for environmental monitoring activities, especially in case of emergency. A noteworthy airborne SAR infrastructure is the one developed at the Institute for Electromagnetic Sensing of the Environment (IREA) of the National Research Council of Italy (CNR), [Natale et al.: Monitoring volcanic areas through the IREA-CNR airborne SAR infrastructure, EGU General Assembly 2024, Vienna, Austria, EGU24-21176, 2024]. The aim of this facility is to plan and execute SAR data acquisition campaigns and to process the acquired data. This infrastructure is currently exploited in the frame of an agreement between IREA-CNR and the Department of Civil Protection of the Presidency of the Italian Council of Ministers for monitoring volcanic areas, especially in case of emergencies. The airborne infrastructure consists of two segments: a flight one, which includes the airborne Multiband Interferometric and Polarimetric SAR (MIPS) system, and a ground segment, which includes the IT platform for data storage and processing and the data processing chain. Concerning the flight segment, MIPS SAR uses two different radar frequencies (L-band and X-band) to acquire high-resolution images [A. Natale et al., "The New Italian Airborne Multiband Interferometric and Polarimetric SAR (MIPS) System: First Flight Test Results," Int. Geosci. Remote Sens. Symp., 2022, doi: 10.1109/IGARSS46834.2022.9884189]. It is based on the Frequency Modulated Continuous Wave (FMCW) technology and, due to its relatively small size and weight, it can be easily mounted onboard different types of aircrafts. MIPS is connected with the modern navigation unit Applanix POS-AV 610, which guarantees along with proper post-flight processing techniques very precise flight parameter measurability. Concerning the ground segment, the specifications of the IT platform are tailored to manage big SAR datasets and the airborne SAR data processing chain has been jointly developed by IREA-CNR and University Parthenope, Italy. Moreover, the ground segment includes also a series of operational activities for the success of the SAR mission.

This work focuses on the results achieved through this infrastructure to measure the topographic changes related to the eruptive activity of the Stromboli volcano, Aeolian Islands, South of Italy, from 9th July 2019 up to 18th October 2022. In particular, 7 different Digital Elevation Models (DEMs) of the observed area have been generated through the exploitation of Single pass InSAR data acquired in six airborne campaigns spread over the considered temporal interval: comparison of these DEMs allowed retrieving with accuracy on the order of the meter the occurred topographic changes.

Advancing volcano surveillance through soil gas monitoring: insights from Stromboli Island, Italy

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Soil gas monitoring proves to be a powerful tool for studying volcanoes and their subsurface dynamics. Various gas species are examined as indicators of volcanic activity, with a focus on understanding the processes governing gas emissions. Carbon dioxide (CO₂) is of particular interest due to its significant release during both active volcanic periods and periods of dormancy. Hydrogen (H₂) concentration is also analysed to gain insights into the oxygen fugacity of magmatic gases, a parameter that influences the redox state and the distribution of elements among solid, fused, and gas phases.

To effectively monitor volcanic gases, automated geochemical stations are deployed to simultaneously measure multiple gas species. This study presents a comprehensive analysis of reducing capacity monitoring data collected at Stromboli during the 2021–2024-time window. This station records data on molecular hydrogen (H₂) concentration, CO₂ flux, CO₂ concentration, soil water content, atmospheric pressure, temperature, and relative humidity.

The dataset underwent normalization of variables and filtering processes of spurious data to facilitate Principal Component Analysis (PCA), allowing for the identification of linear dependencies among the variables. The results of the PCA reveal insights into the relationships of the monitored parameters, shedding light on potential factors influencing volcanic activity.

These data reveal variations in reducing capacity and soil CO₂ flux that correlate with changes in Stromboli's eruptive activity. The delay in CO₂ variations following shifts in reducing capacity is attributed to the advective-diffusive transport of gases through the volcanic rock formations. This research contributes to a deeper understanding of the volcanic degassing of Stromboli and shows the efficacy of combining multiple regression analysis methods for filtering geochemical datasets. This research enhances our understanding of volcanic behaviour and aids in volcano monitoring efforts.

Multitemporal UAV remote sensing surveys of volcano unstable flanks: the case of Stromboli

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The UAV-based photogrammetric mapping is a cost-effective technique that allows to generate three-dimensional surveys with centimetric precision and accuracy in short times. When carefully performed, the outcomes can be comparable to the ones coming from other expensive techniques that require longer time such as aerial or terrestrial laser scanning. Consequently, it is becoming increasingly popular even in application fields that, until recently, were deemed unsuitable to the technique. Depending on the characteristics of the investigated scenario, the generation of three-dimensional (3D) topographic models may in fact be affected by significant inaccuracies unless site-specific adaptations are implemented into the data collection and processing routines.

In this context, we present a tailored approach using high-resolution aerial photogrammetry for the multitemporal analysis of the unstable Sciara del Fuoco (SdF) slope on Stromboli Island, Italy. Landslides in this region have the potential to generate tsunamis that could affect the shores of Stromboli and the adjacent coastline. The surveys were carried out using the Saturn drone developed by the Civil Protection Centre of the University of Florence. Ongoing experimentation and technical improvements allow the drone to be adapted to different scenarios, thus facilitating comprehensive modelling of the entire SdF and extending the applicability of photogrammetry. In this region, the use of this technique presents inherent challenges due to the uniform appearance of the grey ash slope, making it difficult to easily identify matching points across continuous images. Moreover, due to site accessibility issues, Ground Control Points (GCPs) cannot be positioned to constrain georeferencing. Therefore, 3D point clouds were georeferenced using GCPs acquired in a 2019 survey together with stable Virtual Ground Control Points (VGCPs) belonging to a LiDAR survey carried out in 2012. Alignment refinement was then performed by means of an iterative algorithm based on closest points.

The procedure succeeded in correctly georeferencing 11 high-resolution point clouds acquired from April 2017 to February 2023, whose time-focused analysis made it possible to track several geomorphological structures associated with the continued volcanic activity, including minor structures not identifiable by aerial/satellite surveys. The procedure can be further extended to smaller-scale analyses such as the estimation of locally eroded/accumulated volumes and pave the way for rapid UAV-based georeferenced surveys in emergency conditions at the SdF.

At the same time, accurate and up-to-date 3D models provide the basis for analysing ground deformation data obtained from terrestrial and satellite sensors. They also provide essential input for carrying out stability analyses of the SdF slope.

Tsunamigenic landslides at Stromboli volcano over the millennia: a record from marine volcanoclastic turbidite sequences

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Landslides associated with volcanic activity encompass a variety of phenomena, from the remobilization of shallow debris forming small rockfalls and debris flows, to large-scale events associated with pyroclastic density currents (PDCs) or catastrophic collapses of portions of the volcanic edifice. Particularly on volcanic islands, when landslide material enters the sea or submarine flank sections collapse, such events have the additional risk to produce potentially devastating tsunamis, whose effects can propagate hundreds of kilometers from the source. In marine sediment cores, tsunamigenic landslide events are often preserved as volcanoclastic turbidites intercalated with hemipelagic mud layers. Turbidite compositional and textural features are indicative of the composition of the source of the landslides, and the mode of remobilization of the volcanic material and the transport processes. The intercalation with primary tephra layers deposited during known and dated explosive eruptions provides ideal chronostratigraphic markers that constrain the age of the tsunamigenic events.

Here we focus on the volcanic island of Stromboli (Southern Tyrrhenian Sea, Italy), well-known for its predominantly mild, intermittent and explosive Strombolian activity, punctuated by rare lava emissions and more violent explosions. The eruptive activity, associated with small-volume rockfalls, debris landslides and PDCs of variable energy, also includes the generation of tsunamigenic landslides from flank collapses. Previous studies of onshore tsunami deposits and offshore volcanoclastic turbidite sequences showed that at least six small-scale tsunamis have occurred since 1900 CE; the best documented tsunami in the last century occurred on 30 December 2002, due to two partial collapses of the volcano's NW flank along the Sciara del Fuoco. Minor events have also occurred in 2019 and 2021.

In this study, twenty-two sediment cores, covering a distance from 17 to 60 km in the area facing the Sciara del Fuoco, offshore Stromboli, were recovered during a dedicated cruise. Of these, four cores, ~31, ~43 (2) and ~44 km from the volcano, respectively, were selected and sampled for detailed analysis. For each core, volcanoclastic turbidite deposits and primary tephra layers were visually identified and sampled. Tephra layers that were not visible to the naked eye (cryptotephra) have been identified by XRF (X-ray fluorescence) core scans. All the sampled layers were subsequently characterized for their lithological, sedimentological and geochemical features (with SEM-EDS and EMPA). Relative and absolute ages and glass geochemical compositions allowed us to correlate the turbidite sequences and the primary tephra layers between the cores. The analysed layers mostly show homogeneous glass compositions indicative of a single-source origin, which is well compatible with differing compositions of current and past Strombolian activities characteristic for Stromboli volcano. Most of the turbidite layers are

therefore representative of small-to-large-scale landslides that occurred on the island. While a few volcaniclastic layers can be correlated to a source at the Calabrian arc, most of the primary tephra marker beds derive from more distal origins such as the eruptions of Monte Pilato and Gabelotto-Fiumebianco on the nearby island of Lipari. The chronostratigraphic architecture of the landslide events, as well as the time span covered by the cores, was determined from the primary tephra layers for which both source and age could be unequivocally identified, showing that the cores cover a time window of at least several tens of thousands years. The study of the recovered turbidity sequences allows us to constrain the frequency, age and scale of instability of the events which occurred on the NW flank of Stromboli. These surveys may be of particular interest to the scientific community in order to assess the associated tsunamigenic potential and develop mitigation strategies applicable throughout the Southern Tyrrhenian Sea.

The increased volatiles degassing at Stromboli Volcano inferred by the continuous soil CO₂ fluxes monitoring network

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The Stromboli volcano, Aeolian Islands, Italy, is characterized by persistent Strombolian activity. It is a perfect case study to investigate the relationship between outgassing activity and paroxysmal events.

The discrete soil CO₂ degassing measurements, performed with the portable flux meter based on the accumulation chamber method, were carried out in the summit and peripheral zones. These measurements surveys allowed us to individuate the anomalous degassing areas (Scari, Piscità, and Pizzo Sopra La Fossa), coincident with the main structural faults respectively N64° and N41° as preferential paths for the rising of deep fluids.

Based on the information resulting from the discrete measurements a near-continuous (hourly frequency) geochemical network was installed on Stromboli Island and consists of three stations, one located in the summit part of the Pizzo Sopra La Fossa area (STR02), and two located in the peripheral zone STR01 and STR03 in the Scari and Piscità areas respectively. This network allowed us to acquire a large amount of soil CO₂ flux data to investigate and model the plumbing volcanic system. The analysis of a large dataset of soil CO₂ fluxes collected in the summit crater area (STR02), from 2000 to 2023, showed significant changes in degassing values and style before and in coincidence with major volcanic events like paroxysmal explosions caused by the rapid rise of volatile-rich magma and the changes from explosive to effusive eruptions. In particular, the soil degassing processes of CO₂ peaks showed three main and peculiar behaviors:

- A long-lasting modification, characterized by a slow and continuous increase in CO₂ flux;
- Transient changes, characterized by abrupt changes in the rate of CO₂ outgassing;
- Strong Increase in the Natural Daily Variation, highlighting drastic changes in the degassing style, a few months before the major paroxysmal events.

Petrological monitoring of persistently active basaltic volcanoes: the case study of Stromboli (Aeolian Islands, Southern Italy)

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Investigating the dynamics and timescales of magmatic processes in active volcanoes is crucial for understanding explosive eruptions and assessing volcanic hazards. In this context, we are currently conducting a petrological survey of the Stromboli volcano (Aeolian Islands, Southern Italy), whose persistent activity is characterized by periodic and mildly explosive “Strombolian” eruptions, alternating with episodic lava effusions and more violent eruptive events, namely major explosions and paroxysms. The plumbing system is characterized by a vertically-extended mush column in which the shallow magmatic reservoir (highly porphyritic or *Hp*-magma) is continuously refilled with mafic recharges (low porphyritic or *Lp*-magma) rising from depth. During the paroxysmal events, sustained injections of *Lp*-magmas produce ample and continuous H₂O-rich gas phases that are released with great energy through the vent, together with ash, scoriaceous spatters, bombs and lithics traveling over long distances. With the final scope of deciphering mutual relationships between *Hp*- and *Lp*-magmas, as well as magma-mush interplay within the shallow plumbing system, we present in situ microchemical analyses of plagioclase phenocrysts from nineteen scoria clasts ejected during mild to violent explosions at Stromboli over a timespan of 18 years, from 2003 to 2021. Major and trace element compositions, as well as Sr-isotopic data have been integrated with thermometric modeling and Mg-in-plagioclase diffusion chronometry to constrain the physicochemical changes within the plumbing system and the timescales of magmatic processes. Through this approach, a new eruptive cycle at Stromboli volcano has been identified, where more energetic open-conduit dynamics are associated with an increased intensity and frequency of eruptions due to mush disruption by sustained injections of mafic recharge magmas from depth.

S07 - FROM THE VOLCANO TO THE LABORATORY (AND BACK):
INSIGHTS INTO MAGMATIC PROCESSES AND ERUPTION
DYNAMICS THROUGH EXPERIMENTS, MODELING AND FIELD
OBSERVATIONS

Conveners:

Barbara Bonechi, Alessio Pontesilli, Fabrizio Di Fiore, Alex Scarani,
Fabio Arzilli, Giuseppe La Spina

Fine particles and roughness effects on the granular flows mobility: insights from large-scale experiments

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Dry granular flows are gravity-driven mixtures of discrete grains that belong to the family of multiphase flows and are prevalent in a wide range of volcanological scenarios (e.g. pyroclastic density currents, block and ash flows, debris avalanches, etc.). These flows are polydisperse in terms of grain size and density and their flow characteristics are mainly governed by particle-particle collisions and frictional forces acting at the boundaries. These boundary forces are influenced by several factors, including the presence of fine particles and the roughness of the basal surface, both of which can affect the energy dissipation at the flow base and consequently, the flow mobility. These two factors were investigated through large-scale laboratory experiments, in which dry granular mixtures were released onto a sloped channel. The flow parameters were monitored using various sensors, including 15 laser barriers for flow front velocities, 5 load cells for bottom pressures, 3 highly sensitive pore pressure sensors, 1 high-speed camera (2000 fps) and 2 medium-high speed cameras (120 fps – 240 fps) for flow velocimetry. Different granular mixtures and experimental set-up were used to study the behaviour of granular flows under various conditions: i) ratio between the coarser and finer solid phases ($d_{\text{ratio}} = d_{\text{coarse}}/d_{\text{fine}}$); ii) weight percentage of the fine content ($d_{\text{(fine\%)}}$); iii) ratio between the roughness of the sliding surface and size of the finest particles (k). Preliminary results indicated that: 1) the greater d_{ratio} and $d_{\text{(fine\%)}}$, the lower the runouts of the granular flows; 2) the greater k , the higher the runouts. This study explores the dual effect of the fine content and its interaction with the basal roughness on granular flows.

Characterisation of eruptive products from sub-glacial eruptions in the Mount Melbourne volcanic field (northern Victoria Land, Antarctica)

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The Cenozoic volcanism of northern Victoria Land (NVL) is dominated by few central conduit stratovolcanoes and numerous widespread dykes, necks and lava flows from fissural activity, aligned in a north-south-oriented coastal zone. Mount Melbourne is the most important active volcanic edifice of NVL: a 30 km wide and 2730 m high complex stratovolcano, characterised by a varied activity and a composition ranging from basalt to trachyte. Besides the central summit area, volcanic activity occurred by several scattered monogenic edifices and vents since 2 Ma, defining the Mt Melbourne Volcanic Field.

The prolonged and heterogeneous volcanic activity and related products make the Mt Melbourne Volcanic Field a suitable site where potentially deciphering the environmental changes occurred in the Terra Nova Bay by studying glaciovolcanic facies. In the last decade, the analysis and interpretation of glaciovolcanic facies has become a routine to infer environmental parameters such as ice thickness and extent. In this framework, petrological investigations and geochemical analyses are important tools both to study the feeding system of the volcanoes and to determine the provenance of volcanic rocks in sedimentary sequences.

The petrologic study of the samples collected during the 2005/2006, 2011/2012 and 2014/2015 Antarctic expeditions (PNRA – Programma Nazionale di Ricerche in Antartide) were examined to select suitable samples with pristine glass and possible evidence of magma-ice interaction. The area of interest has been focused to the volcanic outcrops in the Mt Melbourne area, namely the Harrow Peaks, Baker Rocks, Edmonson Point, Willows Nunatak, Shield Nunatak, Oscar Point and Cape Washington sites. 31 samples were chosen for SEM-EDS analyses, based on the presence and abundance of pristine volcanic glass. Samples were then analysed to determine their major element glass chemistry and trace element composition using WDS-EPMA and LA-ICP-MS, respectively.

The samples are hyaloclastite and lapilli tuff, characterised by plagioclase, olivine, pyroxene and opaques, embedded in a glassy to microcrystalline matrix. In addition to the microlite content of the glass, the variable texture and vesiculation can be related to the eruptive history and possible magma-ice interaction. The composition of glasses varies from basanite to hawaiite, mugearite and phonotephrite; two exceptions are one foidite from Cape Washington site and one trachyte from Edmonson Point site. Besides small variation among the studied sites, primordial mantle normalised trace element diagrams show an Ocean Island Basalt-like pattern characterised by general enrichment in LILE and LREE, which is commonly observed in magmas from the Western Antarctic Rift System.

The results of this study contribute to outline the eruptive history in the area of Mt Melbourne, in particular in relation to the magma-ice interaction. Moreover, the large dataset obtained during this work, for both major and trace elements, can be used to obtain cross-correlations between different archives (e.g. ice cores, marine records, terrestrial records, etc). In fact, there is still a large knowledge gap concerning the geochemical data on tephra and volcanic products

in general, therefore it is important to fill this gap with new high-quality data. This new dataset will surely contribute to enhance the knowledge of the mineralogy and glass geochemistry of the proximal products in the Mt Melbourne Volcanic Field.

Eruptive dynamics of silicic peralkaline magmas from Pantelleria island

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Peralkaline rhyolites, although less common than their calc-alkaline counterparts, can be nonetheless found in many geodynamic settings including continental rifts, ocean islands, back-arc basins and subduction zone.

Peralkaline magmas are associated with a large range of eruptive styles.

On the island of Pantelleria, Italy, magmas with near-identical major element compositions have produced domes, lava flows (including fountain fed agglutinates), pumice cones, thick tephra fall deposits and pyroclastic flow deposits. The widespread welding and rheomorphism of the ignimbrites and fall deposits correspondingly low glass transition temperature (T_g) of peralkaline melts, which can allow deformation to continue for many days after emplacement. Understanding the mechanisms that allows the fragmentation of these low viscosity magmas and that can cause the shift between large-scale explosive and mild effusive eruptions, as evidenced by the wide spectrum of eruptive styles and intensities, as well as the extended welding and large-scale rheomorphic structures commonly associated with silica-rich peralkaline magmas, represents a fascinating and intriguing question in volcanology.

In order to face this problem, we choose six eruptions, Cinque Denti (125 ka, caldera-forming eruption, P.I. 0.9), Zinedi (189 ka, non-welded ignimbrite, P.I. 1.2), Cuddia Mida (9.7 ka, low-energy strombolian eruption, P.I. 1.68), Green Tuff (50 ka, caldera-forming eruption, P.I. 1.29), Fastuca (sub-plinian eruption, 9.7 ka, P.I. 1.22) and Altura (strombolian eruption, 159 ka, P.I. 1.22) because despite the chemical composition is the same, rhyolite and trachyte, they are different in the eruptive style, from a low energy strombolian eruption to a caldera forming eruption.

In this work we investigated i) the chemical composition of anhydrous glass by Electron Micro Probe Analyzer (EMPA); ii) the rheology of the anhydrous glass at high- and low- temperature regime using concentric cylinder apparatus and differential scanning calorimetry; iii) the structure of glass using Raman spectroscopy; iv) the dissolved volatile content in natural products (pumices) by thermogravimetric analysis and iv) the degassing process by textural analysis.

Here we present the preliminary results of this study through the complex behaviour of Pantelleritic magmas. Our viscosity data are in agreement with the chemical parameters NBO/T, SM, AE, AE/SM and P.I. suggesting that, at a fixed low and high temperature, the viscosity of these magmas decrease at increasing degree of depolymerisation. The energy of the eruptions does not correlate linearly with the increase in the anhydrous viscosities pointing to an important role of the volatile dissolved in the magmas.

Viscous-Flow-to-Fracture Transition: Implications for Magma Fracturing and Infrasound Emission

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How flowing magma breaks like a solid is a fundamental problem that has been investigated for decades. This work introduces the study on the flow and fracture of complex fluids, consisting of experimental work. In volcanology, the glass transition is considered to appear at high strain rates and to control the brittle fracture of magma [Dingwell, D. B. 1996; Papale 1999; Cashman and Scheu 2015; Wadsworth et al., 2018]. In physics, on the other hand, the glass transition is more frequently associated with the appearance of yield strength at low strain rates. The scale experiment aims to bridge this discrepancy and establish the fracture mechanics for complex fluids. The experiments include bubble growth and fracture within and at the surface of the fluids. We emphasize that the observation of elasticity at small strain is not sufficient to infer that the fluid can generate brittle fractures [Sánchez et al., 2023]. This experimental exploration sheds light on the nuanced interplay between fluid properties and gas-flow dynamics in the context of acoustic wave generation during bubble bursting.

We explore acoustic wave generation induced by bubble growth and bursting in two distinct fluids: a Maxwell-type viscoelastic fluid (CTAB) and a Bingham-type yield-strength fluid (GEL). The waveform and frequency of the acoustic signals generated by these fluids display pronounced variations, contingent upon factors such as flux (Q) and also the depth of air injection (h).

When complex fluids are concerned, it is not straightforward to scale the laboratory phenomena to natural volcanic systems. However, we demonstrate that a deep understanding of experimental phenomena can improve our understanding of how volcanic systems work by considering the physical analogy. We name these approaches analogy experiments.

An AI-based Lagrangian CFD emulator to model volcanic phenomena

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Lava flows are destructive for inhabited areas and infrastructures, and dangerous for the population, although hardly fatal. The long distances that they can travel depend on their physical properties, such as rheology and composition, and on the initial and boundary conditions, as vent location, ground topography, eruption temperature and effusion rate [Del Negro et al., 2020]. Due to the complex dynamics of lava, physical-mathematical analytical and numerical models can be used to make accurate predictions of the evolution of the flows, helping to monitor hazards and mitigate damages without in field risks [Cordonnier et al. 2016; Del Negro et al., 2016]. Computational Fluid Dynamics (CFD) numerical models can help to reproduce complex fluids with high fidelity simulations for obtaining accurate and fast predictive scenarios [Anderson and Wendt, 1992]. Among CFD models, Smoothed Particle Hydrodynamics (SPH) [Monaghan, 2005] is a powerful method for complex fluid simulations [Zago et al., 2017, 2018]. It is a Lagrangian mesh-free particle-based numerical method based on a discrete approximation of the Navier-Stokes equations. It is capable to manage the viscous and thermal details of the fluid. SPH is parallelizable and executable on Graphics Processing Units (GPU), nevertheless, highly detailed simulations can require long execution time and substantial computational resources (even taking weeks to get few minutes of simulation), making impossible real-time applications. A way to overcome these limitations is to combine numerical models with Artificial Intelligence (AI) [Goodfellow et al., 2016; Bonaccorso, 2017], pushing forward the frontiers of CFD, improving their performances, and allowing new forms of analysis [Kim et al., 2019; Bortnik and Camporeale, 2021]. An example of this approach is found in emulators, models in which AI algorithms are combined with the equation-based mathematical representation of physics, using CFD simulations to train the AI models, learning how to reproduce the behavior of volcanic phenomena solving fluid dynamics problems in shorter times [Kasim et al., 2021].

Here, we present an AI-based CFD emulator of an SPH model, based on the use of an Artificial Neural Network (ANN). This AI architecture is trained over high fidelity SPH simulations of visco-thermal complex fluids, thus referable to viscous and high temperature lava flows. In this way, the emulator becomes capable to predict the spatio-temporal evolution of lava, replicating the underlying physical laws. We have already validated the emulator for inviscid and isothermal fluids and for viscous fluids, also testing the ability to generalize for problems not seen during the training phase with varying levels of complexity, and for changes in the model resolution [Amato et al., 2023; Amato, 2024]. We will show an extension of this AI-based SPH emulator, with an increased ability to reproduce the spatio-temporal evolution of the lava. In particular, we will show the simulation of fluids with temperature-dependent viscosity, in which when the temperature decreases, the viscosity of the fluid increase. We will also show how the emulator can be used to extrapolate physical information of lava flows. By imposing theoretical constraints to the ANN (thus implementing a Physics-Informed NN, PINN), it is possible to extrapolate physical information not present in the training dataset, enhancing the model functionalities and opening to a deeper understanding of the dynamics of volcanic phenomena.

S07 - Oral Presentation

New insights into the dynamics of vulcanian activity through a comparative analysis of three different ballistic bomb fields

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Vulcanian eruptions are typically associated with the launch of different types of cm-to-m sized ballistic ejecta and with the production of large amount of ash typically transported by transient atmospheric plumes. Although detailed morphological, textural and compositional studies of the ash have provided deep insights into the processes controlling the dynamics of these eruptions. The study of coarse ballistic materials can also give crucial information about the large scale pre- and syn-eruptive characteristics of ejected magma

Vulcanian explosions typically involve the expulsion of various types of ballistics, characterized by variable shapes, internal and external textures, and vesicularity. Analyzing the texture of Vulcanian bombs can provide clues to understanding the temporal and spatial changes in conduit structure and illuminate the complex interactions among conduit processes, such as magma vesiculation, crystallization, and fragmentation, which play a crucial role in the erratic behavior of these eruptions. In this study, we draw a comparative analysis between the morpho-texture and dispersion of the products associated to two significative eruptions controlled by a clear vulcanian-like dynamics of the activity (the historical eruption occurred in 1888-90 at La Fossa Cone of Vulcano, the 1th February 2014 eruptive event at Tungurahua volcano) with the study of the ballistic bomb field produced by the third eruptive phase of Guagua Pichincha volcano during September-December 1999 described by Wright et al. (2006). Here we compared the main features of these three case-studies including external or internal textural characteristics, grain size, and spatial dispersion of ballistic products from the considered case studies. This comparison aims to underscore the typical features commonly linked to Vulcanian activity and to demonstrate the key insights that can emerge from the analysis of these products. Strong similarities are evidenced among all the considered case-studies. Despite the presence of bread-crust bombs has been considered as peculiar of this activity, in all these cases dense highly crystallized blocks are dominant between all the products, This clearly indicates that progressive gas accumulation below a dense, nearly totally degassed portion of a magma plug is the dominant process driving the eruption, so clearly indicating a bottom-up onset of fragmentation that can then extend below the initial fragmentation depth through a downward propagating decompression wave. . The study of the textural features of vulcanian bombs can help to solve the time-space evolution of conduit stratigraphy and to shed light on the complex interplay between conduit processes that actively control the unsteady dynamics of such eruptions.

Numerical modelling integrated with field observations and analytical data of the 2021 Cumbre Vieja eruption improves understanding of eruption dynamics in mafic systems

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Abrupt transitions in eruptive style are common during eruptions at low-viscosity mafic volcanoes. The unexpected resulting activity may strongly affect volcanic risk, potentially damaging infrastructures and threatening people living in the surrounding area. During the recent 19th September - 13th December 2021 Cumbre Vieja eruption on La Palma, Canary Islands, these changes in eruptive style occurred, and, for this reason, that eruption represents an ideal case for investigating mechanisms underlying such transitions.

We used a numerical 1D steady-state magma ascent model to study the driving processes. This model captures the complex and non-linear interdependence amongst the major processes occurring during magma ascent: temperature and viscosity evolution, non-ideal gas behaviour, outgassing and disequilibria in crystallization and volatile exsolution [1, 2]. The input parameters of the simulations (such as inlet pressure, initial magma temperature, water and CO₂ content, and crystal content) are constrained by empirical data and results compared with field observations. We investigated several scenarios by varying the input conditions in plausible ranges for the event. The simulations show that the system tends to produce mainly effusive and fountaining behaviour, in agreement with the observed dominant eruptive style. We also observed that a change in the degree of coupling between gas and melt might have triggered a shift from the effusive to the explosive eruptive style.

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Outgassing behaviour during highly explosive basaltic eruptions

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Plinian eruptions represent the highly explosive endmember of volcanic activity. At basaltic volcanic systems, Plinian eruptions are rare due to the low viscosity of crystal-poor basaltic magma, which precludes magma fragmentation during ascent. However, the occurrence of several Plinian eruptions at basaltic volcanoes, such as the 1886 eruption of Tarawera (New Zealand), highlights the highly explosive activity which can occur at such volcanic systems, with considerable impacts on society and the environment.

The explosivity of a volcanic eruption relates to the efficiency in which gas can exsolve and separate from magma during ascent, referred to as outgassing. If outgassing is facilitated during magma ascent, an effusive eruption is likely. Instead, if gas-melt coupling is maintained, an explosive eruption can occur. Generally, it is magma permeability that controls the efficiency of outgassing. Understanding the 3D geometry of the pore network is important for quantifying magma permeability and, in turn, outgassing, where knowledge of the connectivity, morphology, anisotropy and tortuosity of connections can provide insight into eruption dynamics.

Here, we use phase-contrast synchrotron X-ray computed microtomography (micro-CT) to provide a 3D quantification of the pore network for samples of several basaltic Plinian eruptions, to constrain parameters such as connectivity, tortuosity and the throat-pore size ratio. Our sample suite includes the Fontana Lapilli (60 ka) and Masaya Triple Layer (2.1 ka) eruptions of Las Sierras-Masaya volcanic system (Nicaragua), and the 122 BC eruption of Etna (Italy). We then incorporate our data into a 1D steady-state numerical conduit model, to investigate how these parameters influence outgassing and the dynamics of magma ascent.

By combining our X-ray micro-CT data with a conduit model, we find that amongst the permeable parameters, it is the bubble number density and friction coefficient which have the greatest influence on eruptive style. However, we also find that the occurrence of basaltic Plinian eruptions cannot be attributed to bubble growth and nucleation processes alone. For fast ascending magmas, such as those characterising basaltic Plinian activity, gas-melt coupling is maintained independent of the magma permeability. In this case, pre-eruptive conditions such as crystal content and temperature, have greater influence on eruptive style. Therefore, close monitoring of pre-eruptive conditions may provide important information for mitigating the risk posed by basaltic systems which exhibit a wide range in explosivity.

Novel insights into dynamics and timescales of vesiculation in basaltic magmas by in situ HP-HT X-ray synchrotron radiography experiments

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Transitions between effusive and explosive styles at basaltic volcanoes are strongly dependent on how easily gas can decouple from magma during ascent. Stronger gas-melt coupling favours highly explosive eruptions, whereas a weaker coupling promotes lava fountaining and lava flows. However, the mechanism fostering the transition from closed- to open-system degassing is still poorly understood, due to a lack of direct observations of bubble dynamics under natural magma ascent conditions. A series of in-situ experiments were performed at Diamond Light Source (United Kingdom) combining X-ray synchrotron radiography with a novel high-pressure/high-temperature X-ray transparent Internally Heated Pressure Vessel apparatus to directly observe and quantify in 2D bubble growth and coalescence in a basaltic magma from 100 MPa to the surface, in real-time. This new study provides unique quantitative information on bubble growth, expansion and coalescence through time. We found that for low-viscosity basaltic magmas, bubbles coalesce and recover a spherical shape within 3 s, implying that, for lava fountaining activity, both gas and melt remain coupled during the ascent up to the last hundred metres of the conduit. For higher viscosity magmas, instead, the recovery time becomes longer, promoting connected bubble pathways leading to some degree of decoupling that we directly observed as bubbles expand until they connect to an open pathway and then contract as gas escapes. This new apparatus combined with X-ray synchrotron radiography is an invaluable tool to capture and quantify bubble kinetics in basaltic magmas at natural pre- and syn-eruptive conditions, which are fundamental to improve our understanding of magma behaviour and mitigating the volcanic risk associated with basaltic systems.

Shallow magma rejuvenation sustained by the infiltration of CO₂-rich fluids: a case for Campi Flegrei unrest

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Magma rejuvenation is the process by which magma is reactivated and mobilized within a mush system. This can occur in a variety of ways, including the injection of new magma into an existing system due, for example, to the upward migration of hot buoyant magma from deeper levels, or the mechanical deformation of the solid matrix that allows previously trapped interstitial liquid to become mobile. Another mechanism may involve volatile fluxing, exsolved from larger depths given the presence of abundant CO₂. Overall, understanding the processes involved in magma remobilization in mush systems can shed light on the complex dynamics of magmatic systems and their associated hazards.

Here I show under which thermodynamic and chemical conditions the fluxing of CO₂-rich fluids may promote remobilization of shallow magma batches, such that volcanic hazard may be extremely high because associated with the remobilization of apparently inactive magma batches. In contexts where discharged fluids come essentially from deep magma reservoirs, the possibility of rapid and abrupt remobilization of shallow magma batches in a mush system cannot absolutely be discarded,

even if such shallow batches do not appear to be involved in melt-fluid exchanges and are then ruled out as possible sources of the fluid either discharged at surface or infiltrating hydrothermal systems. The implications of rapid shallow magma remobilization are then discussed with reference to Campi Flegrei, where the active source releasing magmatic fluids is known to be at least 8 km deep.

The thermodynamic treatment adopted here shows that heating promoted by the deep fluid ascent may silently (from a geophysical point of view) lead to the remelting of the shallow magmatic rock and produce buffered H₂O:CO₂ gas compositions. Therefore, we cannot discard the possibility that a shallow magma is rejuvenating or has already rejuvenated. It follows that any scenario which considers detectable magma migration from 8 km depth or so, may seriously be underestimating the volcanic hazard, independently of any consideration about magma ascent times.

Deep vs shallow magmatic systems controlling pure Plinian vs caldera-forming eruptions: experimental evidence

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Magma storage depth is of fundamental importance for volcanic hazard assessment. Quaternary potassic volcanoes of Central Italy (e.g., Vulsini, Vico) commonly record a shift from Plinian activity without accompanying caldera collapse, which usually characterizes their early activity history, toward caldera-forming events that take place later in the activity history. Here, we focus on Ventotene Island (Pontian Islands, Tyrrhenian Sea), where the volcanic activity shows an analogous change in eruptive style from repeated, pure Plinian events (Cala Battaglia eruptions; UCB below) to an underpressure caldera-forming eruption (Parata Grande eruption; PGT below).

The detailed textural and chemical analysis of UCB and PGT juvenile (pumice and scoria) clasts allows us to put constraints on deep vs. shallow pre-eruptive magmatic systems feeding pure Plinian and underpressure caldera-forming events, respectively. UCB and PGT juveniles differ in composition (volatile-rich phonolite UCB vs. latite to tephri-phonolite PGT), type and amount of crystalline charges (UCB <3 vol% vs. PGT= 10-25 vol%). Of note is the occurrence of primary analcime in UCB pumice, absent in PGT juveniles. These observations point out that the collapse-free, pure Plinian scenario (UCB) was driven by polybaric differentiation of a magma batch at varying depths along the ascent path from source to surface and/or by a pre-eruptive magma storage at high depth ($P_{H_2O} > 200$ MPa). Conversely, a relatively shallow ($P_{H_2O} < 200$ MPa), sill-like, magma chamber (low roof depth/width aspect ratio), would have favored the PGT underpressure caldera collapse event. We explored the hypothesis of polybaric differentiation (leading to pure Plinian) vs. isobaric differentiation in a sill-like magma chamber (leading to underpressure caldera-forming) through a series of crystallization experiments on an oversaturated ($H_2O \sim 10$ wt%) UCB phonolite composition at pressures of 150 and 600 MPa, and temperature range of 700-900 °C. The experiments were performed in a piston-cylinder apparatus and held at the target P-T conditions for 3 hours.

All the experimental products comprised vesicular glass coexisting with crystalline phases.

Under high pressure conditions (600 MPa), biotite+plagioclase+oxides±K-feldspar crystallized along with a volatile-bearing, feldspathoid mineral phase with euhedral, hexagonal habit and micrometric size ($\leq 20 \mu m$). Moreover, in these experiments, the occurrence of euhedral microcrystallites ($10 \mu m$) of sylvite and less abundant halite inside the uniformly distributed spherical vesicles, indicates their precipitation from a free aqueous fluid phase in equilibrium with experimental residual melt and crystals. In the low-pressure (150 MPa) experiments, a paragenesis consisting of K-feldspar (the most abundant mineral phase), plagioclase and Ti-magnetite oxides crystallized.

The preliminary findings of our experiments have revealed a significant effect of pressure on the crystallization behavior of UCB volatile-rich phonolitic magma. Indeed, the crystallization of volatile-bearing feldspathoid microliths, which requires pressure conditions exceeding 150 MPa, implies a high ascent rate from a deep pre-eruptive magma system. Furthermore, the high-pressure, volatile-saturated experiments also highlight the significant partitioning of alkali in the fluid phase and its effect on the liquid line of descent, ultimately resulting in the formation of potassic rhyolites (e.g., pure Plinian events of the early Vico activity).

Continental crust experimental refining: exploring the deep storage zone of Campi Flegrei and Vesuvius magmas

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Mantle magmas interact with surrounding rocks during their ascent and storage in the continental crust, leading to open system, magmatic processes in the crustal reservoirs. The degree to which crustal reservoirs have contributed to the geochemical signatures of volcanic rocks is frequently assessed through combined assimilation and fractional crystallization models. The assimilation component is generally represented by partial melts derived from a fertile (i.e., not melted) continental crust in spite that multiple melting episodes are the rule, rather than the exception, in many orogenic zones. This scenario is of primary interest, for example, in the peri-Tyrrhenian orogenic zone where, the emplacement of anatectic crustal magmas, predates the mantle derived volcanism. The above considerations provide a strong motivation for the present study, which aims to directly investigate the differentiation of ascending mantle-derived magmas in the lower continental crust. By means isobaric, open system experiments we investigated the interaction at level of crustal-mantle boundary between a primitive K-basaltic magma and a restitic continental crust, represented by a biotite-bearing, leucosome depleted migmatite. As a primitive K-basaltic magma we used a K-basalt composition from Campi Flegrei (Italy). Using a piston-cylinder apparatus, the experiments were made at a pressure of 0.8 GPa in a range of $T = 1050\text{ }^{\circ}\text{C}$ - $1250\text{ }^{\circ}\text{C}$, in both isothermal and thermal gradient conditions. The experimental products consist of biotite-free migmatite, glass and crystals of clinopyroxene, olivine, plagioclase and Cr-spinel with proportions that vary as a function of temperature. In the isothermal experiments the chemistry of melts and phase relationships are controlled by the high Al_2O_3 content of leucosome depleted migmatite producing glasses which composition shifts from K-trachybasalt towards shoshonite as the temperature decreases from $1200\text{ }^{\circ}\text{C}$ to $1125\text{ }^{\circ}\text{C}$. At temperatures $\leq 1150\text{ }^{\circ}\text{C}$, migmatite assimilation is not exclusively due to the assimilation fractional crystallization process because evidence of mingling and mixing is observed. Melt composition in the T-gradient experiment varies from shoshonite to phono-tephrite moving from the slightly crystalline zone ($T = 1250$ - $1210\text{ }^{\circ}\text{C}$) at the bottom of the capsule towards the highly crystalline zone ($T = 1160$ - $1140\text{ }^{\circ}\text{C}$).

The peculiar SiO_2 -constant trend indicates that the assimilation of leucosome depleted crust at temperature below the basalt solidus, is accounted for almost exclusively by the biotite breakdown, leading to the increase in Al, Mg, Fe, Ti, and K activities in the system. Finally, the shoshonitic composition produced by our experiments could potentially reproduce the parental magma for both Campi Flegrei volcanic district and Vesuvius magmatic systems, indicating modifications in a deep storage zone through mixing with the partial melts derived from restitic continental crust.

Influence of Acoustic Wave Dynamics in Granular Media: Implications for Volcanic Infrasound Analysis

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Comprehending the mechanisms that govern the amplitude and frequency of these acoustic signals is of essential importance. This understanding aids in constraining the source parameters necessary for accurately modeling the dispersion of volcanic ash in the atmosphere [Ripepe et al., 2013, Lamb et al., 2015]. Furthermore, the mass discharge rate is a key parameter for initializing volcanic ash dispersal models [Ripepe et al., 2013]. In recent years, several theories have been developed to explain the acoustics of volcanic explosions in terms of source dynamics, assuming the linear theory for a simple, compact acoustic source [Johnson et al., 2004, Johnson et al., 2008, Gerst et al., 2013]. This assumption aligns with high-speed image analysis, which demonstrates how the acoustic wave field radiates from the vent throughout the entire explosive process [Genco et al., 2014].

The nature of the acoustic source and the influence of ash are still subjects of debate [Woulff et al., 1976, Johnson et al., 2004, Vergnolle et al., 2006, Caplan et al., 2010, Ripepe et al., 2010, Delle Donne et al., 2012, Ripepe et al., 2013, Lane et al., 2013, 2015, Delle Donne et al., 2016]. Experimental studies [Sánchez et al., 2014] intend to explain in the framework applicable to the analysis of volcanic data within the constraints of weak shock waves, specifically for straightforward and impulsive explosions arising from slug bursting. This equivalence allows for the calculation of the mass flow rate from the acoustic measurement. However, the linear theory model is only valid when flow dynamics are subsonic, and it assumes an equivalence between the velocity of the air parcel and the gas-particle exit velocity in experimental results [Sánchez et al., 2014].

This study explores into the complex dynamics of acoustic wave interactions with granular materials, shedding light on their implications for volcanic infrasound analysis. Through designed experiments in a controlled laboratory setting, we systematically explore the behavior of gas-particle mixtures during rapid decompression within a cylindrical cavity. While utilizing a straightforward open-end pipe geometry at an analog scale, the incorporation of a granular bed introduces a complexities such as attractive forces and size-dependent effects on acoustic dissipation. Our research confronts traditional assumptions by elucidating the complex correlation between acoustic pressure and observable volcanic ash characteristics.

Furthermore, we present infrasonic data from the eruption of Mount Etna, Sicily during December 3rd to 5th, 2015, along with estimations of mass using various methods [Vulpiani et al., 2016]. Significantly, our experiments highlight the non-trivial task of accurately estimating mass flow rates in eruptions based solely on infrasonic records, due to the complex interplay between acoustic and granular phenomena.

The dynamics of explosive basaltic volcanism: insights from laboratory experiments, numerical modelling and field observations

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Basaltic volcanism is the most common type of volcanism on Earth. Usually, basaltic volcanoes generate low intensity effusive eruptions, with lava flows propagating on the flank of the volcano. However, they can also produce more energetic and powerful explosive eruptions, creating lava fountains and ash columns of several kilometres height. Understanding the dynamics which govern these energetic and powerful eruption is fundamental to policymakers tasked with mitigating the risks associated with this type of eruptions.

In order to better understand the dynamics of explosive eruptions of low viscosity magmas, we employed a brand new apparatus combining a shock-tube rig together with a high-speed Schlieren shadow photography and acoustic and pressure sensors. With this apparatus we performed jet flow experiments using either particles or a low viscosity analogue fluid, to mimic either more fragmented or lava fountaining eruptions, respectively. Thanks to the high speed Schlieren shadow photography we are able to track the shock waves and the acoustic waves propagating during the jet emission. Moreover, analysing the acoustic signals we are able to constrain the main characteristics of the different jet flows. To provide a more comprehensive understanding of dynamics within the conduit we also performed numerical simulations of jet flow dynamics, comparing numerical results with laboratory experiments and with multiparametric data collected during Strombolian activities at Stromboli volcano. All of these data will provide unique multiparametric datasets which will help us to characterize explosive eruption dynamics at basaltic volcanoes.

Magmatic degassing dynamics at Halema'uma'u Crater, Kilauea, Hawaii

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Lava lake activity within Halema'uma'u crater on Kilauea volcano, Hawaii, between 2010 and 2018 provided a remarkable opportunity to observe the dynamics of magmatic degassing occurring in both lava lake surface and lava-spattering degassing regimes.

We collected open-path FTIR absorption spectra of magmatic gas in December 2015, when distributed diffuse degassing across the lake surface, coexisted with episodic spattering activity on the SE margin of the lava lake. We quantified seven volcanic gas species, H₂O, CO₂, SO₂, HCl, HF, CO and OCS, distinguishing between spattering and lava lake surface degassing. The retrieval of carbonyl sulfide (OCS), a redox-sensitive species, enables an evaluation of gas redox state with high-temporal resolution. Passive and solar traverse measurements allowed quantification of compositions and relative SO₂ emission rates between spattering and surface degassing. These are quantified by performing a mass balance between the HF/SO₂ ratios of the surface and spattering plumes and that of the overall mixed downwind plume, revealing that ~40% of SO₂ is released by surface degassing and ~60% by spattering degassing. Spattering gas has a CO₂/SO₂ molar ratio of 0.88 compared with 0.56 for surface degassing, consistent with a partial sulphur loss from magma during spattering. Diffuse gases possess a greater abundance of H₂O and HF, reflecting the melt-affinity of fluorine and late-stage degassing at the surface. The reconstruction of equilibrium temperature and oxidation state from measured redox pairs show that diffuse, spattering and rockfall degassing from the lava lake surface have a range of temperatures from 750-1050 °C, and all follow a rock-equilibrium redox profile of between NNO and FMQ.

We propose that spattering is the result of continuous formation of multiple gas bubbles, driven by coalescence, which promotes gas loss from 10s-100s of metres within the lake. Both degassing regimes provide a mechanism for partial degassing of magma within the Halema'uma'u lava lake, and production over time of a large volume of partially degassed magma. This is in agreement with petrological models indicating that summit-derived partially degassed magma accumulated in the MERZ in the decade prior to the 2018 LERZ eruption.

Magma titanium and iron contents dictate crystallization timescales and rheological behaviour in basaltic volcanic systems

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Magma ascending through Earth's crust undergoes complex chemical and physical changes that may induce crystallization, a process that contributes to lead the magmatic system toward a thermodynamic state of equilibrium. The diverse cooling and deformative regimes suffered by magmas heavily influence crystallization rates, solidification timescales, and consequently, the rheological evolution of magma. This, in turn, significantly impacts the dynamics of volcanic plumbing systems and the associated eruptive styles.

Here, we investigate the rheological changes in Stromboli magma (Italy) during disequilibrium crystallization under non-isothermal sub-liquidus conditions. By systematically varying the cooling rate (1-10 °C/min) and the shear rate (1-10 s⁻¹), we find that cooling rates significantly influence the solidification path of the basalt, whereas shear rates have a subordinate effect. By comparing our results with literature data on basalts from Mt. Etna (Italy), characterized by higher TiO₂ and FeO_{tot} contents, we observed distinct timescales and rates of solidification, contributing to unique eruptive dynamics in these volcanic plumbing systems.

A review of plagioclase growth rate and compositional evolution in mafic alkaline magmas: Guidelines for thermometry, hygrometry, and timescales of magma dynamics at Stromboli and Mt. Etna.

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Mafic alkaline magmas, such as those feeding the persistent eruptive activity of Stromboli and Mt. Etna volcanoes in Italy, are dominated by the crystallization of plagioclase via cooling and degassing phenomena related to the dynamics of shallow crustal reservoirs and eruptive conduits. Because plagioclase textures and compositions are extremely sensitive to the changes of intensive variables in subvolcanic plumbing systems, the phenomenological variability of erupted crystals preserves detailed evidence of complex growth histories. From this point of view, we reappraise the textural maturation and compositional complexity of plagioclase by allying thermodynamic and kinetic principles to natural and experimental observations, with the purpose of drawing up guidelines for reconstructing magma dynamics in mafic alkaline volcanic settings. A multifaceted statistical method is adopted to parameterize the decay of crystal growth rate with increasing crystallization time, as relaxation kinetics prevails over melt supersaturation effects. This model parameterization is combined with the textural analysis of natural plagioclase crystals to quantify the residence time of phenocrysts in equilibrium with magmas at Stromboli and Mt. Etna and/or the timescale of rapid microlite growth during disequilibrium ascent of magmas within the conduit. The role played by temperature and melt-water content on plagioclase components and major cation substitution mechanisms is also evaluated under both isobaric-isothermal and decompression conditions. The emerging paradigm is that the influence of dissolved water on anorthite-albite exchange between plagioclase and melt is overwhelmingly mitigated by changes in temperature at conditions of $P = 30\text{--}300\text{ MPa}$, $T = 1050\text{--}1150\text{ }^{\circ}\text{C}$, $f\text{O}_2 = \text{NNO}+1.9\text{--}\text{NNO}+2.3$, and melt- $\text{H}_2\text{O} = 0.6\text{--}4.4\text{ wt.}\%$. As a corollary, anorthite and albite melt activities are almost fully encapsulated in the variation of anhydrous melt components as the crystallization of plagioclase proceeds during magma cooling. Following this line of reasoning, we propose an integrated modeling approach to decipher complex zoning patterns in natural plagioclase phenocrysts from mafic alkaline eruptions. Key findings from our re-assessment of equilibrium, thermometric, and hygrometric models indicate that temperature and dissolved water can be iteratively estimated for different plagioclase textural patterns if crystals are sufficiently strongly zoned and probability-based criteria are applied to determine the maximum probability distribution from kernel density analysis.

Understanding post-eruptive processes in lava-like ignimbrites of southwestern Sardinia

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During catastrophic volcanic explosions, material is erupted and transported away from the volcano by a variety of processes (e.g., as pyroclastic density currents or ashfall). The different cooling rates experienced by different portions of pyroclastic deposits have been shown to control where lithium is stored within the Nuraxi ignimbrite found in the Sulcis volcanic province (SW Sardinia, Italy).

The lava-like Nuraxi (NU) ignimbrite found in the Sulcis volcanic district consists of a lithic-poor, rhyolitic ignimbrite, overlying a relatively thin fallout deposit, showing evidence of crystal enrichment towards the top of the unit, potentially due to remobilisation of cumulates during the later stages of magma withdrawal. Nonetheless, geochemical identification criteria can correlate ignimbrites across the Sulcis region [Gisbert & Gimeno, 2017].

Lithium contents of feldspar crystals show large variations that are associated with the groundmass texture of the sample and so the cooling rate. Lithium contents of plagioclase (avg. 52.7 ppm, n=102) and sanidine (avg. 15.9 ppm, n=59) crystals from the glassy, rapidly cooled portion of the deposit are lower than those of the slower cooled interior of the deposit (plagioclase avg. 83.9 ppm, n=132; sanidine avg. 29.9 ppm, n=58). These variations exist while other trace elements, such as Rb and Sr, are the same between the different portions of the deposit, thus making a magmatic origin unlikely. Rather, we propose that slow cooling promotes the ingress of Li into the feldspar crystals, potentially replacing hydrogen lost during dehydration of the magma upon eruption.

Lithium contents of groundmass glass average 16 ppm, lower than what would be predicted based on equilibrium partitioning from the plagioclase crystals [Neukampf et al., 2019]. We tentatively suggest that this may reflect the effect of magmatic degassing, but additional work is required to better understand this process.

A new viscosity model for Colli Albani: study and implications of nanolites formation in the melt

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Explosive volcanic eruptions pose a significant threat, generating ash plumes up to 40 km in height and ejecting vast volumes of material (hundreds of km³) into the atmosphere. Recent eruptions, such as Mount St. Helens (1980), Pinatubo (1990), and Eyjafjallajökull (2010), highlight the critical need for robust volcanic hazard assessments. Magma rheology, primarily controlled by melt viscosity, dictates eruptive style. Higher viscosities limit outgassing rates, triggering fragmentation at depth, and enhancing explosivity. Fe-Ti nanolite precipitation during ascent further increases viscosity by increasing melt polymerization and physically impeding flow. Viscosity models are crucial for understanding magma dynamics, enabling estimation of melt viscosity at specific temperatures and compositions to model eruption behavior. However, the link between chemical composition and explosivity remains a subject of debate. Mafic-alkaline magmas are generally expected to erupt effusively, yet several volcanoes exhibit a history of mafic Plinian and Sub-Plinian eruptions. Here, we investigate the viscosity of tephri-phonolite magma from the Pozzolane Nere Plinian eruption (407±4 ka) in the Colli Albani volcanic district. We propose a novel viscosity model for Colli Albani that incorporates the influence of Fe-Ti nanolite precipitation during magma ascent. Hydrous, nanolite-free glasses were synthesized from the Pozzolane Nere ignimbrite using a piston cylinder apparatus. High-temperature viscosity measurements, Brillouin spectroscopy, and calorimetry analyses were employed to parameterize the nanolite-free viscosity of Pozzolane Nere magma. Our findings indicate a lower viscosity for Pozzolane Nere magma at eruptive temperatures than previously thought, with important implications for magma ascent dynamics.

Rheological analysis of lahar interstitial fluids: the importance of the measurement protocol

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Lahars are complex mixtures of sediment and water that flow down volcanic slopes under the influence of gravity. The physical behavior of lahars depends on the interaction between the liquid (interstitial fluid) and solid (large clasts) phases of which they are composed. The interstitial fluid is composed of fine sediment up to 63 microns and water [Iverson et al., 1997]. Therefore, understanding the rheological behavior of the interstitial fluid provides insights into the lahar mobility.

We studied lahar deposits from Popocatepetl volcano, Mexico, selected based on their volcanic origin and lithic components. The deposits were classified as syn-eruptive (occurring during the volcanic eruption), and secondary lahars (occurring after the eruption). The syn-eruptive deposits were mainly composed of pumice clasts, while the secondary deposits contain varying amounts of pumice and lava clasts. These volcanic deposits also exhibited different emplacement temperatures, from ambient temperature in the case of secondary lahars to up to 100 °C for syn-eruptive lahars.

We propose a standard methodology to characterize the rheological behavior of the interstitial fluid of the lahars, considering the volumetric concentration and temperature of the samples as proxies for natural conditions. This methodology was performed using an M702e Anton Paar rheometer with a cup and bob geometry, within a shear rate range of 10^1 to 10^2 s⁻¹, e.g. in a laminar flow regime, applied in a logarithmic ramp for 300s. The measurements were carried out under precise reproducibility conditions, ensuring a homogeneous sediment suspension and a stable flow regime. Some of the measurement parameters were similar to those reported in the literature on the rheology of sediment suspensions [Jeong, 2010; Xu and Huhe, 2016; Shakeel et al., 2021].

The apparent viscosity values are on the order of 10^{-1} Pa s. These results align with those previously observed in Tranquilino [2023], which were obtained using a constant shear rate method in a Fungilab viscometer, under the same measurement conditions in terms of sample characteristics (maximum grain size and volumetric concentration of sediments) and instrument characteristics (shear rates).

One of the main contributions of our work will be to establish relationships between well-studied variables (e.g. granulometric distribution and volumetric concentration) and variables that have not been extensively studied (e.g. clast composition and temperature).

Crystallization of primary analcime in K-phonolites: experimental evidence

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Analcime is a hydrous sodium aluminosilicate, the origin of which as either a primary or secondary mineral in alkaline volcanic rocks has been long debated on the basis of mineralogical, chemical and isotopic data [e.g. Henderson et al., 2014 and references therein]. The petrologic importance of analcime has been highlighted by many researchers, and most experimental studies have been carried out on analcime crystals or on the analcime-leucite transformation system to validate either a magmatic (primary) or hydrothermal (secondary) origin [e.g. Putnis, et al., 2007]. The hypothesis of the primary origin of analcime assumes that this mineral crystallizes directly from relatively evolved alkaline magmas, probably at H₂O-saturated pressure >200MPa [e.g. Henderson, et al., 2014], pointing to differentiation stages that does not occur in shallow depths magmatic chambers (depth <8 km).

The juvenile pumice clasts sampled from the Cala Battaglia Plinian deposit (UCB below) on the Ventotene Island (Pontine Islands, Tyrrhenian sea) have a K-phonolitic composition and contain widespread euhedral analcime crystals, up to 100 µm in size. These grains appear to be fresh and devoid of inclusions. Furthermore, the chemical composition of UCB analcime exhibits the characteristics attributable to a primary, magmatic origin of these crystals represented by the relatively high Fe₂O₃ content (up to 0.51 wt%; [Luhr & Kyser, 1989]) and the slight enrichment of K₂O content in the analcime rims in contact with the glassy groundmass of the pumice clasts (on average K₂O= 0.26wt% at rim and 0.15wt% at core of analcime crystals).

In order to test the hypothesis of a magmatic origin of the analcime observed in UCB pumices, we performed a preliminary set of crystallization experiments with a piston cylinder apparatus using as starting material the above mentioned UCB over-saturated (H₂O ~ 10 wt%) phonolites. The experimental pressure conditions studied were 150 and 600 MPa in a temperature range of 700-900 °C. The target conditions were held for 3 hours.

Experimental results indicate that under high-pressure conditions a feldspathoid volatile-bearing phase is a liquidus phase. At 900°C, it occurs both adjacent to vesicles and dispersed in the glass associated with rare plagioclase. These crystals are euhedral with hexagonal habit and are ≤ 20 µm in size. Moreover, their composition shows high SiO₂ content (~ 60 wt%), the Na₂O/ K₂O ratio is ~ 1 and Fe₂O₃ content is about 2 wt%. The high K₂O content could suggest an enlargement of the analcime stability field in K-rich silicate melts. In high-K trachytes the cotectic crystallization of K-rich analcime and plagioclase seems predate k-feldspar. The latter could occur as reaction K-analcime+melt=K-feldspar+Na-analcime. On the other hand, the existence of metastable K-analcime phase could be used to model the reaction that turn the leucite in analcime at low pressure. In any case, run products of experiments at lower pressure (150 MPa) do not show the presence of feldspathoid phase. In agreement with the literature, preliminary experiments performed show that the pressure parameter plays an important role in controlling the differentiation of a H₂O-saturated K-phonolitic magma and that analcime-like feldspathoids are unable to crystallize from such magmas in the shallower (150 MPa) magma reservoirs.

Magma differentiation in dynamic mush domains from the perspective of multivariate statistics: open- vs closed-system evolution

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Open-conduit conditions characterize several of the most hazardous and active volcanic systems of basaltic composition worldwide, persistently refilled by magmatic inputs. Eruptive products with similar bulk compositions, chemically buffered by continual mafic inputs, exhibit nevertheless heterogeneous glass compositions in response to variable magma mixing, crystallization, and differentiation processes within different parts of the plumbing system. Here we document how multivariate statistics and magma differentiation modeling based on a large data set of glass compositions can be combined to constrain magma differentiation and plumbing system dynamics. Major and trace elements of matrix glasses erupted at Stromboli volcano (Italy) over the last twenty years provide a benchmark against which to test our integrated petrological approach. Principal component analysis, K-means cluster analysis, and kernel density estimation reveal that trace elements define a multivariate space whose eigenvectors are more readily interpretable in terms of petrological processes than major elements, leading to improved clustering solutions. Comparison between open- and closed-system differentiation models outlines that steady state magma compositions at constantly replenished and erupting magmatic systems approximate simple fractional crystallization trends, due to short magma residence times. Open-system magma dynamics imply lower crystallinities pervade the magmatic storage than those associated with closed-system scenarios, allowing efficient crystal-melt separation toward the top of the reservoir, where eruptible melts continuously supply the ordinary activity at the volcano. Conversely, a mush-like environment constitutes the bottom of the reservoir, in which poorly evolved magmas result from mixing events between mush residual melts and primitive magmas injected from deeper crustal levels.

A new viscosity model for hydrous andesitic magmas: insights from Sakurajima volcano

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The study of magma viscosity is crucial for understanding volcanic processes, as it controls magma transport, deformation response, and ultimately the eruptive style. Previous research [Sokolov et al. 2007; Cassetta et al. 2021] suggests that the viscosity of silicate melts can be parameterized by combining glass transition temperature with sound velocity data. However, our recent studies [Valdivia et al. 2023, 2024] indicate that these relationships fail to predict crystal-free viscosity measurements for andesitic and basaltic compositions.

In this proposal, we introduce a simplified empirical equation that correlates the fragility index (m) of volcanic glasses with sound velocity data obtained from Brillouin spectroscopy for compositions ranging from rhyolitic to basaltic. Utilizing this new equation, we present a novel viscosity model for the hydrous andesitic melt of Sakurajima volcano (Japan) as a function of temperature and water content. Our results suggest that the viscosity of Sakurajima's andesitic magma at eruptive conditions is significantly lower than previously predicted. Our findings advance the understanding of volcanic melt rheology by providing a more accurate tool for predicting crystal-free magma viscosity. Finally, this improvement has crucial implications for the numerical modeling of volcanic eruptions and the management of associated risks.

Large-scale experimental investigations on debris flows in the Sarno area: exploring the influence of soil properties and moisture content on triggering processes

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Volcanic debris flows, characterised by highly concentrated mixtures of water, mud, and rock debris of volcanic origin, typically occur in regions with unconsolidated sediments, steep slopes, and adequate moisture levels. They are among the most common mass movement processes and the most dangerous types of landslides due to their high flow velocity, strong impact forces, extended runout, and unpredictable temporal patterns.

This research aims to enhance predictive capabilities regarding future debris flows within the Campanian Volcanism area, with a specific focus on the Sarno region. Sarno, situated on the western side of the Campanian Apennines, gained notoriety due to catastrophic debris flow events on May 6, 1998, resulting in the destruction of the town and claiming approximately 150 lives. The susceptibility to hazards in this area is heightened by several factors: i) the presence of calcareous bedrock with steep slopes (30–45°), overlain by ii) alternating layers of pyroclastic and colluvium deposits, and iii) natural and man-made scarps exacerbating stability conditions. This study employs a multimethodological approach, encompassing i) laboratory analyses of soil properties, including geotechnical and rheological assessments of sediments with a particular focus on identifying clay minerals that significantly influence soil-water mixture rheology; ii) large-scale experiments to simulate rainfall-induced water infiltration and slope failure.

The rheological analyses are carried out at the Chemistry Department of the University of Bari using an Anton Paar M702e rheometer. Specifically, the Mohr envelope of failure of sediment is characterised at different water contents, while the rheological properties of sediment-water mixtures are quantified through shear stress vs. shear rate analyses using both standard concentric cylinder and relative geometries.

The large-scale experiments are conducted at the CAMIIlab held at the University of Calabria. The laboratory features a specialized 6-meter-long, 1-meter-wide facility equipped with an array of sensors and instruments, including rain gauges, laser distance metres, cameras, Time Domain Reflectometry (TDR) sensors, tensiometers, and pore pressure sensors that offer continuous monitoring of suction, degree of saturation, and other pertinent parameters throughout the entire duration of the experiments.

The facility's dimensions allow for the implementation of large-scale physical models, enabling the analysis of substantial terrain volumes, faithful reproduction of natural phenomena, and mitigation of boundary effects to the extent feasible.

The Kencherra Ignimbrite (Central Main Ethiopian Rift): a case study for assessing emplacement mechanisms of high-grade, welded ignimbrites

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Many studies have been conducted in the last decades aimed at understanding the eruption and emplacement processes of high-grade, densely welded ignimbrites. Hosting numerous examples of these deposits dispersed over a wide area, the Central Main Ethiopian Rift (CMER) represents in this view a highly valuable study area.

In the present work we focus on the Lower Pleistocene “Kencherra Ignimbrite”, an important marker bed within the volcanic stratigraphy of CMER. Within the present study we collected extensive stratigraphic and structural data, microscopic observations, density measurements, rheological experimental data, geochemical and geochronological analyses to provide a description of the stratigraphy and the characteristics of this ignimbrite, shedding new light on the potential source and on the peculiar emplacement processes producing its diagnostic features. This rhyolitic ignimbrite crops out along the eastern margin of the rift, covering a minimum area of 1000 km² with a nearly constant thickness between 10-20 m. Its internal stratigraphy is defined by a characteristic sequence of facies, typified by basal and top vitrophyres enclosing the main body of the ignimbrite. This is formed by a pervasive, sub-horizontal foliation defined by laterally discontinuous parting planes, clearly indicative of progressive aggradation and strain from a sustained current. Although in the absence of folding, macro- and micro-scale strain indicators are abundant and well preserved in this facies of the ignimbrite, allowing to discuss in detail the main mechanisms controlling flow and emplacement in association with the collected data on the rheology of the juvenile component.

Being emplaced on a relative flat topography, with the present topography mainly post-dating the Kencherra Ignimbrite emplacement, we can exclude the effects of topographically-induced rheomorphism in determining the well exposed deformative structures. For this reason, as all the observed structures are related to the shearing imparted by the overriding particulate flow, the Kencherra ignimbrite represents an interesting and peculiar case to study the syn-eruptive sequence of agglutination, deposition and deformation which characterize the emplacement of high-grade ignimbrite deposits.

High-temperature Raman spectroscopy investigation of volcanic glasses

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Nanocrystals (i.e., nanolites) exert a significant influence on magmatic processes, shaping the properties and behavior of magma. These include their role in crystal nucleation and growth, element partitioning, melt structure and bubble nucleation. In addition, their presence profoundly impacts magma rheology and viscosity (the formation of nanolites results in a viscosity increase of up to two orders of magnitude), pivotal factors in magma fragmentation, which subsequently dictates the eruptive style.

This study marks the first in situ observation of nanolite formation within andesitic glass at elevated temperatures employing Raman spectroscopy. Beyond gaining insights on nanolite formation, our research pioneers a methodology for high-temperature Raman investigation of nanocrystals.

The starting material is a synthetic anhydrous andesitic glass that mirrors the melt from Sakurajima volcano, Japan. Spectra were obtained in UV configuration at 355 nm and 405 nm, as well as in the visible range at 488 nm and 514 nm, covering the range of 150-2000 cm⁻¹. The heating rate applied was typically 20°C s⁻¹, except for the last 100°C before reaching the target temperature, where it was 5°C s⁻¹. The duration of maintaining the sample at the target temperature was typically 60 minutes. The cooling rate employed was consistently 10°C s⁻¹.

The inspection of the spectrum of the starting material collected at room temperature using the green laser (514 nm) affirmed the crystal-free amorphous nature of our sample. Subsequently, we investigated room-temperature Raman spectra obtained after heating at T_g and two higher temperatures. Notably, the room temperature Raman spectrum after heating at T_g exhibited no significant change in spectral features. However, following heating at higher temperatures, there was an increase in the regions 300–330 cm⁻¹ and 660–690 cm⁻¹, and a decrease in the Raman signal at 850–1150 cm⁻¹. Thus, heating a nanolite-free glass above T_g induces crystallization of Fe-TiO₂ nanolites, which is marked by distinct peaks at 300–330 and 660–690 cm⁻¹. In addition, the higher the temperature and the longer run duration, the higher the intensity of these peaks.

Raman spectra using the green laser were also obtained at high temperatures. An enhancement in the intensity of the 300–330 and 660–690 cm⁻¹ regions, coupled with a reduction in the intensity of the 850–1150 cm⁻¹ region was observed during an isothermal hold at temperatures above T_g. It is noted, however, that the Raman spectra of glasses exhibited a distinct peak at 660–690 cm⁻¹ at room temperature, but a very broad spectral feature at temperatures above T_g. To investigate this phenomenon further, we acquired spectra during heating from room temperature using the nanolite-bearing sample. The 660–690 cm⁻¹ peak intensity gradually decreased with increasing temperature, disappearing around 500°C, and reemerged similarly upon cooling. The cause of this temperature effect on the peak intensity remains unclear. Conversely, the intensity of the 300–330 cm⁻¹ region appears to be less sensitive to the temperature effect and we can clearly observe the formation of this peak during increasing temperature. Thus, the evolution of the 300–330 cm-

1 peak is solely dependent on the degree of nanolite crystallization, while the appearance and evolution of the 660-690 cm^{-1} peak are temperature-dependent, being challenging to observe above 500°C.

With the green laser, we also observed that beyond temperatures of approximately 700°C, the background intensity experiences a rapid rise attributed to black body radiation. Consequently, this effect poses challenges in discerning glass-related features at temperature significantly higher than 700°C. While keeping the sample at a target temperature, both the relative and absolute background intensity persistently remain at the same levels. Upon cooling, the background intensity decreases in a similar fashion, aligning with the principles of black body radiation.

In addition to utilizing the green laser (514 nm), we explored the effects of three other laser frequencies on Raman features: blue (488 nm) and two UV lasers (355 nm and 405 nm). The blue laser exhibited greater destructiveness compared to the green laser and proved to be much less sensitive to changes in the 660–690 cm^{-1} region. Spectra obtained using the HF UV laser did not display significant variations, suggesting that the HF UV laser is relatively insensitive to the glass structure changes at 300–330 and 660–690 cm^{-1} . Spectra obtained with the lower-frequency UV laser (405 nm) exhibited dramatically different spectroscopic features compared to the other lasers. Although further test experiments are desired, the green laser appears to be a more suitable choice for investigating the evolution of Raman spectra of volcanic glasses at high temperatures.

Impact of Carbonate Assimilation and Deformation on Vesuvius Phonotephrite Rheology

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The intrusion of magma chambers into a carbonate basement develops a series of thermochemical reactions that gradually progress from the carbonate wall-rock towards the magma, leading to alterations in the chemical composition of the entire system (crystal + melt). Recent petrological and experimental investigations emphasize that different levels of limestone/dolostone assimilation play a critical role in regulating the liquid line of descent of magmas, thereby influencing the initiation of crystallization for specific mineral phases.

In this study, we investigate how limestone/dolostone assimilation and deformation regimes impact the rheology of a leucite-bearing phonotephrite magma from Vesuvius (Italy). Using starting materials doped with 0, 10, or 20 wt.% of CaO and CaO+MgO, to mimic the effects of limestone/dolostone assimilation, we conducted two sets of crystallization experiments at 1180°C under static and dynamic conditions (shear strain rate of 1 and 5 s⁻¹). We observe distinct rheological behaviors among melts, which vary based on composition and applied shear rate.

These differences manifest in terms of crystallizing mineral phases, with CaO-doped samples showing variations such as $\pm$ clinopyroxene $\pm$ melilite $\pm$ leucite $\pm$ nepheline, and CaO+MgO-doped samples showing variations such as $\pm$ clinopyroxene $\pm$ melilite $\pm$ olivine $\pm$ leucite $\pm$ nepheline, alongside differences in crystallization onset and final crystal contents. Higher alkaline earth content (both Ca and Ca+Mg) combined with increased shear rates promote crystallization, resulting in elevated crystal fractions (up to 51%) and larger crystals. Consequently, heavily doped samples subjected to high shear rates experience a viscosity increase of up to 1.5 Log Pa s due to crystallization. This increase leads to a rheological transition from coherent flow to shear localization, ultimately culminating in physical separation, such as viscous rupture.

Additionally, our experiments reveal that the interplay between carbonate assimilation and deformation conditions not only influences the mineralogical and rheological properties of the magma but also affects its overall behavior during ascent. The presence of higher crystal fractions and increased viscosity can significantly alter the transport properties of the magma, potentially impacting eruption dynamics and the morphology of the resulting volcanic deposits

New viscosity data of volcanic melts

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The viscosity of magma is a crucial physical property that influences its ascent. This property determines the timescale of magma transport, its viscoelastic response to deformation, and ultimately the eruption style. Melt viscosity is also a key parameter in numerical simulations of volcanic eruptions, essential for probabilistic forecasts of their (effusive or explosive) behavior. Over the past four decades, melt viscosity has been extensively studied experimentally. It is well-established that chemical composition (including dissolved volatiles) and temperature are the primary factors affecting melt viscosity, which can vary over 14 orders of magnitude. However, recent research suggests our understanding of melt viscosity may be less accurate than previously thought. This is attributed to the formation of nanocrystals throughout the synthesis of starting materials and/or viscosity measurements. Nanocrystal formation can increase viscosity, and without proper material characterization, measured viscosities may not reflect the true viscosity of nanocrystal-free melt.

Here, we present the latest advancements in melt viscosity characterization procedures and introduce new viscosity data for a series of volcanic melts with diverse chemical compositions. We employ a multipronged approach based on Raman and Brillouin spectroscopies, thermomechanical, conventional and flash calorimetry analyses, supported by transmission electron microscopy imaging. We explore a chemical landscape spanning low-SiO₂ melts (e.g., tephrite) to extremely polymerized melts (e.g., rhyolite) with and without iron. We identify critical chemical domains where nanocrystal formation has significantly impacted previous measurements, paving the way for a more accurate understanding of melt viscosity. This improved understanding will refine volcanic eruption forecasting models, leading to more robust predictions.

Quantifying dissolution kinetics of clinopyroxene in hydrous basaltic magmas through 4D in situ experiments

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Crystallization and dissolution of minerals are important processes in the petrogenesis of igneous rocks, especially at magmatic storage conditions in which formation of crystal mush, magma mixing and assimilation may occur.

Disequilibrium textures that range from simple normal zoning to complex textures reflecting resorption, rapid crystal growth, and diffusive re-equilibration are associated to a transition from subliquidus to superheating conditions, and vice versa. Superheating with respect to liquidus temperature can be produced by injections of hot fresh magma into a magma storage region, and by magma mixing, anatexis and decompression. Crystallization and mineral dissolution under water-saturated conditions at crustal pressure are fundamental to estimate magma residence times before the eruption and they have strong implications for the locking and unlocking of basaltic magmas, affecting their mobility and eruptibility. This feeds into volcanic risk assessment and mitigation models and management in active volcanic areas. However, relationships between crystallinity, rheology and eruptibility remain uncertain because of the challenges associated with documenting magma crystallization and mineral dissolution in real time.

In basaltic magmas, crystallization kinetics has been extensively investigated using quench experiments with an ex situ view. Only recently they have been studied using real time experiments with an in situ view. Here we show the results of in situ 3D time-dependent, high temperature experiments under water-saturated conditions performed using synchrotron X-ray microtomography to investigate crystallization and dissolution kinetics in a basaltic magma at crustal pressure. This new 4D approach provides unique quantitative information on the growth and dissolution kinetics of pyroxene in basaltic magmas as function of time, undercooling and superheating. This study shows for the first time the dissolution kinetics and the textural evolution of pyroxene in 3D through time.

The porosity and pore connectivity evolution of Vesuvius pyroclasts – a database

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Vesiculated volcanic rocks conserve the records of degassing processes in magmas. Therefore, the vesicle size distributions (VSD), vesicle number densities (VND), vesicle shapes, as well as the overall porosity and pore connectivity can be linked to physical processes that drive magma ascent and eruption. The pore connectivity describes the fraction of the interconnected pore space. It is hence fundamentally related to permeability, which controls magma outgassing and the explosive potential of a magma during ascent in the shallowest part of the crust.

Here, we present a database of VSDs, VNDs, porosity (Φ) and pore connectivity (C) for several explosive eruptions of Somma-Vesuvius of various intensities. To do so, we take advantage of the recent advances in X-Ray Micro-computed Tomography (Micro-CT), which allows us to calculate these values from the actual 3D distribution within a clast without the previously necessary 2D-to-3D conversion. Three preliminary observations can be made: i) the overall total porosity of the eruptive products increases (from $\Phi \sim 40\%$ up to $\Phi \sim 80\%$) as eruption intensity increases (violent Strombolian to sub-Plinian to Plinian), ii) the pore connectivity (C) remains system-spanning and at high values ($C \sim 1$) for highly explosive eruptions (sub-Plinian and Plinian) and iii) most of the erupted clasts show an isotropic vesiculation trend, with some minor contribution of shear-induced vesiculation (evidenced by elongated bubble forms with stretched glass films in between). All this evidence suggests that all highly explosive eruptions of Somma-Vesuvius follow a similar vesiculation trend and, hence, similar pre-eruptive degassing behaviour and magma ascent.

We finally compare our results to literature data of porosity and connectivity of eruptive products of other volcanic systems with different magma composition and draw some generalized conclusions on how the vesiculation pattern in phonolitic to phonotephritic melts is distinct from other composition.

X-ray microtomography and in-situ experiments as tools to investigate hydrothermal unrest conditions of phreatic events at Vulcano Island (Italy)

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Periods of volcanic unrest are characterized by deep uncertainty for those managing the emergency. A restless volcanic system could rapidly evolve, leading to the onset of a new eruptive event or transitioning into a new dormant phase. Volcanic unrests at quiescent volcanoes are often driven by important variations in the hydrothermal system and, even in absence of magma uprising and eruptive activity, may culminate in hazardous phenomena like: phreatic eruptions, due to rapid heating and vaporization of fluids at shallow levels, or landslides, due to failure of altered pyroclastic units.

Vulcano, the southernmost island of the Aeolian archipelago (Italy), has potential eruptive activity and other interconnected hazards that can strongly enhance the volcanic risk, especially during the summer period when a high tourism rate, occurs. In 2021, one of the most significant unrest at La Fossa crater in the last decades began, triggering a new possible path-to-eruption. The increase in many monitored parameters (fumaroles temperatures, steam output, concentration of acidic gas species as CO₂ and SO₂, etc.) observed in September lead Civil Protection to raise the alert level for Vulcano from green to yellow on October 1. This prompted new research for a better understanding of the volcano-hydrothermal system which controls the ongoing unrest conditions and dynamics.

In this work, we present a systematic dataset of rock microstructural parameters (e.g., pore and crystal content and size distribution), physical properties (e.g., permeability, strength, elastic moduli) and mechanical behaviour of Vulcano bedrocks samples. Volcanic rocks features are explored using the innovative and non-destructively imaging technique X-ray microtomography which allows to obtain high-resolution (1 µm) 3D digital images of rock-samples; these analyses are integrated with in-situ experiments (uniaxial compression/tension) allowing 4D time-resolved imaging. The characterization of the layered bedrock offers a framework useful for constraining numerical modelling and geophysical prospections of the hydrothermal fluid circulation to better explore conditions that promote the onset of phreatic events at Vulcano.

S08 - MULTI-HAZARD AND RISK ASSESSMENT IN VOLCANIC AREAS: MODELS, APPLICATIONS AND CHALLENGES

Conveners:

Agnese Turchi, Annalisa Cappello, Silvia Massaro,
Beatriz Martinez-Montesinos, Andrea Bevilacqua, Vera Pessina

Reconstructing the Campanian Ignimbrite super-eruption combining plume dynamics and tephra dispersion models

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Explosive volcanic eruptions can inject high quantities of magmatic materials into the atmosphere representing a risk to life and society. The Campi Flegrei (CF) caldera in southern Italy has generated several explosive eruptions in recent geological times, including the ~39 ka Campanian Ignimbrite (CI) super-eruption that is the largest explosive eruption in Europe in the last 200 ka. Characterized by two distinct plume-forming phases, Plinian and co-ignimbrite, the CI eruption is credited with inducing a volcanic winter in Eastern Europe and influencing the Middle to Upper Paleolithic transition.

Numerical models require as input data several eruption source parameters (ESPs), which are poorly constrained, making assessment of eruption impacts challenging. An estimation of such ESPs can be achieved through the reconstruction of past eruptions and is even crucial in order to reduce model errors and produce reliable assessments of volcanic hazards for future eruptions. In this work, we take advantage of recent advances in computational capabilities and numerical modeling to produce a robust reconstruction of the dynamics of past super-eruption plumes aiming to enhance the accuracy of volcanic hazard assessment. We use a combination of atmospheric dispersion models and eruption plume dynamics models, alongside novel inversion methods based on data assimilation techniques to estimate ESPs using geological data of tephra deposits. In particular, we use the dispersion model FALL3D for long-range atmospheric transport of volcanic ash, the SK-3D model for simulating the dynamics of eruption columns, and the GNC (Gaussian with Non-negative constraints) method to assimilate tephra deposits observations. The proposed strategy has been applied to the CI super-eruption as follows. In a first step, we determined an initial volcanic scenario (VS) establishing the most probable ranges for each eruptive parameter and for the meteorological conditions, as estimated from previous studies in the scientific literature. Then, we built a set of 64 different VS by perturbing the ESPs of the initial guess within the established range and developed numerical simulations of tephra dispersal and fallout for all of them with FALL3D. After that, the GNC method was applied to the 133 measurements of deposit thickness of tephra associated with this eruption available in the region. This process provided us with a numerical reconstruction of the tephra deposits, an estimation of the time evolution of the eruption column, and a set of optimized ESPs. This information is used for SK-3D in order to reconstruct the volcanic column and, in particular, simulate the column collapse conditions that generated the ignimbrite and coignimbrite clouds.

The 10 February 2022 pyroclastic density current at Etna: unraveling the trigger mechanism and propagation dynamics

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In recent years, pyroclastic density currents (PDCs) generated by volcanoes with mafic to intermediate compositions have garnered a greater interest within the scientific community. These types of granular flows at high-particle concentrations can be generated by the failure of pyroclastic fall deposits emplaced on steep slopes, and in some cases they are characterized by an extreme mobility reaching unusual long runout distances.

An increase in the frequency of this type of PDCs has been observed at Mt. Etna volcano (Italy) during the recent 2020-2022 volcanic activity, characterized by a series of intense paroxysmal eruptions which took place at the Southeast Crater (SEC). In particular, at least four PDCs have been emplaced during one single, powerful lava fountaining episode on the evening of 10 February 2022. The largest PDC was detected by a real-time monitoring camera at 21:26 UTC and was generated by the gravitational collapse of a large portion of the south flank of the SEC, forming a deep scar visible after the PDC formation. The result of the PDC is a reddish-brown deposit which has been subdivided into four main stratigraphic units. These are mainly composed of fine ash to lapilli in the lower part and fine lapilli to blocks in the upper part, extending south up to ~1.4 km from the source area and covering the upper scoria cone of the 2002-2003 eruption located ~640 m to the south.

In this work, we present a multidisciplinary approach which combines field surveys, textural analysis on selected samples, and remote sensing data to reconstruct the triggering mechanisms and flow dynamics, integrated and supported by numerical modeling of the PDC propagation. The results of this study can contribute to improve the knowledge of this complex type of volcanic phenomena in contexts of basaltic volcanism, and therefore also the assessment of the associated hazard, especially at highly touristic volcanoes as Etna.

VolcFire: a novel numerical tool for mapping volcanic-induced fire hazards

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In recent years, extensive research has been dedicated to the development of numerical models for forest fire propagation, utilizing a range of approaches from complex physical models to simpler graph or cellular automata-based ones. These models rely on various input parameters, such as humidity, vegetation, wind, and topography to accurately replicate the rate of fire spread (ROS). When integrated with Geographic Information Systems (GIS), these models facilitate the classification of soil and mapping of burnt areas.

However, despite advancements in forest fire modeling, a dedicated model for volcanic-induced fires was lacking. To address this gap, we developed VolcFire: a novel numerical model based on cellular automata, which tackles issues related to accessibility, usability, and computational costs inherent in existing applications. This new model is able to generate fire hazard scenarios, providing insights into the likelihood of combustion in volcanic areas.

Using topography and environmental indices (derived from satellite data), VolcFire reproduced the fires that occurred on Stromboli Island on July 3, 2019, and May 25, 2022, showing good spatial accuracy, with Brier scores of 0.188 ± 0.002 and 0.073 ± 0.001 , respectively.

These advancements are crucial for mitigating the risks posed by volcanic-induced fires and enhancing disaster preparedness.

Modeling the priming mechanism of phreatic eruptions

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Phreatic eruptions are non-magmatic explosions consisting in the sudden expansions of groundwater due to the input of hot magmatic fluids and heat. Although such eruptions are intrinsically less hazardous than magmatic eruptions (i.e. the energy released in the process is relatively low) the lack of clear and early precursory signals increases the associated risks. Moreover, the priming mechanisms of phreatic eruption are still not completely understood. In this work we propose a physical model for the priming mechanism of phreatic eruptions. This model is based on the mixture theory and describes the dynamic and energetic evolution of a two-phases fluid composed of several chemical species within a porous matrix. In particular, we decided to not use the Darcy flow approximation as momentum conservation equation in order to relax a set of assumptions. The system must be coupled with an equation of state in order to describe the relations between thermodynamic properties of the fluid and phase transitions. The complexity of this model requires the solution to be numerical. In this regard, we created Phreer, a module for the finite-element solver Alya. To the present date, the model is coupled with an equation of state capable of describing the thermodynamic properties of a water-carbon dioxide mixture with pressures up to 10.0 GPa and temperatures in the range of 673.15 K and 2573.15 K, i.e. the pressure-temperature ranges we expect to observe within volcanic domains.

Increase of volatiles output in the atmosphere at Vulcano Island inferred by SO₂ plume monitoring in the 2021-2023 period

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The volatiles emitted in different way from the active volcanoes have been responsible of the increases of gases in the atmosphere like H₂O, SO₂, CO₂, and H₂S.

The volatiles are exsolved from the magma batch located below the volcano edifice, during the rising towards the surface interacts with surficial fluids, and come out from the soils, the aquifers, the fumaroles and the main conducts.

Near continuous plume SO₂ fluxes, measurements have been carried out by a network system of SO₂ measurements at Vulcano Island, Italy. Two Scan-DOAS stations belonging to the NOVAC Project are located respectively at NE and SW of volcanic cone. This configuration allowed tracking over 80% of plume emission during the solar year.

NOVAC is a permanent network for the measurement of volcanic gas emissions, born in 2005 from a European project to creating and installing automated prototypes capable to monitor gases by volcanic plumes, around the world. The main objective was to quantify global volcanic gas emissions and increase knowledge on changes in volcanic activity by estimating the gases emitted by each individual volcanic system.

The fluxes of SO₂ plume acquired by the UV-scanning DOAS network showed, in the study period (2021 – 2022), monthly average values between 20 and 121 t d⁻¹. Starting from June 2021 onwards, the SO₂ output showed a positive trend with an abrupt increase reaching the highest monthly value in September 2021 (monthly average value= 121 t d⁻¹) and the highest daily measurement 16 November 2021 (daily average = 248 t d⁻¹).

The atmospheric dispersion model (AERMOD), designed for simulate the dispersion of air pollutant from stationary anthropogenic and natural emission source, have been utilized to produce the dispersion SO₂ maps and evaluate the air SO₂ concentrations in the neighboring areas of the Vulcano Island. These maps have been constructed using environmental parameters such as wind speed and direction measured by the local network installed in different points of the island and at different altitudes. These SO₂ iso-concentration maps compared with the limit values shown in the human health tables have made it possible to identify the most harmful areas. The lowest concentrations of SO₂ were recorded in the outermost isoline (white line), with values of µg m⁻³, which is 2.8 times higher than the 24 h exposure limit (40 µg m⁻³) proposed by the WHO (World Health Organization). While considering the 24 h exposure limit proposed by Italian norms (125 µg m⁻³), no adverse health effects were detected. Ex-posure to low concentrations of SO₂ by the inhabitants of the island does not seem to produce adverse health effects in the short term. The long-term effects have yet to be studied in detail (monthly and yearly exposure), especially considering periods of anomalous activity and the direction of the prevailing winds. Furthermore, the increase in the concentration of volcanic gases in the atmosphere has also caused an environmental alert for public health. Consequently, the Italian Civil Protection declared an environmental state of emergency and ordered the evacuation of the population from the inhabited center of Vulcano Porto in November 2021.

Assessing ballistic hazard at Stromboli (Italy)

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Ballistic projectiles are one of the main hazards associated to the explosive activity of Stromboli. In particular, this hazard is remarkable during major explosions and paroxysms which interrupt the persistent mild strombolian activity of the volcano. In this work we aim to developing first quantitative hazard maps of this phenomenon by relying on the large number of information describing the explosive activity of the volcano and by analyzing it through statistical analysis and probability models. The assessment of ballistic hazard was based on the development and analysis of two catalogs of explosive eruptive activity at Stromboli, particularly major explosions and paroxysms. The first catalog, named “historical catalog”, covers the period from 1879 to 1960, whereas the second catalog, named “recent catalog”, covers the period from 1970 to 2023. Both catalogs are open datasets and can be downloaded from the INGV Data Repository of the Pisa Section. Using the information in the two catalogs, we mapped the area reached by ballistic projectiles using circular sectors with varying radii and angles. In each simplified map, an axisymmetric component was defined, followed by 1 to 3 circular sectors with greater distance ranges. Three classes of uncertainty on radii and angles were considered: low uncertainty (up to 100 m in distance), moderate uncertainty (up to 200 m in distance), and high uncertainty (for paroxysms, up to 600 m in less constrained distances). From 1970 to 2023, it was possible to schematically map the ballistic projectiles of 43 major explosions, covering 85% of the total number of these events. Similarly, from 1879 to 2023, it was possible to schematically map the ballistic projectiles of 24 paroxysms, representing 60% of the total. Using the dataset of these 43 and 24 maps, we calculated the statistics of the radius, directional angle, and the extent of the area affected by projectile dispersion. Specifically, all relevant circular sectors were considered, weighted in proportion to their angular width. Based on the distance and direction statistics, first probability maps were defined to indicate the likelihood of being in an area affected by ballistic projectiles, conditional on the occurrence of an explosion (major or paroxysm). Two complementary approaches were used to statistically combine the distributions of directions and distances. The first approach, called Model 1, directly utilizes the frequency of past events. Specifically, at each point on the map, the hazard value is equal to the percentage of explosions that affected that point. The second approach, called Model 2, samples the direction and distance independently from each other. In other words, it assumes there is no physical link between the launch direction of the projectiles and the distance they reach. This allows for mixing distances and directions observed in different events, reducing the effects of possible undersampling in the less accessible parts of the island. The differences between the two approaches highlight that, for major explosions, Model 1 dominates towards the NE direction, while Model 2 dominates towards the SE direction. Viceversa, for paroxysms, Model 1 dominates towards the two villages, particularly Ginostra, whereas Model 2 dominates towards the Sciara del Fuoco. Maps combining Models 1 and 2 were also produced for a conservative assessment of the conditional hazard associated to major explosions or paroxysms. Finally, we produced preliminary hazard maps of ballistic projectiles of major explosions and paroxysms considered together. This was done by combining the occurrences of major explosions and paroxysms using data from the two catalogs to estimate the relative frequency of these phenomena. Specifically, paroxysms accounted for

7.3% of events between 1970 and 2023, and 12.1% of events between 2003 and 2023 (a more conservative estimate), excluding uncertain major explosions. Based on this, we also generated first hazard curves at fixed elevations and fixed distances from the craters, which are useful both for individual/societal risk assessments and for estimating the probability of fire ignition.

Dynamic lava flow forecasting with real-time data integration

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The integration and assimilation of observation's dataset into lava flow forecasting workflow is a significant advancement in quantitative hazard assessment for effusive volcanic eruptions. Within the framework of the DT-Geo project and utilizing High-Performance Computing (HPC) capabilities, we combine an ensemble-based approach with various data assimilation techniques to forecast the propagation of lava in real-time during an eruption.

The forecasts are calculated from VLAVA's results, a numerical model that simulates a temperature-dependent viscous lava flow propagating from one or more vents over a complex topography. The simulation is performed for a selected period of time with a set of parameters characterizing the eruption's chronology and the rheology of the lava. Multiple combinations of these parameters cover the uncertainties regarding the eruption sources, leading to the creation of an ensemble of scenarios and probabilistic forecasting.

The observational dataset varies greatly (in nature, space, and time) depending on the availability of measured data from direct field observations or remote sensing from airborne, drone, or satellite sensors (e.g., Pléiades, ASTER, SEVIRI, MODIS, VIIRS, OLI, TIRS, MSI). This data is integrated into the workflow by adjusting the scenarios' weights based on their similarity to the observations or by directly assimilating the data into the VLAVA simulation at the corresponding observation time.

The forecast includes both the thickness and temperature distribution of the lava field. It can be calculated for individual scenarios (to estimate the impact of a single lava flow) and for a series of weighted scenarios (to produce probabilistic hazard maps).

We will present the detailed workflow and share preliminary results from past eruptions of Mount Etna.

A target-based approach for multi-hazard assessment: application to volcanic hazards

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Volcanic activity is intrinsically a multi-hazard problem. Different phenomena accompanying volcanic activity, such as seismicity, static deformation, lava flows, gas emission and tephra fallout, can be dangerous to the society and economy with a wide range of impacts. Moreover, the physical parameters representing the intensity measure of such hazards are of different nature and therefore their integration in a single analysis is not straightforward.

The most frequent approaches for multi-hazard assessment usually start from considering each hazard as the primary subject of the analysis; afterwards, the multi-hazard analysis is generally based on the integration of multiple volcanic hazards independently assessed, often without any effort of harmonization of the results. Afterwards, the final multi-hazard integration is done using different approaches as e.g., the definition of subjective indexes (for example “Low”, “Medium” and “High” hazard zones) or by the spatial overlap of hazard maps representing a specific (sometimes termed “reference”) scenario.

From a decision-maker point of view, these multi-hazard analyses may not be sufficiently informative, and may be biased by the subjective choices taken by the hazard analysts.

In this work, we introduce a target-based approach for multi-hazard assessment in which the target (objective) of the analysis is the starting point of the process. The method is implemented using a fully probabilistic approach that allows also propagating epistemic uncertainties (often quantified while evaluating single hazards separately). The approach is based on a system for the solution of “fault trees” and “event trees” called MERGER [1], and involves: (i) the definition of a clear objective for the analysis (i.e., the “target”), which is probably a more clear task for a decision maker; (ii) the identification of hazardous events that can potentially contribute to the achievement of the “target” objective; and (iii) the definition of possible logical relationships between the events that identify the way in which they can contribute to achieving the target objective.

As a demonstrator of our approach, we present some preliminary results obtained in the framework of the PANACEA project (INGV’s project “Pianeta Dinamico”, funded by the Italian Ministero dell’Università e la Ricerca, MUR) regarding the multi-hazard assessment around Mt Etna volcano. In particular, we identify a few target objectives related to mobility disruption due to Mt Etna activity, and we show how the MERGER model can integrate the probabilistic hazard for seismic events, lava flow inundation and tephra fallout.

References

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Ensemble model-based reconstruction of the 3-5 December 2015 Etna eruption

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In recent years, ensemble model-based inversion and data assimilation techniques have been developed to estimate the eruptive source parameters (ESPs) of an explosive eruption from observational data of both ash burden in the atmosphere and tephra loading on the ground. This is important as the reconstruction of the dynamics of past eruptions allows the potential ESPs ranges of future events to be characterized and therefore improve the accuracy of their hazard assessment. The objective of this work is to apply these novel techniques to better estimate the ESPs of Mount Etna focusing on the eruptive events that occurred from 3 to 5 December 2015. During those days Etna produced four volcanic explosions at the summit craters. The intense lava fountains caused several violent explosions with consequent formation of volcanic plumes that reached heights up to 15 km above sea level and generated significant ash emissions. In previous works, the evolution of the eruptive column has been studied through remote sensing observations, estimating exit velocities and heights of the volcanic column, as well as total eruptive mass released during each episode. For this work, 22 samples of tephra deposits associated with this eruption dispersed from proximal-medial to distal zones were thoroughly collected a few hours after the paroxysmal events and were characterized in terms of tephra loading and subsequently analysed with the sieving and the CAMSIZER optical method obtaining the grain size distribution (GSD) at each location. The total grain size distribution (TGSD) was estimated through the Voronoi tessellation method.

From this information and using the atmospheric dispersion model FALL3D and the novel GNC (Gaussian with non-negative constraints) data assimilation method, we addressed our goal as follows. In a first step, we estimated the eruptive conditions (EC) of these eruptions characterizing the proper ranges for the ESPs. In a second step, by perturbing its ESPs, we created a set of possible EC and run FALL3D simulations of tephra dispersion and fallout. We then apply the GNC method to solve an optimization problem and find the optimal combination of simulations that minimize the differences between the calculated and measured tephra deposits. This provided us with a weighting factor for each member of the ensemble that has been used to reconstruct the tephra deposits and evaluate the temporal evolution of the volcanic columns. The obtained results agree well with the available independent observations and make the model suitable to be implemented for automatized procedures aimed at improving volcanic plume forecast through Data Assimilation techniques.

How does substrate affect the dynamics of volcanic granular flows: Towards small-to-large scale experiments and numerical simulations

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Particle-laden gravity flows, such as rock avalanches, landslides and pyroclastic density currents, are frequently encountered during volcanic activity. Because of their hazardousness, intermittency, and complexity, a better understanding and modeling of these volcanic flows require laboratory studies through small-scale experiments, theoretical description and numerical modeling. For more than twenty years, dry and dense granular flows have been satisfactorily described for idealized laboratory configurations. However, actual models are unable to describe them at the field scale, which suggests that physical mechanisms are missing. In particular, natural flows reveal higher mobility than expected from experimental flows, which promotes higher propagation velocities and longer distances, and consequently prevents reliable prediction of vulnerable areas for hazard assessment. A mechanism that may be responsible results from the interaction between the flow and the substrate, which will be not well considered in up scaling from laboratory to field. Here, we investigate how the substrate may affect the propagation dynamics of dry and dense granular flows through small-to-large scale experiments. By varying the grain size of both the flow and the substrate, we show the importance of grain-substrate interaction on the macroscopic properties of granular flows, which are then compared to numerical tools to provide guidelines for improving the modeling of volcanic granular flows.

A probabilistic volcanic risk evaluation for the Eastern flank of Mt. Etna

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Mt. Etna is the largest active volcano in Europe with effusive and explosive eruptions, and intense seismic activity. Its effects on the densely urbanized area located on the Etna flanks were investigated within the PANACEA project (Probabilistic AssessmeNt of volCano-related multi-hazard and multi-risk at Mount EtnA), an innovative and extensive research project aimed to assess the risk consequent to lava flow, tephra fallout, and earthquake hazards.

The assessment of risks at Etna is a multidisciplinary matter: the frequent tephra emissions cause problems for aviation and infrastructure; lava-flows destroy lifelines and invade inhabited zones; recurrent earthquakes damage buildings and infrastructure. Unfortunately, these different typologies of threatening events can occur at the same time, as occurred during the 2001 and 2002 eruptions.

In this work, we illustrate how seismic and volcanic probabilistic hazard scenarios have found their practical application in risk estimation for built-up environment, electric power systems and roads infrastructures. Risk scenarios were assessed at very different scales, from local to sub-regional, and have been done in case of lava flows, tephra fallouts and volcanic earthquakes, leaving out pyroclastic flows as they only affect the summit area of the volcano that is devoid of exposed elements.

Risk assessing methods have been previously calibrated on single-hazard deterministic scenarios in order to calibrate the damage models for the Etna area [Pessina et al., 2024 GNGTS], and estimate direct losses in terms of structural damage, victims, and loss of functionality. Afterwards, probabilistic damage scenarios were calculated, with a view to multi-risk analysis.

The data of the elements exposed to risk were collected and organized on a GIS for the test area of 6 municipalities (Milo, Santa Venerina, Zafferana Etnea, Acireale, Giarre e Riposto) located on the Eastern flank of Mt Etna. The data on the roads and the electricity distribution network come largely from a previous European project [UPStrat-MAFA, Sigbjörnsson et al., 2016], as do those on the strategic structures (hospitals, barracks, schools, etc.). The data on the population and residential buildings were acquired from the national census [ISTAT, 2011]; the high resolution of data, disaggregated at the census section level, was appropriately processed for the assessment of a seismic vulnerability index using the fragility curves developed for the national seismic risk map [Dolce et al., 2021].

The vulnerability of building roofs subject to the tephra loading was assessed through a preliminary analysis of satellite data aimed at recognizing and identifying pitched and terraced roofs; subsequently, this information was integrated with field observations, coming from the AeDES survey collected after the 2002 Etna events. The roof vulnerability was classified according to the European tephra fall vulnerability curves proposed by Spence et al. [2005].

The availability of probabilistic hazard maps in the NetCDF format, generated by the PANACEA team, allowed the elaboration of probabilistic risk maps with fixed intensity or fixed probability, for different exposure times. Exposure times common to the different hazards (TE = 10 years and 30 years) were chosen and events of exceedance probability (PEXC 5% and 10%) were set

to proceed with risk assessment (single risk analysis) for residential buildings and residents, for the road network, and for the elements of the electricity distribution. For given values of exposition time and exceedance probability, it is possible to calculate the damage to exposed elements for each hazard.

These analyses show that the risk of heavy damage to the considered structures is mainly attributable to seismic hazard. Only at long exposure times (30 years), the average annual damage values due to lava flows are significant and comparable to those due to earthquakes.

2.5D Shallow Water Model For Lava Flows

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Volcanic eruptions, while unstoppable, often unfold at a pace that allows for real-time hazard assessment and response. Effusive lava flows typically advance at a few hundred meters per hour, giving scientists and civil protection the opportunity to simulate potential scenarios and prepare evacuation and safety plans during the event.

We present a new shallow water model designed to simulate lava flows with high physical accuracy and computational efficiency, enabling its use in real-time forecasting of potential lava flow paths during ongoing eruptions.

This depth-averaged model surpasses traditional shallow water models by incorporating several key enhancements: (i) a parabolic velocity profile to capture vertical variations within the flow; (ii) a non-constant vertical temperature profile to more accurately represent thermal gradients; (iii) a viscoplastic temperature-dependent viscosity model to account for the non-Newtonian behaviour of lava; (iv) a transport equation for temperature that includes thermal exchanges with the environment and the ground. The first two modifications allow us to describe, under reasonable assumptions, the vertical structure of the flow, placing our model within the category of 2.5D models.

The model's performance was rigorously tested against both laboratory experiments and real-world data related to the 2014–2015 Pico do Fogo eruption, Cape Verde, [1, 2]. The results demonstrate that the model accurately captures essential flow features, such as the advancement of the flow front and cooling processes, even when applied to complex real-world topographies.

Our model's ability to deliver accurate results with short execution times makes it a valuable tool for real-time hazard assessment and the generation of probabilistic hazard maps. Its application on the Fogo eruption highlights its potential for real-time event description and hazard quantification. This capability is crucial for volcano observatories aiming to provide timely and accurate risk assessments during eruption crises, enhancing the preparedness and response strategies of civil protection agencies.

S09 - PLUMBING SYSTEM AND VOLCANO DYNAMICS:
PETROLOGIC TOOLS FOR TRACKING MAGMAS FROM
STORAGE TO ERUPTION

Conveners:

Gabriele Lanzafame, Federico Casetta, Marisa Giuffrida, Nicolás Nardini

The magma storage capacity of Etna plumbing system: constraints from 3 decades of lava compositional change and magma degassing budget since the early 1970s

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Deciphering the magma plumbing system of volcanoes is crucial to improved understanding and forecasting of their eruptive behavior. This can be attempted by combining seismic tomography, ground deformation modelling, petrological and geochemical studies. In the case of Mt. Etna, the plumbing system is known to consist of a huge plutonic body, emplaced in the crustal basement, that is surrounded by magma drains and magma ponding zones coinciding with main lithological discontinuities in the upper 10 km of the crust. However, its overall capacity of magma storage still remains poorly constrained. Here we provide a quantitative estimate of this magma storage capacity by using, as a tracer, the remarkable compositional evolution of Etna lavas that initiated in the early seventies and lasted for about three decades. During this time laps temporal changes in K_2O/Th , Rb/Th and $^{87}Sr/^{86}Sr$ ratios – which are parameters unaffected by crystal fractionation process – tracked the replenishment of Etna's plumbing system by a new, more alkaline and more radiogenic basaltic magma that gradually mixed with and replaced the former resident magma, promoting a significant increase in the lava extrusion rate. On a few occasions (e.g. 1974, 1998, 2001-2002) this new magma could reach the surface without interacting with the pre-70s resident magma, whereas on other occasions the pre-70s magma returned to prevail. This implies a complex storage system, made of sills and dykes, in which some magma batches can remain preserved for a significant time span, while others can directly reach the surface in bypassing the central volcano conduits. Complete renewal and homogeneization of Etna's magma storage cell with the post-70s alkali-richer magma is suggested by the lack of further chemical evolution after the 2004-2005 eruption and the more or less constant K_2O/Th and Rb/Th ratios of subsequently erupted products. Combining this lava compositional trend over ca. 3 decades with the cumulated amounts of co-erupted and co-degassed magma – the latter being inferred from SO_2 emission rates and the original magma S content – we compute an overall magma storage capacity of order 3 km^3 beneath Etna. Unerupted degassed magma should make a large part ($\sim 2/3$) of this storage system, contributing as crystal mushes and gradually solidifying bodies to lateral growth of the huge plutonic body emplaced in the crustal basement. Our proposed estimate is larger than early ones based on radioactive tracers, but can be usefully compared with more recent results obtained from seismic tomography and ground deformation modeling at Mount Etna.

Geochemistry and volatile contents of olivine hosted melt inclusions from Mt. Etna tholeiitic and alkaline magmatism

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The analysis of olivine-hosted melt inclusions (MIs) from the whole sub-alkaline and alkaline magmatic suites of Mt. Etna provides fundamental information about the composition of undifferentiated magmas and their pristine volatile content. Olivine crystals (Fo₈₈₋₆₆) were selected for Secondary Ion Mass Spectrometry (SIMS) analysis of volatile species (H₂O, CO₂, F, Cl and S) contained in their host MIs, after preliminary high-pressure/high-temperature re-homogenization, which allowed to reduce the developing of cracks in the host olivine and diffusion-driven outgassing of volatiles from the melt inclusions.

This permitted to explore the compositional variability of volatiles of undifferentiated melts and the degassing behavior through the feeding system. The studied MIs show significant major elements compositional heterogeneities (44.57–52.37 wt% SiO₂; 3.60–7.51 wt% Na₂O+ K₂O). Fractionation modelling was performed with Rhyolite-MELTS under variable fO₂ regimes (Δ FMQ + 1.5 to + 3), starting from the less evolved MIs compositions and ultimately reproducing most of the observed compositional trends. Mantle melting modelling was used to replicate the observed MIs composition, starting from a spinel-lherzolitic source, accounting for the alkalinity and Fe content of reproduced melts by varying the eutectic contribution of Amph/Phlog and Opx/Cpx respectively. Although most of the studied MIs were degassed in an open-conduit regime, the observed range of volatile concentration in MIs (2.42–6.14 wt% H₂O; 308–8474 ppm CO₂; 132–697 ppm F; 221–1766 ppm Cl and 16–1992 ppm S) is correlated with a slight decrease in the molar H₂O/(H₂O + CO₂) ratio from early tholeiites to the recent 2015 alkaline products. This observation allows to estimate a minimum 12,250 ppm CO₂ and a maximum of 6.14 wt% H₂O in primary melts of the current activity.

Cryptic amphibole at Mt. Etna (Sicily, Italy): insights from the 2001 lava and an amphibole-rich cumulitic xenolith

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The rapid change toward more explosive activity observed on Mt. Etna since the lateral rift-related eruptions (2001-2003) and during the more recent paroxysmal events (2011-nowadays) attracts the attention of petrologists and volcanologists interested in investigating the physical state of open-conduit basaltic systems. Recent studies have highlighted the importance of volatiles (H₂O, CO₂) contents and solubility in magmas along the vertically extended feeding system of Mt. Etna. Geochemical studies of melt/fluid inclusions and experimental investigation on volatiles solubility and phase stability, depicted a scenario where crystallization in the feeding system is strongly affected by the primary content of volatiles and their degassing behavior, ultimately resulting into very different eruptive styles without significant change in the magma composition.

Despite the very high H₂O content measured in undifferentiated melt inclusions (up to 6.1 wt%) [Giacomoni et al., 2024] amphibole is very rare in basaltic products of Mt. Etna. Studies on the amphibole phenocrysts of 2001 eruptive event restricted their stability to a narrow range of P-T conditions (300-200 MPa and 980-1000°C), thereby pointing to crystallization at relatively shallow depth and minimal effect on magmatic differentiation and eruptive behavior.

However, since amphibole stability is strongly dependent on the PH₂O, its absence in the erupted products does not necessarily imply that it never crystallized in the deeper portions of the feeding system, but rather suggest that amphibole breakdown could have occurred during prolonged residence time at open conduit conditions and/or upon decompression prior to the eruption.

Starting from this hypothesis, this research aims at investigating the stability field of amphibole in the Mt. Etna feeding system by studying the chemical and textural features of amphibole phenocrysts found in 2001 lavas and from an amphibole-rich cumulitic xenolith found in Rocca Musarra, ultimately contributing to decipher its “cryptic” behaviour.

Studied amphiboles from the 2001 eruptive event range in size from 2 mm up to 6 cm along the C-axis with strong pleochroism ranging from light green to dark brown. They can be classified as Mg-hastingsite and Ti-pargasite with slightly normal core-rim zoning. All studied amphiboles crystals show thick (up to 500 µm) opaxitic, strongly resorbed rim.

Cumulitic xenolith from Rocca Musarra are made of 70% Ti-Pargasite amphibole, 18% clinopyroxene and 12% olivine. Here amphiboles are euhedral, ranging in size from 1 to 4 mm (along the C-axis).

Clues on amphibole crystallization condition were obtained by traditional and machine learning-based thermo-barometry; together with data on H₂O content and composition of equilibrium melts. Both amphibole populations retrieved from 2001 products and from cumulate record crystallization pressures of 500–600 MPa, temperatures of 950–1000 °C and H₂O in the melt of 5–7 wt.%. Machine learning thermodynamic modelling indicates a melt in equilibrium with amphibole having SiO₂ of 51–55 wt.% and MgO of 2–4 wt.%.

Results show that amphibole crystallization requires magma stationing and cooling in batches between 12 and 16 km b.s.l, significantly deeper than previously estimated. High H₂O content in primary magmas and further increase during closed-system fractionation, promotes amphibole stability and suppress the crystallization of plagioclase. Magmatic inputs of less evolved and hotter melts could eventually intercept the amphibole-bearing batches, resulting in two plausible scenarios: i) fast ascent rate that allows preserving the amphibole crystals as they are observed during the 2001 event or ii) decompression-induced degassing causing amphibole breakdown. These first results highlight the importance of determining the P-T crystallization conditions of amphibole in Mt. Etna magmas and future work will be dedicated to an experimental characterization of amphibole crystallization and thermodynamic modelling that ultimately will assess the effect of amphibole crystallization and breakdown in the final chemical and rheological conditions of erupted products.

Amp-TB2 protocol: how to use Amphibole for tracking the storage and movement of magma into the Crust and Upper Mantle

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Amphibole plays a crucial role in the study of several earth and planetary processes. One of its most common applications is thermobarometry for volcanic systems. Amphibole thermobarometers occasionally require the melt composition as input data, that is not always available in volcanic products, some are only dedicated to granitic/rhyolitic rocks, and most of them show rather high errors for characterizing the pressure (P) and depth of crustal magma chambers. By contrast, Amp-TB2.1, [1], presents the advantage of being a single-phase thermobarometer with relatively low errors ($P \pm 12\%$, $T \pm 22^\circ\text{C}$, $\log f\text{O}_2 \pm 0.3$, $\text{H}_2\text{O}_{\text{melt}} \pm 14\%$) and is valid for most of the calcic amphiboles in equilibrium with calcalkaline or alkaline melts across a wide T-P range (up to 1130°C and 2.2 GPa).

Amphibole occurs as phenocryst in the majority of the products of subduction-related volcanoes along the Circum-Pacific belt (i.e. Ring of Fire) and in several mantle-alkaline magmas in the form of megacrysts (e.g. Eifel and Rosenberg, Germany). The crystallization of amphibole is indicative of fluid ($\text{H}_2\text{O}-\text{CO}_2$)-saturated conditions and its occurrence can be due to a temporary closure of the feeding system such as that of Stromboli volcano (Petrizza products, Paleostromboli I).

This study reports a protocol on the application of Amp-TB2 based on detailed electron microprobe analyses performed on homogeneous natural standards and amphibole crystals of Bezymianny volcanic products. The application of this protocol is facilitated by a new version of the model (Amp-TB2.1.xlsx) including an equation to identify heterogeneous domains (disequilibrium; not suitable for thermobarometric constraints) and homogenous (equilibrium) zones within amphibole crystals, which can be used to quantify the physico-chemical parameters of magmatic crystallization. The depth (and P) estimated by Amp-TB2.1 for Bezymianny volcano are compared to seismic tomography results. Amp-TB2.1 results show that (1) amphibole can give insights in the movement of the magma within storage regions in the crust (convection magma chambers), and on its ascent and path from the mantle to shallow crustal regions, (2) Bezymianny is characterized by a very dynamic feeding system where the magma is stored at shallow crustal levels before recent activity periods characterized by climatic events and (3) the pre-eruptive depth of magma storage generally increases with the age of the investigated products.

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Evidence of magma mixing within the clinopyroxene populations in volcanic and plutonic rocks from the Dolomites (Southern Alps; Italy): how to enhance plumbing system investigations untangling the volcano-plutonic link

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Preserving volcanic and plutonic records can significantly enhance our understanding of plumbing systems. It is well established that many magmatic complexes are supplied by crystal-rich magma accumulating at mid to shallow crustal levels, which is occasionally reactivated by the intrusion of hotter melts over long periods. The Dolomites (Southern Alps; Italy) contain extensive Middle Triassic volcanic and plutonic outcrops that are exceptionally well-preserved. The exceptional preservation enabled us to identify systematic compositional zoning patterns in the clinopyroxene of the volcanic products. The recurrent zonation consists of different step zoning patterns between augitic compositions with lower Mg# and Cr₂O₃ contents (Mg# 67-78; Cr₂O₃ 0.1 wt%) and diopsidic regions with higher Mg# and Cr₂O₃ levels (Mg# 78-91; Cr₂O₃ up to 1.2 wt%). The diopsidic domain appears to a lesser extent and is more frequently present as a variable thick single or multiple bands between augitic cores and rims. It could be documented in cores as resorbed or mottled. Oscillatory zoning and sector-zoned crystals are also present in minor numbers. This has been a valuable tool for revealing the previously unknown architecture and dynamics of the plumbing systems of the main magmatic centres of this area. Thermobarometric calculations indicate the presence of a shallow- to mid-crustal crystal-rich ponding zone dominated by augite in equilibrium with a trachyandesitic melt (T from 1044 to 1118 °C). This main level was periodically refilled by mafic pulses of primitive, hot basaltic magma (T from 1056 to 1170 °C) which led to the formation of high-Mg# domains within pre-existing augitic crystals and remobilized diopsidic clinopyroxenes from deeper levels of the plumbing system.

Diffusion chronometry computations based on Fe–Mg diffusion in clinopyroxene have been applied to evaluate the residence times for the crystals in each compositional zone with the NIDIS model [Petrone et al., 2016]. Calculations have indicated that the time span from injection to eruption varies from less than a year to several decades across different volcanic centres, constraining differences among them.

Uncommonly, similar zoning patterns have been also observed in clinopyroxene populations hosted in the intrusive rocks. These preliminary data, together with thermobarometric modelling, confirm what was recorded by the volcanic counterparts and constrain better the deepest levels of the systems providing a powerful volcano-plutonic link and new horizons in the plumbing system studies. Our final aim is to discuss this ancient magmatism as a proxy for active volcanic complexes thanks to the preservation of mechanisms rarely recorded in plutons, such as compositional zoning, making this part of the Alps a volcanological laboratory for testing the approaches/models currently adopted for active volcanoes.

Petrological evolution of the trans-crustal plumbing system of Marsili volcano (Tyrrhenian Sea, Italy): insights into crystal mush heterogeneity from glomerocrysts variability

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Located in the Tyrrhenian Sea, the Marsili seamount is a submarine volcano that formed within a back-arc setting. Aiming to define the complexity of its trans-crustal plumbing system, we investigated the compositional and textural variability of crystal cargoes found within basaltic to andesitic lavas collected from three different sectors of the volcano (northern, axial, and lateral). Lavas erupted from the northern sector are only basalts and generally more primitive in character compared to lavas erupted from the lateral and axial sectors, the latter dominantly basalts and basaltic andesites with a broader variability in terms of mineral assemblage and chemistry. Crystal-poor andesitic magmas were only erupted at the summit axial sector of the volcano. The large abundance of glomerocrysts of different mineralogy and composition is a peculiar feature of samples from all these sectors, providing evidence of a laterally extended and petrologically heterogeneous crystal mush. Thermobarometric calculations performed on clinopyroxene coupled to mass-balance and thermodynamic modeling collectively support the petrographic evidence of a polybaric plumbing system, where relatively less differentiated basaltic magmas reside at depth (300-450 MPa, 1040-1080 °C) and either feed eruptions at the northern sector or evolve to form andesitic magmas stored at shallow depth (250 MPa, 920-980 °C) in the axial sector. Furthermore, basaltic and basaltic andesitic magmas erupted from the lateral sector testify to intermediate storage conditions (200-400 MPa, 980-1060 °C). The variable content of incompatible (TAI and Ti) and REE in clinopyroxene contained in lavas from the three sectors relates to different undercooling conditions, with magmas erupted from the northern sector recording higher undercooling compared to those erupted from the lateral and axial sectors. The emerging scenario is that basaltic magmas erupted from the northern sector experienced a more rapid ascent (also testified by the occurrence of high-Fo olivine and dendritic clinopyroxene in the groundmass) compared to magmas erupted at the lateral and axial sectors, otherwise experiencing prolonged time within the crust.

Thermobarometric and Microthermometric insights into the Monte Amiata magmatic reservoir

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Monte Amiata is a Pleistocene hybrid volcano with lava flows and domes outpoured between 300 and 232 ka [Laurenzi et al., 2015] by a SSW-NNE fissure direction [Ferrari et al., 1996; Brogi, 2008; Marroni et al., 2015]. Volcanic activity took place in two-short lived eruptive episodes [Ferrari et al., 1996; Conticelli et al., 2015; Marroni et al., 2015], apparently separated by a level characterised by a strong weathering alteration [e.g., Certini et al., 2006; Wilson et al., 2008; Principe & Vezzoli, 2021]. The Basal Trachydacitic Complex (BTC) represent the early period and is distributed in the lowermost portion of the volcano and they are characterised by lava flows of trachydacitic composition, with abundant angular crustal xenoliths ranging from phyllites to micashist and hornfels [van Bergen, 1984; Ferrari et al., 1996; Orlando et al., 2010] and rare and small ellipsoidal microgranular igneous enclaves. The Dome and massive Lava flow Complex (DLC) represent the late period of activity concentrated, all but one (Trauzzolo dome), along the feeding apical fracture. They are characterised by lavas and minor ejecta of trachydacitic to trachytic and latitic compositions, with rare crustal xenoliths but abundant microgranular ellipsoidal to rounded microgranular igneous enclaves (decimetric to metric in size) with trachytic to potassic trachybasaltic composition [Ferrari et al., 1996; Conticelli et al., 2015; Marroni et al., 2015; La Felice et al., 2017]. Two small olivine-latitic lava flow (OLF) close the eruptive event [Ferrari et al., 1996; Conticelli et al., 2015; Marroni et al., 2015].

The region around the Amiata and Radicofani volcanoes was characterised by an uplift of about 2,000 m, possibly caused by a magmatic intrusion of uncertain age [Acocella & Mulugeta, 2001]. The igneous intrusion that triggered the doming was suggested to be either a crustal-derived anatectic magma [Gianelli et al., 1988], on one side, or mantle-derived magma [Conticelli et al., 2015], on the other one. These two hypotheses implicate different thermodynamic and thermochemical conditions related with the history of the magmatic reservoir from the initial intrusion to the eruption event. The heat source of Monte Amiata volcanic field feed, with its thermal energy, two water-dominated high-enthalpy geothermal reservoirs. A shallow one represented by a carbonate-evaporite formation of the Tuscan Nappe with temperature ranging between 150 to 230 °C, and a deeper one hosted in a highly-fractured layer of the metamorphic basement with temperature > 300 °C [Sbrana et al., 2021].

This study investigates the P-T conditions of equilibrium of Monte Amiata volcanic rocks that might help to shed some lights on the heat source of the related geothermal field. To achieve this goal we used a multimethod approach, using traditional experimental derived algorithms, a machine-learning method, and eventually the melt inclusion investigation. The aim is to

reconstruct the temperature condition and the storage level of the magmatic reservoir during the eruption. For Monte Amiata lavas, classical geothermobarometer and modern machine learning tools on minerals and glass revealed a temperature in the range between 950 and 1170 °C, with a largely variable storage pressure between 0.1 and 0.8 GPa. Microthermometry experiments on sanidine melt inclusions revealed temperatures in the range between 990 and 1075 °C. Sanidine crystals ideally represents the lower temperature limits of the magmatic reservoir. The P-T condition suggest a volcanic nature referred to the magmatic reservoir, supporting the idea of a mantle-derived magmas and a storage depth from 7 to 25 Km.

Exploring the geochemistry of tholeiitic basalts and hyaloclastites formed in submarine volcanoes for comparison with Venus lavas

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Underwater basaltic lavas exhibit distinct rock textures, mineralogy and morphological differences compared to those formed on land, primarily due to rapid cooling caused by contact with cold seawater instead of air and to high pressures – similar to Venus. The geomorphological similarities between terrestrial submarine volcanoes and some morphological classes of Venusian volcanoes have been investigated, but a comprehensive comparison in geochemical terms has yet to be conducted.

Only three missions to Venus (Venera-13, Venera-14, and Vega-2) were able to report bulk composition of Venusian rocks, while other four missions (Venera-8, Venera-9, Venera-10, and Vega-1) provided limited geochemical information. Using X-Ray fluorescent (XRF) analysis, we saw that rocks analyzed on the surface of Venus are tholeiitic and alkalic basalts.

This study, as part of the “Analogues for VENUS’s GEologically Recent Surfaces” (AVENGERS) initiative, aims to examine the possibility of seamounts/submarine volcanoes lavas serving as analogues to Venus lava geochemistry and morphology/formational processes. By sampling and analyzing submarine lavas from three distinct tectonic settings on Earth - hot-spot, convergent margins, and divergent margins - we will assess in which tectonic context the analogy with Venus is most comparable.

Fieldwork will be conducted in further detail for submarine volcanoes located in Sicily, Hawaii, and the Southern Pacific (Fiji, Vanuatu, Tonga, Samoa); we will use previously collected samples where these submarine areas are not accessible. Sampling efforts will target areas likely to yield submarine tholeiitic lavas and/or hyaloclastites.

Samples collected during fieldwork will undergo detailed whole-rock geochemical analysis, including XRF, X-Ray diffraction (XRD) and Inductively Coupled Plasma Mass Spectrometry (ICPMS). Thin sections will be used to constrain differences in morphology/textures. The obtained geochemical data will then be compared with existing data on Venusian lava geochemistry, allowing for a comprehensive evaluation of potential analogies between submarine lavas from Earth and volcanic rocks on Venus. By elucidating these similarities and pinpointing specific tectonic contexts, our study has the potential to enhance our understanding of Venusian geology and the possibility of ephemeral plate tectonics on the planet.

S09 - Poster

Trace elements zoning in olivine crystals unveils short-term volcanic processes controlling the 2020-22 lava fountaining at Mt. Etna

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Lava fountains are volcanic phenomena consisting in a quasi-continuous jet of a lava and gas mixture emitted in atmosphere. Between December 2020 and February 2022, 62 lava fountains characterized the paroxysmal sequence occurred at Mt. Etna, displaying heterogeneity in terms of volumes of magma emitted, height of the lava fountain and duration. Investigating the shallow and fast magma dynamics that take part in generating such heterogeneity in lava fountains (e.g. magma ascent rates, degassing modes) is a hard task. In this work, a set of 20 olivine crystals have been hand-picked by ash and small lapilli samples emitted during paroxysms characterized by variable volcanological features throughout the sequence. Analysis and quantification of some trace elements (Li, P, Cr, Ni) have been carried out through LA-ICP-MS and results displayed as elemental maps for each element. A core-to-rim transect has been extrapolated for each element and compositional profiles compared to assess possible correlations. Within the framework of the Li behavior, it was possible to distinguish between coupled and non-coupled trends, which are decisive for interpretation of the zoning patterns reflecting various volcanic processes such as interaction with compositionally different magmas, decompression-driven degassing and/or flushing by volatiles. In particular, we focused on the lithium concentration profiles which content vary from 2 to 10 ppm across all the olivines analyzed and exhibiting both normal and reverse zoning towards the outer rim. Furthermore, when conditions were considered appropriate, diffusion chronometry models have been applied to the Li profiles in order to retrieve the timescales of fast pre-to-syn eruptive processes bound to late-stage of magma uprising. The application of such petrological techniques to fast diffusing elements is precious to shed light on the trigger mechanisms occurring shortly before the lava fountain onset.

The 2021 eruption of Pacaya volcano (Guatemala): timescales of storage and transport as revealed by olivine zoning

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Pacaya is a volcanic complex in Guatemala, located along the volcanic front parallel to the subduction of Central America's convergent plate boundary. The volcanic activity of Pacaya develops dominantly as an open-vent system, which has been characterized by prolonged periods of low-intensity eruptions during the recent decades. In spite of this prevalent behavior, a period of energetic and more voluminous activity occurred between February and May 2021, when mild to moderate explosive eruptions took place from the MacKenney cone, producing severe ash fallout and lava flows from vents placed on the northwestern, western and southern flank of the volcano that have caused vegetation fires, crop destruction and road blockages.

Lava rock samples of the 2021 eruption were collected on the lava field located on the northwestern side of the volcano and were subsequently inspected by optical and electron microscopy. Olivine crystals have been analyzed using a SEM-EDS/WDS acquiring core to rim transects to assess possible Fe-Mg zoning patterns such as oscillatory, normal, reverse and/or more complex trends. Based on the identified compositional plateaux, we have distinguished olivine populations corresponding to storage zones where the magma is under equilibrium at specific T, P, fO_2 and volatile contents. In order to understand the portions of the Pacaya's plumbing system that were activated before the 2021 eruption, we developed a thermodynamic model by constraining the conditions of magmatic environments in which these olivine populations formed. Based on this information, we modeled the diffusive relaxation of profiles in zoned olivine in an attempt to extract the timescales of magmatic processes drawn out from the examination of olivine composition and types of zoning. A better understanding of the pre-eruptive magmatic dynamics of Pacaya provide additional information that could also be useful in mitigating the hazard associated with ballistic fallout and lava flow invasion during explosive and effusive eruptions at the volcano, which can have major repercussions on the communities that inhabit its slopes.

Magma storage and transfer before the 2021 eruption at Pacaya volcano (Guatemala) as revealed by plagioclase textural and compositional variations

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The Pacaya volcanic complex, which is located on the southern fault zone of the Amatitlan Caldera (only 20 km south of Guatemala City), is one the most active in Central America. It comprises an old andesitic stratovolcano, a series of rhyodacitic to andesitic lava domes, and the modern Pacaya basaltic composite volcano (2,552 m high). Pacaya is one of the three open-conduit volcanoes of Guatemala together with Fuego and Santiaguito, oscillating through periods of mild intra-crateric activity and phases of more intense explosive (Strombolian to lava fountaining) and effusive activity. Between February and May 2021, the last eruptive cycle culminated with the production of energetic Strombolian activity, ash emission and multiple lava flows localized on the flanks of the Mackenney cone. We collected lava flow samples in order to get concentrations of major and minor elements of the whole rock. Furthermore, x-ray maps on selected thin sections have been obtained by SEM-EDS/WDS. Through the Q-XRMA image-processing tool [Ortolano et al., 2018; Computers & Geosciences], all the minerals species have been quantified by means of some cycles of elaboration that also allowed the classification of the dominant plagioclase textural types. With specific reference to plagioclase crystals, we identified seven main textures: 1) oscillatory zoning, 2) dissolved or resorbed core, 3) patchy core, 4) coarsely-sieved, 5) resorbed rim, 6) fine melt inclusion trains, 7) shallow-tailed. The distribution of such textures appears to be correlated to specific dimensional classes of crystals (e.g., shallow-tailed textures are frequent in microlites, whereas coarsely-sieved are representative of the medium to large crystals). The compositional variation of An% and Fe has been also assessed through core-to-rim transects on a selection of 30 plagioclase crystals. The correlation between composition and textures has been then explored in order to constrain the pre-eruptive magmatic processes leading to both equilibrium vs. disequilibrium conditions. Integration of these data with those coming from other petrological investigations (i.e., thermodynamic simulations for the reconstruction of the entire differentiation process, olivine zoning and diffusion chronometry) will allow a better understanding of processes occurring before the eruption and their timescales, with consequent implications for an updated hazard assessment in the area.

Understanding a Volcano from Inception to Death: Case Study of Aegina Volcano, Greece

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The South Aegean Arc showcases large silicic caldera-forming eruptions in the south and southeast (Kos-Nisyros, Santorini, Milos) and smaller more dacitic to andesitic systems in the northwest (Methana, Aegina). The exact factors leading to the development of the significant differences in type of magmatic reservoirs remain highly debated. Here we focus on the system of Aegina, an extinct volcanic island close to Athens, to better understand the evolution of this magmatic province from inception to death. By integrating mineral and melt chemistry with zircon petrochronology, we can reconstruct magma chamber conditions during the lifetime of the Aegina magmatic province. Using in-situ Hf isotopic data in the dated zircons, we also attempt to better understand the evolution of the mantle source through time, and the importance of crustal assimilation on the paths of magmas towards the surface.

The andesitic to dacitic volcanism on Aegina occurred in three distinct pulses of activity throughout nearly 2 My, lasting from ~ 4.25 Ma to 2.25 Ma. The pulses are separated by periods of ~0.2 My of volcanic quiescence. Hf isotopic ratios in zircon crystals show significant fluctuations, starting with positive ϵ_{Hf} (+5) in the early part of the magmatic activity and ending at negative values (ϵ_{Hf} ~ -5). Those changes correlate with shifts in volcanic centers. The main mineralogy in those rocks consists of amphibole, plagioclase, and occasionally pyroxene (primarily cpx). Amphibole and plagioclase yield a wide range of compositions suggesting highly varied conditions during crystallization, with compositional peaks at high Mg# / high AlIV and low Mg# / low AlIV for amphibole and high An and low An for plagioclase. Those peaks indicate the presence of a vertically-extensive plumbing system with storage areas at deep and shallow crustal levels, which remained fairly stable through time. However, pre-eruptive dissolved water contents in the magmas seem to reduce towards the end of the lifetime. The extremely high Mg# (between 0.7 and close to 1) of the high pressure and temperature amphiboles, together with the low orthopyroxene to clinopyroxene ratio, suggest the presence of extremely wet source magmas, which became more anhydrous over time.

Matching crystal chemistry with geochemical and geophysical monitoring signals to track the 2022-23 magma dynamics at Etna

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A multidisciplinary approach, which integrates petrological, geochemical and geophysical observations, has been here used to reconstruct the magma dynamics between the late spring 2022 and the summer 2023 at the South East Crater of Mt. Etna volcano. Specifically, our investigations focused on the two phases of dominant effusive activity that occurred on May - June 2022 and November 2022 - February 2023 and, later, on the two lava fountaining episodes of May 21 and August 13, 2023. In order to detect the dynamics of magma supply, olivine chemical zoning and diffusion chronometry data were elaborated and integrated together with the temporal trends of the SO₂ flux and volcanic tremor amplitude and source location collected from the INGV-OE permanent monitoring network of Mt. Etna.

Olivine crystals were selected and grouped in populations based on their core compositions and zoning types in order to detect the presence of magmas with distinct differentiation degrees. Olivine cores, spanning from more mafic (Fo84) to slightly evolved compositions (Fo70), reflect crystal residence and growth in distinct magmatic environments. A detailed investigation of the diversity of the olivine chemical zoning allowed the identification of some dominant paths of ascent and mechanisms of interaction between different magmas. This has led us to detect those environments that were reactivated before the eruption. Petrological data indicate prolonged periods of magma storage of ca. 4-6 months in the shallow plumbing system, anticipating the effusive eruptive phases. In contrast, the reactivation of the deepest environments occurred before the paroxysmal eruptions of May and August 2023. This has been associated to episodes of deep replenishment of mafic magma displacing the resident one stored at around 240-180 MPa, then leading to the eruption in less than one month. The occurrence of volcanic unrest is highlighted by abrupt changes in the volcanic tremor and SO₂ flux, both in accordance with the petrological evidence of magma movements into the plumbing system. Results from diffusion chronometry also demonstrate that the episodes of magma intrusion correlate temporally with increasing volcanic tremor amplitude and SO₂ emissions, providing evidence that such monitoring signals are directly related to the magma dynamics in the upper plumbing system.

Quantitative X-ray image analysis for unraveling chemical and textural features of plagioclase crystals from volcanic rocks of the Marsili seamount

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There has been a growing adoption of semi-automated image processing methods combined with many Geographic Information Systems (GIS) software to investigate numerous geo-petrological processes in recent years (e.g., Belfiore et al., 2022 – Constr. Build. Mat.; Visalli et al., 2023 – G3; Caso et al., 2024 – J. Struct. Geol.). Utilizing multivariate statistical analysis of X-ray maps, these methods effectively extract quantitative textural, chemical, and modal parameters from selected thin sections or micro-domains in volcanic samples, whose constituents can show peculiar textures due to the magmatic processes involved.

For the purpose of this study, we have obtained a large set of X-ray maps for major elements from eighteen samples collected in different portions of the Marsili seamount during the MAR98 and TIR2000 cruises carried out by the CNR ship R/V Urania. X-ray maps have been processed through the Quantitative X-ray Map Analyzer (Q-XRMA) software (Ortolano et al., 2018 – Comp. Geosc.), whose processing strategy is based on the sequential application of the Principal Components Analysis and the supervised Maximum Likelihood Classification algorithms. These latter allow us to identify textural and chemical features in a simplified and quick process, permitting, in turn, to distinguish among mineral phases, vesicles, and glasses, to quantify their modal abundances, and to identify in-depth chemical variations within the main constituents.

The software's capability has been applied particularly on plagioclase crystals, whose textural and chemical complexities are faithful recorders of the physical and chemical conditions and processes controlling the evolution of the magmatic system. Plagioclases from different sectors of the volcanic edifice exhibit variable extents of disequilibrium at the core and rim and growth textures developed to varying degrees of undercooling. The procedure applied in this study allows us to document quantitatively the complex variations in the texture and composition of the Marsili mineral cargo. At the same time, it enables the categorization of plagioclase crystals into groups based on their mutual differences in crystal habit, zoning, and resorption textures within a GIS-based multi-scale and multi-source geodatabase, ready to be used in turn for further geostatistical analysis. Results demonstrate that the chemical zoning of crystals can be fully discerned at a microscopic scale and can be adopted as a template for the ensuing interpretation of magmatic processes.

The volcanic activity at Yali Island, Greece: plumbing system architecture and implication for hazard assessment

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Yali island is the remnant of a relatively young volcano that was active within the last 40,000 years and is part of the Nisyros-Kos volcanic field. It represents the most recent evidence of active magmatism in the eastern part of the South Aegean Active Volcanic Arc, together with the post-caldera lava dome activity occurred in the nearby Nisyros volcano.

The Yali volcanic activity (both explosive and effusive) is still poorly studied, and the plumbing system architecture and magma ascent pathways are barely defined, although it represents an important element for the evaluation of the volcanic hazard, as well as the potential volcanic risk in the area, associated to the accumulation of evolving magma body in the crust.

The aim of our study is to detail the nature of the juvenile materials and the interaction between the corresponding variably differentiated magmas, to evaluate the magmatic processes occurring in the plumbing system and to define the relationships between the different eruptive events occurring during the Yali volcano evolution.

The present-day edifice is constituted by the remnant of the original volcano after intense tectonic and erosion processes. It is composed by two distinct parts with poorly defined stratigraphic correlations, due to the limited exposure and continuity of the deposits. The SW part is built up by a thick succession of pyroclastic materials, generated by the eruption of a submarine pyroclastic deposit (Lower Pumice -YLP), followed by a subaerial activity leading to the emplacement of a pumice-rich pyroclastic fallout (Upper Pumice-YUP). The succession is topped by two layers of reworked pumice-rich deposits (YRL), separated by a thin paleosoil. The NE part is formed by large perlitic lava flows and obsidian lava domes, associated to an explosive deposit generated by the Kamara tuff ring. The effusive event, dated to 24 ky, represents the last magmatic occurrence on the island. However, offshore hot fumaroles are present on both side of the island and testify for a still active heat release from a degassing magma chamber.

The main volume of the erupted products (pumices and lavas) is composed by evolved juvenile of rhyolitic composition. All the pyroclastic deposits, including the Kamara tuff cone, host a variable amount of dense, mafic (SiO_2 from 52.5 to 67.5 wt.%), crystal-rich clasts, suggesting the occurrence of mingling processes between different evolved magmas in the feeding reservoir/s and implying a refill of the shallow plumbing system by mafic melts from below. Our data show that YLP and YUP pumices are homogeneous in composition, with the latter having a slightly less evolved character. Sr and Nd isotopes are clearly different between YLP and YUP, with the YUP isotopes overlapping those of the YRL pumices. The perlitic lavas are even more evolved than pumices but have similar Sr and Nd isotope ratios to the older YLP. The mafic components reveal on the contrary limited compositional heterogeneities and isotopic variability congruent with a stable deep feeding system.

Our interpretation points to the presence of a complex plumbing system feeding the different explosive and effusive eruptions during time. At least two different, independent shallow/crustal, evolved magma pockets are refilled and recurrently unlocked by mafic magma inputs generating

the eruptions. Through time these reservoirs may remain thermically isolated and can be reactivated by a mafic recharge from below. This interpretation advocate for a scenario with important implications in the evaluation of the volcanic hazard assessment of the area.

How do mafic feeding dikes interact with carbonate host-rock? – Insights from the Taverna San Felice Dike intrusion (Roccamonfina, Italy)

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The interaction of magma with carbonate host rocks has been widely observed in many volcanic settings, including Somma-Vesuvius, Colli Albani (both Italy), Merapi, Kelud (both Indonesia), Popocatepetl (Mexico), Lascar (Chile), Pacaya (Guatemala) and Yellowstone (USA). However, most of the studies focused on long-term interactions (i.e., skarn formation) at the magma chamber(s) level(s) or on the variations in carbon isotope ratios if measured at the surface. Recently, some advances have been made on short-term (or syn-eruptive) interactions of magma with carbonate host-rocks along the volcanic conduit down to the magma chamber. Most of these studies were experimental, but one on the Avellino-eruption of Somma-Vesuvius is instead based on carbonate xenoliths within the eruptive products.

Here we explore a new unstudied environment for the magma-carbonate interaction: the chilled margin of a feeding dike at the Taverna San Felice (TSF) locality. The TSF is a limestone quarry in which a mafic feeding dike intruded the Meso-Tertiary carbonates and the overlying Lower Pleistocene breccias of Mt Cesima. It is located north of Naples and NE of the Roccamonfina volcanic complex, with which it most likely shares a common magma origin. The dike is older than the Brown Leucitic Tuff (BLT) eruption (>354 ka) of Roccamonfina and shares some petrological features with other monogenetic pre-BLT eruptions which have been ascribed to the Roccamonfina volcanic complex. The excavation in the quarry revealed the uppermost part of the feeding dike which is in direct contact with the carbonate host-rocks offering a unique chance to study the dike-host-rock interactions, which otherwise remain concealed.

We performed petrological analyses of both the dike and the carbonate host-rocks, as well as of the proximal eruptive products, to investigate the results and degree of this interaction. Preliminary results include evidence of CO₂-liberation and addition to the feeding dike from the progressive decarbonatization of the limestone host-rocks. Furthermore, compositional changes of the melt and of its crystal cargo (as highlighted by Ca-Mg-Al complex zoning textures) have been found, but remain confined to the dike margin. Further development of this work will provide insightful constraints on shallow and short-lived interactions at the magma-limestone interface during sedimentary-hosted fissure eruptions.

Decoding Magma Dynamics: Crystal Zoning Insights for Volcanic Hazard Assessment

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In volcanic risk mitigation strategies, it is crucial to understand the mechanism governing magma ascent prior to eruption. Typically, models designed to understand this process rely on geophysical monitoring and petrological analysis of erupted materials. However, these models often lack the required spatial and temporal resolution necessary to precisely assess magma ascent times.

Crystals serve as excellent recorders of magmatic processes. As they grow in response to changes in temperature, pressure, and melt composition, they accumulate distinct chemical and textural layers that carry important information. Because decompression and cooling operate on very different time scales, resolving the driving force behind crystallization is of fundamental importance for determining magma dynamics and eruption hazard.

Our proposed study combines methodologies to infer magma ascent times, placing tighter bounds on the timescales of magmatic processes that precede eruptions. We analyze the size and complexity of crystal zoning features using advanced techniques such as Laser Ablation-ICPMS and SEM imaging. These findings are then validated within a finite-element model of magma flow within the conduit feeding system.

We apply this new method to the well-studied Pomici di Avellino (PdA) eruption of Somma-Vesuvius (Italy), which occurred approximately 3.9 thousand years ago [Sulpizio et al. 2010, Massaro et al. 2018]. The focus of our study lies on the magmatic Plinian phase (EU2-EU3), with analysis conducted on different crystal size classes (ranging from 125 micrometers to 2 millimeters). Preliminary results reveal interesting correlations between chemical elements for different crystal size populations.

Geochemistry and petrology of the Bellecombe lava sequence at Enclos Fouqué caldera, Piton de la Fournaise volcano (Réunion, France)

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Piton de la Fournaise is an active shield volcano sited in the eastern area of the Réunion Island (Indian Ocean) whose activity consists of lava flow effusion and explosive episodes. The emitted products are generally scarcely differentiated magmas with mostly tholeiitic affinity. The presently active edifice has grown within the Enclos Fouqué caldera, a polylobate plain bounded on its western side by the Bellecombe vertical cliffs that reach a high of 200 m. This escarpment exposes a vertical sequence of 12 lava flows cut by a dike with an age > 5.5 kyrs.

The well-defined geometry of these lava flows and the easy accessibility of the Bellecombe cliff allowed the sampling of all the outcropping lavas with the aim of investigating the evolution over time of the magmatic system feeding the eruptive activity prior to the Enclos Fouqué caldera collapse. A petrological study of the products was conducted by means of X-ray fluorescence, Inductively Coupled Plasma Mass Spectroscopy, Scanning Electron Microscope and X-ray computed microtomography techniques. The results indicate that lava flows share a geochemical affinity with the two main series documented at Piton de la Fournaise, namely, Steady State Basalts (SSB) at the bottom and top of the sequence and Abnormal basalt Group (AbG) with different degrees of differentiation in the central part. The emission of these two different series of products in a restricted area and in a relatively short timespan highlights the dynamic activity of the plumbing system, able to rapidly shift from central to eccentric activity in the recent past.

Experimental constraints on the pre-eruptive conditions of the Caxias do Sul dacite: Implications for high temperature silicic volcanism of the Paraná Magmatic Province, Brazil

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Large igneous provinces (LIPs) represent exceptionally large emissions of magma that are emplaced within a short period of time (1-5 Myr). Their emplacement can release large quantities of volatiles and metals into the atmosphere, with the potential to cause global climatic perturbation and mass extinction. The Paraná-Etendeka Magmatic Province is the second largest continental LIP known, yet, its emplacement has not been associated with major environmental change. The province is characterised by an unusually high proportion (~3 %) of silicic erupted products, ranging from dacitic to rhyolitic in composition. However, for the Paraná portion of the magmatic province exposed in Brazil, devitrification and rheomorphism has rendered it difficult to assign the silicic sequences to a particular eruptive style. Consequently, the silicic units of the Paraná Magmatic Province have been interpreted as effusive lava flows, domes, rheomorphic ignimbrites and also hybrid activity. Understanding the eruptive style of the silicic units is important for assessing their environmental impact.

We present experimental constraints on the pre-eruptive crystallisation conditions of the Caxias do Sul dacite, the first endmember erupted in the Paraná Magmatic Province silicic sequence. We use crystallisation experiments to establish the pre-eruptive mineralogical assemblage of the Caxias do Sul dacite and compare our experimental results with observations of natural samples to define pre-eruptive conditions. Combining the results from crystallisation experiments with mineral-melt thermometry performed using natural samples, we find that pre-eruptive crystallisation conditions are most consistent with temperatures of 975-1000 °C, 150-350 MPa and 2 wt.% H₂O. Quantitative textural analysis also indicates that the majority of crystallisation occurred within the pre-eruptive storage region, crystallising 15-29 vol.% of phenocrysts and microphenocrysts.

The high pre-eruptive temperature and low H₂O content estimated for the Caxias do Sul dacite likely maintained low undercooling during ascent, crystallising only a small syn-eruptive crystal cargo. Therefore, the Caxias do Sul magma likely experienced minimal rheological change during ascent within the conduit. Our experimental results confirm that, compared to other dacitic eruptions, the Caxias do Sul represents an atypical, high temperature and H₂O-poor endmember. These properties likely influenced the unusual eruptive style and emplacement of the Caxias do Sul dacite.

Petrogenesis of the peralkaline Golja Ignimbrite (Main Ethiopian Rift)

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The volcanic activity in the Main Ethiopian Rift, Ethiopia, displays a bimodal distribution of volcanic rocks, with abundant mafic and felsic compositions and rare or absent intermediate magmas. This characteristic, common to other volcanic settings (e.g., the Yellowstone caldera), is known as the Daly Gap. In the Main Ethiopian Rift, mafic and felsic magmas are rarely found together in the same volcanic system, except for few cases (e.g., Erta Ale). The most evolved magmas typically feed large explosive eruptions producing widely dispersed ignimbritic deposits and consequent caldera collapses of, while the mafic compositions are more commonly associated with fissural eruptions, monogenetic cones and lava flows. Consequently, the genetic relationship between the felsic and mafic magmas still represents a matter of debate with interpretations ranging from pure fractional crystallization to more complex scenarios involving magma mixing and crustal melting.

In this contribution, we present the first volcanological, petrological and geochemical characterization of a pyroclastic sequence erupted from an uncertain location in the Main Ethiopian Rift at ~1.3 Ma, the Golja Ignimbrite (GI). The GI was emplaced during a large explosive eruption involving about ~100 km³ of crystal-poor magma. Unlike other eruptions from the region, the GI encompasses basaltic and intermediate compositions (trachydacites and trachyandesites) in addition to peralkaline rhyolites, which represent the main component. Therefore, the GI represents an ideal case study to investigate the genesis of the rhyolitic products and their relationship with the more mafic compositions. To achieve this goal, we conducted in-situ and bulk ⁸⁷Sr/⁸⁶Sr analyses of feldspar crystals as well as ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd of matrix glasses within the different units of the GI. Our results show that Ca-rich plagioclase crystals hosting basaltic melt inclusions display Sr isotopic compositions akin to the Main Ethiopian Rift basalts and slightly more radiogenic than those of the Afar Plume. Bulk ⁸⁷Sr/⁸⁶Sr of K-feldspars and matrix glasses exhibit notable variations ranging from mantle-like signatures to more crustal-like ones. Bulk ¹⁴³Nd/¹⁴⁴Nd of matrix glasses do not show significant variations between mafic and evolved compositions within the ignimbrite, but are significantly lower than typical Afar Plume mantle values. Overall, our data point towards a complex geochemical and isotopic evolution, where the most evolved and intermediate magmas are genetically linked to the mafic compositions via fractional crystallization with assimilation of crustal material mostly occurring in the deep part of the plumbing system. Repeated isotopic analyses of matrix glasses before and after leaching show differences in the ⁸⁷Sr/⁸⁶Sr ratios, with the leached samples being less radiogenic than their unleached equivalents, despite the absence of textural or geochemical signs of post-eruptive alteration. Notably, the amplitude of the shift in Sr isotopic compositions decreases from matrix glasses within pumiceous samples to those from the vitrophyre indicating that syn- or post-eruptive fluid circulation might have modified the original Sr isotopic signatures. Although these results do not significantly affect our interpretation, we suggest that caution should be taken when analysing Sr isotopes even in fresh-looking vesicular glasses.

Timing of magma-carbonate interaction before the 3950 yr BP Avellino eruption (Somma-Vesuvius, Southern Italy)

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Skarn clasts co-erupted with phonolites at Somma-Vesuvius record interaction between magma and carbonate wall-rocks during pre-eruptive storage in the shallow crust. The timing of magma-carbonate interaction is poorly constrained due to the scarcity of dateable minerals in the skarn ejecta. Nevertheless, it is important to assess when and how such interactions occur because carbonate assimilation is associated with significant CO₂ release, potentially affecting the timing and style of eruptions. In this study, we employ recently developed analytical protocols for in-situ U-Th geochronology by LA-ICPMS to date garnet and vesuvianite from skarn and syenite clasts co-erupted with phonolite magmas during the 3950 yr BP Plinian Avellino eruption of Somma-Vesuvius. Garnet U-Th dates of syenite ejecta record ~3,000 years of protracted magma evolution and solidification of the peripheral parts of the magma reservoir and are resolvably younger than previously published garnet U-Th dates from the host phonolites. Vesuvianite and garnet U-Th dates of skarn ejecta tightly cluster between 6.04 ± 0.39 to 6.65 ± 0.25 ka. This suggests that skarn formation and associated crustal CO₂ degassing preceded the Plinian eruption by more than 2,000 years. Our findings have important implications for eruption forecasting at Somma Vesuvius, as a shift towards more crustal CO₂ emissions may not indicate an imminent eruption.

Timing and evolution of rhyolitic magmatism on Lipari

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Making rhyolites in a volcanic arc takes time, space and heat. It requires a prolonged flux of primary magma to create thermal conditions conducive to extreme magma differentiation, a process which leaves behind a pile of crystal cumulates. How these processes operate, however, is often difficult to disentangle from complex volcanic systems with jumps in composition or eruptive style and overlapping edifices.

In the Aeolian Islands, rhyolitic volcanism is nearly exclusive to the island of Lipari. Based on available stratigraphic data and partial geochronologic context, rhyolitic magmas appear to have developed following an extended magmatic buildup characterised by mafic to intermediate (basaltic andesite to andesite) volcanism of eruptive epochs (EE) 1-6 (267–81 ka). Then, following an apparent period of quiescence of ca. 40 ky, the magmatic system peaked by generating alternating dome-style effusive and explosive rhyolitic eruptions from ca. 43 ka to historical times (EE 7-9). Eruptive centres progressively migrated from the S of the island, along the E coast, towards the N, where the most recent eruptions of M.te Pilato and the iconic Rocche Rosse lava flow took place at 1243-1304 CE. This spatial development offers a unique opportunity to extensively sample the volcanic products, and through them understand the variable nature of the magmatic system developing under Lipari for the last ca. 40 ky.

We will present new data probing the suite of rhyolitic eruptive products of Lipari, including glass and major mineral compositions, revealing distinct spatio-temporal grouping in the products erupted in the ca. 43–20 ka time span (EE 7-8). Zircon U–Th disequilibrium ages will be used in concert with existing geochronology to refine the absolute time framework of eruptive activity, and to constrain a newly recognised eruption pushing the onset of rhyolitic volcanism further back in time. Our new zircon data indicate short periods of zircon crystallisation before each eruption despite clear evidence of extensive fractionation (e.g. low Zr/Hf, Eu/Eu* in glass) en route to generating the rhyolites, indicating the existence of a volumetric cumulate body beneath Lipari. Our new data form a basis to understand the past temporal and spatial development of the magma reservoir under Lipari, and can further be used to investigate controls on the composition and eruptive style, as well as the future direction of volcanism on the island. Finally, we contribute on-land (proximal) compositional data that will help refine the Quaternary tephrochronological record of the Mediterranean.

S10 - VOLCANIC RISK MANAGEMENT: LESSONS LEARNT AND OPEN QUESTIONS FROM RECENT VOLCANIC CRISES

Conveners:

Rosella Nave, Antonio Colombi, Mauro Rosi, Costanza Bonadonna,
Chiara Cristiani, Eugenio Privitera

UK Health Security Agency public health risk assessment for volcanic eruptions

Emily Cheek¹, Christina Mitsakou¹, Beth Taylor¹, Sam Thompson¹, Sarah Dack¹, Alec Dobney¹, Andrew Kibble¹

¹Health Security Agency, UK

The UK Health Security Agency (UKHSA) prepares for and responds to infectious diseases, chemical and environmental hazards, to keep all our communities safe, save lives and protect livelihoods. We provide scientific and operational leadership working with local, national, and international partners to protect the public's health and build the nation's health security capability. While the UK does not have any active volcanos, historic Icelandic eruptions have had impacts on both UK travel and air quality. As part of our preparedness, UKHSA must therefore be ready to respond in the event of a volcanic eruption that has the potential to affect the UK. To do this, we have sought out the most recent scientific evidence to support our public health response.

For there to be a risk to health in the UK, there would need to be a significant and / or protracted explosive or effusive eruption which, together with the right meteorology, results in volcanic emissions able to travel to, and cause elevated pollution across parts of the UK. The reasonable worst-case scenario for a volcanic eruption considered in the UK National Risk Register (NRR) 2023, is based on an ash-rich volcanic eruption into UK airspace that results in sporadic severe disruption to flights in parts of the UK or international airspace. However, there are higher impact, lower probability variations relating to larger eruption scenarios which could generate ash and gas that are dispersed across the northern hemisphere. The key health hazards identified for volcanic eruptions affecting the UK are exposure to respirable ash (particulate matter below 10µm diameter or PM₁₀) and sulphureous compounds, particularly sulphur dioxide (SO₂) and sulphate aerosol (a mixture of H₂SO₄ and SO₄²⁻).

Respiratory health effects associated with the exposure to volcanic ash have been reported in other countries; acute (short-term) effects of heavy ash fall include asthma attacks and bronchitis, increased breathlessness and coughing, tightness in the chest and wheezing which is caused by irritation of the airways lining. People with the highest risk of experiencing adverse effects from volcanic ash inhalation are those who currently have pre-existing conditions, in particular respiratory conditions.

The aim of this proactive piece of work is to develop robust guidance which will support an effective response, providing responders and the public with current information, and to reduce any public health impacts in the UK. Guidance for British citizens overseas will also be included. The guidance has been developed in collaboration with subject matter experts, including academics and the MET Office.

This work has enabled UKHSA to better understand scenarios where a volcanic event has the potential to impact the UK based on the most recent evidence, historic eruptions, monitoring and modelling, and meteorological conditions. During the 2010 Eyjafjallajökull eruption, which emitted a volcanic ash plume from Iceland that spread across the UK and mainland Europe, real-time syndromic surveillance systems were used to monitor community health during the incident and which did not identify any unusual increases in any of the monitored conditions.

The guidance includes a dynamic risk assessment process which can be utilised during incident response and allows for a consistent and robust method of assessing the risk and providing a

proportionate response to protect public health. Following on from the guidance, public facing infographics will be produced to support the key public health messaging for UK citizens.

From hazard to risk assessment during the recent volcanic unrest of the Svartsengi volcanic system, Reykjanes peninsula, southwest Iceland

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The ongoing volcanic unrest, affecting the region of Svartsengi on the Reykjanes peninsula since October 2023, is the third case in the last 50 years of volcanic activity with a direct effect on local populations in Iceland. During the eruption in Vestmannaeyjar in 1973, the entire population of the Heimaey island was evacuated for the whole duration of the eruption (~5,000 inhabitants), and the eruption of Eyjafjallajökull in 2010 caused the temporary evacuation of about 800 people from their homes close to the volcano. These events are still remembered for the severe impact they had on the local communities. However, their impact was less extensive compared to the impact of the ongoing volcanic crisis on the Reykjanes peninsula, which began with the long-term evacuation of the town of Grindavík (~3,500 inhabitants) on 10 November 2023.

Since the emplacement of a NE-SW oriented 15-km long magma intrusion, which formed on 10 November, crossing beneath Grindavík and extending into the sea, four effusive eruptions have occurred from the Svartsengi volcanic system at almost monthly intervals. All four eruptions originated from eruptive fissures that opened along the initial dyke orientation and aligned with the pre-existing Sundhnúkur crater row. The eruption that started on 16 March 2024 and lasted until 9 May is, so far, the most persistent (54 days), and the largest in terms of erupted lava volume. The proximity of the four eruptive fissures to critical infrastructure (a geothermal power plant, a major tourist attraction and a densely populated town), and the prolonged level of activity (even expected to continue for decades), makes the ongoing volcanic unrest in the Svartsengi region an important case for hazard and risk integration analysis.

The Icelandic Meteorological Office (IMO) is responsible for assessing the hazards associated with the ongoing activity, and this assessment is one of the components used by the Icelandic Civil Protection (NCIP) for an integrated risk assessment, used for managing the ongoing crisis. This includes emergency responses including the planning of mitigation measures and evacuation plans, as well as the long-term economic and social consequences.

This presentation highlights the short-term multi-hazard assessment procedure that IMO designed in response to the dyke intrusion on 10 November. It has been developed to account for a variety of hazardous phenomena potentially affecting target areas, selected either for the presence of critical infrastructure or for the existence of features directly connected to the ongoing volcanic unrest. Similarly, the risk assessment tool developed by NCIP for the daily assessment of safety and accessibility to the different areas is presented to show the complexity of a multi-factors decision making process.

Examples of this collaboration between hazard monitoring institutions and those responsible for the operations are provided:

- 12-19 November 2023 when additional monitoring was needed while the inhabitants of Grindavík went back in town, in a controlled way, for collecting their properties for a temporary relocation in other houses;

- 14 January 2024 when the eruptive fissures opened less than 2 km from Grindavík, resulting in properties being inundated by lava;
- 8 February 2024 when the lava flows hit the district central heating pipe from the Svartsengi power plant, disrupting the heating system that supplied homes and businesses along the peninsula (~30,000 people affected).

Volcanic risk assessment: insights from the advisory mission of the European Union Civil Protection Team in Iceland

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At the beginning of November 2023, following a rapid evolution of pre-volcanic activity in the Grindavík area on the Reykjanes Peninsula (ground deformations and earthquakes due to the rising magma with the evacuation of 3,700 people), the Icelandic Government activated the Union Civil Protection Mechanism (UCPM).

The UCPM (see institutional website) is a tool that allows the rapid deployment of capacities, resources and experts from European Union member states and participating states. When a country in Europe and beyond is affected by an emergency and its response capabilities are overwhelmed, it can request assistance through the UCPM. It can also request support and expertise in the form of advisory missions/peer reviews outside of emergencies or, in this case, in the incipient hazard of an emergency.

At the request of Iceland, a European Union Civil Protection Team (EUCPT) composed of five experts and one Emergency Response Coordination Center (ERCC) Liaison Officer deployed for an advisory mission. An advisory mission, in addition to supporting local authorities in carrying out reporting and evaluation activities, must also define a possible framework for capacity development, provide solutions to mitigate volcanic risk, transfer know-how and offer recommendations and strategies to the country affected by the probable emergency.

The mission aims were a) supporting the Local Authorities in assessing the situation and preparations to deal with the emergency; b) discussing scenarios, possible escalation of the situation, and some lines of action and coordination; c) discussing response options with High-Capacity Pumping Modules (HCP) to cool and/or divert lava flows; d) reporting and providing operational recommendations to the Local Authorities.

Considering that the population of Grindavík had already been evacuated as a precautionary and preventative measure, the mission had to provide technical-operational help to the Local Authorities both in the pre-emergency phase and in the first moments after a possible volcanic eruption.

The critical points to be analysed jointly with the Icelandic Civil Protection (ICP) were: i) a probable volcanic eruption and subsequent consequences (which occurred once the mission was concluded and is still ongoing), ii) the possible impact on the city of Grindavík, iii) the possible involvement of the Svartsengi geothermal power plant, iv) a technical assessment and proposal for cooling the lava, and v) a potential mass evacuation on the Reykjanes Peninsula.

The main concern of the ICP was related to the Svartsengi geothermal power plant, which produces and distributes electricity and heating to a wide range of Reykjanes Peninsula. Severe damage or an outage of the power plant could lead to the “worst-case” scenario of a power cut and heating failure, causing the mass evacuation of roughly 40,000 people living in the affected area. During the assessment of the Reykjanes Peninsula and after a series of meetings at different

levels (operational, management, and political), the EUCPT developed a report presented to the Local Authorities and later shared with the UCPM community consisting of recommendations and scientific considerations, as well as managerial, and technical-operational suggestions. The main content related to possible lava cooling operations was a decision model and suggestions to the Icelandic government if deemed feasible, for operating through high-volume pumps provided by the UCPM HCP modules and water distribution systems. The mission was within the UCPM framework with the support of the ERCC.

Assessing the effectiveness of evacuation: the case of Vulcano Island, Italy

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Emergency planning and management represents a key aspect of volcanic crises because they can increase people protection as well as minimize the potential impact on the economy, properties, and infrastructure of the affected area. Evacuation scenarios must be explored in pre-event contexts to support the development of emergency plans by authorities and inform decision-making outside the highly stressful time period that characterizes crises. We present here an agent-based model (ABM) in GIS space relying on the AnyLogic® software platform to assist emergency managers and assess the effectiveness of specific evacuation parameters. ABM allows exploring the complex relationship between agents (e.g. population, hazards, weather conditions, warning times) in a stochastic way to investigate and optimize evacuation scenarios. We applied our ABM to Vulcano island (Italy), characterized by possible sudden hydrothermal and magmatic events with little warning signals, and investigate how spatio-temporal properties of agents (e.g. number of people present on the island during the low and high seasons) and evacuation schemes (simultaneous evacuation of the whole island or staged evacuation of different areas) affect evacuation efficiencies. Simulations show that the overall time needed to evacuate people should be analysed together with the percentage of people evacuated as a function of time. In particular, both the simultaneous and the staged evacuation are shown to be slightly faster during the low season with respect to high season, with the simultaneous evacuation being more efficient at removing people from the island than the staged evacuation, especially in the low season.

We have also compared our ABM with information collected during the full-scale civil protection exercise performed on Vulcano by the Italian Civil Protection Department on April 9, 2022 and investigated two scenarios developed as a results of this drill: (i) evacuation from Porto Gelso (in the south of the island) and (ii) evacuation from both Porto Gelso and Porto Ponente (in the north of the island). Both cars and buses were used in both scenarios. Considering multiple evacuation exits and reducing travel journey for evacuees makes the whole evacuation process more efficient with evacuation from the two ports being significantly faster than the evacuation from Porto Gelso only. Given the criticality of the timing and of the routing of evacuation to remove people from the hazardous zone before it is impacted, the use of models such as our ABM evacuation simulator is key to the development of efficient emergency plans.

Lessons from the 2019 Stromboli eruption (Aeolian Islands, Italy): understanding multi-risk perception in volcanic tourist hotspots

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Volcanic and geothermal sites, known for their spectacular phenomena such as lava flows, explosions and geysers, attract tourists from all over the world. In fact, these areas, shaped by volcanic processes, are often so rich in biodiversity and historical and cultural significance that they are protected or even included in the UNESCO World Heritage List for their unique value. Volcanic regions often attract travellers with their hot springs, which are renowned for therapeutic and regenerative properties, thus playing an important role in health and wellness tourism. In addition, in contexts where hot springs have a spiritual-cultural value, hot springs are celebrated for their purifying powers.

However, the risk associated with eruptive events has surged considerably, mainly because of the flourishing tourism industry in volcanic and geothermal sites. Overtourism exposes a wide range of people to pyroclastic density currents, lava flows, ash fallout and volcanic gases and, from 2000 to 2017, tourism-related accidents in volcanic areas resulted in 561 deaths, most of which occurred during eruptive events due to ballistic projectiles. Moreover, there is a proliferation of new services and infrastructures aimed at catering to the needs of tourists, thereby escalating the risk of heightened exposure, vulnerability, and related direct/indirect damages following one or more hazardous events.

These sites may also face combined (coincident or consecutive) events such as wildfires, earthquakes, landslides, tsunamis or floods with potentially catastrophic consequences. Disaster Risk Management (DRM) authorities need to equip both permanent and transient populations with adequate tools to respond to sudden adverse conditions (i.e., coping capacity), anticipate crises (i.e., adaptive capacity), and proactively enhance local well-being and sustainability (i.e., transformative capacity). Measures such as updated emergency plans, monitoring systems, risk perception analysis and risk awareness campaigns are essential to minimise the impact of natural hazards. Therefore, fluctuations in tourist flows inevitably play a key-role as they represent a critical factor to be taken into account.

In particular, understanding and preparing for volcanic eruptions and related events requires addressing different perceptions of risk, especially in areas where locals and tourists coexist. Locals, due to their familiarity with the environment, interact with natural hazards more than tourists. They are often knowledgeable about preventive measures to minimize the impact of such events, showcasing their predisposition and ability to live in a hazardous area. In contrast, tourists, being unfamiliar with the surroundings, may lack the skills to navigate or manage potentially dangerous situations and this lack of preparedness can exacerbate the consequences of one or more hazardous events.

A study conducted on Stromboli Island during the 2019 eruption sheds light on these dynamics. The study aimed to understand how both locals and tourists perceived the multi-risk environment during the crisis. In this regard, data was collected through semi-structured interviews with inhabitants and questionnaires with visitors just prior to the declaration of a

state of emergency on 19 September 2019 (Delibera del Consiglio dei Ministri 18 settembre 2019, n. 227). This timing provided a unique opportunity to understand the interaction and behaviours of people living permanently (locals) or temporarily (tourists) on the island during the crisis. The findings not only enhance our understanding of multi-risk perception on Stromboli, but also provide valuable lessons that can be applied to other touristic destinations facing similar geo-environmental hazards.

Territorial-scale bradyseismic vulnerability analysis of private Phlegraean buildings using the PLINIVS survey form

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Campi Flegrei (Italy) is an active caldera in a phase of unrest since 2005, consisting of ground uplift with a maximum near the historic centre of Pozzuoli, with a consequent increase in seismic activity (i.e., bradyseism) and increased fumarolic and diffuse degassing [Perelli et al. 2023]. The area is densely populated and comprises 7 municipalities, including some districts of the city of Naples. Since December 2012, based on monitoring data, the Department of Civil Protection has raised the alert level to yellow and the operational phase to “warning”, on the recommendation of the Major Risks Commission. The most worrying phenomena within the area are volcano-tectonic earthquakes, as they could be correlated with a possible pre-eruptive phase. These events have the potential to cause significant damage to vulnerable assets (i.e., buildings and roads), which are critical during evacuation procedures.

To assess the vulnerability and risk of the area, the “Extraordinary plan for the analysis of the vulnerability of the areas directly affected by the bradyseismic phenomenon” (Piano straordinario di analisi della vulnerabilità delle zone direttamente interessate dal fenomeno bradisismico), coordinated by the Civil Protection Department, has been approved on 26 February 2024 (implementation of Art., D.L. No. 140 of 12 October 2023). It has been applied to the so-called “area of interest”, characterised by earthquakes with a magnitude greater than 2 since 1983 (from PLINIVS processing of INGV-OV data) and by ground uplifts of at least 10 cm since 2015 (from PLINIVS processing of data produced by CNR-IREA and updated to September 2023), which corresponds to approximately 20 cm since 2006 (from INGV-OV processing).

Among the measures envisaged in the Plan, one is devoted to analysing the seismic vulnerability of ordinary private buildings to quantify the financial resources needed for the seismic upgrading of the building stock. This is achieved through several steps, starting from a preliminary survey of the structural characteristics of buildings and a classification of vulnerability at the territorial scale. The PLINIVS-LUPT Study Centre (National Competence Centre on Volcanic Risk under the coordination of the Civil Protection Department, Presidency of the Council of Ministers) has carried out a comprehensive survey within the “area of interest”, using the PLINIVS survey form to collect data relating to both seismic characteristics (e.g., vertical and horizontal structure, regularity, mitigation measures, etc.) and volcanic characteristics (e.g., roof structure and geometry, type of infill/doors/windows) of buildings. The survey was carried out by teams of technicians using tablets with the QGIS application. This allowed an automated compilation of the form based on a rapid visual survey from the outside of ordinary buildings.

To date, the survey is almost complete and, by the end of activities, approximately 8,000 buildings will have been surveyed. Together with the 4,000 previous surveys carried out by PLINIVS, the stock of buildings will consist of 12,000 surveyed buildings. Once completed the rapid visual surveys, data will be processed to provide a first-level vulnerability assessment within cells of

250m x 250m. Each cell will contain a variable number of buildings, up to a maximum of 120 in the most densely populated areas. The methodology for the classification of vulnerability is defined by a statistical procedure named SAVE, developed by the PLINIVS-LUPT Study Centre [Zuccaro & Cacace 2015] and further implemented through the CAESAR II analysis model [Zuccaro et al. 2021]. This procedure provides a synthetic and aggregated vulnerability index, cell-by-cell (average vulnerability, classified as very low, low, medium or high), starting from the information collected for each building.

The following products will be provided to the Civil Protection Department: i) the complete database containing all the information needed to characterise buildings surveyed; ii) the vulnerability assessments at the territorial scale and related cartographic representations, based on which dwellers of buildings located in most vulnerability cells, will have the chance of asking for a more detailed investigation. This additional investigation will be conducted by the ReLUIS Consortium. Once completed, a report detailing the financial costs and a mitigation plan for the area will be submitted to the Civil Protection Department to provide the Government with a comprehensive overview.

Challenges posed to the management of the ongoing crisis of the Campi Flegrei caldera - INVITED

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The unrest emergency of the Campi Flegrei caldera, is putting a strain on the socio-economic stability of an area characterized by intense urbanization and where a large number public, commercial and industrial activities are present. The increasing shallow seismic activity, linked to the uplift of the caldera center, already represents a threat to vulnerable buildings while the related prospect of a volcanic eruption within the caldera is bringing to light the errors of the post-II World War development, which has completely ignored the presence of the active volcano.

In light of these elements, the challenges that the ongoing crisis is placing on the different players: citizens, National Civil Protection System, local and national administrations, public and private economic entities, is huge. This is in consideration of the scale of the problems that the crisis is already posing, but even more in the prospective of the complexities of volcanic threats whose characteristics are largely unfamiliar to the majority players.

The prevention effort made so far is already considerable. It has consisted in the adoption of a dedicated law decree by the national government aimed at dealing with the seismic vulnerability assessment of buildings, in the intensification of volcano monitoring and forecasting activities, in the information to the population, in the implementation of seismic and volcanic exercises, and in updating emergency plans.

The uncertainty regarding the future evolution of crises combined with the scale and complexity of its impact, makes necessary to promote a permanent synergy and coordination among all the actors (citizens, scientists and operational and institutional subjects). Moreover, the possible evolution towards an eruptive scenario with consequences hard to imagine, makes highly necessary to take full advantage of the scientific and operational experiences already gained at a global level to incorporate them in the prevention activities before the volcano would eventually strike.

Risk reduction measures related to bradyseism in the densely populated area of Campi Flegrei

Antonio Ricciardi¹, DPC Campi Flegrei Team*

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“Bradyseism” refers to a geological phenomenon occurring at Campi Flegrei, a volcanic area located near Naples, Italy. This term comes from the Greek *bradýs*, meaning “slow,” and *seismós*, meaning “movement,” which describes the gradual uplift or subsidence of the Earth’s surface due to the movement of magma or fluids beneath the ground, with phases of more rapid uplift generally accompanied by shallow and low-magnitude earthquakes easily felt by the population living in the area.

The Campi Flegrei caldera has experienced bradyseism over centuries, with significant effects on the landscape and local communities. A new phase of uplift began in 2005, indicating a resurgence of bradyseism activity in the area that it is still ongoing. Since 2023, there has been a gradual increase in the frequency and magnitude of earthquakes.

In response to the ongoing bradyseismic crisis, volcano monitoring activities and prevention actions of the Civil Protection System have been strengthened. Decree-Law No. 140 of October 12, 2023, provided for urgent measures to prevent seismic risk related to the bradyseismic phenomenon in the Campi Flegrei area. The major lines of ongoing activity are the following: a) the analysis of vulnerability of built-up areas, b) the elaboration of an emergency plan dedicated to bradyseism, c) the definition and development of a communication plan, d) the assessment of the functioning of the transport network and infrastructures and other essential services, e) the strengthening of the territorial operational civil protection response.

According to the Decree-Law, the Civil Protection Department (DPC), Campania Region, and representatives from the scientific community are engaged, working closely with the affected municipalities and the metropolitan city of Naples.

To assess the ongoing phenomena and the state of activity of the Campi Flegrei, the National Commission for the Forecasting and Prevention of Major Risks (CGR) met several times for technical and scientific analysis, upon request of the DPC. For the first time, the CGR invited to contribute volcanologists and seismologists from the international scientific community with the aim of broadening the spectrum of information and gaining a better understanding of situations that have occurred in other volcanoes. Within the activities outlined by the Decree-Law, training sessions are being conducted for civil protection volunteers, journalists, and public officers on topics related to volcanic risk, bradyseism risk, and civil protection exercises. Additionally, communication campaigns and exercises are being carried out to promote accurate and effective information dissemination to the population.

There is a strong expectation on the effectiveness of all the initiatives put in place for the first time to mitigate the effects of the bradyseism. At the same time, it is necessary to avoid that these actions induce a false feeling of safety among people living in one the highest volcanic risk areas in the world.

Volcanic risk policies at global, european and national scale: state of the art, gaps and challenges

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Volcanic eruptions are among the most powerful and destructive natural hazards on Earth, capable of causing widespread human suffering and extensive economic losses, from direct impacts or cascading effects (e.g., disruptions of air transport, tsunamis, etc.).

Therefore, strategies and policies for Disaster Risk Reduction (DRR) and Disaster Risk Management (DRM) should include it but, although many efforts are ongoing related to DRM (including emergency), much more nuanced are those related to DRR.

At the international level, the Sendai Framework for DRR represents the cornerstone of formalized actions aimed at reducing the risk of natural hazard-related disasters. It provides a strategic direction for Nations to strengthen their resilience to disasters through a holistic, multi-risk approach involving all segments of society.

In the context of volcanic risk, it is crucial to pay attention to the progress made towards Sendai's Global Target E, which calls for governments to increase the adoption of Local and National DRR strategies. Similarly, Target G evaluates the current global status of Multi-Hazard Early Warning Systems (MHEWS). For this purpose, the UN Secretary-General launched the "Early Warnings for All" initiative in March 2022, with the aim of ensuring that every person on Earth is protected by early warning systems by 2027.

The significance of achieving these targets underlines the need to galvanize political support and unite all relevant stakeholders, particularly the scientific community and governmental agencies. At the European Level, the Union Civil Protection Mechanism (UCPM) was formally established in 2013 [<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32013D1313>]. This Decision applies to cooperation in the field of civil protection, which includes both prevention and preparedness actions, and actions to assist with the response to immediate adverse consequences of a disaster. Following the subsidiarity principle, the volcanic risk and related disasters are therefore considered at supra-national scale for their cross-boundary and cross-sectoral impacts. In addition, the Decision envisages the development of National or sub-National risk assessments, along with a risk management capability assessment and a disaster risk management planning. Moreover, for key risks having cross-border impacts and risks related to disasters which cause or can cause multi-country transboundary effects, as well as, for Low Probability risks with a High Impact (HILP), priority prevention and preparedness measures have to be described. Some eruptive scenarios of the Italian volcanoes perfectly fit with the HILP definition.

Concerning scenarios, the Decision establishes that the European Commission and Member States have to work together to improve cross-sectoral disaster risk management planning at Union level, taking into account the work carried out in relation to the Union Disaster Resilience Goals [https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_600] and by the Union Civil Protection Knowledge Network [<https://civil-protection-knowledge-network.europa.eu/>]. To implement this prescription, the so-called Scenario-building Initiative [https://drmkc.jrc.ec.europa.eu/Portals/0/Knowledge/AnnualSeminar/presentations/Session3B/Session_3b_Scenario_building_under_the_recently_revised_UCPM_legislation_3-0.pdf] was aimed at creating a portfolio of scenarios with the support of Member State experts and other Commission Services (e.g., the JRC), that will serve as a basis for a more systematic approach to

evidence-based decision making of the UCPM.

Indeed, the most recent volcanic eruptions around the globe (e.g., Eyjafjallajökull 2010, Merapi 2010, Ontake 2014, Fuego 2018, Krakatau 2018, Whakaari 2019, Taal 2020, Cumbre Vieja 2021, Semeru 2021, La Soufrière 2021, Hunga Tonga–Hunga Ha’apai 2022, Sundhnúkur 2023) have shown that, beside their size and intensity, their impact makes the difference (human lives, direct and indirect economic losses, social impact, etc.). Scenarios can be useful to manage these kind of disaster events in their earlier phases, whereas risk models can better support long-term prevention strategies.

However, notable gaps persist - alongside their associated financing considerations - and is therefore essential to strengthen National disaster risk management strategies and ensure the efficacy of preparedness and response measures.

S11 - PROBING ARCHITECTURES AND TIMESCALES OF VOLCANIC PLUMBING SYSTEMS BY MULTIDISCIPLINARY APPROACHES AND ADVANCED METHODOLOGIES

Conveners:

Carlo Pelullo, Maurizio Petrelli, Chiara P. Montagna,
Gianmarco Buono, Claudia D'Oriano

Linking timescales of mafic recharge and radiative power during the February-March 2021 lava fountains events of Mt. Etna South-East crater.

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Timescales of mafic recharge have been calculated from diffusion modelling of clinopyroxenes population erupted during the first phase (December 2020 – April 2021) of 2021 paroxysmal events at the South-East crater (SEC) of Mt. Etna. We investigated textural and chemical characteristics of the clinopyroxenes population erupted during 6 paroxysms from February 16 to March 10 2021, including the February 28 paroxysm which erupted the most primitive magma. Clinopyroxenes show frequent sector zoning superimposed on complex concentric zoning showing two main compositional domains: 1) augitic composition (Mg# 68-75) which mostly characterises rims and is less frequent in cores and mantles; 2) diopsidic composition (Mg# 74-80) mainly found in cores and less abundant in mantle and rims. Fe-Mg diffusion timescales point to the occurrence of a mafic recharge from the intermediate to the shallow storage zone starting in June-July 2020 and continuing until February 2021. These timescales have been compared with the continuous volcanic radiative power (VRP) from MIROVA data. An increasing radiative power from July 2020 until March 2021 is linked to the gradual rise of the magmatic column feeding the activity at the summit crater. The perfect correspondence between the timeline of increasing radiative power and arrival of the mafic recharge suggests a causal link between magma replenishment at shallow depth, paroxysmal events, and radiative power, which is a promising avenue for enhancing interpretation of monitoring data.

Timescales of terminal magma transfer during Mt. Etna May-June 2022 lateral effusive eruption inferred from ^{222}Rn in erupted lavas

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The short-lived radioactive isotopes contained in the solid and gaseous volcanic products offer numerous possibilities for inferring the timescales of shallow magmatic processes, including magma degassing and its transfer towards the surface. Since 2021, as part of a Franco-Italian collaboration between nuclear physicists and volcanologists, we have been measuring the radioactivity of the lava and tephra emitted during the most recent eruptions of Mount Etna (Sicily, Italy).

While radon (^{222}Rn) is generally completely degassed and thus absent in lavas at eruption time, we report here for the first time the significant presence of dissolved ^{222}Rn in the products of a basaltic effusive eruption, namely the May-June 2022 eruption of Mt. Etna. During this eruption two vents were sampled, located at two different altitudes (respectively, 2700 m asl and 1800 m asl). Furthermore, both the amount of radon present and the ($^{222}\text{Rn}/^{226}\text{Ra}$) radioactive disequilibrium differ in the two eruptive vents studied.

In order to explain these measurements we propose a simple model of total radon loss followed by ingrowth from ^{226}Ra decay, making it possible to determine the magma transfer time between the volcano's main conduit, where degassing occurs, and the eruptive vents. By integrating the transfer times thus obtained both with the effusive rates estimated at each vent and with field observations, it is possible to constrain the length of the dykes that were feeding the eruption and thus to gain a better understanding of the deep anatomy of Etna's lateral eruptions.

A digital twin for dyke intrusion – induced unrest at Mount Etna volcano

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Surface deformation at active volcanoes often mirrors subsurface magma dynamics, reflecting pressure variations in magma sources. This deformation, induced by magma dynamics, alters stress patterns in surrounding rocks, propagating signals to the surface, where monitoring networks detect them.

Having an automated tool that can quickly analyze surface signals and provide information about the evolution of the location and magnitude of pressure variations during volcanic unrest is extremely valuable. However, existing inverse methods face challenges due to the ill-posed nature of the problem, non-uniqueness of solutions, and heavy simplifications in the assumed source geometry.

We present a new approach: a digital twin tailored for Mount Etna volcano, harnessing the synergy between numerical simulations and artificial intelligence (AI). Comprising two AI models, our digital twin offers an innovative solution. The first AI model (AI1) uses multi-parametric data to detect unrest conditions, while the second AI model (AI2) interprets surface deformation by providing the distribution of forces that generated it. In particular, AI2 is trained on a very large number (order 10^6 / 10^7) of 3D numerical simulations of elastostatic deformation for dyke intrusions with real topography and heterogeneous rock properties.

Employing the advanced open-source multi-physics finite element software Gales [<https://gitlab.com/dgmaths9/gales>] on Fenix HPC resources, our methodology ensures accuracy and efficiency. Upon activation, AI1 monitors real-time data streams, prompting AI2 to analyse potential volcanic crises by characterizing the time-wise evolution of the source of deformation thus providing valuable crisis-managing resources.

The software will be shared as an open-source package, enabling its replica for use on other volcanoes thus extending its applications for civil protection purposes.

Mt. Etna feeding system and eastern flank: a 3D image from 18 years earthquake distribution and Marching Cube algorithms

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Understanding the complex dynamics of volcanic plumbing systems is essential to decipher volcanic behavior. Here the Marching Cubes (MC) algorithm, generally used in the videogames industry and medical visualization, is applied to image seismic clusters within Mt. Etna volcanic system. The MC algorithm defines three-dimensional -500m resolution- seismic clusters analyzing 18 years of earthquake data, relocalized using the NonLinLoc algorithm for precise relocation. The results show 1) a very-low seismicity volume beneath the central craters, representing a portion of the plumbing system located between 1 and 4 km b.s.l., constrained by the seismic clusters that spatially match the tomographically imaged high-velocity body. And 2) a 5 km thick and 7.4 km length seismic cluster that deepens to 8 km b.s.l. beneath the eastern flank. The top surface of this cluster is in agreement with previous works that model the element known in literature as “décollement” or detaching plane and it may represent a portion of flank affected by instability.

This multidisciplinary approach may overcome the limitation of standard tomography emphasizing the significance of integrating diverse datasets and methodologies. Our findings contribute to a deeper understanding of volcanic plumbing systems, from deep crustal magma storage to eruption triggers, facilitating improved hazard assessment and eruption forecasting strategies.

New insights on the evolution of the primordial plumbing system of Etna

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The Etnean tholeiites (542-320 ka) preserve the record of the first volcanic processes and characteristics of the embryonic plumbing system that fed both submarine and subaerial eruptions in the area of the present edifice of Mt. Etna volcano. Rocks analyzed in this study belong to the Aci Trezza Synthem (542-496 ka) and the later Adrano Synthem (332-320 ka). In this presentation, we document how the petrological differences between basalts belonging to the two sythem units draw a different plumbing system architecture, which resulted in contrasting modes and kinetics of magma transport. Petrological investigations have shown one single high-Fo olivine population in products of the Aci Trezza Synthem phase, and at least three additional populations in volcanic rocks erupted during the later Adrano Synthem phase, the latter bearing evidence of magma hybridization during crystallization. Olivine chemical heterogeneities in combination with thermodynamic modeling indicates a common, 9-14 km deep reservoir for the Aci Trezza and the Adrano Synthem magmas. However, the Aci Trezza crystals record direct migration paths from the deep storage region upward to the surface. In contrast, olivine crystals from distinct lava units of the Adrano Synthem record intricate transport histories throughout a polybaric plumbing system composed of at least three main storage regions. The re-equilibration of olivine zoning via chemical diffusion also allowed us determining the durations of magma storage and transfer dynamics. Crystals experiencing crystallization in multiple storage zones give either short (18-46 days) or significantly longer timescales (106-200 days), suggesting the control of tectonics in accelerating or preventing magma supply during the Adrano Synthem volcanic phase.

The general picture arising from the olivine chemical and temporal records emphasizes the transition towards a more complex plumbing system configuration due to the decreasing role of transtensional tectonics over time. This process culminated at around 130 ka, causing the shift to volcanism dominated by central-type edifices.

Timescales and dynamics of magmatic processes: inferences from compositional zoning in clinopyroxene crystals of the A.D. 79 eruption of Mt. Vesuvius

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The A.D. 79 (Pompeii eruption), is one of the first well-documented and most studied Plinian eruption occurred in the last two millennia. Several studies have explored the eruptive history of Somma-Vesuvius and its impact on both ancient and contemporary societies. Millions of people currently live in the volcano-surrounding areas that, despite the recurrence of volcanic eruptions of variable magnitude and eruptive dynamics, have been populated for millennia. In this study, we performed whole rocks and minerals chemical and isotopic (Sr and Nd) analyses and investigated the compositional zoning pattern in clinopyroxene crystals of selected eruptive units of the Pompeii eruption, in order to gather information on the architecture of the magmatic feeding system and on the magmatic processes preceding such a Plinian event. Representative samples of the “white” and “grey” pumice have been analysed for major and trace elements and Sr-isotopic composition. In detail, we performed a chemical characterization of clinopyroxene zoning pattern by acquiring major elements concentration (Si, Ti, Al, Fe, Mg, Mn, Ca, Na) along core-to-rim profiles in 35 clinopyroxene crystals. Clinopyroxenes are mostly diopsidic and Fe-diopsidic (Wo₅₃-45En₄₉-17Fs₃₀-6) in composition, and compositional profiles highlight normal, reverse and multiple zoning patterns, with several crystal cores being characterized by patchy zoning. The Mg# [molar Mg/(Mg+Fetot)*100] of clinopyroxene ranges between 91 and 39. Considering the Mg# variation along the core-to-rim profiles, the 63% of the analysed clinopyroxenes are normally zoned, 14% are reversely zoned while the 23% present complex zoning pattern. The huge clinopyroxene chemical variation is composed by five different compositional populations (ME0 to ME4), which can be related to distinct set of crystallization conditions (i.e., P-T-X-H₂O-melt-fO₂), each one defining a specific magmatic environment. We used clinopyroxene, whole rock and glass (melt inclusions and matrix glasses) compositions to calculate the magma temperature on the base of clinopyroxene-liquid equilibrium conditions. The calculated temperature values show a good linear correlation with the Mg# of clinopyroxene across the detected populations. The relationship among the compositional populations in the clinopyroxene zoning pattern tracks the sequential growth of crystals in different magmatic environments, reflecting crystallization at different temperatures. The diffusion modelling yields crystals residence times, at the different magmatic environments, from few months to few decades with 88% of the crystals recording less than 10 years. The knowledge of the magmatic processes and their timescales from products erupted in the recent past can provide information on the complex behaviour of the plumbing system. Over a decadal timescale, monitoring systems can detect signals resulting from the same processes recorded by crystals. This information is useful for assessing volcanic hazards and developing strategies for risk mitigation.

Optimization of Lithium diffusion modeling in plagioclase: implications for timescales assessment in open-conduit volcanoes

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Mineral phases provide valuable insights into the physical and chemical dynamics within volcanic plumbing systems, aiding in constraining the timescales of pre-eruptive processes. Plagioclase stands out as a particularly relevant mineral phase due to its versatility in diffusion chronometry. The variability of diffusion rates of various elements in plagioclase, spanning ten orders of magnitude, enables the derivation of several diffusion models, delineating processes occurring across a broad spectrum of timescales within magmatic reservoirs.

Recent studies explored the potential of diffusion modeling of fast diffusive trace elements such as Li. With its exceptionally rapid diffusion rates ($\log D = -13.0$ to -11 m² s⁻¹), Li diffusion in plagioclase can elucidate rapid processes ranging from seconds to hours, allowing to decipher pre- and syn-eruptive processes such as magma degassing and cooling, thereby capturing the final stages of magma ascent and the timescales of volatile loss in explosive eruptions, also in open conduit basaltic volcanoes.

In this study, we employ Li diffusion modeling in plagioclase crystals recovered from eruptive products of the violent explosion occurred on January 9th 2005, at Stromboli volcano (Aeolian Islands, Italy). Core-to-rim concentration profiles of Li acquired using LA-ICP-MS were fitted for Li diffusion timescales. Plagioclase crystals were cut in two halves along the c-axis: one half was mounted in epoxy exposing the [010] surface, in order to visualize and analyze the concentric layering; the second half was mounted exposing a surface parallel to the c-axis and passing through the core of the crystal. Multiple parallel slices of the latter section were repeatedly exposed, in order to collect multiple core-to-rim profiles at increasing distance steps (~100-150 μ m) from the section passing through the core.

The Li diffusion modeling was complemented by a bootstrapping method to find the optimal timescale of Li diffusion, considering a bootstrap distribution of 1000 possible time values and accounting for uncertainties related to boundary conditions and analytical errors in Li measurements.

The resulting maximum timescales (medians of bootstrap distributions) were obtained in profiles parallel to the c-axis in sections closer to the core of each crystals, and, depending upon the choice of diffusion coefficient D , ranged from 129 s to 1134 s ($D_1 = 4.5 \times 10^{-11}$ m² s⁻¹) and 803–7405 s ($D_2 = 6.7 \times 10^{-12}$ m² s⁻¹). Timescales obtained in other sections (i.e., toward crystal surfaces) parallel to c-axis, show smaller median values ranging from 52 s to 545 s (D_1) and from 357 to 3570 s (D_2), and are comparable to timescales obtained in sections parallel to [010]: 98–722 s (D_1) and 624–1734 (D_2).

We discuss the choice of appropriate plagioclase sections to derive Li diffusion timescales and all factors influencing the estimates, including the selection of the correct D and the propagation of errors arising from analytical uncertainties.

Finally, we examine the contrasting Li gradients observed in the investigated crystals, either

increasing or decreasing toward the plagioclase rim, in the context of degassing processes occurring within the shallower portion of the Stromboli plumbing system, where interactions between volatile-rich, low-porphyritic recharging magma and degassed, high-porphyritic magma occur.

Reconstructing the plumbing system structure of a K-alkaline caldera: the case of the Bracciano caldera and the eruption of the Tufo Rosso a Scorie Nere

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K-alkaline magmas can generate intermediate to large volume caldera-forming eruptions despite their low viscosity, as it is the case of the Quaternary caldera volcanoes of the Roman Magmatic Province.

Recent studies have demonstrated for the ignimbrites of Colli Albani, a quiescent caldera located south of Roma (Italy), that tephritic to phono-tephritic magma can be stored at different levels in complex and multistorey plumbing systems and rapidly assembled immediately prior to and syn-eruption.

In this study we investigate the largest caldera-forming event of the Sabatini Volcanic District (SVD), another multiple caldera system located just north of Rome, recently reappraised as long quiescent.

We present the integration of new field and petrologic data associated with the VEI6-7, 450ka Tufo Rosso a Scorie Nere ignimbrite (Black Scoria Red Tuff, RNR).

The new geological mapping of the RNR ignimbrite allows us to quantify the erupted volumes, and geochemical characterization of the glass accompanied by numerical modeling (MELTS) allows us to discuss the geometry and structure of the plumbing system leading to the RNR caldera-forming event.

Long-term precursors to large explosive eruptions of Vesuvius: evidence from the opening phase of the Avellino Plinian eruption

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Opening phases of mid-to-high intensity explosive eruptions are often related to weak transient activity, frequently consisting of phreatomagmatic explosions, and precede the dominant event by a variable time between hours and days. Opening phases are frequently recognized at the base of Plinian and sub-Plinian sequences from volcanoes all over the world (e.g.: 1815 Tambora Eruption; AD 79 Vesuvius Eruption) and they are often limited to thin proximal beds of small volume and limited dispersal, making them generally under-studied. In fact, the majority of studies mostly concentrate on the paroxysmal event of Plinian eruptions, not allowing an accurate evaluation of timing and dynamics of the processes involved in the very initial stages of magma ascent to the surface. The study of such phases of large eruptions provide a unique record of pre- and syn-eruptive processes and preserve key information on eruption triggering processes on the onset of magma ascent. Understanding these processes is essential for interpreting monitoring signals at high-risk volcanoes.

In this work, we investigate the pre- and syn-eruptive state of the magma and the eruptive dynamics at the onset of the Avellino Plinian eruption (3945 ± 10 yr BP), one of the largest explosive eruption of Mt Somma-Vesuvius. The eruptive history of Mount Somma-Vesuvius is characterized by large Plinian and sub-Plinian eruption (i.e. Avellino, and Pompei, 79 AD, eruptions) each characterized by a succession of different eruptive phases: an initial phase, followed by the dominant activity and the final phreatomagmatic event.

The products of the eruption onset are characterized by a larger heterogeneity of the juvenile material respect to the following paroxysmal phase, with the identification of at least three main components: white pumice, dense clasts, and dense blocks. Using an interdisciplinary approach with volcanological, morphological, compositional, textural, and geo-barometric investigations, we demonstrate that the large variability of products emitted reflects the remobilization and subsequent destabilization of an intrusive, semi-rigid magma body emplaced at shallow crustal levels ($\sim 3 - 4$ km of depth). Fe-Mg diffusion modelling of the band-rim boundary in clinopyroxene from blocks help to constrain timing of this shallow magma emplacement, which occurred over a maximum of about 50 years; while the last mafic recharge, triggering the eruption, has been estimated in a short period of time variable from few days to maximum ten of years.

Deciphering time scales of pre-eruptive mixing at Stromboli volcano: insights from plagioclase dissolution-reaction experiments

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Plagioclase is a widespread mineral component in basaltic magmas across all geodynamic settings. The physico-chemical (P-T-Xi) conditions of a magma primarily determine the stability field of plagioclase in silicate magmas and the composition of the An-Ab solid solution. For this reason, plagioclase is commonly used to decipher pre-eruptive conditions, whilst the diversity of textures and chemical zoning patterns of plagioclase phenocrysts can provide clues on the magmatic processes in active volcanoes. Several experimental works have constrained the stability and composition of plagioclase in hydrous basaltic systems, but only a limited number investigated the behaviour of plagioclase crystals under disequilibrium conditions. Here we present the results of time series experiments designed to constrain the time scale of plagioclase dissolution and reaction in a hydrous basaltic magma from Stromboli volcano (Italy). Experiments were performed at 1150 °C and 150 MPa, under both anhydrous and hydrous conditions (H₂O=3 wt.%) and with time varying from 30 to 240 minutes, using natural crystals separated and selected from basaltic mingled-pumices erupted during major explosions and paroxysms. The experimental strategy is based on the comparison of textural and chemical features of plagioclase phenocrysts before and after the experiment. Plagioclase dissolution and reaction occurs only at hydrous conditions and in phenocrysts initially characterized by a homogeneous (low-An) outer rim. In these crystals, an An-rich reaction zone forms at the interface with the hydrous silicate melt and increases in width with increasing experimental duration. The reaction zone is very similar in terms of texture and composition to reaction bands observed in natural phenocrysts. The experimental parametrization of the width of the reaction zone allows to quantify the time scale of dissolution-reaction processes, simply by measuring the thickness of the reaction bands of natural plagioclase phenocrysts. Specifically, in the case of Stromboli volcano, reaction bands are attributable to the periodic interaction between a deeper volatile-rich magma (lp-magma) with a degassed magma residing at shallow depths (hp-magma). By employing this methodology to reaction rims of natural plagioclase phenocrysts, it is possible to identify a characteristic time scale of 160±40 minutes for mixing events preceding the more energetic explosions examined in this study.

LA-ICP-MS analyses of trace elements in groundmass glasses as a tool for petrological monitoring of magmatic processes: the time series of Dec 2020-Feb 2022 lava fountains at Etna

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The open-vent basaltic volcanic system of Etna is characterized by periods of explosive activity of variable intensity at the four summit craters, which, in some cases, last months. In the period December 2020-February 2022, about sixty paroxysmal episodes of lava fountains occurred at the South East Crater, whose frequency largely varied throughout the period. The activity was divided into two eruptive sequences: 1) December 2020-April 2021 and 2) May 2021-February 2022, separated by 48 days of stasis. The strong impact of the erupted pyroclastic material on aviation, traffic, agriculture and human life leads us to investigate whether it is possible to predict the evolution and possibly the end of paroxysmal activity. Previous studies based on major elements, mineral compositions, and diffusion timescales, have been conducted in order to link the magma dynamics and eruptive activity, and, thanks to the sampling of most lava fountains, a near real-time petrological monitoring was addressed mostly based on the analyses of major elements in groundmass glasses [Corsaro and Miraglia, 2022]. Here for the first time, we present LA-ICP-MS trace element analyses of groundmass glasses of products from the whole 2020-2022 eruptive period. The goal of this study is to detect possible trends of magma evolution during the eruptive activity, considering that trace elements are more sensitive than the major oxides in revealing magmatic processes such as mixing and crystal fractionation. LA-ICP-MS is a complementary technique to SEM/EMP analyses, with the same procedure of sample preparation, and allows the fast acquisition of about 30 trace elements, including also the highly incompatible ones. Trace elements have been used to perform a hierarchical cluster analysis allowing the fast and accurate recognition of different types of magmas involved in each lava fountain, the detection of mafic recharges into the resident magma, as well as the involvement of magma stored in different portions of the plumbing system during the 2020-2022 paroxysmal activity. The repose time between consecutive lava fountains has been correlated with the degree of evolution of the erupted magma: longer intervals result in more differentiated compositions, while more continuous supply of deeper mafic magma induces shorter intervals. This information, associated with the geochemistry and texture of volcanic products, provides a more complete knowledge of the eruptive dynamic. We expect that the application of this methodology during a volcanic crisis might improve petrological monitoring, also providing preliminary hints on the evolution of long-lasting eruptions.

Exploring the magmatic plumbing system of the Arcuentu volcanic complex through the study of Monte Nureci intrusion (Sardinia, Italy)

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The Arcuentu Volcanic Complex (Sardinia, Italy) comprises abundant effusive rocks, and minor gabbroic products, with subduction-related chemical features, emplaced in a long-time span [30–17 Ma; Brotzu et al. 1997]. The Monte Nureci intrusion (Plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ age = 19.2 ± 0.07 Ma) consists of coarse-grained orthopyroxene bearing olivine gabbro and olivine bearing gabbro-norite composed of plagioclase, clinopyroxene, olivine, orthopyroxene and Cr-spinel, and fine-grained diorite with zoned plagioclase and pyroxene, rare alkali feldspar and quartz. The Monte Nureci intrusion is likely a magma chamber apophysis of the Arcuentu plumbing system, which was uplifted by normal faults related to the opening of the Campidano Graben. According to the typical liquid-mineral Mg# partitioning, the orthopyroxene bearing olivine gabbro is composed of mineral phases that were in equilibrium with a melt of basalt/ basaltic andesite composition. These crystals represent the accumulated minerals fractionated by the Arcuentu magmas with basaltic andesite composition during evolution in open system conditions, as testified by major oxides mass balance calculations and Assimilation + Fractional Crystallization modeling. Indeed, the chemical composition of the Monte Nureci mineral phases, bulk rock chemical and isotopic composition ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70881\text{--}0.70958$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512265\text{--}0.512283$) match those of the Arcuentu basaltic andesites.

The slight differences in Sr-Nd isotopes of the intrusive rocks may indicate different events of magma refill in the ephemeral magma chamber by variably contaminated basaltic andesite magmas. The coarse grained cumulates could represent the outer portion of the apophysis, where minerals accumulated and remained isolated by the evolving magma. Conversely, the diorite, which has no volcanic equivalent in the Arcuentu sequence, could represent the inner portion of the reservoir where minerals crystallized continuing to interact with the evolving magma, as testified by the normal zoning in the plagioclase. Indeed, it is composed of minerals fractionated by more variable and evolved magma.

Exploring microstructure and petrophysical properties of porous volcanic rocks through 3D multiscale and super-resolution imaging

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Digital rock physics offers powerful perspectives to investigate Earth materials in 3D and non-destructively. However, it has been poorly applied to porous volcanic rocks due to their challenging microstructures, although they are studied for numerous volcanological, geothermal and engineering applications. Their rapid origin, in fact, leads to complex textures, where pores with different sizes and shapes are hosted within the matrix, and records valuable information about the mechanisms and timescale of magma ascent and tephra deposition, as well as on the industrial exploitability of the rocks. We propose a framework to optimize their investigation and face innovative 3D/4D imaging challenges. A 3D multiscale study of a microporous tuff was performed through X-ray microtomography and image-based simulations, finding that accurate characterizations of microstructure and petrophysical properties require high-resolution scans. However, high-resolution imaging of large samples may need long times and hard X-rays, covering small rock volumes. To deal with these limitations, we implemented 2D/3D convolutional neural network and generative adversarial network-based super-resolution approaches. They can improve the quality of low-resolution scans, learning mapping functions from low-resolution to high-resolution images. This is one of the first efforts to apply deep learning-based super-resolution to unconventional non-sedimentary digital rocks and real scans. Our findings suggest that these approaches, and mainly 2D U-Net and pix2pix networks trained on paired data, can strongly facilitate high-resolution imaging of large porous (volcanic) rocks. The implemented approaches will be used to conduct detailed multiscale, multimodal and multidimensional imaging of pores and crystals in volcanic rocks.

Pre-eruptive crystallization conditions preserved in zoning pattern of clinopyroxenes from the vesuvian 1631 CE sub-Plinian eruption

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One of the major goals of modern volcanology is defining the physicochemical conditions of plumbing systems and the timescales of pre-eruptive magmatic processes to ultimately assess volcanic hazard at active volcanoes. Mt. Vesuvius is one of the most active volcanoes in the world and its explosive eruptions pose high risk, since more than 700,000 people live around its slopes. The 1631 CE eruption was the most destructive sub-Plinian event of the past millennium and represent one of the reference values for the emergency plan at Mt. Vesuvius. It was a closed-conduit eruption, and this event inaugurated a new period of minor open-conduit eruptions, lasting until the 1944 CE eruption.

In this work, we aim to investigate the background story of the magma involved in this eruption through the chemical zoning in clinopyroxene crystals. Our final aim is to integrate the information obtained from the clinopyroxene zoning patterns with ongoing studies on melt and fluid inclusions, experimental petrology, numerical modeling, and historical sources. This comprehensive approach will provide new constraints on dynamics of magma(s) feeding the plumbing system before the 1631 CE eruption.

Samples were collected from selected units of the proximal stratigraphic section at Cognoli di Ottaviano (Monte Somma), less than 2 kilometers from the current Vesuvius crater. Crystals have been preliminarily characterized in terms of texture at the Field Emission Scanning Electron Microscopy (FESEM). Electron microprobe analyses were carried at the CAMPARIS centre (University of Paris La Sorbonne, France). Specifically, mineral chemistry (Si, Ti, Al, Fe, Mg, Mn, Ca, Na and Cr) has been obtained for 50 unzoned crystals, showing homogeneous core-to-rim compositions. In addition, mineral microanalysis has been performed along core-to-rim transects, varying from 40 μm to 500 μm in length, in 59 chemically zoned crystals.

Pyroxenes are all diopsidic/Fe-diopsidic in composition. The unzoned crystals show Wo53-48En46-27Fs20-6 and Mg# (molar Mg/(Mg + Fetotal) *100) between 88 and 57. The zoned crystals displaying various zoning types, such as patchy, normal, reverse, and complex (including

oscillatory) zoning, show $\text{Wo}_{52-48}\text{En}_{47-30}\text{Fs}_{17-5}$ and $\text{Mg\#}$ in between 91 and 30, with variations observed in different zones of the crystals. The characterization of zoning patterns offers insights into the set of conditions in which the crystals formed. Distinct compositional populations were identified within the zoned clinopyroxenes, each reflecting growth under a specific set of thermodynamic conditions (most importantly, P , T , $f\text{O}_2$, melt composition, H_2O activity). One of these parameters is the temperature that has been calculated through clinopyroxene-liquid thermometers, by considering equilibrium mineral-melt couples (through $\text{Fe/Mg}_{\text{KdcpX-liq}}$ from to the same eruptive phase. The relations among the different compositional populations recorded by clinopyroxene zoning patterns provides a detailed record of sequential changes occurred in the plumbing system before the eruption. Overall, the zoned clinopyroxenes from the 1631 CE eruption exhibit a wide array of compositions, indicating a multifaceted crystallization history under varying conditions from mantle environment ($\text{Mg\#} > 90$) to crustal ($\text{Mg\#} 80-50$) and sub-volcanic ($\text{Mg\#} 40-30$) reservoir(s).

Understanding eruptive dynamics of Ischia's trachytic magmas, from shallow reservoir conditions to explosive and effusive eruptions

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Ischia Island is a volcanic area that has been very active in the last 10 ka, with eruptions occurring from multiple eruptive vents mostly in the eastern part of the island. While being all relatively small volume events (most voluminous: Cretaio, 0.075 km³ DRE), all these eruptions occurred in what is currently a densely populated area. Such events were characterized by a wide range in eruption dynamics, from effusion of lava domes to violent strombolian and sub-Plinian explosive events - yet all were fed by trachytic magmas. We aim to quantify the critical parameters that control the eruptive style of Ischia. The focus will be on i) the pre-eruptive parameters and environment; and ii) the magma ascent dynamic, considering the differences inherited from different pre-eruptive states.

For this purpose, we are studying the Montagnone volcano (2.4-0.9 ka). It is one of the rare recent polygenetic cones of Ischia and was mainly built by 6 eruptions of both effusive (lava flows and a lava dome) and explosive (violent strombolian and sub-Plinian) behavior, all of very similar trachytic composition. The entire eruptive sequence of Montagnone was sampled, and juvenile fragments were prepared for textural and geochemical characterization. Preliminary results show that crystallinity (phenocrysts and microlites content) is different between explosive products and lavas. Further calculation using Crystals Size Distribution (CSD) analyses allows us to have a first estimate of crystal growth rates. Together with the study on natural samples, new calculations of volatile solubility and phase equilibrium are compared to existing literature data and allow us to better constrain our current model of Ischia's shallow reservoir zone (depth, differentiation processes, etc.). Those calculations are obtained combining rhyolite-MELTS simulations with existing literature of trachytic phase diagrams using high-T high-P experiments. Future perspectives include more detailed characterization of the sets of pre-eruptive conditions characterizing the Montagnone plumbing system, through geochemical analyses of the minerals' zoning patterns. The application of diffusion chronometry on crystals zoning patterns, together with information obtained with CSD will allow to investigate the timescales of pre- and syn-eruptive magmatic processes. Glass, melt inclusions and apatite crystals will be analyzed to obtain information about the pre-eruptive volatile contents and degassing process, that are critical to understand the eruptive dynamics. This multidisciplinary approach will allow us to elucidate magma dynamics, encompassing the processes from the accumulation of magma in shallow reservoir conditions to its explosive or effusive behaviour during the Montagnone eruption.

Machine Learning in Petrological and Volcanological Investigations: State-of-the-Art and Perspectives

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This contribution reports on the state-of-the-art and future perspectives of Machine Learning (ML) in igneous petrology and volcanology. To do this, it starts reviewing established methods mainly concerning clustering, dimensionality reduction, classification, and regression. Among these, clustering and dimensionality reduction are particularly valuable for decoding the chemical record stored in the crystal cargo of an eruption and enhancing geochemical data visualization, respectively. Classification and regression tasks find applications, for example, in tephra studies and geothermobarometry. The main core of the discussion will consist of depicting the near future of ML in petrological and volcanological applications.

I propose a future scenario where ML methods will progressively integrate and support established petrological and volcanological methods, potentially leading to a paradigm shift. In this framework, the use of multimodal data, data fusion, physics-informed neural networks, and ML-supported numerical simulations will play a significant role. Additionally, the use of ML hypotheses formulation and symbolic regression could significantly boost new findings.

In the proposed scenario, the main challenges are: a) progressively linking machine learning algorithms with the physical and thermodynamic nature of the investigated processes, b) making deep learning algorithms more transparent, as they often operate as “black boxes,” c) advancing in exploring cutting-edge tools that arise from research in Artificial Intelligence, and overall, d) initiating a collaborative effort among researchers from different disciplines in both research and teaching.

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The Shear Strain Rate effects on Crystallization Dynamics and Residual Glass Composition: Implications for the Chemical Evolution in Natural Volcanic Systems

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The crystallization processes occurring in trans-crustal magmatic systems significantly influence the rheology of magma, thereby affecting the conduit dynamics and the resulting eruptive style. Deformation fields in magma storage regions and plumbing systems strongly influence crystal nucleation and growth processes. We designed novel experiments with the aim of assessing the influence of deformation rates on crystal texture and zoning patterns, crystal nucleation and growth rates, mineral phase proportions and residual glass composition. The experiments, conducted on natural trachybasalts from Mt. Etna, were performed under controlled pressure and temperature conditions. Mineral zoning was forced by oscillating the temperature (1170 - 1130 °C) with a constant strain rate ($1s^{-1}$) using a concentric cylinder apparatus. Major element single spot analyses and elemental maps were collected with an electron probe microanalyzer (EPMA) at the University of Geneva. The obtained data were characterized using custom-built unsupervised and supervised machine learning algorithms (e.g., Hierarchical Clustering and Random Forest). The strain rate impact on nucleation, growth, and mineral phase proportions was quantitatively analysed through backscattered electron diffraction (EBSD) scans conducted at the University of Vienna. The EBSD analysis also allowed quantifying the strength of crystallographic preferred orientations (CPO), used to define the degree of deformation experienced by the crystals in different regions of the experiments. The experimental results showed that a small increase in strain rate can lead to a large increase in nucleation rate and thus in crystal number density. This process has a direct influence on the growth competition between different mineral phases, controlling their growth rates, the final proportion of mineral phases, and the composition of the residual melt. These results allowed us to quantify the impact that conduit dynamics and varying ascent rates might have on texture and chemical composition of erupted products, highlighting the need to take deformation processes into consideration to robustly link petrological variations to pre-eruptive dynamics.

Deciphering the Holocene magmatic plumbing system dynamics beneath El Hierro (Canary Islands)

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Ocean Island Basalts (OIBs) provide a unique window into the deep Earth dynamics that govern the formation of volcanic islands. A comprehensive understanding of OIB systems often requires multidisciplinary approaches, providing insights into which processes operate from source to surface along complex pathways of magma transport and storage. Investigating these processes during the Holocene allows for the characterisation of magmatic architectures and eruptive dynamics over a period sufficiently prolonged and yet close to the present day, making it representative of the current and future behaviour of volcanic areas. The Canary Archipelago (NW African coast) represents an exceptional natural laboratory for these purposes. Here, we provide an integrated approach to the dynamics of the magmatic plumbing system beneath El Hierro, which is the westernmost and youngest island of the Canaries. Through the investigation of 59 Holocene subaerial eruptions, we provide a detailed petrological and geochemical characterisation of volcanic products ranging from felsic pyroclasts to ankaramitic lavas with crystal contents up to 51%. Results are integrated within fractional crystallisation modelling and mass balance calculations, revealing different degrees of crystal accumulation and melt extraction on magmas with MgO contents above 10 wt%. These results are combined with recently updated geological mapping, as well as with new geochronological data supported by stratigraphic and geomorphological constraints. This holistic approach allows us to illustrate the spatial and temporal distributions of the subaerial volcanism at El Hierro, as well as their implications for magmatic evolution and plumbing architecture. Our findings shed light on the complex magmatic processes that have governed the evolution of El Hierro's volcanic system during the Holocene, with broader implications for the study of OIB magmatism in similar settings worldwide.

S12 - REVEALING THE DYNAMICS OF OPEN-VENT VOLCANIC EXPLOSIVE ACTIVITY: A COMPREHENSIVE JOURNEY FROM MAGMA ASCENT TO ASH GENERATION

Conveners:

Flora Giudicepietro, Sonia Calvari, Lucia Pappalardo, Elena Cubellis

Relationship between low-frequency volcano seismicity and gas flow at Mt. Etna (Italy) in the period January 2004-December 2015

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The link between low-frequency volcano seismicity and crater outgassing is a key tool for the understanding of eruptive mechanism and activity. Here, we explore the strength between Mt. Etna's activity, seismic volcanic parameters (low-frequency seismo-volcanic transients and volcanic tremor) and bulk plume SO₂ flux in the period between January 2004 and December 2015. By statistically processing the signals we retrieved a parameter named pressurisation index. Results show correlations and anti-correlation between the parameters and waxing-waning cycles of the Pi index, together with changes in eruptive activity. Change in the relative relationship between parameters and eruptive activity, might reflect a pressurization of the shallowest portion of the volcanic conduit, governed by the balance between the permeability/viscosity of the apical feeding system and the gas/magma flow rate from depths. The Pi index appears a promising tool for understanding the dynamic of eruptive activity at Mt. Etna and generally at basaltic volcanoes, with implications for monitoring and early warning systems.

The effects of pyroclastic flows on plume dispersal during mafic eruptions

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Paroxysmal mafic explosive eruptions are capable of producing up to several kilometres high column and disperse lapilli and ash over long distances. In this work, we analyse the lava fountain occurred at Etna (Italy) on 10 February 2022, which was associated with a partial collapse of the cone and with the formation of hot, dense flows that run beyond the cone slopes to hundreds of metres to a few kilometres over the summit area. We quantify for the first time, with the support of cameras, radar and satellites, if and how the cone collapse affected the dynamics of the eruption column and the associated tephra fallout deposit. In fact, the interaction between the eruptive plume and the cone collapse has never been studied before. During this fountain, metric-sized bombs fell within a few kilometres from the summit crater; the volcanic plume reached the north coast of Sicily, about 60 km from the vent. The associated tephra deposit was sampled from 1 to 23 kilometres from the vent. We found that the total mass and mass eruption rate was comparable to the largest lava fountain events of Etna of the last decade. Moreover, the presence of the hot flow has increased the column height by less than 2 km, and modified the total grain-size distribution which is slightly bi-modal. We retain that our paper can help better understand the contribution of small intensity pyroclastic flows on the dynamics of eruption columns and on the process of tephra dispersal and fallout.

Ground Deformation Modeling of Conduit Flow Dynamics: Etna Lava Fountains Case Study

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At Etna in recent decades, sequences of dozens of lava fountain events occurred in a short time period during 2011-2013 (44 events) and during 2020-2023 (more than 60 events). This paroxysmal activity has often been dramatic because of the formation of a huge eruptive column that, depending on wind intensity and direction, produces ash plume dispersal and fall-out deposits with consequent damages in the surrounding area. Despite this impressive behavior, at Etna volcano, due to its open conduit characteristic, a typical lava fountain produces small deformation (<1 microstrain), difficult to detect with classic geodetic measurements. Instead high-precision borehole dilatometers revealed to be an effective technique to monitor lava fountains since they measure the strain with a very high resolution (order of 10^{-10}). The ultra-small strain variations detected by the borehole dilatometers network made it possible to define the durations of the events, their size and the relative strain-rate accompanying the magma source decompression feeding the lava fountain. Moreover, the modeling of the cumulative strain variations during the fountaining event inferred the position of the depressurizing source at 0 km a.s.l. (e.g. Bonaccorso et al., 2013; 2021). Furthermore, the strain signals allowed us to distinguish 4 main clusters of lava fountains (Carleo et al. 2023), and also to estimate the total erupted volume associated with each fountain event (Bonaccorso et al., 2023).

Nevertheless, despite of all these results, it is still missing a simplified but robust fluidynamics modeling able to analyze the coupled behavior of the feeding source and the properties of the conduit flow during the evolution of these events.

In this contribution we present a model able to describe the withdrawal of magma contained in the source, through a vertical conduit. We adopt the model of Macedonio et al., 2005 and Costa et al., 2009, which accounts for gas exsolution, bubble formation and magma fragmentation associated to the pressure decrease along the conduit. The source is approximated by spherical, ellipsoidal, or cylindrical geometry, and the conduit is assumed cylindrical. Both in the reservoir and inside the conduit, we assume a quasi steady-state (slowly varying) homogeneous flow at constant temperature. The model furnishes the temporal evolution of the pressure distribution in the source and along the conduit, responsible of the signal recorded by the dilatometers.

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Cone collapse triggered by paroxysmal eruptions at Etna: impacts and dynamics of the associated flows

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Cinder cones are rapidly growing volcano edifices; their shapes arise from the accumulation of scoria, spatter and lava from granular flow and is controlled by the repose angle of scoria/cinder. Their gravitational instability is enhanced by dike intrusion, vent shifting and lava outpouring, causing formation of unconformities and layers with variable mechanical properties. Cone stability is often difficult to assess, and collapse events are hard to forecast. We are presenting a detailed reconstruction of the 10 and 21 February 2022 SEC collapses at Mt. Etna (Italy) associated with paroxysmal eruptions, combining visual, thermal and both UAS and satellite data with field surveys. Field surveys were done from a few days after the event to observe the flow and scar structures and in several campaigns in April, May, June, September 2022 for sedimentological and stratigraphic studies. Trenches or exposures were analyzed in 44 locations. Some trenches were excavated in the snowpack covering the deposit.

On February 10, the paroxysmal explosion triggered a series of 9 collapses generating flows running to the W and S, forming 2 deposit lobes, with max thickness of several m in the proximal areas and 0.5 to 1 m in distal areas, and runout of 1.5 and 1 km, respectively. The flows had high temperature and heavily interacted with the snowpack. On February 21, during another lava fountain episode, further collapses deposited scoria and cone agglutinates in the same areas affected by the previous collapse. In this case, single collapse events were difficult to recognize with surveillance cameras and no clear chronology of these events was recovered. Three lobes were generated by the flows, with runouts ranging from 0.9 to 2 km and average thickness ranging from 0.3 to a few m. This study reveals the complexity of collapse dynamics, highlighting the necessity of more accurate studies for an accurate hazard assessment.

Long-term thermal emissions at open-vent volcanoes: insights on activity transition from the MIROVA database

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Along with magmatic-related products, open-vent volcanoes continuously emit a large amount of heat that can be measured from space. In this work, we used the global archive of thermal anomalies detected by the MIROVA system to characterize the open-vent activity that occurred at tens of persistently active volcanoes. The combination of data from multiple IR sensors (MODIS, VIIRS, MSI, OLI) reveals that open-vent volcanism is characterized by two distinct thermal regimes: (i) a degassing regime, where the heat emission is focused at the vent(s) and sourced by a convective/degassing magma column and (ii) an effusive regime, where the thermal flux is mostly sourced by the outpouring of lava flow(s)/dome(s), possibly accompanied by explosions. Often the two regimes alternate over time, causing variable patterns of radiated energy that reflect repeated transitions between periods dominated by magma convection and periods dominated by lava effusion/extrusion. In some cases, these transitions are also associated with explosive activity that can precede or follow the effusive one. We will show the thermal trends of some volcanoes which over the last two decades have shown repeated transitions of this type (Etna, Stromboli, Fuego, Bezymianny). We suggest satellite thermal analysis is a useful tool for tracking spatiotemporal changes in thermal emissions that may anticipate, accompany or follow the transition from the steady-state to more energetic eruptions.

Analysis of seismic signals preceding the overflows at Stromboli volcano

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In the last few decades, Stromboli volcano, located in the Aeolian Islands (Southern Italy), has undergone changes in its activity, exhibiting an increase in eruptive behavior and giving rise to hazardous phenomena such as explosive paroxysms, lava overflows, crater collapses, and pyroclastic density currents (PDCs). The primary objective of this research is to identify seismic signals that indicate the transition from Strombolian to effusive eruptive activity and possible processes affecting the volcano's crater rim, such as crater collapses, with or without generation of pyroclastic density currents (PDCs), and consequent lava overflows.

This research employed various methodologies, including seismic data collected from the East-West component of the STRA station, chosen for the analysis of crater activity and associated phenomena. We carried out the spectral analysis of the seismic signals recorded before some selected overflow events to define the frequency bands of greatest interest, i.e. those most characteristic of the pre-effusive phase. Then, we calculated the Real-time Seismic Amplitude Measurement (RSAM) time series computed using a 30-second sliding window in different frequency bands. The first band, ranging from 1 to 7 Hz, indicates spattering, summit tremors, and ordinary explosive activity at the craters, while frequencies above 10 Hz are particularly responsive to block rolling on the Sciara del Fuoco slope, highlighting block detachment from the lava flow front and possible landslides. We utilized the Obspy system to filter the signal.

The results of seismic data analysis, supported by thermal camera data analysis, ground-based Interferometric Synthetic Aperture Radar (InSAR) measurements of displacement, and strainmeter measurements demonstrate how the selected overflows are preceded by precursor signals from 40 to 58 minutes and up to one day before the events. These findings enhance our understanding of the mechanisms that prepare the short effusive phases, here called overflows, and can help in assessing the risk posed by processes such as crater collapses and consequent pyroclastic density currents.

Volcanological, Geochemical and Textural analysis of Mount Vesuvius 1906 eruption

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Mount Vesuvius is one of the most famous volcanoes in the world. It has been the cradle where the seed of “volcanology” as a science has been planted ever since its eruption in 79 AD that destroyed the Roman cities of Pompeii, Herculaneum, Oplontis and Stabiae. Since then, Vesuvius erupted many times until the last eruption in March 1944 making its study even more compelling as more and more people became affected by its activity. Today, about 700,000 people are potentially exposed to a resume of activity underscoring Vesuvius’s status as one of the world’s most hazardous volcanoes.

The eruption of Mount Vesuvius of April 1906 is regarded as a classic in volcanology as it represents a prime example of how unpredictable and variable the behavior of an open-conduit volcano can be.

The eruption began on April 4 with the extrusion of lava flows from newly formed and reactivated lateral vents. On the April 7 the explosive activity at the crater intensified and at same time some greatly felt earthquakes occurred. The acme was on April 8 when the paroxysmal event generated an eruptive column that peaked at 13 km of height, according to Perret’s reconstruction (but it may be overestimated and should be closer to ~5.5-6 km of height). The column mostly directed NE towards the towns of Ottaviano and San Giuseppe Vesuviano where the tephra fallout caused severe damage and most of the deaths (~216 people). The later phases of the explosive activity were characterized by an evident hydromagmatic component, which is typical of the so-called “final eruptions” of Mount Vesuvius. This component became prevalent during the final phase as testified by the presence, in the tephra deposits, of accretionary lapilli, hydrated surfaces and various salts; also, lithic fraction prevailed on the very minor juvenile material. The eruption officially ended on April 21 when the crater became completely obstructed and the only visible phenomenon were the fumaroles that showed a change in chemical composition. During the following days and up to May 17-18, the pyroclastic material was remobilized forming lahars that invaded Ottaviano, San Sebastiano al Vesuvio, Pollena Trocchia and Cercola continuing to cause damage to the already affected Vesuvian towns.

This research aims at demonstrating how much Vesuvius can still be a laboratory for all volcanologists and how much there is still to learn about its eruptions by: i) collecting and summarizing the previous knowledge provided by the scientific literature both contemporary and subsequent to the eruption. In fact, Raffaele Vittorio Matteucci and Giuseppe Mercalli, directors at Vesuvius Observatory between 1903/1909 and 1911/1914 respectively, followed the eruption and collected ash accumulated on the terrace of the historical building of the Observatory. In particular, Matteucci collected systematically ash during the various eruptive stages and described step-by-step volcanic activity in daily bulletins that he sent to the authorities for risk assessment and defense of people that lived around volcano; ii) providing new chemical, isotopical and textural analysis on samples both collected at the time of the eruption,

currently part of the Osservatorio Vesuviano Museum collection, and recently sampled in an outcrop close to the town of Ottaviano; iii) using geothermobarometry to estimate both the temperature and depth at which the magma bodies, that fueled the eruption, were stationing; iv) reconstructing the eruption dynamic and provide an interpretative model of the magmatic system that alimented it; v) finding hints and patterns in the chemical, isotopical and textural data that could provide insights on processes and timescale of magma ascent in volcanic conduit i.e degassing, magma mixing/mingling, crystallization, that could have caused changes into the eruption dynamic; vi) hypothesizing on how a paroxysm actually occurs and works.

Vesuvius, 1631-1944: Beginning and end of a cycle of persistent activity

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Vesuvius had a period of persistent activity between 1631 and 1944 with long periods of lava emission interspersed with violent Strombolian eruptions.

The period began after a rest of several centuries with a sub-plinian eruption that caused a collapse of the central cone and the formation of a summit caldera. Subsequent activity resumed in 1638 with short explosive phases and emissions of lava flows that slowly filled the caldera. The first emission of lava outside the cone occurred in 1694. From this date onwards, periods of slow emission of lava alternated with violent Strombolian episodes which caused partial collapse of the cone. Within this period, three lateral eruptions should be noted in 1760, 1794 and 1861. The one in 1794 coincided with an Apennine earthquake and caused a new relevant collapse of the cone. Over time, a progressive decrease in explosive events and prolonged phases of reconstruction of the volcano were observed, with slow emissions of lava that sealed the fractures and subterminal vents and permitted the growth of the cone at the magma buoyancy height.

After the violent eruption of 1906, the newly formed summit caldera was slowly filled with lava from 1913 until 1944 when a violent strombolian eruption marked the end of the period of persistent activity.

The violent strombolian eruptions were characterized by an initial high-eruption rate lava flow followed by lava fountains and sustained eruption plume. The lava were crystal rich with little water content. The explosive products were aphyric and water rich. We infer that the lavas crystallized in the upper conduit and were later driven out by water rich magma batches ascending with high velocity.

A progressive filling of the ascent system occurred as magma resided and crystalized at shallow depth for prolonged time. The process became increasingly efficient because of the little buoyancy of the water depleted magma. The last eruptions were no more able to clear the ascent system and the last partial collapse of the vent, occurred in 1944, finally sealed the system.

We infer that a critical role in controlling the style of activity of the volcano is played by its height. Slow effusive eruptions are not allowed when the critical magma buoyancy level is attained and only water rich magma can ascend at the surface.

Vesuvius in the 16th century

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Current reconstructions of the eruptive history of Vesuvius suggest that the volcano was quiescent for a prolonged period from 1139 to 1631. This extended dormancy has often been linked to the high explosivity of the 1631 eruption, which had a Volcanic Explosivity Index (VEI) of 4. Some models attribute the severity of this eruption to the long preceding period of rest. However, historical records mention volcanic activity in 1306, 1500, and 1568, but these accounts have generally been considered unreliable. Recently, a new source has been found indicating an eruption in 1570, though this evidence is considered not yet sufficient to conclusively confirm Vesuvius' activity during the sixteenth century. Nevertheless, artistic evidence and literary references suggest that Vesuvius may not have been completely inactive during this time. One significant piece of evidence is a fresco from the Church of San Gennaro dei Poveri, dated 1525-1530, which depicts San Gennaro protecting Naples from an erupting Vesuvius. The depiction of the volcano in the background is highly realistic, resembling scientific illustrations rather than imaginative artwork. This fresco shows a striking resemblance to the detailed representations collected by Luigi Palmieri, a historic director of the Osservatorio Vesuviano and a pioneer in modern volcanology. Specifically, the fresco is similar to the depiction of the 1794 eruption found in Palmieri's book "Il Vesuvio e la sua storia."

Another piece of artistic evidence is the Fontana della Spinacorona, renovated in the early 16th century. This fountain portrays the Siren extinguishing Vesuvius' eruption, with lava flows represented as curls of lava on the volcano's slopes. Additionally, there are historical accounts, such as one by Ambrogio da Nola, describing an eruption in 1500. Although some scholars have dismissed this report due to claims that Ambrogio da Nola was not in Nola at the time, it does not preclude the possibility that he documented events based on other sources. Given Ambrogio da Nola's reputation as a reliable scholar, this testimony warrants reconsideration.

Further support comes from a re-examination of an ancient letter from which the famous phrase referring to Naples "A Paradise inhabited by Devils" derives. The expression "a Paradise inhabited by Devils" was taken up and made his own first by Goethe and then by Benedetto Croce. A similar expression is contained in a letter written by Berardino Daniello, on 22 March 1539. The author wrote that Naples was such a beautiful city that other cities could be envious of such beauty. Then, Nature, to prevent other cities from sending their ambassadors to protest with her for having given so many gifts to Naples, decided to give this earthly Paradise to the Devils to live in. The letter praises Naples extensively and never refers in a negative sense to its inhabitants. Instead, it suggests that Naples, blessed with natural beauty, was given by Nature to "Devils" to maintain balance. Knowing the eruptive history of the Neapolitan volcanoes, it seems clear that Berardino Daniello, with the term "Devils" was referring to volcanoes. In fact, in 1538, about five months before he wrote the letter, there had been the eruption of Monte Nuovo (29 September - 6 October 1538) in Campi Flegrei, and in the following years the volcanic phenomena continued,

accompanied by numerous earthquakes, often felt even in Naples. Furthermore, if we hypothesize that Vesuvius was not in a state of total quiescence, but that it probably showed the typical activity of open conduit volcanoes, for example Strombolian activity, it seems plausible that Daniello was referring to the volcanoes of the region.

Considering these artistic and literary clues, along with the historical context, it appears likely that Vesuvius was not entirely dormant during the sixteenth century. Instead, it may have exhibited signs of activity typical of open conduit volcanoes, such as Strombolian activity. This reinterpretation provides a more nuanced understanding of Vesuvius' behavior during this period and underscores the importance of integrating diverse sources of evidence in reconstructing volcanic histories.

Unsupervised clustering of seismic events recorded at Campi Flegrei caldera during the current unrest

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The current phase of unrest of Campi Flegrei caldera is characterized by a general increase in seismicity, ground uplift and geochemical activity. Given the intensification in the number and magnitude of earthquakes, in this work we focus on the study of Campi Flegrei earthquakes in order to identify the existence of possible families of events. The dataset we considered consists of approximately 100 earthquakes recorded at a seismic station located in the Solfatara area, which is the zone most affected by seismic activity. The data are acquired at a sampling frequency of 100 Hz and transmitted to the Osservatorio Vesuviano, INGV Naples.

The technique used to cluster the data is the Self-Organizing Map (SOM). The SOM (Kohonen et al., 1996) is a particular class of unsupervised artificial neural network (ANN) widely used for clustering and exploratory data analysis. The main advantages of SOM are that it does not require any a-priori assumptions about the data structure, is able of detecting hidden structures in the data, and allows easy visualization and interpretation of the results. Before applying the SOM, we carried out a feature extraction phase on the data. This phase is important to identify the distinctive characteristics of the seismic signals and to obtain an alternative representation of them by removing redundant information. The crucial aspect is to choose the most appropriate characteristics for the task to be carried out. In our case we used the Linear Predictive Coding (LPC) technique (Makhoul, 1975) to extract information in the frequency domain. LPC is advantageous because it returns a more compact representation of the information on the frequency content of the signals through a combination of prediction coefficients. The SOM clustering results reveal clusters of events that could characterize different aspects of the seismic activity of the Campi Flegrei.

Generation of deposit-derived pyroclastic density currents by the failure of the crater rim on Stromboli volcano

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The sliding of incandescent material deposited during eruptive activity can lead to the formation of deposit-derived pyroclastic density currents (PDCs). These hot avalanches have the potential to travel considerable distances, from hundreds of metres to several kilometres from their source, while maintaining extremely high temperatures, posing a catastrophic hazard to areas surrounding steep-slope volcanoes. At Stromboli, the occurrence of deposit-derived PDCs is often associated with crater rim failure, generally associated with lava emission or, less commonly, with powerful explosions. Crater rim failure has occurred at the onset of flank eruptions and during the early stages of lava overflows from the crater terrace. Failures usually resulted in the remobilisation of 10^3 to 10^5 m³ of material, which propagated as PDCs along the NW slope of the volcano and reached the sea in a few tens of seconds.

Detailed analysis of various monitoring data, including video surveillance, seismic activity and ground deformation, together with remote sensing, has improved our understanding of recent crater rim collapses at Stromboli volcano. Stability assessments have investigated factors leading to collapses, including increased explosive activity preceding collapses. This phase was marked by rising Real-time Seismic Amplitude Measurement (RSAM) within the 1-7 Hz frequency band and volcano summit displacement rate. Effusion events associated with crater rim failure were preceded by significant spattering activity and a shift in deformation patterns from inflation to slope motion, indicating material destabilisation just prior to collapse.

These signals were interpreted as follows: first, an ascent of the magma column occurred due to increased magma vesicularity, leading to an increase in deformation. This was followed by gas release when the percolation threshold was reached. This release was manifested as increased explosive activity, particularly spattering, and a corresponding increase in RSAM. The resulting explosive degassing led to magma densification, which increased the thrust on the conduit walls due to the increased magmastatic pressure. This was evidenced by a marked increase in the magnitude and geometry of summit displacements in the hours prior to collapse. These phases thus foreshadowed crater rim failure and often preceded or coincided with lava overflow phases. Stability analysis suggests that crater rims are close to a tipping point, requiring minimal force for destabilisation. Increased magmastatic pressure from rising magma, leading to densification, requires additional overpressure for destabilisation, associated with the ascent of more gas-rich magma batches. This is consistent with observed phenomena.

A similar mechanism may explain phenomena in other volcanoes. A multi-parametric, multi-platform approach is essential to understand such complex events. The integration of seismic, deformation and remote sensing data helps to identify the phases leading to crater rim failure and subsequent pyroclastic density currents (PDCs).

Characterization of pyroclast in-flight fragmentation at mafic volcanoes

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Magma fragmentation is usually considered the main process determining the grain size distribution of pyroclastic deposits. While fragmentation is mostly assumed to occur within the volcanic conduit, there is growing evidence that, especially in mafic magmas, it continues also after pyroclast ejection from the vent, both in-flight and upon impact. Why and how much in-flight fragmentation occurs is still poorly known, but fragmentation remains to be one of the most elusive parameters to measure in the field. Here, we document extensive in-flight fragmentation that occurred during (i,ii) the fountaining and spattering activity of the Tajogaite eruption (September 19, 2021 – December 13, 2023) of the Cumbre Vieja volcano (Canary Islands, Spain), (iii) the February 2021 fountaining activity of the New South-East Crater of Mount Etna (Sicily, Italy), and (iv) ordinary Strombolian activity of Stromboli volcano (Aeolian Islands, Italy). High-speed and high-resolution videos were acquired during the eruptions using Optronis (1280 x 1024 pixels, 500 to 502 Frame Per Seconds (FPS)), DS-CAM-60 (1088 x 1016 pixels, 205 FPS) and Sony (3840 x 2160, 24 FPS) cameras, enabling detailed observations of pyroclast dynamics. For each case study, we analyzed 8 to 10 seconds of the videos to characterize in-flight fragmentation. The processing involved both Optical Flow Matlab© routines and manual tracking techniques. Our analysis revealed diverse fragmentation processes, including four distinct modes of in-flight fragmentation: (i) inflating fragmentation: large pyroclasts fragment upon expansion, with the darker exterior due to cooling during transit; (ii) deformation fragmentation: pyroclasts exhibit visible deformation prior to fragmentation, including stretching, bending, and rotation; (iii) detaching fragmentation: pyroclasts break without visible deformation, likely due to internal instability; (iv) collision fragmentation: fragmentation occurs upon collision between differently sized pyroclasts traveling at different velocities. The total of the pyroclasts fragmented represents 6% to 32% between all the four videos. Deformation dominated the Tajogaite fountaining (80%) and the Strombolian cases (65%), while collision prevailed in the Tajogaite spattering (72.5%) and the Etna fountaining (46.4%). Within the deformation mode, stretching slightly dominates but, again, there is quite a variability between the different cases. Detachment fragmentation is largely subordinate but still present in all cases, and inflating is rare, with a maximum of 6.6% on the video of Tajogaite fountaining activity. Our findings provide insights into the dynamic processes governing volcanic eruptions and highlight the importance of considering in-flight fragmentation in hazard assessments for mafic magmas.

Pyroclastic Density Currents at Mount Etna: investigating triggering mechanisms and emplacement dynamics

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Pyroclastic Density Currents (PDCs) represent one of the most dangerous sources of hazards produced by volcanic activity. Typically, these types of phenomena are associated with volcanic systems that emit particularly evolved magmas. However, in the recent past some open-conduit volcanoes erupting magmas with basaltic composition have also been capable of producing PDCs. Among them, the most striking case is Mount Etna (Italy), where several dozens of small PDCs have occurred over the past 40 years from the summit craters, with triggering mechanisms sometimes differing from those involving closed-conduit systems.

In particular, some of the most important ones occurred on November 16, 2006, February 11, 2014, December 13-14, 2020, and February 10, 2022.

Most of the PDCs observed on Etna have occurred at the South East Crater (SEC), the most active of Etna's four summit craters, which has grown several hundred meters in recent years, making this cone particularly unstable. Although these kinds of phenomena do not represent a danger to those who live on the slopes of the volcano, they can instead be a source of hazard to the large number of tourists who visit the summit area of Etna, especially on the high southern slope of the volcano, which is the preferred zone for guides to bring tourists to admire the summit area. In the following study, we analyze two of the most significant PDCs occurred at the SEC, on November 16, 2006 and February 10, 2022, respectively, which were triggered by two different mechanisms, run-out distances and deposits.

Specifically, the November 16, 2006 PDC occurred during an eruptive episode characterized by mild Strombolian and effusive activity at the SEC. Some authors have proposed several mechanisms for triggering this PDC, such as the interaction of intruding magma with wet rocks on the flanks of the cone [Behncke et al., 2008], a flank collapse affecting the unstable SE slope of SEC [Norini et al., 2009] and the failure of the SE flank of the SEC as a consequence of fast magma decompression and fracture opening [Ferlito et al., 2010].

In contrast, the PDC of February 10, 2022 occurred during a violent lava fountaining episode at the SEC, due to the collapse of the southwestern flank of the cone triggered by the formation of an eruptive fracture.

We then analyzed the representative samples of the two deposits by Scanning Electron Microscopy (SEM), to compare them and study the morphological characteristics of the constituting clasts. This type of approach will be essential to carry out further laboratory experiments to model the behavior of PDCs produced by open-conduit volcanoes, in order to improve knowledge of these phenomena, which is still underestimated on volcanoes of basaltic composition, such as Etna. In addition, this work is the first step toward a more detailed hazard assessment of PDCs, contributing to the final goal of volcanic risk reduction especially in areas densely frequented by tourists.

Understanding the dynamics of explosive volcanoes by investigating volcanic thermal emissions using MODIS Land Surface Temperature data

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Understanding the dynamics of open-vent volcanic explosive activity in populated areas is crucial for volcano observatories in their efforts to mitigate associated risks. From this perspective, the emission of thermal energy from volcanic systems plays a crucial role in monitoring volcanic activity. Anomalies in land surface temperature often indicate magma movement beneath the Earth's surface, which can lead to volcanic eruptions or other hazardous events. For example, an increase in surface temperature, as indicated by thermal anomalies, may suggest magma ascent toward the volcano's summit, potentially leading to an eruption. Furthermore, the persistence or intensification of thermal anomalies over time can signify sustained volcanic activity, thereby increasing the likelihood of an imminent eruption. Therefore, accurate detection and monitoring of thermal anomalies are essential for understanding the long-term dynamics and unrest of volcanic systems, typically complemented by other geophysical parameters, which may prompt alert level changes. Monitoring high-temperature volcanic features allow us to enhance our understanding of volcanic phenomena and our ability to identify renewed volcanic activity, forecast eruptions, and assess hazards. Thermal Infrared (TIR) satellite remote sensing data holds promise in providing crucial insights into the thermal behavior of active volcanoes worldwide, facilitating the assessment of volcanic activity levels and identifying significant changes during periods of volcano unrest.

This work aims to investigate volcanic thermal emissions to better understand volcanic explosive activity and classify explosive intensity for use during eruptions, using MODIS Land Surface Temperature (LST) data. We employ an unsupervised Machine Learning (ML) model for anomaly detection, capable of identifying patterns in MODIS Land Surface Temperature (LST) data and clustering detections based on data similarity. The ML model reconstructs error time series to automatically detect significant changes without external bias and a priori choices. The anomaly detection process is data-driven. We specifically employ an Isolation Forest (IF) machine learning algorithm, an unsupervised decision-tree-based algorithm originally designed for outlier detection in tabular data. We exploit the capability of the Isolation Forest algorithm to recognize anomalies to distinguish the activity levels. Our determination of activity level considers not only differences in intensity but also the challenge of isolating sample points within the time series using the Isolation Forest technique. By utilizing IF score parameters, we successfully classify the thermal activity level, thereby associating the thermal state of the volcano with the level of concern regarding ongoing volcanic activity. We have developed a framework on Google Colaboratory, commonly referred to as Colab, aimed at automating the processing of MODIS LST datasets. This framework enables the extraction of detected anomalies and various activity levels, thereby enabling global monitoring of volcanic thermal activity. The incorporation of volcanoes with diverse explosive activity and characteristics in our analysis showcases the versatility and applicability of our proposed approach on a global scale.

Quantifying volcanic SO₂ emissions with Sentinel-5 TROPOMI, Artificial Intelligence and GEE

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Identifying changes on volcano unrest condition and tracking the evolution of eruptive activity are fundamental for volcanic surveillance and monitoring. Under this perspective, magmatic gases play a key role; therefore, monitoring changes in sulphur dioxide (SO₂) emissions amounts is essential. New technologies have improved the ability to identify SO₂ emissions in volcanos worldwide through satellite remote sensing, thanks to the advent of new sensors with higher spatial resolution and sensitivity. However, traditional fixed-threshold algorithms fail to automatically discriminate volcanic SO₂ emissions from non-volcanic sources. In response to this challenge, we have developed a Random Forest (RF) model, a supervised Machine Learning (ML) algorithm, to identify and quantify volcanic SO₂ emissions in near real time. The proposed ML approach, fully developed in Google Earth Engine (GEE), was applied to data acquired from the TROPOspheric Monitoring Instrument (TROPOMI) aboard the Copernicus Sentinel-5 Precursor (S5P) satellite to automatically retrieve daily volcanic SO₂ plumes. Moreover, we verified its performance by comparing it with a state-of-the-art tool, i.e., the Radius classifier. Finally, to assess the versatility of the RF model, we generalized the SO₂ plume classification across various satellite images. We tested it on different volcanoes characterized by varying degassing activity with lower emission rate of SO₂, considering different concentrations and plume geometries. Our findings indicate that the RF model approach has the potential to be used for automatically identifying and quantifying the SO₂ plumes emitted by different volcanoes thus allowing to investigate volcanic SO₂ emission time series reflecting magma dynamics.

S13 - LINKING SURFACE OBSERVABLES TO SUB-VOLCANIC PLUMBING SYSTEMS AT ACTIVE CALDERAS

Conveners:

Lucia Pappalardo, Stefano Caliro, Anna Tramelli, Elisa Trasatti

The dynamics of bradiseism: the recent unrest of Campi Flegrei, 1950-2024

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The geological history of the Campi Flegrei shows that the caldera's ground movements have been active for the last 10,000 years. This phenomenon, known as "resurgence", is not new and has also affected the bottom of large calderas in North America.

Among the various hypotheses that are put forward to explain the resurgence, there is that of the low-depth intrusion of magmatic masses that deform the layers of rock above.

A notable uplift of over ten meters, which lasted until a few days before the eruption, was observed in the century preceding the eruption of Monte Nuovo in 1538.

Campi Flegrei experienced a renewed phase of unrest after more than 370 years since 1582. Such activity has been interpreted either due to magmatic intrusion or pressurization of the local aquifer. We favor the earlier interpretation as the uplift and the seismic activity follow a pattern like those that led to the eruption of Monte Nuovo and the last phase of activity of Epoch 3.

This pattern is interpreted as the ascent at shallow depth of magma batches that intrude as sill like bodies within the upper layer of low-density rocks that act as a density barrier to their ascent. The earthquakes recorded in the last two years define the margins of the resurgent block and the fracture zones where the magma can rise again. Their focal mechanisms also confirm a complex uplift dynamic, identifying a progressive raising of the northern part of the block with the possible opening of fractures that can favor the rise of the magma.

Recent changes in the spatial distribution of earthquakes along with differential displacements suggest a possible accumulation of stress in the Solfatara area.

The current constantly evolving dynamics make it difficult to make long-term predictions on the outcome of the current crisis.

Investigating the ongoing unrest dynamics of Campi Flegrei caldera (Italy) by mathematical analysis of geophysical monitoring data

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Since 2005, the Campi Flegrei caldera shows a slow but progressive inflation of the ground, with associated intensification of seismic activity and degassing. In this study we aim to characterize the temporal trends of geophysical data, such as deformation and seismic activity, and to explore the close relationships between them. At the time of writing (May 2024), results show the continuation of an accelerating decadal parabolic increase of vertical uplift, with an acceleration of ca. 0.7-0.8 cm/yr² (at RITE GNSS station taken as reference for the caldera behavior), and a super-exponential increase of number of earthquakes and seismic energy release. Inspection of data finds an exponential-type relationship, with an exponent increasing in time, between ground uplift and number of earthquakes. In particular, the data is well-represented by two exponential functions with increasing exponents and a transition period between 4/2020 and 9/2022. Differently, the cumulative total number of earthquakes versus the ground uplift during the unrest crisis of 1982-84 the correlation between the two geophysical variables results quasi-linear, and not exponential. Such a different relationship between deformation and seismic activity appears as further evidence of the different forcing source associated to the 1982-84 crisis with respect to the present one. Oscillations of various periods are also recognizable in both deformation and seismic data. The main periods of these oscillations range from approximately 2 and 5 months (shorter periods) to periods of about 1.5 and 3 years (longer periods). In recent years, there has been a trend towards a reduction in these periods (by about 10-15%). Periods of reduced seismic activity are not, therefore, necessarily indicative of major changes in the future evolution of the ongoing phenomenon. These relationships have been interpreted in terms of quasi-elastic behavior of the upper crust of the caldera under an increasing stress and suggest a progressive mechanical weakening of it. Patterns of fracturing of brittle rocks in laboratory studies clearly show that at low stresses fracturing activity is null or very low and the behavior is close to elastic, i.e., there is a quasi-linear relation between stress and strain. At stresses of about half of the values at bulk failure the fracturing activity begins to increase in an exponential way until the strain has typically reached about 90-95% of the failure value. The identified trends and relationships also allow quantifying the potential future seismic activity as a function of a possible further increase of caldera inflation under the assumption of continuation of the same trends. In particular, in November 2023, by assuming a further uplift of the caldera of 20 cm the above-described relationship and the magnitude-frequency law forecasted a significant probability of earthquakes with magnitude higher than 4.5. Of course, such a scenario is just one of the possible evolutions of the volcanic system.

Seismic sequences with very short earthquake intervals at Campi Flegrei during the ongoing unrest

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Campi Flegrei (Italy) is a caldera with a diameter of approximately 12 km. This volcanic area has a complex history of eruptive and seismic activity, with the last eruption occurring in 1538, which led to the formation of Monte Nuovo. Today, the region is densely populated, with about 500,000 residents, and the main city within the caldera is Pozzuoli, located in the caldera's center.

Ground deformations, which alternate between subsidence and uplift, are characteristic of this caldera, a phenomenon known as bradyseism. The latest phase of bradyseism began around 2005 and continues to the present day. This phase is marked by increasing seismicity, rising fumarolic tremor amplitude (indicating intensified hydrothermal activity), increasing fluid emissions, and significant ground deformation. These deformations have resulted in approximately 1.3 meters of uplift in the Rione Terra area, located at the center of Pozzuoli. The uplift decreases radially from the center, creating a characteristic bell-shaped deformation pattern. In response to the ongoing geological unrest, Italian Civil Protection elevated the alert level to yellow in December 2012, signaling heightened vigilance. Since then, the unrest has continued to accelerate, as evidenced by increasing rates and magnitudes of earthquakes, more pronounced ground deformation, and significant geochemical changes. Recent studies have indicated that the unrest phase has intensified notably since 2021. From 2021 to 2024, a geodetic anomaly was detected in the Monte Olibano area, characterized by a 12 cm uplift deficit compared to the surrounding regions. Additionally, in the same period seismic sequences with very short intervals between earthquakes were recorded, along with relatively large magnitude events, the most significant reaching a magnitude of $M_d=4.4$. Our study analyzes the seismicity during this period to explore the relationships between earthquake characteristics, seismogenic processes, the evolution of the deformation field, and associated geochemical variations. Special attention is given to seismic sequences with very short intertimes, distinguishing between burst-like swarms and regular VT (volcano-tectonic) events. These sequences provide valuable insights into the seismogenic processes occurring amid the accelerating unrest, helping to better understand and monitor the evolving geological hazards posed by the Campi Flegrei caldera.

Tracking transient changes in the plumbing system at Campi Flegrei Caldera

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Increase in seismicity, gas emission and ground uplift are symptoms of unrest in Quaternary calderas. Since the raising of the alert level in 2012, their continuous increase in the Campi Flegrei caldera is generating growing concerns for such a densely populated area. Until now, we never detected the injection of fresh magma in the shallow system, leaving uncertainties on the proximity of an eruption. Here, we show evidence for episodic refills of magma and magmatic fluids in shallow and deep reservoirs beneath the resurging area, revealed by a new fully non-linear 4D (in space and time) seismic tomography. Transient signatures in tomograms depict the ascent of magma batches at shallow depth, which could have started in 2019, perturbing the shallow circulation of hydrothermal fluids. The existence of a similar signature also during the 1982–84 episode, suggests that accumulation of magma batches may be a common way of caldera to grow. Anyway, the ability to fast track changes associated with magma ascent is crucial to forecasting and modeling how restless calderas evolve and may become prone to erupt.

Exploring architecture and dynamics of caldera systems during volcanic unrest: The example of the Campi Flegrei caldera (Italy)

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Large silicic calderas feed the most explosive and catastrophic eruptions on Earth. These volcanic systems may experience extended periods of unrest originated by magmatic processes (movements of magma), non-magmatic sources (e.g., hydrothermal or tectonic processes), or a combination of causes. An intriguing case is the densely populated caldera of Campi Flegrei (CFc), southern Italy. Since 2005, the caldera is in a new phase of an unrest that has persisted intermittently for several decades (main crises during 1950-1952, 1970-1972, and 1982-1984), characterized by increasing ground uplift, seismicity and fumarolic activity.

In this study, we conducted a multidisciplinary investigation aimed at assembling a broader and clearer picture of the CFc system to shed light on the role of different sources in the recent unrest phases. We performed a multiscale analysis, integrating results from 4D X-ray microtomographies at the well core-scale with a 3D high-resolution seismic tomography at the crustal-scale, to accurately reconstruct anatomy and properties of the shallow (0-4 km depth) volcanic structure, where deformation source, seismogenic volume and hydrothermal system are localised. To strengthen our conclusions and provide the background for some of our most remarkable observations, we performed numerical simulations for the ascent of magmatic dykes starting from the 8 km deep magma reservoir and entering the shallower layers above 4 km depth, that are the domain of our tomographic study, and mark the transition from the carbonate basement to the shallower, low-density caldera-filling tuffs.

Our study reveals that crustal rocks progressively strengthen and compact with depth into brittle, stiff, tough, and low-permeability layers down to ~2-2.5 km. Below this depth, however, there is an unexpected mechanical deterioration of the crustal layers, which around depths of 3-4 km become porous, permeable, and less resistant. This zone constitutes a trap for magmatic fluids, allowing them to accumulate and potentially reach overpressured conditions, leading to deformation and seismic activity. We suggest that this zone could be common to other calderas and formed due to the emplacement of dikes over the caldera history at these depths where lithologic transitions occur, as indicated by our dyke propagation simulations. In this region, varying amounts of gas, magma, or both can accumulate over time, leading to different conditions of unrest observed in calderas.

Current status of the Campi Flegrei caldera: Can monitoring fluid migrations using shear wave splitting parameters and seismic interferometry help in adding constraints? Some results and perspectives

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The current status of the Campi Flegrei caldera suggests ongoing volcanic and seismic activity, making continuous monitoring essential.

Monitoring fluid migrations within the caldera can be enhanced by utilizing shear wave splitting parameters, which provide insights into subsurface stress and fluid pathways. Shear wave splitting occurs when a shear wave, which typically travels as a single wavefront, splits into two orthogonal polarized waves due to the anisotropic properties of the rock it traverses. This phenomenon provides valuable insights into the stress and strain conditions within the Earth's crust, which are influenced by the presence and movement of magma.

Seismic interferometry is another powerful tool that can improve the resolution of subsurface imaging, helping to detect small changes in the caldera's structure and behavior. Seismic interferometry works by cross-correlating seismic signals recorded at different locations. This process essentially transforms ambient seismic noise into coherent seismic waves, allowing to visualize changes in the subsurface structures over time. These visualizations are critical for identifying the movement of magma, as shifts in magma chambers and conduits can alter the seismic velocity of the surrounding rock.

Combining these advanced monitoring techniques may offer more accurate constraints on the caldera's dynamics, leading to better risk assessment and mitigation strategies for the surrounding regions.

At Campi Flegrei, studying shear wave splitting parameters and seismic interferometry, alongside comparisons with time series of all geophysical and geochemical observations, offers significant benefits. This comprehensive approach enhances the understanding of subsurface processes, improves the accuracy of volcanic activity knowledge, potentially may aid in identifying early warning signs of potential eruptions, contributing to more effective risk management strategies.

Geochemical monitoring at Solfatara, Campi Flegrei, during 2000-2024

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The systematic sampling of the main fumaroles of Solfatara (Campi Flegrei, Italy) started during the bradyseismic crisis of 1983-84. In the late 1990s, diffuse CO₂ emissions measurements also became part of the monitoring activity through systematic campaigns. In these 40 years of investigations almost unique databases were created including thousands of chemical and isotopic analyses of fumaroles and hundreds estimations of the diffuse CO₂ emission. These databases provided the base of numerous geochemical and interdisciplinary scientific works to understand the processes occurring in the hydrothermal-magmatic system of Campi Flegrei. Here in particular we focus on the data of the current, post-2000, volcanic unrest. The comparison of the geochemical data with seismicity and ground deformation indicates the pivotal role of magma degassing in the current crisis of Campi Flegrei. The deep magmatic fluids are injected into the hydrothermal system during episodes of magma degassing. These injections cause pressurization and heating of the hydrothermal systems, earthquakes, ground deformations, changes in fumarole compositions and escalating CO₂ emission at the surface. The expulsion of these fluids constitutes the most energetic process currently occurring at Campi Flegrei; it is, in fact, more energetic than ground deformation and seismic activity. In this work, we present a review of these different aspects and new data concerning the recent sulphur anomaly observed at Solfatara fumaroles.

Evolution of the plumbing system at Campi Flegrei caldera (Italy) during 2007-2023 from geodetic data inversions and petrological simulations

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The current unrest phase at Campi Flegrei Caldera (Italy) is characterised by increasing gas emissions, rising seismicity rates and magnitudes, and remarkable ground deformation, with a cumulative uplift of 119 cm at the caldera centre in Pozzuoli from 2005 to October 2023. During 2012 a seismic swarm occurred and since 2014, the seismicity rate has been increasing nearly exponentially culminating in the latest seismic crisis starting in February 2023, which included several events with magnitude greater than 3.5 and depths less than 3 km.

We consider multi-technique geodetic data from 2007 to 2023 to constrain the recent surface deformation and assess potential hazard implications. Time series from the ENVISAT (2007-2011) and COSMO-SkyMed (2011-2023) satellite missions, along with inland GNSS data, indicate an increasing rate of uplift at the caldera centre. Additionally, GNSS seafloor measurements, collected in the Gulf of Pozzuoli from 2017 to 2020, provide valuable insights into the 3D deformation pattern in the submerged part of the caldera.

A two-source plumbing system is considered the geodetic inversion. Seven time intervals were defined over the 16-year long window, considering shorter nearly linear trend changes over time. The geodetic inversions are computed in a Bayesian framework, employing a 3D finite element model with an elastic heterogeneous structure based on the newest seismic tomography of the area. The forward model accounts for a two-source plumbing system comprising a central shallower source and a deeper one. The location, shape and overpressure of the central shallow source are determined during the inversions, whereas the deep source is fixed at 8 km depth, with only its volume variation constrained by the inversions.

Results show a gradual decrease in depth for the central shallower source placed slightly south of Pozzuoli. Its depth decreased from 5.9 km to 3.9 km during the 16 years considered, lying below the seismicity swarms observed. The source shape is an ellipsoid that grows alternating widening of its axes and has volume variation rates spanning from 1.4×10^6 to 8.3×10^6 m³/yr during the seven-time intervals. The deeper source shows limited but persistent deflation through the seven-time intervals, with volume variation rates of the order of -104 m³/yr to -106 m³/yr. We computed the equivalent strain distribution in the 3D finite element models, resulting in agreement with the seismicity location observed during the unrest.

To better investigate any possible involvement of magma within the two-source plumbing system, petrological simulations are considered, evaluating five scenarios considering fluids and magma migration, volatile exsolution, decompression or a combination of them. These calculations are constrained by the volume variations results of the two-source system. The most plausible scenarios imply magma ascent from the deep source at 8 km depth, but not necessarily reaching the shallow source.

This approach of merging geodetic and petrological methodologies enables the tracking of the evolution of the Campi Flegrei plumbing system, providing timely constraints on the possibility of eruptions at volcanoes undergoing unrest.

Time-lapse gravity observations during the current unrest at Campi Flegrei caldera

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Since 2005 Campi Flegrei caldera, Italy (CFc) is experiencing a new unrest episode, characterized by relevant uplift rates (> 10 cm/yr), increased seismicity and augmented gas emissions at Solfatara-Pisciarelli. Deformation and seismic data point to an inflating source located at about 4 km depth, that is believed to be fed by gas and magmatic fluids that migrate from a deeper reservoir. The accumulation of such volume of fluids causes pressurization of the reservoir at about 4 km that, in turn, results in uplift and in a diffuse seismicity. Albeit this is the dominant interpretation, the involvement of magma injection at shallower depths as a potential contributor to the unrest cannot be completely ruled out.

Among the various geophysical techniques, gravimetry, being sensitive to mass variations, plays an important role to discriminate the type of unrest (hydrothermal or magmatic) presently observed at CFc. The joint interpretation of the temporal variations of gravity and deformation contributes in detecting whether or not the unrest is accompanied by a relevant mass accumulation, and to obtain estimates of the mass density.

In this contribution we provide an overview of the recent gravity changes observed at the CFc. Gravity data are periodically measured (at least twice per year) on a network of about 30 benchmarks spread all over the caldera. Time series of gravity in the central sector of CFc show a dominant effect due to the vertical displacement of the benchmark and to the density changes induced by rock deformation. Such effects, that can exceed in absolute value $200 \mu\text{Gal}$, may mask the actual contribution due to the source mass variations if not properly accounted and removed. We consider the most recent modelling of the plumbing system at CFc to simulate the deformation underwent by the caldera in the time-span 2015-2023. The model is based on the Finite Element Method (FEM) and includes a realistic definition of the underground density and mechanical properties constrained by seismic tomography. The plumbing system is constrained by satellite (Interferometric SAR) and GNSS geodetic data. By modelling the gravity contributions at the gravity benchmarks due to the deformation and internal density changes in the FEM model, we are able to isolate the gravity contribution due to the source. The preliminary results obtained are discussed and compared with a more standard approach, which employs exclusively the observed vertical movement measured at the benchmarks.

Defining deformation scenarios anticipating a future eruption at Campi Flegrei caldera, Italy

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The Campi Flegrei (CF) caldera is a 13-km-wide caldera that formed following at least two large explosive eruptions about 39,000 and 15,000 BP. Following the last Neapolitan Yellow Tuff eruption (NYT), about 80 smaller-size eruptions ensued, scattered across the caldera. The most recent eruption in 1538 CE led to the formation of the Monte Nuovo cinder cone. CF encompasses part of Naples, housing approximately 800,000 residents. Defining pre-eruption scenarios, including anticipated magma pathways, eruptive vent locations, and deformation signals and their evolution with time, is crucial for enhancing preparedness for future events. In this study, we employ recently developed 4D magma pathway models to simulate the reactivation of a sill-shaped melt lens below CF and the subsequent ascent of magma batches towards various directions. Initially, we examine simplified synthetic ascent scenarios and caldera settings, followed by application to CF. From the evolving shape of the ascending dykes we calculate expected deformation signals and employ standard inversion techniques to retrieve deformation source parameters. Subsequently, we employ semi-analytical expressions to calculate the velocity of ascending magma batches along the simulated pathways. Applying our model, we determine the expected velocity of dykes.

b value enlightens different rheological behaviour in Campi Flegrei caldera

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The Campi Flegrei caldera is one of the most dangerous volcanoes in the world and since 2005 it is in unrest. During unrest periods the number of recorded earthquakes increases allowing to perform their statistical analysis, which can lead to a better comprehension of the unrest mechanism and its origin. Here we evaluate the 3D tomography of the b value at the Campi Flegrei volcanic area using the method of Godano et al. [2022] and a high quality instrumental seismic catalogue. The obtained b value map reveals a very good correlation with the structure of the hydrothermal system involved in the bradiseismic phenomenon. The map enlightens the presence of three different ranges of b value. The first one (in [0.7,1.1)) includes the deepest seismicity, namely all earthquakes at a depth larger than 2 km. However, the same value is observed in a shallow cell ($z < 1.25$ and defines what we call the b value anomaly at Campi Flegrei. This anomaly appears to be correlated with the hydrothermal system where the medium allows the passage of the volcanic gases toward the surface. Since changes in the b value may reflect variations in stress levels, magma movement, or the presence of fluid migration within the volcanic edifice our results can be used as a reference model to evidence future meaningful variations indicating the evolution of the volcano toward a critical status. Monitoring changes in the b value can help assess volcanic hazards, identify periods of volcanic unrest, and improve volcanic risk mitigation strategies.

Machine Learning Based Earthquake Catalog in Campi Flegrei

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Campi Flegrei is the most populated caldera in the world and is currently in an unrest phase since 2006. This unrest is characterized by a slow uplift, a change in the fumaroles composition and an increment in the seismicity. In particular, the seismicity rate of earthquakes with $M_d \geq 0$ increased from 45 earthquakes per year between 2006 and 2018 to 573 events/year between 2019 and 2022 reaching 2699 events/year in 2023. The earthquakes are currently manually detected and located by INGV-Osservatorio Vesuviano and the magnitude is estimated using the duration of the recorded signal at a reference station. Such an increment in the seismicity calls for algorithms that can help the manual activities in detecting and discriminating earthquakes.

We applied a machine learning-based workflow to analyze Campi Flegrei caldera's seismic activity recorded in 2023 using continuous waveforms from 26 local stations (18 broadband stations and 8 short-period stations). We used PhaseNet, a deep learning-based phase picker, for phase picking, and further using GaMMA-1D, successfully associating 31,617 events. We then used VELEST, and HypoDD 2.0b to locate and relocate the events incorporating the local 3D velocity model. The final catalog counts 12,115 events, marking an almost three-fold increase compared to the Osservatorio Vesuviano seismic catalog, which reported 3,349 located events. Additionally, 95% of the events reported in the local catalog were successfully re-detected. Depths of most events in the relocated catalog are above 5 km, and the seismicity illuminates a prominent ring fault system beneath the Campi Flegrei caldera at depths of 3-4 km.

Real-time seismo acoustic observations of the hydrothermal outgassing at the Pisciarelli active field in the Campi Flegrei caldera (Italy)

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Fumarolic and hydrothermal activities are clear indicators of volcanic degassing within calderas, providing essential information for monitoring volcanic activity. In this regard, the Pisciarelli fumarolic field in the Campi Flegrei caldera (Italy) holds significant importance within the Campi Flegrei Caldera (Italy), where a continuous and vigorous degassing of hydrothermal and magmatic fluids takes place. This outgassing is accompanied by a persistent harmonic tremor and a consistent subtle infrasonic wavefield.

In the aim of the LOVE-CF and INGV-DPC B2 Projects, in response to the recent bradyseismic crisis at Campi Flegrei, we installed a permanent seismo-acoustic array in order to improve real-time monitoring of temporal changes in fumarolic outgassing in the Pisciarelli area and characterize the seismic tremor in the Pisciarelli area, to elucidate the potential source mechanism and the linked hydrothermal gas flow dynamics.

We specifically utilized the seismo-acoustic wavefield generated by the outgassing to evaluate its intensity and dynamics. Remarkably, we identified two distinct infrasonic sources that were simultaneously active: one associated with intense boiling in a water pool and the other with the release of overpressurized steam from fumarolic vents. The well-correlated temporal variations in infrasonic and seismic amplitudes provide insights into the outgassing mechanism of the hydrothermal system. These variations reveal changes in the pressure of the shallow hydrothermal reservoir that drive the release of hydrothermal gas. By integrating acoustic and seismic observations, we gain a deeper understanding of the dynamic nature of fumarolic outgassing at the Campi Flegrei caldera. This enhanced understanding aids in assessing the volcanic risk for the caldera, as alterations in fumarolic outgassing can signal pressure changes in the hydrothermal reservoir.

This could improve our ability to assess volcanic risk within the caldera, as changes in fumarolic degassing may signify alterations in ongoing unrest dynamics. Additionally, it may offer insights into the potential mechanism of tremor generation, possibly linked to the collapse of gas bubbles as volcanic gas ascends towards the earth's surface.

Fifteen years evolution in the experts' opinion on the current unrest of Campi Flegrei: where are we now?

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The Campi Flegrei caldera represents one of the most densely populated volcanic areas in the world and is currently undergoing an uplift phase that began in 2005. Forecasting the evolution of the volcano's unrest is of paramount importance to effectively and timely implement risk reduction measures like evacuation plans. However, despite the advancement of research and the development of new monitoring techniques, the interpretation of unrest dynamics remains a daunting challenge nowadays. The ambiguity in the interpretation of pre-eruptive processes suggests that the use of probabilistic methods is better suited to describe unrest evolution than that of deterministic procedures. To obtain a collective view on the evolution of the volcano's unrest dynamics, seven elicitation sessions have been carried out, with the aim of defining a list of parameters indicative of the magmatic origin of unrest and a possible impending eruption that are input to a Bayesian Event Tree (BET) model. In this work we illustrate how the experts' view has evolved over the years by showing how the probability of magmatic unrest and eruption during the current unrest at Campi Flegrei change when applying the BET model with the results of the different elicitations. The results of this work show a significant evolution of experts' collective view of the volcano over the years.

Detection of a ground deformation anomaly at Campi Flegrei during the 2021-2024 unrest phase, revealed by DInSAR and GNSS measurements

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The Campi Flegrei caldera has been undergoing increasingly intense long-term uplift, accompanied by rising seismic activity and enhanced geochemical emissions over the past two decades. The pattern of ground deformation exhibits an axisymmetric bell-shaped profile, with a maximum uplift of approximately 125 cm since 2005 in the central area of the caldera. However, there is an anomalous deviation from this expected bell-shaped pattern in the Mt. Olibano-Accademia area, located to the east of Pozzuoli. To identify and investigate this geodetic anomaly, which has become prominent since 2021, we utilized Sentinel-1 and COSMO-SkyMed Multi-Temporal DInSAR measurements, along with GNSS data. The anomaly spans an area of about 1.3 km² and exhibits a maximum uplift deficit of around 12 cm between 2021 and 2024 compared to the surrounding regions. To delve into the causes of this anomaly, we analyzed the caldera's seismic activity and inverted the DInSAR data to pinpoint the primary source associated with the Campi Flegrei ground deformation pattern. Our findings indicate a penny-shaped source, situated roughly 3800 meters beneath Pozzuoli, with a radius of about 1200 meters. Moreover, we discovered a strong correlation between the temporal evolution of the uplift deficit in the anomalous area and the occurrence of earthquakes, with the most significant seismic events occurring in this region. These observations suggest that the geodetic anomaly is linked to the tensile stress regime of the primary deformation source. This interpretation is further supported by the concentration of earthquakes and hydrothermal fluid emissions in this area, indicative of the presence of faults, fractures, and hydrothermal fluid circulation. However, the geodetic anomaly cannot be solely attributed to a deflating source beneath the region. In fact, if a contracting source were acting in the geodetic anomaly area, it would reduce the increase in distance (related to the uplift caused by the primary source) between two GNSS stations (ACAE and SOLO) located at the boundaries of the anomalous area. Our analysis shows no evidence of such an effect. The phenomenon can be more plausibly explained by the lithological heterogeneities of the Mt. Olibano-Accademia lava domes, which might induce a localized response to ground deformation during the inflationary phase. Therefore, the geodetic anomaly area represents a zone of crustal weakness amidst the ongoing unrest, necessitating careful monitoring and further study.

Exploring Degassing and Crystallization processes in magmatic ascent: the case study of the western sector of the Campi Flegrei Caldera

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The Campi Flegrei caldera (CFc) is one of the highest risk volcanic areas on the Earth and it is considered the most dangerous volcano in Europe. The CFc has been experiencing a new phase of unrest since 2005. The aim of this study is reconstructing the degassing and crystallization processes as well as the timescale during magma ascent in volcanic conduits in the post-Neapolitan Yellow Tuff eruptions occurred in the W-sector of the caldera. This sector, compared to the eastern one, has been fewer eruptions with more evolved compositions and smaller erupted volumes. Here we present the results of a study carried out on samples of the proximal pyroclastic sequence and the distal deposit of Baia-Fondi di Baia eruption. While analysis of the products of other eruptions that occurred in this sector, such as Averno 2 and Mt.Nuovo, are in progress. The samples were representative of the different phases of the eruptions (magmatic and phreatomagmatic phases), with particular attention to the initial phases as they are indicative of the processes and timing of volcanic conduit opening and therefore of early warning signals. Geochemical analysis showed mostly an uniform trachytic composition according to TAS (total alkali silica). SEM-EDS analysis revealed that the plagioclases showed a predominantly sodium composition (oligoclase-andesin); the alkali feldspars were mainly sanidine and to a lesser extent anorthoclase. The clinopyroxenes were identified as belonging to the diopside-hedembergite series. These results were used for the application of geothermal barometers: we obtained temperatures of 910 °C, pressures of 2.2 kbar for the Baia samples and 902°C, 1.6 kbar for the Fondi di Baia samples. The data will provide a quantitative estimate of the main variables that regulate the pre- and sin- eruptive processes.

New Insights Into the Recent Magma Dynamics Under Campi Flegrei Caldera (Italy) From Petrological and Geochemical Evidence

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The Campi Flegrei caldera is considered the most dangerous volcano in Europe and is currently in a new phase of unrest (started in 2000 and still ongoing) that has persisted intermittently for several decades (main crisis occurred from 1950 to 1952, 1970–1972, and 1982–1984). Here, by combining the petrological and geochemical data collected in recent decades with numerical simulations, we place new constraints on the source(s) of the current dynamics of the volcano. In particular, we show that the measured (N₂-He-CO₂) geochemical changes at the fumaroles of Solfatara hydrothermal site are the result of massive (about 3 km³) magma degassing in the deep portion (200 MPa, 8 km of depth) of the plumbing system. This degassing mechanism would be able to flood the overlying hydrothermal system with hot gas, thus heating and fracturing the upper crust inducing shallow seismicity and deformation. This implies that the deep magma transfer process (8 km) has been decoupled from the source of deformation and seismicity, localized in the first kilometers (0–4 km) of caldera-filling rocks. Moreover, we show that the intense physical-chemical perturbation of the hydrothermal system during the current unrest phase is driving the decarbonation of hydrothermal calcite stored in reservoir rocks, providing non-magmatic CO₂ that can contribute up to 20%–40% of the total fumarolic CO₂. These insights on depth and nature of fluid sources can have important implications for defining the best monitoring strategies and for forecasting a future eruption.

Effusive eruptions at Campi Flegrei: Petrological characterizations and emplacement mechanisms of Mt. Olibano and Accademia lava domes/flows

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Campi Flegrei is a caldera in a densely populated area of southern Italy. It was formed by two major collapses associated with the 40-ka Campanian Ignimbrite and the 15-ka Neapolitan Yellow Tuff (NYT) eruptions. In the last 15 ka, three temporal epochs of volcanic activities were distinguished at Campi Flegrei. The post-NYT effusive activity, however, took place only in the last epoch [i.e. ~5.5-3.5 ka BP; Di Vito et al., 1999; Isaia et al., 2009]. Forni et al. [2018] reported that eruption of Monte Nuovo probably shows accumulation of a large magma body at depth and marks the beginning of a new epoch of activity at Campi Flegrei. The onset of a new phase of volcanic unrest in 2005 led to raising the alert level from base to warning in 2012. These pieces of evidence highlight the need to better understand eruptive mechanisms of the volcano to assess volcanic hazards and consider volcanic risk mitigation measures. Contrary to the explosive eruptions at Campi Flegrei, the lava domes and lava flows were investigated in a few studies which might hinder obtaining a comprehensive insight into the shifts in magma storage conditions and style of the next eruptive event. To bridge this knowledge gap, Mt. Olibano and Accademia effusive eruptions were studied in this research. The eruptions occurred following the uplift phase after the Plinian eruption of Agnano-Monte Spina [4.5-4.6 ka BP; Smith et al., 2011]. Some studies provided pieces of evidence that Mt. Olibano and Accademia are two different eruptions [e.g., Isaia et al., 2015], but others explained that both names refer to the same eruption [e.g., Melluso et al., 2012]. To date, these two eruptive events are referred to as both lava dome [e.g., Isaia et al., 2009; Melluso et al., 2012] and lava flow [e.g., Morra et al., 2010; Isaia et al., 2018]. It is worth mentioning that limited observable eruptions of highly viscous and silicic alkaline lavas hindered a deep understanding of their emplacement worldwide. Therefore, in this work, the pre-eruptive topography together with the chemical, petrological and structural properties of the eruptive products of Mt. Olibano and Accademia were investigated. Specifically, we studied: (1) the spatial distribution of the erupted products by mapping the surface extension of the lava domes/flows; (2) the variation in the petrological characteristics inside the lava domes/flows by collecting samples from different locations; (3) the geochemical composition of the rocks by determination of major and trace elements using electron microprobe analysis (EMPA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analysis; (4) the crystal size distribution (CSD) analysis of the rocks; and (5) the viscosity of the eruptive products through rheological models from literature. The results help understand how lava domes/flows are formed and emplaced at Campi Flegrei, improving our knowledge of the volcanic systems and providing new data for generating a better map of volcanic hazard.

Radionuclides behavior in hydrothermal volcanic systems: Preliminary investigations at high and low gas flux emission sites

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Studies over long periods at many active volcanic systems in the world revealed that radionuclides measurements in volcanic plumes provide useful indications of degassing processes in terms of volume of degassing magma, timescales of magmatic processes, chemical composition and depth of the reservoirs. In this study, we describe the preliminary results obtained from two radiometric surveys carried out between January and April 2024 at Pisciarelli (Campi Flegrei caldera, Italy) and Stephanos crater (Nisyros island, Greece), sites characterized by high and low gas flux emissions, respectively. Radioactivity measurements were collected through a scintillation gamma-ray detector in order to find potential correlations between volcanic gas (i.e., CO₂ and H₂S) and radionuclides concentrations at ground level and in atmosphere. We provided scans at four different altitudes from the ground, aiming to disentangle the contributions of the radionuclides (i.e., ²²²Rn, ²²⁰Rn, etc.) transported by the gas species diffused in the air from those contained within the rock and soil. Different volumetric profiles and 2D maps of gamma rates and gasses concentration have been plotted considering short (60 seconds) and long (600 seconds) acquisition times in multiple field spots for each scan altitude.

Intrusive bodies controlling the unrest in Campi Flegrei

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Campi Flegrei is one of the largest active calderas which experienced several unrests in historical times characterized by a high number of earthquakes and soil uplifts reaching several centimeters or even meters within each cycle. The occurrence of seismicity in these region causes great concern being one of the main precursors for volcanic eruptions. Additionally, the extreme anthropization of the area amplifies the seismic and volcanic risk increasing the population concern.

The last unrest started in 2006 and is currently ongoing. It is accompanied by a large number of earthquakes mainly located beneath the Solfatara-Piscarelli system, together with the increment of gas emission in Piscarelli and strong variations of geochemical and geophysical parameters.

Here we show two classes of seismic models generated using passive methods employing both Earthquakes and Ambient Noise recorded from 2005 till November 2023.

These models enabled us to demonstrate the existence of high P-wave velocity bodies within the caldera: one onshore, located between Pozzuoli port and Solfatara, and another one offshore, located only few kilometers south of Pozzuoli. The body beneath Pozzuoli and Solfatara is about 3.0 km deep and exhibits high V_p/V_s suggesting that is rich in fluids and is possibly participating to the current unrest. However, both structures are clearly associable with the border of the resurgence dome which involved the uplift of the marine terrace forming the central part of the coast of the Pozzuoli's gulf, suggesting that the peripheral structures may regulate the upward fluid migration, contributing to the ongoing unrest.

Statistical analyses on groundwater compositional data from Campi Flegrei caldera wells

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Groundwater analyses in volcanic calderas are fundamental for the comprehension of the hydrogeochemical processes due to unrest phenomenon affecting these areas.

We performed statistical analyses on 41 water samples collected from Campi Flegrei caldera wells to define the main chemical and physical characteristics of the groundwater body and to analyze their spatial distribution. The selected groundwater dataset consists of 10 compositional geochemical constituents (Na, K, Mg, Ca, NH_4 , Cl, NO_3 , SO_4 , F and Total Dissolved Inorganic Carbon) and physico-chemical variables (pH, temperature, total dissolved solids, CO_2 pressure). As first, geochemical data were log-centered following the compositional data analyses (CoDA). On this data we performed the principal component analyses (PCA). The explained variance of the first three PC is 85% and the relative biplot reveal the variability structure of the compositional samples.

In particular, NO_3 , NH_4 , Mg and F, having the longest rays, are characterized by a greater variability compared to the other compositional species. Moreover, we performed a Hierarchical cluster analysis using the scores from the first three PCs derived from PCA. The obtained dendrogram allows to individuate two main classes which can in turn be divided into two more homogeneous subclasses. Basically, the analysis well distinguishes water samples characterized by higher/lower values of temperature, total dissolved solids, CO_2 pressure and pH.

Finally, the PC1 and PC2 scores maps were performed to explore spatial patterns associable to geological and geophysical features likely related to tectonic and volcanic processes.

S14 - HYDROTHERMAL ALTERATION IN ACTIVE AND EXTINCT VOLCANIC SYSTEMS: INTEGRATED APPROACH, OUTCOMES AND PERSPECTIVES

Conveners:

Monica Piochi, Angela Mormone, Teresa Caputo, Patrizia Contursi

Landscape changes and hydrothermal alteration along the acid sulfate slopes at the northern side of the Ischia Island, Italy

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This research explores relations between acidic sulfate alteration, landscapes changes and slope instabilities that can be observed at the Monte Epomeo of the Ischia Island, the westernmost long lasting active volcanic hydrothermal system in the Gulf of Naples.

Ischia is a volcanic resurgent caldera with an exhumated deep the active hydrothermal system [Sbrana et al., 2009], nowadays slowly subsiding, tilting toward N [INGV, bulletins] and affected by slope instabilities [e.g., de Vita et al., 2006] and earthquakes [e.g., Nappi et al., 2021]. The northern sector of the island is particularly interesting. It shows zones of sulfate alteration and sulfurous emissions. The sector has been interested by landslides, among the catastrophic one in 2022, with damages from the relief to the coastal areas. Here, localized the most stronger seismic events in 1883 and 2017, both destructing a narrow zone of the Casamicciola municipality.

Hydrothermal alteration together with weathering, transport, hydrodynamics can strongly contribute to variability of the processes of volcanoclastic sedimentation and can influence the slope stability, particularly in areas shaken by seismic and ground deformation processes.

For the purposes, we selected the Montagnone-Monte Cito area on the northern slope of the Monte Epomeo where a diffuse acidic sulfate alteration and an active hydrothermal dynamics have been described at the least since Roman time and was under mineralogical survey through time since 2012 [Piochi et al., 2019].

In this study we carried out a photogrammetry survey with a Unmanned Aerial System (UAV) on March 2022 and July 2022 and then we have combined results with mineralo-petrological investigations of the Montagnone-Monte Cito area. The acid sulfate slopes with high temperature geothermal activity can lead at flank instability, causing a progressive deterioration of landscapes. For each UAV survey we obtained a vertical Digital Elevation Model (DEM) and a true color RGB orthomosaic that has provided the setting of the area at the different times and its evolution through their comparison showing a general loss of outcropping deposits fastly occurred from spring to summer. Major loss of material is observed along a steep valley running in the NNE-SSW direction and along a EW direction within the alteration area, this latter miming an already know fault. Furthermore, volume's loss is evidenced along an alignment with a NW-SE direction, probably joint to unmapped fracture, with a trend parallel to some faults characterizing the area further upstream.

X-Ray field- handheld Fluorescence and onsite Diffraction techniques supporting convectional mineral and geochemical analyses in mapping hydrothermal alteration: a first application at Montagnone-Monte Cito on Ischia (Southern Italy)

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Delineating and mapping the hydrothermal alteration and acid sulfate caps can contribute to understand the volcanic dynamics, investigate structures that are affected by ongoing processes and mitigate for hazards in hydrothermally active environments.

In this study we investigate the acid sulfate weathering and mineral alteration distribution that can be observed at Montagnone-Monte Cito, an active volcanic hydrothermal system, characterized by high temperature geothermal activity, sulfate discharging and flank instability. Indeed, the target area is an emblematic case because is the one closest to the city of Casamicciola that was located along the faults where the last strong earthquake occurred on August 21, 2017 and was involved by a powerful landslide on November 26, 2022.

We have studied and characterized altered outcropping deposits by geological field campaign, mineralogical and geochemical analysis with on lab Optical Microscopy (OM), X Ray Powder Diffraction (XRPD), Electron Microscopy and Energy Dispersive microanalysis (SEM-EDS), and handheld X-Ray Fluorescence (pXRF) and on-site X-Ray Powder Diffraction (pXRPD). Soil Rn emissions were also measured on-site by the RAD7 solid state alpha detector. A thermo-couple was used to assess soil temperatures. The activities were performed in the frame of Ricerca Libera 2019 project, funded by INGV.

Comparison of XRPD and pXRPD spectra confirmed more reliable background noise obtained in situ, accurate for the determination of dominant phases, and with uncertainty for accessory phases. As regard, SEM-EDS has been resolving in their recognition. Portable fluorescence analyses have been useful in helping us to conduct targeted and detailed sampling. The combination of all different methods used, allowed us to define the neogenetic mineralogical assemblage mostly constituting by alunite and clay minerals, with subordinate alunogen, alum-(K), sulfur, halotrichite, gypsum, tamarugite and amorphous phase. Alunite mostly constitutes the whitish powdery geoderma and together with sulfur, alunogen and alum-(K) developed along the northern slopes of the ca. 800m height Monte Epomeo block-relief. Furthermore, clay minerals (mainly represented by interstratified illite/montmorillonite and kaolinite), halotrichite and gypsum are mostly located in the reddish and crumbly terrains. Soil radon emission increases across the sulfate alteration area. Thank to field study and combining our methodological approach appears promising to evaluate hydrothermal alteration evolution and rock degeneration susceptibility of solfataric terrains subjected to degassing and tectonic dynamics. Finally, the handheld X-Ray Fluorescence, RAD7 and thermo-couple probes are versatile instruments, not only to gain information on-site for survey and sampling, but also for scientific, technological and cultural transfer purposes. The quite active solfataric environments of

Montagnone-Monte Cito are fascinating sites where the volcano dynamics, the hydrothermal alteration and the volcanologist work can be easily and safely appreciated by students, hikers and tourists.

Discovery of novel glycosyl hydrolases from extreme environments: the case from magma degassing at the Vulcano island

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The exploration of extreme environments has long attracted researchers for its potential to discover nature's remarkable adaptations to physico-chemical conditions approaching the limits of life. Among the myriad of biological treasures hidden within these extreme habitats, glycosyl hydrolases (GHs) are particularly relevant [Ashcroft et al. 2024]. Indeed, these enzymes play a key role in the degradation of complex carbohydrates such as cellulose, hemicellulose and pectin present in the lignocellulose wastes [Berenguer et al. 2022]. The utilization of these residues to produce nanocellulose represents a promising opportunity towards sustainable resource management and applications span across multiple sectors, including packaging, textiles, biomedical engineering, and environmental remediation [Kim et al. 2015].

Traditional approaches to discover novel GHs have largely relied on cultivation-based methods, which often overlook the vast genetic diversity present in complex microbial communities of the various terrestrial ecosystems. However, in recent years, metagenomics has emerged as a powerful tool to bypass limitations of those traditional methods, by enabling the direct exploration of environmental DNA [Santos-Pereira et al. 2024]. In this contest, the extreme environments such as deep-sea hydrothermal vents, acidic hot springs, and alkaline hypersaline lakes, are populated by microorganisms adapted to thrive under harsh conditions (high temperature and salinity, acidic or alkaline pH, etc), possessing enzymes with exceptional biochemical properties [Ashcroft et al. 2024].

This work focuses on the application of metagenomic techniques to uncover novel GHs from two samples of soil from the extreme environment of Vulcano island (Italy), characterized by their harsh conditions and unique microbial communities. Samples were taken at the acidic SO₂-bearing fumaroles with temperatures greater than or equal to 100°C at the La Fossa cone, during the 2021 unrest, on November. We investigated the microbial communities and their functional potential by using KBase to analyse metagenomic data [Chivian et al. 2022]. Mineralogical and chemical composition have been determined by convectional petrological techniques with the aim to unravel eventual relations between inorganic and organic signatures. We here show that the communities in the two sulfurous soil samples at temperature of ca. 100°C (Fum5 and Fum7) diverge significantly and show different phyla abundance profiles. We obtained 23 and 19 metagenome-assemble genomes (MAG)s from Fum5 and Fum7, respectively (with completeness greater than or equal to 90% and contamination less than 10%), distributed among several bacterial and archeal phyla. MAGs selected for further evaluation included members of the genus *Acidithiobacilla* with the purpose of revealing their functional potential in the production of nanocellulose. The results integrate those in the literature and could have a volcanological relevance in the future.

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Thermo-baric evolution of hydrothermal alteration along the SH2 deep-borehole, Sabatini Volcanic District (Italy)

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This work describes the in-depth distribution of the hydrothermal alteration within the Sabatini Volcanic District (SVD) as reconstructed along the SH2 borehole, drilled by ENEL-AGIP in 1982-1983 for geothermal exploration. The petrographic analysis of over 1200 m of drilled calcsilicate skarn deposits is presented. At 1500 m depth, just below the contact between the Ligurian Flysch and calcsilicate Tuscan succession, a complex high temperature (HT) hydrothermal mineral assemblage in which two main stages are discriminated by textural relationships. The HT early stage made of wollastonite-garnet (stage-1) is overprinted by a secondary HT assemblage of garnet, vesuvianite, k-feldspar and phlogopite (stage-2) succeed by low temperature (LT) phases characterized by anhydrite, calcite, pyrite, chlorite, hematite and magnetite mineralization. These HT paragenesis indicate a transition from an anhydrous stage (metamorphism) to a hydrous stage (metasomatism), during cooling, crystallization and infiltration of highly oxidizing released magmatic fluids, with a peak metamorphism and metasomatism between 500-600°C and 1-4 kbar. Assuming a paleo-geothermal gradient of ca. 80-100 °C/km, these thermobaric estimates constrain the skarn formation to depths greater than 4 km, not compatible with the thickness of the drilled column of rocks above the skarn deposits. Therefore, evidence for an exhumed paleo-geothermal system is documented within the SVD. While still preliminary, it is proposed that the skarn can be associated with a deep-sited intrusive body that predated the Quaternary volcanic activity of the Roman Magmatic Province in the region.

Hydrothermal processes and variations in elemental sulfur viscosity. Implications for volcanic hazard assessment.

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Hydrothermal eruptions are a serious hazard in active volcanic areas and forecasting this kind of activity is affected by a great degree of uncertainty. Several eruptions unheralded by precursory signals occurred in historical times at several volcanoes, causing casualties. Deciphering the causes behind these unpredicted eruptions is important to improve volcanic hazard assessment.

Layers of elemental sulfur accumulated by magmatic degassing, have been discovered below water at volcanoes hosting crater-lakes. In these settings, the variations of sulfur viscosity, as pure element, were considered responsible to cause not only lake water temperatures' cycling, but also a temporary sealing of the vent system, causing eruptions. Pure sulfur viscosity is highly temperature dependent, because of its complex polymerization behavior: at ~160 °C, a four-orders-of-magnitude increase in viscosity occurs up to a maximum of 93.2 Pa·s between 186 and 188°C. Besides viscosity, step-changes in density, compressibility, and electrical conduction, have been measured in pure sulfur at temperatures ~160 °C. However, in the presence of hydrogen sulfide, organic material, hydrocarbons, ammonia, or halogens gases significant different viscosity-temperature relationships occur with respect to the pure S case, as noticed since the 1940s. This behavior is critical in volcanic settings, where these components are common, and sulfur is not pure. Several volcanoes have shown transitions between periods of dome growth and periods with crater lakes, and sulfur melts have been reported at volcanoes with no records of historical eruptions, and no crater lakes. In recent years, elemental sulfur presence has been reported at submarine calderas. These evidences suggest that elemental sulfur accumulation within hydrothermal systems is indeed a common process, not restricted to crater lakes. Landforms produced by phreatic explosions, driven by processes occurring at very shallow depths are reported in several volcanic settings. Following chemical reactions within impure S, both types and amounts of gases released at the surface, critical for volcano monitoring, would be altered, invalidating signals to issue alerts. Chemical reactions within impure sulfur, and viscosity variations can explain confounding geochemical and geophysical signals reported at volcanoes, and restless calderas, worldwide. Implications for volcanic-risk-mitigation strategies are envisaged.

Hydrothermal alteration of the highly weakened lava dome of La Soufrière volcano, Guadeloupe (Lesser Antilles)

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The andesitic lava dome of La Soufrière de Guadeloupe (Eastern Caribbean, France) unrest volcano is seat of an active hydrothermal activity and the consequent alteration which takes place in a marine-tropical environment characterized by huge rainfalls throughout the year.

Because of its format and size the lava dome represents also an ideal field laboratory to track the ongoing long-standing unrest and define the connections of recorded activity with the 1) tectonic context, 2) the deep magmatic system and 3) the morpho-structural setting.

All available measurements as well as their interpretations show that the hydrothermal alteration has a heterogeneous distribution related to the afore mentioned factors and finally related to the interaction with waters circulating throughout the volcanic dome.

In literature, the degree of Soufrière rock alteration has been correlated to oxygen isotope values, whereas a lack of correlation emerged with reference to deuterium. These data are here revisited together with water isotopic data from fumarolic emissions and Thermal springs. The combined rock-water-steam datasets show that the Soufrière case is particularly interesting, given the high $\delta^{18}\text{O}$ and low δD values in the rock which contrast with the high δD values that at those latitudes are found in the circulating waters.

Data analysis show that the lack of correlation between $\delta^{18}\text{O}$ and δD rock values may results by the overlap of the effects due to primary magmatic degassing and secondary low-T hydration, mainly by kaolinite formation. This overlap, however does not appear to disturb significantly the H_2O vs δD correlation which is instead observed in rock samples.

Despite in the Soufrière environment the transition from chemical weathering to hydrothermal alteration is blurred, data analysis show correspondence between the extent of isotopic exchange and the degree of rock alteration, closely associated with the local morpho-structural condition of the dome and the impact this has on the subsoil hydraulic patterns of hydrothermal fluids currently emitted by summit fumaroles.

The Fourier transform infrared spectroscopy (FTIR) analysis for the clay mineralogy studies to characterize different hydrothermal systems

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The study of active and fossil hydrothermal systems shows clay minerals to be a fundamental tool for the identification and characterization of hydrothermal alteration facies. The occurrence and composition of hydrothermal alteration facies could provide useful information on the physicochemical conditions of the hydrothermal activity affecting rocks. Clay minerals (i.e., smectite group, chlorite, illite, kaolinite group, pyrophyllite, biotite) are pivotal for extrapolating important parameters that strongly affect the development of water/rock interaction processes such as the temperature and pH of the hydrothermal environment. To identify a wide group of these minerals (i.e. 1:1 vs 2:1 clay minerals and their trioctahedral vs dioctahedral character), we used Fourier transform infrared (FTIR) technique that is a rapid and non-destructive technique. The sample preparation doesn't affect the sample considerably and the duration of analysis and evaluation is only a few minutes. The IR spectra of clay minerals are rich with information that reveals much about their structure and chemical composition. The absorption bands present in the mid-infrared (MIR) spectra ($4000\text{--}400\text{ cm}^{-1}$) of clay minerals can be related to the fundamental stretching and bending vibrations of their basic functional groups, that is, OH and Si-O groups. The bands present in the near-infrared (NIR) spectra ($8000\text{--}4000\text{ cm}^{-1}$) of clay minerals are related to overtones of fundamental stretching vibrations or combinations involving stretching and bending modes of the structural OH groups [Madejová, 2003]. The analysis was made by a FTIR is50 equipped with a Continuum™ Microscope, controlled by a OMNIC Data Collector 9.11© operating at the laboratory of the Istituto Nazionale di Geofisica e Vulcanologia in Naples. To obtain MIR spectra, we used the ATR (Attenuated Total Reflectance) accessory; the scanning range was $5000\text{--}400\text{ cm}^{-1}$, with a resolution of 4 cm^{-1} . The NIR spectra were collected through the diffuse scattered radiation technique using the Smart Integrated Sphere Accessory; the scanning range was $12000\text{--}4000\text{ cm}^{-1}$, with a resolution of 8 cm^{-1} . In this work, we treat two different contexts of application study of clay minerals with the FTIR technique:

Tolfa Volcanic District, an extinct volcanic complex of the Roman Comagmatic Province, where we found different clay minerals that allow to discriminate different alteration facies linked to ore mineralizations and to possible mining perspectives [Marchesini et al., 2024].

Campi Flegrei, an active volcanic caldera of the Neapolitan area, characterized by an intense hydrothermal activity, with continuous exhalation of gases in Solfatara and Pisciarelli and formation of different clay as consequence of changing temperature and pH of the fluids.

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Mineralogical data on the hydrothermal alteration zones and mineralizations of the Allumiere-Tolfa district (Central Italy)

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The Allumiere-Tolfa district is located approximately 60 kilometers northwest of Rome (Italy) and has been characterized by a long mining history for base metals (Pb, Fe), and alunite and kaolinite mineralizations, dating from prehistoric times [Field & Lombardi, 1972].

These deposits are genetically associated with the emplacement in arc setting, of a Plio-Pleistocene volcanic dome system consisting of latites and rhyolites, which intruded sedimentary carbonate and siliciclastic country rocks and that are part of the Roman Comagmatic Province. The magmatic event first produced contact metasomatism of the limestones, and lately triggered hydrothermal activity, which caused a widespread epithermal alteration of the volcanic rocks, resulting in the alteration of the volcanic rocks and emplacement of polymetallic proximal association of Hg-Sb, Pb-Cu, Fe, Zn, Ag, Ba-Sr, F and distal U, Th, Ce, La, Be, Ba, Sr mineralizations [Masi et al., 1980; Della Ventura & Patanè, 2020].

The present work is part of a bigger project investigating various geological features of the Allumiere-Tolfa district [Marchesini et al., 2023] and aims to deepen previous knowledge and examine in detail the nature of the polymetallic mineralizations of the area. Samples, collected in old pits and outcrops, were analyzed through various techniques: optical microscopy, X-ray diffraction, SEM-EDS investigations, bulk-rock chemical analysis and stable isotope determinations.

In the area, it was possible to identify distinct alteration facies, residual silica, advanced argillic and argillic facies, with specific ore minerals. The residual silica facies is commonly sulfide-bearing, containing pyrite, As-pyrite, cinnabar, with sphalerite, galena and chalcopyrite. In the advanced argillic facies, pyrite is disseminated in between the aggregates of planar crystals in veins and cavities. Pyrite is also associated with smectite and dickite in the argillic alteration zone. The metasomatized carbonates contain several sulfides such as pyrite and cinnabar with molybdenite, Sr-sulfates, thorutite, thorianite, and fluorite. Supergene alteration affected this epithermal assemblage causing the formation of gossans with Fe-oxy-hydroxides and secondary sulfides. Preliminary bulk-rock chemical analyses report trace to ultra-trace concentrations of Au.

The identified alteration zones and ore minerals in outcropping rocks indicate low-temperature ore-forming conditions, similar to those occurring in epithermal ores [Simmons et al., 2005], suggesting that possibly the mineralized system extends in depth.

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Copper sulfates of fumarolic environment from Vesuvius volcano (Southern Italy)

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Fumarole activity on the Earth's surface usually provides minerals with a small set of major elements (mainly S, O, Cl, F, Na, K, NH₄, Mg, Ca, Al, and Fe). At present, few volcanoes are characterized by fumarolic mineralization with an extremely varied mineralogical associations, as in Southern Italy and Russia. Among the European fumarole localities, Vesuvius (Campania) and Vulcano (Sicily) are the two volcanoes with the richest mineralogy [Balić-Žunić et al., 2016]. This is partly due to the exceptional enrichment of "ore" metals (Cu, Pb, Cr, Mn, Ni, B, Tl, As, and Se have been detected in Vesuvius) and its mechanisms of formation.

Sulfates are of particular interest for the scientific community both for the definition of genetic conditions in volcanic sublimate occurrences [Balić-Žunić et al., 2016] and for extraterrestrial bodies. For the latter, as revealed by the exploration of our solar system during the last decades, from the surface of Mars to the icy moons of Jupiter and Saturn or even veinlets in chondritic meteorites, sulfates of Mg, Fe, Mn, Ni, as well as Ca and Na represent an important constituent of planetary and meteoritic material [Talla et al., 2023; Meusburger et al., 2020].

A set of 17 copper sulfates-bearing samples from Vesuvius volcano (Italy), preserved in the Vesuvian Collection of the Royal Mineralogical Museum of Naples University Federico II, have been investigated to characterize their mineral assemblages and give clues on their genetic characteristics. The studied samples, consisting of thick green and yellow patinas or encrustations and blue crystalline crusts, coating ejecta from the last period of the Somma-Vesuvius volcanic activity, have been mainly studied by combined optical microscopy, SEM-EDS, XRPD, Raman and FTIR spectroscopy. The copper sulfates correspond to heterogenous associations of both hydrated phases, i.e., antlerite Cu²⁺₃(SO₄)(OH)₄, chalcantite Cu(SO₄)·5H₂O, cyanochroite K₂Cu(SO₄)₂·6H₂O, kaliochalcite KCu₂(SO₄)₂[(OH)(H₂O)], kröhnkite Na₂Cu(SO₄)₂·2H₂O, leightonite K₂Ca₂Cu(SO₄)₄·2H₂O, and anhydrous ones, i.e. chalcocyanite Cu(SO₄) cryptochalcite K₂Cu₅O(SO₄)₅, dolerophanite Cu₂O(SO₄), eleomelanite (K₂Pb)Cu₄O₂(SO₄)₄. Variable amount of Zn, Mg, Al and Mn, together with a Cu-Zn-sulfate are also detected in these minerals. Some undetermined phases, as an anhydrous K-Cu sulfate, an anhydrous copper phosphate and a hydrated copper arsenate are still under investigation. Cu-bearing oxides and hydroxychlorides have been detected, together with Cu-free sulfates such as steklite and apthitalite. The presence of both OH/H₂O-bearing and OH/H₂O-free minerals, often found together, indicates a complex relationship between primary sublimate minerals and alteration process in supergene conditions.

While copper minerals at Somma-Vesuvius do not have economic relevance, they are important for enhancing our understanding on the mineralogical systematics of the volcanic copper deposits and on the concentration mechanisms of copper.

Study of hydrothermal alteration paragenesis of lithic clasts of the Solfatara eruption deposits (Campi Flegrei, Italy)

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The Solfatara volcano (Campi Flegrei, Italy. 4.2 – 4.3 ka) is a maar volcano located in the central sector of the Campi Flegrei caldera. The eruption began with a phreatic phase, which deposited a stratified sequence of ash and lapilli beds bearing abundant altered lithic clasts and scarce juvenile material, followed by a series of magmatic Vulcanian explosions forming low eruption columns [Pistolesi et al., 2016, and reference within]. At present, fumaroles, hot pools and steaming ground occur in the Solfatara area, indicating the presence of an active hydrothermal system in the subsoil. The aim of this study is the characterization of the hydrothermal system, which was active in the area immediately before the Solfatara eruption by investigating the mineral paragenesis of the lithic clasts ejected in the early phases of the eruption (i.e. from the lowest part of the tephra deposits), studied through a petrographic and mineralogical approach. Analyses show that the main hydrothermal alteration paragenesis is formed by the association of mixed layers biotite-vermiculite, albite, adularia with subordinate illite and sulfides. This mineralogical assemblage is typical of a propylitic environment. The mineral chemistry allowed the application of the illite geothermometer [Battaglia, 2004] which suggests a formation temperature around 310 °C. These first results show some analogies with the hydrothermal alteration paragenesis found in the deep geothermal wells drilled in the area in the '80s [De Vivo et al., 1989], and may suggest the involvement of a high-T hydrothermal system in the dynamic of the Solfatara eruption.

The hydrothermal system prior to the 1873 phreatic eruption at La Fossa di Vulcano (Vulcano Island, Italy): first insights from a petrographic and geochemical approach

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Understanding the dynamics and triggers behind phreatic eruptions is crucial for assessing the hazard in inhabited and tourist volcanic areas. In this context, the study of hydrothermal alteration, which affects the mechanical properties of volcanic rocks by modifying (either increasing or decreasing) their strength and permeability, can help characterizing the magmatic-hydrothermal system active prior to eruptions. Specifically, the preservation of alteration facies in phreatic deposits provides information about the pre-eruption pH and temperature conditions of the hydrothermal system. La Fossa di Vulcano hosts an active magmatic-hydrothermal system characterized by significant degassing, evident in both the high-temperature fumarolic activity in the crater area and widespread soil degassing. In the fifteen years leading up to the last magmatic eruption of 1888-1890, La Fossa experienced explosive activity interspersed with intense fumarolic activity at its summit. Historical chronicles and stratigraphic and sedimentological analysis indicate that this period included phreatic events. Our analysis focuses on lithic material from the Breccia De Fiore deposit, associated with the phreatic activity of 1873, potentially the most significant phreatic phase of the 1873-1888 period. Petrographic and SEM-EDS analyses of the alteration of lithic clasts, combined with the trace element composition of the fine ash fraction (<63 micron), provide insights into the chemical and physical (pH and temperature) conditions of the shallow portion of the hydrothermal system before the eruption. The occurrence of hydrothermally altered clasts showing advanced argillic and silicic alteration facies suggests the presence of a shallow hydrothermal system at La Fossa before 1873 similar to the present system, corresponding to alteration conditions in which fluids with low pH ($2 < \text{pH} < 4.5$) and temperatures not exceeding 200-250°C were involved. On the other hand, evidence of high-temperature fluid fluxing was recorded by lithic clasts representing a poorly altered rhyolitic plug. These findings suggest that integrated petrographic and geochemical studies on lithic clasts from phreatic eruptions can provide insights into the pre-eruptive conditions of the magmatic-hydrothermal system and potentially identify trigger mechanisms for such eruptions.

Combining Rn and Sr isotopes measurement to track fluid-rock interaction at the active Campi Flegrei volcano: a framework study

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Isotopes are widely used in the Earth sciences providing exclusive information to unravel geochemical processes, especially when variable isotope systematics are combined. Hydrological processes are generally investigated by coupling major elements contents (e.g. Cl, SO₄, HCO₃, K, Mg, Na etc) with isotopes constituting fluids, i.e., oxygen (O), hydrogen (H), carbon (C), sulphur (S), whilst minor applications involve radon (Rn) and strontium (Sr). Radiogenic Rn and Sr isotopes have peculiar features that help to track several hydrogeological processes such as i. complex fluid-rock exchanges, ii. ascending vs. infiltrating dynamics and iii. groundwater-marine water interaction/mixing. These processes contribute to the formation of a wide range of mineral deposits and could be associated to wall-rock alteration in hydrothermal and geothermal volcanoes.

Sr isotope systematic is a powerful method to distinguish fluid components and trace their mixing and contamination processes, allowing to follow saltwater intrusion in coastal settings or long-lasting deep aquifers. ⁸⁷Sr/⁸⁶Sr of groundwater, in fact, reflects the isotopic signature of the source water plus its interaction with the surrounding rocks, along the flow path through the permeated rocks. Strontium, as the O, H and S isotopes also integrate conventional minero-petrological techniques into the investigation of the altered solid matrix.

On the other hand, ²²²Rn is a non-reactive and high mobile noble gas that occurs in hydrogeological settings with a relatively short half-life (3.82 days) as an effect of rock pore-water exchanges, plus faraway radiogenic sources supply and/or aquifer boiling. It provides a way to track inputs from endogenous venting or surface waters, to distinguish between deep-derived radioactive saline waters and radon-free marine waters, to assess different physical conditions and to investigate sealing vs. fracturing processes.

In this work, we combine ²²²Rn and ⁸⁷Sr/⁸⁶Sr data with the aim of building a framework to discriminate hydrothermal fluids and furnishing additional tools to investigate water-rocks interaction at the active Campi Flegrei volcanic caldera, southern Italy. We analysed 22 intra-caldera waters with temperature and pH values ranging from ca. 17 to 91.5°C and from 1.5 to 8, respectively, and compositions from chlorine to bicarbonate to sulphate. Samples represent different hydrological settings within the caldera with the hotter acidic sulfate waters characterizing the active discharge and hydrothermally altered areas of Solfatara and Pisciarelli. Water sites can show: 1) constant ²²²Rn and ⁸⁷Sr/⁸⁶Sr, 2) variable ²²²Rn and ⁸⁷Sr/⁸⁶Sr, 3) variable ²²²Rn and constant ⁸⁷Sr/⁸⁶Sr. As a whole, ²²²Rn and ⁸⁷Sr/⁸⁶Sr are generally scattered. Most waters have the Sr isotope ratio of 0.7076-0.7077, likely in equilibrium with the most common host rocks reservoir, whilst the radon ranges between 0 and 1300 Bq/L reflecting more complex physico-chemical processes associated to the pore-rock interaction and/or deeply geothermal supply. Waters closer to the coastline characterize for a ²²²Rn decrement as the ⁸⁷Sr/⁸⁶Sr increases towards the seawater values over time. These variations could be related to tides, seasonal fluctuation and/or groundwater-marine water interaction, which in turn are possibly affected by the current ground uplift occurring in the caldera.

The water sampling was repeated in order to check data reproducibility and track possible

chemical variations through time of Rn and Sr isotopes. These isotopes were determined for the first time at the Campi Flegrei, in order to further investigate known processes and integrate monitoring outcomes.

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Inferences from plants studies and environmental radioactivity at the Maccalube natural reserve (Ag)

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This research is devoted to the characterization of the Maccalube di Aragona reserve (Ag, Italy) in terms of environmental radioactivity and plants' activity. The interest for such area is born in the context of mud volcanoes dynamics, being the reserve a wide area where several gryphons and pools are located. The latter emit for 97% methane and, in a small quantity, hydrocarbons and water with high salinity [Etiope et al. GRL 2002; Bonini, Tectonophysics 2009; Cangemi & Madonia 2013]. Time to time, one of these volcanoes undergoes a paroxysmal as occurred in the past 2014, when two children died for a sudden explosion. The shallow activity of these emitting centers and/pools is related to the fluid in overpressure state which make their way to the surface producing the typical cone shape. It is well known the mud volcanoes are hazardous and recently much attention is devoted to them. Promud project (<https://progetti.ingv.it/it/promud>) aims at characterizing the reserve from geophysical, seismological, geodetical, and plant biodiversity point of view in order to develop a protocol also for civil protection. In line with previous thoughts, we performed two field surveys for assessing the environmental radioactivity. Thus, we measured, in the first campaign, radon in soil gas, coupling the detector RAD7 DurrIDGE with a surface soil accumulation chamber. Then, in the second one, we performed radon (²²²Rn) and thoron (²²⁰Rn) measurement by using the same instrumentation, set up and protocol. Such recordings allowed us to better constrain the source location in a compact clay layer.

Additional information about the interaction between soil properties and the reservoir can be obtained by investigating the plants able to survive in this extreme environment. Abiotic stressors in agriculture, such as drought, salinity, heavy metals and other environmental conditions, pose significant challenges to agricultural productivity [Agudelo et al. Foods 2021]. These stressors disrupt vital physiological processes resulting in decreased crop yields and compromised quality. To reduce the impact of abiotic stresses, strategies such as cultivating stress-tolerant plants and implementing effective management practices could enhance plant resilience. Consequently, this aspect of the investigation seeks to enhance comprehension of these species specialized metabolite production and their responses to the stress conditions present within "Maccalube" mud volcanoes. Furthermore, the study aims to obtain data pertaining to the dynamics of these volcanoes. The results of this study may also elucidate the advantages of these plants, and the potential use for agricultural purpose. To this end, Suaeda vera, a halophytic plant belonging to Amaranthaceae family with the ability to survive within extreme environmental conditions, has been collected. A preliminary phytochemical characterisation of the hydroalcoholic extract of S. vera aerial parts was conducted via liquid chromatography-high resolution mass spectrometry (HRESIMS) and NMR. This analysis led to the identification of a plethora of specialized

metabolites belonging to various classes, such as flavonoids, phenolic acids, and their glycosides, alkaloids, and fatty acids. A metabolomic profile of the plant was also compared with that of a sample of *S. vera*, which was collected in a different reserve located in Saline di Cervia (Ravenna, Italy) and environmental conditions. This showed a similar metabolomic profile, with the exception of sulphated flavonoids, which were observed to be synthesised only by the plant collected in the Maccalube area.

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The GNSS - TEC analysis of Mt.Etna lava fountains

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Solid Earth and fluid Earth are two open systems exchanging energy continuously with many geodynamical processes (e.g. earthquakes, volcanic eruptions, tsunamis, thermal radiation). Volcanic eruptions belong to these processes because they determine an interaction between lithosphere (or hydrosphere) and atmosphere. For example, the evolution of an eruptive column is a coupling process between lithosphere and lower atmosphere but, during an explosive volcanic eruption, other energy releasing occur like acoustic – gravity waves (AGWs) that can reach the upper atmosphere too [Astafyeva, 2019; Meng, 2019]. The advent of satellite systems in the last 50 years allowed to work out some detection techniques of volcanic activity, for example those based on microwaves, thermal radiation, radio occultation and ionospheric monitoring.

The ionospheric monitoring in terms of TEC analysis (Total Electron Content) represents a new research field to study volcanic eruptions with satellite technology as Global Navigation Satellite System (GNSS) [Manta et al., 2021]. TEC is an estimation of the total electron density of the ionosphere in terms of TEC Unit ($1 \text{ TECU} = 1 \cdot 10^{16} \text{ e} \cdot \text{m}^{-2}$) [Mannucci, 1993]. We retrieve TEC variations from GNSS observables by Variometric Approach for Real-time Ionosphere Observation (VARION) algorithm [Ravanelli et al., 2023; 2021].

We analyzed fountain activity of Mt.Etna between 2012 – 2021 characterized by Mass Eruption Rate peak $Q_{\text{max}} \geq 1 \cdot 10^6 \text{ kg} \cdot \text{s}^{-1}$. The morning large scale lava fountain (LSLF) occurred on December 4th, 2015 is upon clearest TEC signatures characterized by peak $A \sim 0.5 \text{ TECU}$, apparent horizontal velocity $V_{\text{HA}} \sim 170 - 250 \text{ m} \cdot \text{s}^{-1}$ and frequency $f \sim 1 - 1.5 \text{ mHz}$ by FFT spectral analysis (Fast Fourier Transform). We applied Empirical Mode Decomposition (EMD) technique to verify TEC signature by physical meaning of its components, namely Intrinsic Mode Functions (IMFs) [Huang et al., 1998]. One IMF characterizes TEC signature with TEC peak $A \sim 0.3 \text{ TECU}$ and frequency $f \sim 0.5 - 1.5 \text{ mHz}$. These results, specially V_{HA} and f , agree within literature ones for gravity waves of Co-Volcanic Ionospheric Disturbances (CVIDs).

CVIDs reported in literature are from $\text{VEI} = 2$ to $\text{VEI} = 6$. However, different volcanic explosive eruptions cause different TEC signatures: from impulsive N-shape one-cycle signature for single explosions (like Vulcanian style) to multi-cycle wave train for long-lasting eruptions (like Plinian style) [Cahyadi et al., 2021]. Mt.Etna TEC signatures for December 4th 2015 are an intermediate term. Other TEC signatures are detected for the April 12th 2012 lava fountain from South-East Crater. The picking times in ionosphere for these two lava fountains are different but the frequency content is similar.

The focus of the research is to understand the coupling processes between the lithosphere and the ionosphere induced by volcanic activity. The ionospheric detection of volcanic eruptions (ionospheric volcanology) represents a new research field to classify volcanic eruptions, to study eruptive column uprising processes, to detect remote volcanic activity without ground monitoring network, to implement the study of the LAIC (Lithosphere – Atmosphere – Ionosphere Coupling) in the context of seismology and tsunami early warning systems.

The 2011-2023 lava fountains at Etna unveiled by high-precision strain changes

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Lava fountains at Etna volcano are spectacular explosive eruptions emitting hot and powerful jets of gas and solid particles up to kilometres above the crater rim. The ash dispersal and fallout cause several problems both to the air traffic and to the inhabited areas. For these reasons, the Etna eruptive activity is routinely monitored by the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE) which provides a precious support to Civil Protection Authorities during volcanic events.

From 2011 to 2023, more than 100 lava fountains occurred at Etna volcano. A high variability in terms of portion of effusive flow, explosiveness and duration was observed among such eruptions. Indeed, the lava fountain at Etna is a gradual process starting with a mild Strombolian activity that evolves in lava fountaining and eventually leads to a sustained eruptive column. The duration, the magnitude and the intensity of these different eruptive phases characterize the lava fountain and the related eruptive style.

Lava fountains at Etna produce short-term (about few hours) and very small deformation (less than 1 microstrain) and with the highest resolution (10^{-10} – 10^{-11}) achievable among the geophysical instruments, making this sensors essential to record the tiny co-eruptive strain changes associated with lava fountain events. The analysis of such strain variations provides useful information about such eruptions. In particular: the beginning and the end of the strain variation marks the timing of the event [Bonaccorso et al., 2016, J. Geophys. Res. B: Solid Earth]; the amplitude of the co-eruptive strain variation is related to the total eruptive volume and thus to the magnitude of the event [Bonaccorso et al., 2023, Geophys. Res. Lett.]; the derivative of the strain signal (strain rate) is associated to the speed of magma ascent and thus to the intensity of the eruption. Recently, Carleo et al. [2023, Nat. Hazards Earth Syst. Sci.] applied machine learning techniques to strain data to characterize the 60 lava fountains occurred at the South East Crater (SEC) at Etna in 2020-2022. They found three main strain signal features, the amplitude, the duration and the initial strain rate that highlight the analogies and the differences among the 2020-2022 lava fountains from the related strain variations and group them in four well distinct clusters.

In this work, we use the approach developed by Carleo et al. (2023) to analyze all the lava fountains occurred at the SEC in the time period 2011-2023. The analysis of all the strain variations associated with the eruptive events provides a clearer picture of the different characteristics that the strain signal exhibits during the lava fountains giving insights into the different eruptive styles that these explosive eruptions involve. Such information are fundamental to better assess the hazard associated with these events and thus support Civil Protection Authorities in decision-making tasks for risk mitigation of future volcanic events.

Small-scale intrusive episodes (micro-dykes) at Mt. Etna: The November 15, 2022 case

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On November 15, 2022, tilt changes, accompanied by a shallow seismic sequence at the summit, highlighted the occurrence of a small-scale intrusive episode (here defined as micro-dyke) without leading to the opening of eruptive fissures at the surface.

We propose a multidisciplinary interpretation on the recorded data (tilt, earthquakes and volcanic tremor) within the framework of Etna's volcanic activity. Using tilt data, we image a dyke-like source of about 600x150 [m], located under the summit area at a height of about 1.2 [km] above sea level. We evidence that intrusion, starting from the South-East crater conduit, activated the highly fractured South Rift zone, giving rise to the recorded seismic swarm and causing observed volcanic tremor fluctuations. We find a notable temporal correlation between the main phases of the ongoing dyke-forming intrusion and the occurrence of the seismic swarm. Considering the earthquake's focal mechanisms, we discuss the cause-effect relationships with the intrusion, through a Coulomb stress analysis, finding that the seismic swarm is promoted by the dyke. Contemporaneously, also the volcanic tremor oscillations synchronize perfectly with the opening and stopping phases of the magmatic intrusion, showing the highest peaks when the dyke slows. 'Micro-dyke' intrusions can finally be detected thanks to high-precision instruments such as tiltmeters and/or strainmeters installed in the last decade, otherwise they would currently be "invisible" with other ground deformation monitoring techniques. This aspect becomes crucial to better understand the role that this type of dyke may have in the future development of Etna's volcanic activity.

Framework for Evaluation of Early Detection Systems (FEEDS)

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Monitoring volcanic activity presents a formidable challenge due to the intricate nature of volcanic processes and the diverse eruptive behaviours observed across different volcanoes. Early Detection (ED) systems have emerged as indispensable tools for mitigating potential risks associated with volcanic eruptions. However, the effectiveness of these systems relies heavily on their ability to deliver timely and accurate alerts. False alarms or missed warnings can have severe economic repercussions and jeopardize infrastructure and lives. Additionally, insufficient data on target cases may compromise ED systems' reliability and robustness. Hence, the evaluation of these systems is paramount for effective hazard mitigation and for refining and optimizing their functionality. Nevertheless, developing such systems is a complex and demanding task, requiring a profound understanding of advanced techniques and meticulous parameter calibration.

To address these challenges, we present the Framework for Evaluation of Early Detection Systems (FEEDS). FEEDS is a Python-based package meticulously designed to automate the evaluation of generic ED systems' generalization capability through Monte Carlo cross-validation. The framework introduces a versatile class representing the ED model identified solely through data, facilitating a systematic evaluation based on crucial predictive parameters such as True Positive Rate, False Discovery Rate, prediction time, and Fraction of Time in Alarm, achieved through simulations.

To validate the effectiveness of FEEDS, we leveraged tiltmeter and strainmeter data collected at Stromboli volcano between 2007 and 2019. These datasets, managed by Istituto Nazionale di Geofisica e Vulcanologia and Università di Firenze, were utilized to implement FEEDS with a tailored model for the early detection of paroxysmal activity at the volcano during the study period. This practical application demonstrated the reliability and real-world applicability of FEEDS in volcanic monitoring scenarios.

FEEDS may represent a significant contribution to ongoing efforts aimed at enhancing ED systems and their application in mitigating volcanic hazards. By automating the standard evaluation process, FEEDS simplifies system implementation, reduces user workload, and establishes a standardized approach for assessing the reliability and performance of various ED models, thereby advancing volcanic monitoring capabilities significantly.

Automatic detection and characterization of Very Long Period seismic events: an application on the Stromboli Volcano seismicity

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Real-time seismological applications are nowadays crucial for the monitoring and surveillance of active volcanoes, as they are useful tools for the early detection of possible volcanic unrest. At open-vent active volcanoes, Very Long Period (VLP) seismicity, typically associated with mild and persistent explosive activity, is of crucial importance for volcano monitoring, as its variations in occurrence rate and magnitude may prelude a phase of unrest. Here we show a new method for the automatic real-time detection and characterization of VLP seismicity at Stromboli active volcano (Italy).

The detection algorithm is based on the Three-Component Amplitude (TCA) obtained from waveform polarization and spectral analysis of the continuous recording, providing time of detection, azimuth, incidence, amplitude, and frequency of the detected VLP events. The VLP amplitudes from all stations of the network, provided as peak-to-peak amplitudes and as real-time root mean squared amplitudes (RSAM) are used to perform a real-time automatic localization of the VLP source using a 3D-grid searching algorithm that takes into account the geometrical spreading of the VLP waveform in the very near field.

VLP detections and characterization derived from our automatic algorithm are compared with those obtained from manual inspections of the seismic records available from INGV-OV VLP datasets. Here we show a comparison between manual and our automatic approaches in characterizing VLP seismicity, intending to estimate the reliability of the automatic method. Considering a period of 1 month during 2007, we achieved 7% and 14% of false and missed detection rates respectively. However, further analyses are underway to individuate optimized thresholds and parameters that will increasingly minimize false and missed detection rates.

A comparison over a period of approximately 20 years, from 2007 to 2023, shows that the VLP detection time series produced by the automatic algorithm tracks fluctuations in VLP activity, which are in good agreement with those manually derived by the analysts. This result allows the proposed algorithm to be included in a broader real-time monitoring and surveillance system for the Stromboli volcano.

Neolo: a Modular and Scalable System for Real Time Multiparametric Monitoring of Stromboli Volcano

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Real-time monitoring of an active volcano, due to the great variety of observable signals it produces, requires a multi-parametric approach. The acquisition of all the signals collected by sensors and detectors that are usually installed on volcanoes produces a great variety of data with different formats and sampling rates, and on which various processing and analysis activities must be carried out.

Stromboli, as an open-vent volcano in the Aeolian Islands, is characterized by a continuous mild explosive activity which can dramatically change without clear precursors into a more intense activity with the generation of paroxysmal explosions, pyroclastic flows and tsunamis. Stromboli's persistent activity is monitored in real-time by INGV, together with other research institutes, with the aim of promptly alerting the Civil Protection for any significant change in the volcanic activity which may lead to a more dangerous phenomena.

With the increase in the number of installed stations, measured parameters and acquired signals, and even more with the adoption of innovative analysis techniques (e.g. by using machine learning models), data processing can become more and more demanding in terms of machine resources. Therefore, traditionally designed software can be difficult to configure and operate and may suffer in terms of scalability, especially if proper levels of reliability and availability are to be guaranteed, as in real-time monitoring.

This work presents Neolo, the new system for multi-parametric monitoring of Stromboli volcano. Neolo is based on a modular and scalable platform designed at OV-INGV where several worker modules cooperate together, each with its own task. The modules execute as data-driven microservices in a containerized environment. The communication between them is guaranteed by an underlying high performance and low latency message queuing infrastructure. This is used not only to transport the output of the processing, but also for the data acquired by the sensors in real time. In this way horizontal and vertical scalability can be achieved simply by adding more nodes to the messaging systems and/or more container executor nodes.

Several worker modules have already been developed: importing and exporting of signals, filtering, interfacing with time series databases, seismic event detection, RSAM calculation, seismic VLP activity characterization and location.

Most of the code is written in python language and a base worker module is provided in order to let researchers easily develop additional modules that can be run on the system.

The system has also been equipped with internal monitoring features, with proper metrics exposed. In this sense, some dashboards have also been designed and developed to give full control over the engine, the workers and data processing.

Neolo has been operational for several months at the Osservatorio Vesuviano - INGV, in the testing phase and debugging phase. Recently Neolo has also been deployed at Stromboli to receive locally data from stations, in order to reduce as much as possible, the latencies induced by data transfer via the Internet, which for the island of Stromboli can sometimes become very slow. The original Neolo instance hosted in Naples still continues to operate to guarantee the redundancy of the analyses.

S15 - Oral Presentation

Enhancing Single-Station Seismic Event Detection Using Multiscale Entropy and Self-Organizing Maps

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The Campi Flegrei caldera is currently in an unrest phase and is experiencing both significant ground deformation and increasing seismic activity with magnitude ranging between negative values and the largest magnitude Md 4.2 occurred in September 2023. The availability of continuous recorded data provides a unique opportunity to test new event detection methods. Specifically, this study addresses the challenge of detecting seismic events in data characterized by a very low signal-to-noise ratio, due to high natural and anthropogenic noise that characterizes the area. The task is further hampered when the detection analysis is based on a single station. The present work aims to improve single-station seismic analysis by introducing an innovative methodology that integrates the Multiscale Entropy (MSE) algorithm with the algorithm of Self-Organizing Maps (SOM) and the STA/LTA technique to improve the clustering and analysis of seismic traces. Both MSE and STA/LTA values are employed as encoding features for the input vectors, which are required to configure the training phase of the SOM algorithm.

The proposed approach was applied to a continuous four-month data set recorded at a seismic station located in the Pisciarelli area. The entire seismic recording was segmented into one-minute windows. Subsequently, the STA/LTA ratio and the MSE values were computed for each signal in order to train the SOM Map. The STA/LTA ratio is estimated by selecting a short-time window and a long-time window of 1s and 30s, respectively. Meanwhile, MSE values are calculated over 20 time scales, performing a coarse-graining operation on the original data for each time scale. This feature extraction process aims to effectively distinguish seismic events from background noise and detect transient signals not included in the existing seismic catalogue. The training phase produces a two-dimensional SOM Map consisting of 6x6 nodes, each containing a portion of input vectors. The effectiveness of SOM as a data projection and visualization tool is due to the fact that nearby nodes in the map collect signals that share similarities in the extracted features.

The resulting SOM Map revealed that both catalogued and uncatalogued seismic events fall in a few specific nodes, with non-catalogued events constituting about 20% of inputs in these nodes. These findings underscore that MSE and SOM integration can improve the distinction between noise signals and seismic events, thus facilitating the identification of transient signals.

Moreover, the results highlight the potential for refining seismic data analysis techniques, leading to more efficient event detection - also when a single station is used - within the extensive active volcanic area of Campi Flegrei.

Continuous gravity observations at Campi Flegrei caldera: Analysis of tidal and non-tidal signals as a contribution to volcano monitoring

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We present the results of about 18 months of gravity recording acquired at the active caldera of Campi Flegrei (CFc). CFc is one of the three active volcanoes in the Neapolitan area (Southern Italy), and is currently the most active one. In fact, the CFc is undergoing a period of unrest characterised by slow uplift of the ground, accompanied by seismicity and intense fumarolic emissions. Due to the increased intensity of the volcano dynamics, a permanent gravity station equipped with a gPhoneX spring gravimeter was installed to enhance the geodetic monitoring programmes. The purpose of the continuous recordings is to complement the time-lapse observations carried out periodically on networks of benchmarks, in order to continuously monitor the short-term gravity signals. We report on the various processing steps and analyses performed to obtain reliable parameters of the Earth's tides, non-tidal corrections and gravity residuals. The various methodologies employed to investigate the instrumental drift are also elucidated in depth, because it may masquerade the elusive gravity changes resulting from mass fluctuations within the volcanic and geothermal systems. Residual gravity signals, retrieved from the recordings, after reduction of body and ocean tides, polynomial drift, atmospheric, tilt and change of the Earth Orientation Parameters (EOP) effects, appear to be uncorrelated with hydrology, while they show a clear correlation with the most energetic earthquakes, that strongly characterise the current bradyseismic crisis. The residual gravity signals display peculiar trends characterized by steps or offsets (up to about 600 nm s^{-2}) and transients in coincidence of the most energetic volcano-tectonic events ($M_d > 2.5$) and seismic swarms. The steps in the gravity residuals are likely to be of instrumental origin, while the amplitudes of the observed transients are not consistent with co-seismic or volcanological phenomena, for which there is no evidence from other monitoring techniques. Unfortunately, the lack of repeated absolute gravity measurements severely limits our ability to attribute the observed gravity variations to endogenous signals. From the analysis of the gravity records, reliable tidal gravity models have been derived, which will improve the accuracy of volcano monitoring by allowing a precise reduction of tidal effects for both relative and absolute gravity measurements taken in these volcanic areas.

Experiences of long-term seafloor displacement measurements in the Gulf of Pozzuoli, Campi Flegrei volcanic area

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Various geodetic seafloor measurement techniques are well established and routinely applied, primarily based on acoustic methods. These techniques are broadly used mainly in the deep seafloor where the sound velocity remains stable over time due to the stable physical properties of seawater. Regarding the vertical component of seafloor deformation, measurements of water column pressure are also used, either continuously or in periodic measurement campaigns. However, it should be noted that these techniques are now widely applied mainly for measuring rapid position changes and in deep waters.

In coastal areas, several factors make measurements with permanent seafloor instrumentation challenging. These include:

- A strong proliferation of marine life on the instrumentation, which can alter its functioning; this necessitates the retrieval of the instruments periodically and then repositioning it close to its original location;
- Fishing activities that can cause frequent movements or even partial removal of the instrumentation that can permanently damage it;
- Great variability in the time of the physical properties of the water column, mainly of the temperature and salinity.

All this make it difficult to apply the previously mentioned techniques in coastal areas with shallow waters (depth 200 m). Consequently, for monitoring ground deformations in the Gulf of Pozzuoli, characterized for the most part by a bathymetry of approximately 100 m depth, new methodologies have been developed.

Since April 2016, in the marine sector of the Campi Flegrei caldera, a permanent marine infrastructure, named MEDUSA, has been established to extend the onshore monitoring system managed by OV-INGV to the sea. MEDUSA consists of four marine monitoring stations, each comprising a buoy equipped with a geodetic GPS and connected by cable to a seafloor module hosting geophysical and oceanographic sensors. The cables provide power, communication, and GPS clock timestamps to each of seafloor modules, which includes a three-component broadband seismometer, a MEMS accelerometer, a low-frequency hydrophone and a high-resolution bottom pressure recorder (BPR) based on quartz technology. The buoy's power supply system consists of rechargeable batteries connected to solar panels. Data from the MEDUSA system's scientific and status sensors, comprising of approximately 110 data channels, are transmitted in real-time and continuously via UMTS-4G LTE mobile links to the INGV-OV Monitoring Center in Naples, where they are integrated with data from permanent land networks.

Therefore, the long-term seafloor movements related to volcanic activities in the area have been continuously measured by the GPS of the MEDUSA buoys. The acquired data show continuous uplift, even of the submerged part of the Campi Flegrei, with vertical deformation values of about 65 cm measured for the site closest to the area of maximum deformation and lower values for sites

farther away. The time trend of vertical deformation is clearly similar to that of the onshore stations. Furthermore, GPS measurements are used as a benchmark to develop a new methodology for obtaining seafloor vertical movements using absolute bottom pressure data acquired by the BPRs. The pressure data are transformed into equivalent water level changes by integrating BPR data with tide gauges and atmospheric pressure data. Thus, seafloor vertical deformation measurements from BPRs at two different sites in the Pozzuoli Gulf have been obtained with an accuracy comparable to that of the GPS stations installed on MEDUSA buoys. The comparison between the deformation trends obtained using BPRs and GPSs clearly demonstrates the reliability and accuracy of the BPR sensors in measuring the vertical component, even in shallow water. The advantage of using BPRs is that they are cost-effective instruments capable of working autonomously. Thus, they are particularly suitable for implementing instrumented modules that are easy to manage, allowing the acquisition of seafloor deformation measurements at other sites in the Gulf of Pozzuoli to better define the deformation field in the submerged part of the caldera. In the presentation we will show the data acquired and the ongoing activities for the development of a permanent network of BPRs.

From the detection of monitoring anomalies to the probabilistic forecast of the evolution of volcanic unrest: an entropy-based approach

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Owing to the current lack of plausible and exhaustive physical pre-eruptive models, often volcanologists rely on the observation of monitoring anomalies to track the evolution of volcanic unrest episodes. Taking advantage from the work made in the development of Bayesian Event Trees (BET), here we formalize an entropy-based model to translate the observation of anomalies into probability of a specific volcanic event of interest. The model is quite general and it could be used as a standalone eruption forecasting tool or to set up conditional probabilities for methodologies like the BET and of the Bayesian Belief Network (BBN). The proposed model has some important features worth noting: (i) it is rooted in a coherent logic, which gives a physical sense to the heuristic information of volcanologists in terms of entropy; (ii) it is fully transparent and can be established in advance of a crisis, making the results reproducible and revisable, providing a transparent audit trail that reduces the overall degree of subjectivity in communication with civil authorities; (iii) it can be embedded in a unified probabilistic framework, which provides an univocal taxonomy of different kinds of uncertainty affecting the forecast and handles these uncertainties in a formal way. Finally, for the sake of example, we apply the procedure to track the evolution of the 1982–1984 phase of unrest at Campi Flegrei.

Mefite lake monitoring by high-frequency TIR images

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The high sampling rate of TIR images enabled the detection of unexpected thermal variability in a vent emission. Modern sensors can detect temperature variations, affecting the entire field of view as well as the single pixel, which ranges down to a fraction of a degree Celsius with a short time duration on the order of minutes. However, frequency peaks may occur in the periodogram due to sampling fluctuations. A technique originally designed to analyze light curves in astrophysics, which assesses the significance of peaks in the periodogram within the context of red noise data, is now being applied to thermal series. This method enables the examination of periodic components against a background noise spectrum assumed to exhibit a power law shape. It offers a straightforward and rapid means of evaluating the significance of candidate periodic signals in a short, well-sampled time series. It has been used on temperature time series collected at Mefite D'Ansanto cold CO₂ emission in the frame of FURTHER (The role of FIUids in the pReparaTory pHase of EaRthquakes in Southern Apennines) project. Periodogram fits revealed a $1/f^p$ ($p > 1$) noise with characteristic frequencies of 2.2 min, 3.5 min, 4.5 min, 8 min, 10 min, and 26 min of apparent variations at a 95% confidence level. Factor analysis on the same set of sampled pixels revealed the sectors of the monitored area with the same behavior, which was confirmed by wavelet analysis. The correlation analysis evidenced the interrelation among monitored pixels underlying the complexity of the site, probably due to the presence of water. This technique has demonstrated its efficacy and versatility, making it a valuable asset in the realm of geothermal monitoring. Its applicability extends across various aspects of geothermal monitoring, from detecting subtle variations in temperature gradients to identifying periodic patterns indicative of underlying geological processes.

Advanced SHM Techniques for Aerospace Structures: Potential Applications in Volcanology

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In this paper, an overview of recent work in the field of structural health monitoring for aerospace structures, with a focus on ultrasonics, time reversal, and thermal wave imaging will be presented. Latest research significant advancements in nonlinear ultrasonic-based Non-Destructive and Structural Health Monitoring systems, impact detection systems, and smart multifunctional materials will be discussed.

The talk will potentially stimulate ideas on how these techniques can be applied to the monitoring and prediction of volcanic activities. For instance, the use of ultrasonics and time reversal methods can enhance the detection and localization of acoustic emissions, while thermal wave imaging can provide valuable anomalies in thermal properties of volcanic areas.

Furthermore, the integration of these advancements with digital twins, virtual replicas of physical systems, opens up new possibilities for real-time monitoring and prediction of volcanic activities. This integration could provide valuable contributions to the field of volcanology, offering more precise and efficient methods for hazard assessment and risk management.

A temporary seismic network to study the seismicity of Pantelleria Island

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Pantelleria is an active volcanic island with a fumarolic and hydrothermal activity so much so that it represents an interesting geothermal target as it presents high temperature gradients. This peculiarity has made it the protagonist of a project (Panta-Rei) which aims to characterise the geothermal reservoir of the island and to assets of its geothermal potential. Following the activity of the project we installed a temporary seismic network to enhance the monitoring of seismic activity and characterising background seismicity. Here we describe the design and installation of the temporary network code 'YM', giving also a preliminary analysis on the performance. Although it is an active volcano, the island doesn't show, apparently, typical volcanic-tectonic earthquakes. However, this is due to the lack of a local seismic network to detect earthquakes from 2022 onwards. Thanks to the 4 short period stations of the YM temporary network, on the island, currently, are installed 8 seismic stations. The four temporary sites, mainly concentrated in the central-southern portion of the island, were chosen after a seismic survey carried out in September 2023, performed to test the site response and to evaluate both the background noise level and the logistics of the installations. We installed the temporary stations in march 2024, also minimising visual impact of the solar panels and the instrumentations. All the stations are working regularly and the data are transmitted via LTE in real time stored on a server in Naples. Our analysis, performed on the first month of seismic data acquired, indicates that the stations of the temporary network have low seismic noise levels compared to the reference models, indicating a high quality of the recorded waveforms and a good potential in detecting seismic events with low energy as well.

Multiparametric exploration of active magma degassing at Mt. Etna in 2023

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Active magma degassing is the release of slightly over-pressurized gas pockets from volcanic vents. This activity can shed light on the geometry of the shallow plumbing system of volcanoes and its internal dynamics. During a summer 2023 field campaign, we conducted comprehensive recordings, including thermal infrared, high-speed, and high-resolution video, as well as broadband microphone signals, capturing ten consecutive days of active degassing events at the Bocca Nuova crater of Mt. Etna. Two distinct vents exhibited notable degassing activity. The first, henceforth referred to as 'Sboffer,' was a crater characterized by the emission of loud, low-frequency sounds accompanying each degassing event (hence the name). The second vent, smaller than the first one and designated as 'Ringer,' took the form of a circular pit on the Bocca Nuova crater floor, emitting volcanic vortex rings—reminiscent of smoke rings (hence the name)—during events. We focused our analysis on the thermal data, characterizing emissions from both vents by examining brightness temperature anomalies along horizontal measurement lines in the thermal video recordings. Both vents exhibited a bimodal distribution in the intensity and duration of events. Specifically, Sboffer produced larger events with a mean amplitude of 100-160 °C and a recurrence time of approximately 500 seconds, along with smaller events with amplitudes of 20-24 °C occurring every 200-400 seconds. Ringer, on the other hand, featured larger events with amplitudes of 70-100 °C and smaller events with amplitudes of 20-23 °C, occurring at much higher frequencies of every 4 and 1.5 seconds, respectively. The maximum temperature recorded during the larger events reached nearly 600 °C for Ringer and 500 °C for Sboffer. The exit velocities for large events were measured at 15 m/s for Sboffer and 10 m/s for Ringer. Remarkably, all parameters at both vents remained consistently stable throughout the ten-day observation period. Preliminary investigations were conducted to explore potential correlations between the acoustic signal and thermal data. The aim was to ascertain the depth of the explosive events and examine potential correlations with temperature variations and the intensity of the explosions.

The Central-southern Aeolian islands: Volcanism and tEARing in the Tyrrhenian subduction system (CAVEAT)

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CAVEAT is a multidisciplinary project that aims to unravel the local lithospheric structure, the pattern of crustal deformation and the geochemical signature of the Central-Southern Aeolian Islands. New geochemical and geophysical data will be acquired to provide a broad overview of the ongoing geodynamics of the southern Tyrrhenian region and will allow us to properly study the interplay of present-day tectonics and volcanic deformation and the related role and nature of the fluids and the hydrothermal activity.

The Western and Central-Southern Aeolian Islands (CSAI) nested between two major tectonic structures as highlighted by a large number of geological and geophysical studies in the last decades, the oldest (~2 Ma) Sisifo-Alicudi and the youngest Aeolian-Tindari-Letojanni (~0.8 Ma) fault systems. These two nearly vertical tear structures progressively accommodated the deformation caused by the slab migration beneath the Calabrian Arc that, in turn, caused the opening of the south-eastern Tyrrhenian basin.

The project plan is to provide a complete catalog of 20-years seismicity, including new data from a temporary seismic experiment deployed in the Fall 2023 and previous experiments carried out in Lipari 2018 and Vulcano 2021. Automatic modern algorithms will be applied to the continuous time series to disclose hidden events and to lower the completeness magnitude of the whole catalog. The derived enhanced catalog will be used to reconstruct the 3D seismic structure at local and regional scales through body wave velocity and Q-coda attenuation tomography, and also increasing the spatial resolution of the velocity anomalies at local scale by using Ambient Noise Tomography.

We will also update the surface deformation field of CSAI by analyzing all GNSS data collected in the last decades and we will survey the existing benchmarks to extend back in time (26 years) the history of ground deformation and new self-centering benchmarks on the Salina island to allow a better definition of the crustal deformation over the northernmost sector of CSAI.

We are investigating the spatial distribution of soil gas emissions to define preferential pathways of fluid migration and identify active tectonic structures, which are high permeability vehicles for deep fluids to reach the Earth's surface.

New airborne gravity observations will be compared and integrated with the ground-based gravity data, both available or newly acquired, and with the large-scale information derived by recent satellite missions.

A further relevant objective of CAVEAT is to strengthen the collaboration among INGV researchers in order to advance the understanding of the geodynamic processes and thus to contribute in reducing the impact of natural hazards in the southern Tyrrhenian region. The collaboration of INGV scientists with researchers from CNR-ISMAR, UniGE and UNAM (see the participants list) will bring together different expertise to stimulate and encourage the multidisciplinary approach of the proposed research.

The Pernicana Fault System (Mt. Etna, Sicily): 4 decades of ground deformations studies and inferences to flank and magma dynamics

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Mt. Etna volcano is located along the eastern coast of Sicily. In this region, the general N-S compressive regime related to the Africa – Eurasia collision interacts with the WNW-ESE extensional regime associated to the Malta Escarpment dynamics, observable along the eastern coast of Sicily, which allow a differential rollback of the subducting Africa plate between the continental (Sicily) and oceanic (Ionian) crusts. The complex tectonic setting resulting from this interaction produces an asthenospheric window allowing magma to rise from under the Africa plate to the top of the Ionian slab, and then to Mt. Etna volcano through tensional structures cutting the lithosphere.

A general eastward motion of the eastern flank of the volcano has been measured with always increasing detail and its relationship with the eruptive and magmatic activity is being investigated. The complex interaction between regional stress, gravity forces and dike-induced rifting of Mt. Etna, seems to have a role in the eastward movement of the Mt. Etna eastern flank. In this context, the Pernicana Fault system identifies the northern boundary of the mobile sector, together with the North-East Rift zone (NERZ). It is formed by discrete segments, arranged in a right stepping en-échelon configuration, of a left-lateral shear zone that dissects the north-eastern flank of Etna. Its kinematics is related to shallow seismic events ($M \sim 4.0$) occurring along the western segment, with dip-slip displacement and left-lateral components. The eastern segment, ESE trending, shows only aseismic creep with purely left-lateral displacement.

The Pernicana Fault system is the subject of many structural and geodetic studies since the 70s of the last century. In this contribution, a long lasting multidisciplinary geodetic data set has been analyzed: levelling, EDM, tiltmeters, InSAR and GNSS.

Earliest measurements started at the end of seventy years and were carried out by using levelling and Electronic Distance-meter (EDM) techniques. The levelling route on Mt. Etna is 150 km long and consists of 200 benchmarks; part of which crosses the Pernicana fault, at an altitude of 1500 and 700 m a.s.l. The North-east EDM network covered the NERZ and the uppermost part of the Pernicana. In the same period, the long-base tiltmeter at the Pizzi Deneri Observatory, close the North-East Rift zone, has been installed. The first GPS campaign was carried out on Mt. Etna on 1988 and from then its configuration has been continuously improved. Two local GNSS networks lie across the eastern segment of the Pernicana fault. The first one, located in the “Rocca Campana” area, was installed in April 1997; the second one, located a few kilometers westward, in the “Rocca Pignatello” area, was measured for the first time in July 2002 upgrading a former EDM network. The aim of these networks is to detail the structural framework and displacements along the aseismic sector of the Pernicana fault. Finally, the beginning of the InSAR measurements at the end of nineties allows tracking the path of the Pernicana fault from the NERZ to the coastline.

All these datasets show that the dynamics of the Pernicana Fault system is characterized by episodic accelerations of the movement that can last years, likely related to seismic crises and eruptive activity. The eastwards motion abruptly disappears north of the fault, producing a background left-lateral transcurrent kinematics at a rate of about 20-30 mm/y. Integration of this wide spectrum of geodetic data allows strongly constrain ground deformation pattern to be defined and modeled. Furthermore, the very long time series available for the different datasets on the Pernicana fault, allows its behavior to be investigated in time and its role and relationships in the framework of flank instability and eruptive activity, in order to better understood the transition from rest to unrest phases of this volcano.

Present-day ground deformation of Colli Albani volcanic district from the analysis of remotely sensed data

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Colli Albani is a quiescent volcano located about 20 km South of the city of Rome (Latium, Central Italy) whose activity started about 600,000 years ago [Marra et al., 2016] with the emplacement of pyroclastic flows, lava flows and lahar deposits during different periods of activity [Funicello et al., 2003]. Currently, the caldera is still considered active with periodic seismic swarms, ground deformations and gas emissions located mainly in the south-western part of the volcanic district, where the last phreatomagmatic manifestations occurred about 27 ka ago [Feuillet et al., 2004; Bianchi et al., 2008]. In addition, the numerous landslides that have been recorded through the years, catalogued within the Italian portal of the landslides phenomena, together with the high urbanization of the area and its proximity to Rome, make this area worthy of attention as it is exposed to volcanic risk.

Although the volcanic complex has been extensively studied in terms of geological, volcanological, geochemical and geophysical aspects [Funicello et al., 2003; Tuccimei et al., 2006; Bianchi et al., 2008; De Benedetti et al., 2008, Giordano G., 2010; Carapezza et al., 2012], the high spatial resolution assessment of the deformation state of the area, which can be obtained using satellite data, is lacking. In fact, the most recent results analyse deformations up to 2010 using Envisat and ALOS Synthetic Aperture Radar (SAR) data [Riguzzi et al., 2012; Marra et al., 2016].

This contribution is aimed to explore and update the ground displacement of the Colli Albani Hills through the application of the advanced multi-temporal SAR Interferometry (InSAR) technique named Small Baseline Subset [Berardino et al., 2002]. In detail, to assess the recent ground motion, for the first time, the dataset acquired by both Cosmo-SkyMed (CSK) and Sentinel-1 (S1) satellite missions have been exploited in a time period spanning from February 2016 to September 2023. Thanks to the availability of ascending and descending tracks for both CSK and S1 dataset, we were able to compute not only the motion along the satellite's Line of Sight, but also the horizontal (East–West) and vertical component of the displacement. Our results consist in ground displacement maps and related displacement time series over the Colli Albani caldera and surroundings. The outcomes were validated using geodetic measurements from six Global Navigation Satellite System (GNSS) stations located in the area and managed by INGV for monitoring purposes.

Both CSK and S1 results identified a small uplift area that corresponds to the south-western portion of the volcanic complex, comprising the area SW of Lake Nemi, at the Genzano di Roma municipality. Here displacement time series show an acceleration from mid-2016 until September 2017, then an oscillatory behaviour is noted, even if the oscillations are on the order of only a few millimetres. Generally, the time series trend is upward, characterized by CSK and S1 mean vertical velocity equal to 1.8 mm/yr and 1.2 mm/yr, respectively.

Concerning the S1 results, some uplift and subsidence signals are visible at the NE boundaries of the Colli Albani caldera (e.g., Monte Compatri and Rocca Priora) and at several industrial areas (e.g., Santa Palomba) located further West, respectively. Uplift rates in these areas are

characterized by centimetres oscillations attributable to atmospheric residuals, which were not completely removed during the processing chain. On the contrary, subsidence might be related to compression of superficial soils given by construction loading and/or lowering of the water table level due to intensive groundwater exploitation.

Therefore, the only satellite recorded signal that could be related to volcanic activity is the uplift confined to the south-western part of the caldera, precisely at the Genzano di Roma municipality. The uplift rate (about 1.5 mm/yr considering the average of CSK and S1 rates) appears to be smaller than that found out in previous works [e.g., Salvi et al. 2004] which considered InSAR products, hence suggesting no magma emplacement within the crust at least during recent years.

Vertical movements and seismic activity at Campi Flegrei Caldera (South Italy)

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The Campi Flegrei caldera is an active volcanic area located west of the city of Napoli. It consists in a ~ 12 km wide depression that is the result of at least two large eruptions: the Campanian Ignimbrite (39 ky ago) and the Neapolitan Yellow Tuff (15 ky ago). Last eruption occurred in 1538 and produced the Monte Nuovo tuff scoria cone. The Campi Flegrei caldera is characterized by bradyseismic phenomena, which consists in a slow subsidence or uplift ground movement. Generally, seismic activity accompanied ground uplifts whereas no seismic activity occurred during ground subsidence. To have a general overview on the bradyseismic phenomena, we realized a graph to show the vertical ground movement since 34 A.D to the present utilizing historical published data until 1900 (Di Vito et al., 2016), geodetic levelling data since 1905 (Del Gaudio et al., 2010) and, since 2000, GNSS data (Carbonari et al., 2023). In this graph, the significant ground uplift before the Monte Nuovo eruption is remarkable. An abrupt increment of the uplift rate valuable in about 11 cm/yr, accompanied by relevant seismic activity (Di Vito et al. 2016), occurred in about two years before the eruption. Several seismic events were felt in Napoli. Ground subsidence characterized the caldera after the Monte Nuovo eruption until the end of 1940s. Since 1950, the caldera alternates subsidence and uplift phases. Significant unrest episodes occurred in 1950-1952, 1969-1972 and 1982-1984 with uplift of about 0.7, 1.7, 1.8 meters, respectively, in the area of the maximum deformation, which corresponds to the city of Pozzuoli. Documented instrumental seismic activity accompanied the last two ground uplift episodes. This seismicity concentrates mainly around the area of maximum ground uplift, which correspond with the town of Pozzuoli, and in the Gulf of Pozzuoli, close to the already known structural lineaments. Since January 1985, once the 1982-1984 unrest episode was over, the caldera undergone a general subsidence until the 2004, lowering the ground level of about 1 meter with respect the maximum reached in December 1984. During this subsidence phase very few low magnitude seismic activity was detected and the most relevant seismicity ($M=2.2$) was recorded following some mini-uplift episodes (e.g. 2000; Gaeta et al., 2003). In 2005, signs of a new unrest phase, currently ongoing, detected. Compared to the previous 1969-1972 and 1982-1984 episodes, the ground uplift was much lower and accompanied prevalently by low seismic activity ($M1.5$) until about 2016. Since the second half of 2017, seismicity, often with swarms activity, become more relevant, both in number than in magnitude, following the increment of ground uplift rate. A further increment of the seismicity occurred in recent years following further increases of the ground uplift rate and in the summer of 2023 the ground altitude touched the maximum reached in the 1982-84 unrest episode in the area of maximum ground uplift. Between September and October 2023, two ≤ 4.2 events occurred following short and rapid positive variations in the ground uplift rate. The magnitude of these events is just higher than the magnitude of the most energetic events occurred in Campi Flegrei Caldera during the 1982-1984 unrest episode. Since October 2023, a decrease of the ground uplift rate occurred as well as seismic activity has undergone a sharp decrease. A new increment of seismicity occurred in the spring of 2024, following the recovery of the ground uplift rate, and on May 20 an $M=4.4$ event, followed by a remarkable seismic swarm constituted by about 180 events, occurred. This event is the most energetic one recorded since the first seismic stations, in 1970, were installed in the Campi Flegrei Caldera.

S15 - Poster

Use of signal distortion as indicator of volcanic activity: a practical implementation exploring the gravity data acquired at Etna volcano

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We present preliminary results from the application of a new method that aims to use signal distortions as indicators of volcanic activity. Specifically, we consider 6-year (2016-2022) time series from two iGrav superconducting gravimeters at Mt. Etna, encompassing several lava fountaining episodes.

We focused on data acquired during phases of strong volcanic activity (e.g., periods when strong Strombolian or energetic fountaining activity took place). The ground shaking during paroxysmal activity triggers positive changes in the average level of the gravity signal, as already reported by Carbone et al. [2019]. It is important to stress that these are instrumental effects, triggered by the ground shaking, rather than real changes in the local gravity acceleration.

As a first step, using the date-time stamps of the volcanic events reported by Calvari et al. [2022], we manually defined, in the signal from one of the two gravimeters, the whole duration of each eruptive event. A Matlab® algorithm was used to establish the degree of correspondence between the volcano phenomena, as defined through the gravity signal, and the real occurrence of the phenomena as reported in literature [Calvari et al., 2022]. Subsequently, an exponential fit was implemented in the form: $f(x)=a \exp(b x)$

This type of fit was chosen since it is well suited to impulsive and unidirectional signals, such as those produced by the volcanic activity on the gravity signal. In order to eliminate an offset from the data, a derivative was applied to the results of the exponential fit and then the times at which the derivative exceeds a defined threshold ($\alpha = 0.004$ microGal/min) were defined. It was named 'Time of Failure (TF)'. The TF for 131 lava fountain episodes was estimated and then it was compared with the corresponding date-time stamps of the Etna volcanic activity reported in literature [Calvari et al., 2022]. We calculated that 51,2%, 73,8% and 85,1% of the total number of volcanic events occurred within a time interval of 15, 30 and 45 minutes from a TF, respectively. The second step involved the implementation of a Matlab® algorithm aimed at automatize the data selection. The algorithm splits the 2018-2022 signals from the two gravimeters into smaller time windows of 6 hours, with 1-hour overlap. Subsequently, an exponential fit and a derivative were calculated for all the 6-hours signals, as done in the first step. The derivatives of the signals collected by two iGravs were compared through cross-correlation analysis, in order to determine the degree of similarity between them. This latter strategy allowed us to eliminate the events that were not recorded simultaneously by the two instruments.

We found that, in 91,4% of the cases, the cross-correlation maximum peak exceeds a threshold of 0,7 microGal/min, and each of these peaks corresponds to a volcanic event as reported by Carlavi et al., [2002]. Secondary peaks were also found not related to paroxysmal events and this represents a starting point for future investigations.

In conclusion, our results highlight the possibility to utilize the signal distortion observed in the data from iGrav superconducting gravimeters as an indicator of volcanic activity.

2021 Etna's paroxysmal activity: inference on the dynamics of the magmatic feeding system from joint DInSAR and GNSS ground deformation analysis

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In the final months of 2020, the summit craters of Mount Etna displayed intense Strombolian-type activity as well as an increase in seismicity. In December 2020, a period of paroxysms with powerful, brief bursts of lava fountaining began, which intensified in February 2021 and lasted until March. After a brief rest, in May 2021 a new period of paroxysms started, lasting until the end of the year.

We used both ascending and descending Sentinel-1 SAR images along with daily GNSS solutions at 33 stations to evaluate the surface deformation at Mount Etna in order to understand the dynamics of the shallow plumbing system, which fed the observed paroxysmal activity. According to the InSAR and GNSS time series, the volcano edifice entered a period of intense and continuous deflation from mid-February to end of March, matching the prolonged paroxysmal activity characterized by the occurrence of 17 lava fountain episodes. This period was followed by a brief inflation phase that lasted until May 19, when a new paroxysmal period began, extending through October 2021. However, this second period of paroxysms did not show a significant deflation pattern compared to the preceding one.

To integrate the two geodetic data sets, we have applied the 3D SISTEM algorithm, which allows to estimate 3D ground displacements by combining GNSS measurements of deformation and Differential Interferometric Synthetic Aperture Radar (DInSAR) maps of surface displacement. We have used analytical models to detect the sources of the paroxysmal activity and to evaluate the deflating source parameters by inverting the displacement obtained with the 3D SISTEM algorithm. The results reveal a centripetal deformation pattern that might be linked to a shallow source below the area of the summit craters. However, a detailed analysis of the deformation pattern suggests the presence of contributions other than those related to the magmatic source, probably attributable to tectonic or geomorphological processes (e.g. seismicity, emplacement of volcanic products).

The aim of this work is therefore twofold. First, to infer the shape and dynamics of the magmatic feeding system of Mount Etna and its magma discharging regime. Second, given the complexity of the deformation signals at Mount Etna, to analyze how to deal with their different contributions including volcanic, tectonic, and geomorphological processes, as well as atmospheric noise.

The 2021 unusual deep seismicity recorded on the eastern flank of Mt. Etna volcano (Italy): regional tectonic or intrusive processes?

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Mount Etna is an open conduit volcano characterized mainly by effusive activity interspersed with explosive activities. Its eruptive activity occurs frequently from the main summit craters Voragine, Bocca Nuova, North East Crater, South East Crater as well as along eruptive fissures that open on the flanks of the volcano. Two geodynamic domains affect eastern Sicily: the first, in the northern sector, is represented by the Apennine–Maghrebian thrust belt; and the second, in the southern sector, is formed by the Iblean Foreland. Mt. Etna volcano is located between these two important geodynamic systems, and it is also crossed by other regional fault systems such as: the NE-SW Messina Fiumefreddo alignment and the WSW-ESE Mt. Kumeta Alcantara System (MKAS). Another important structure is the Malta Escarpment with NNW-SSE orientation which presents a continuation towards the Ionian Sea. Instrumental and historical seismic analyses show that 80% of the earthquakes of Mount Etna involve the eastern side with depths of less than 5 km, and the strongest earthquakes occur on the western part of the volcanic edifice. In the eastern sector of the volcano, surface extensional seismicity originates from the NNW-SSE seismogenic orientation of the structures. The eastern flank of the volcano is mainly characterized by normal faults called ‘Timpe’, with NNW-SSE trend, which represents the northern extension of the Hyblean Maltese escarpment where, along this alignment, several earthquakes of high magnitude and intensity occurred. We focused on the seismicity recorded by the permanent seismic network of Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Etneo - Sezione di Catania (INGV-OE) in an area located between the villages of S. Alfio, Milo, S. Venerina and Macchia di Giarre on the eastern flank of volcano, in the period between January 2021 and May 2021. At Mount Etna, during 2021, the eruptive activity was characterized by fifty-seven paroxysms that occurred at the South East Crater from 16 February to 23 October and gave rise to lava flows and lava fountains. We have analysed seismic swarms that occurred in an anomalous depth range (up to 20 km) for this sector of the volcano. We performed an analysis of seismicity and focal mechanisms for the purpose to characterise the space-time evolution and kinematics of the seismicity. In particular, cross-correlation analysis was performed to distinguish earthquakes into distinct families based on their waveform characteristics. Additionally, some clustering techniques were used to classify seismic events according to their hypocenter locations, magnitude, and frequency content. The results revealed interesting spatial and temporal patterns, providing insight into the dynamic of seismic activity within the region. It is worth noting that no seismic activity has ever been recorded in this sector of the volcano in recent years. We believe that this seismicity could represent an anomaly in the seismic picture of the last twenty years and, based on very preliminary considerations, could be explained in the context of regional geodynamics and related to intrusive processes that preceded volcanic activity.

25 years recording of the long-base fluid tiltmeter installed at 2.850 m a.s.l. observatory of Pizzi Deneri on Etna volcano

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Since 1996, at Etna volcano the network of short-base borehole tiltmeters network has been integrated with a long-base fluid tiltmeter installed in two 80 m long connected tunnels at the high altitude (2,850 m a.s.l.) volcanological observatory of Pizzi Deneri (PDN) located on the volcano's summit. The instrumentation was devised with an innovative configuration composed of mercury, free to move along the entire length of the tiltmeter in response to the ground tilt, and laser sensors to measure the changes in the mercury levels. We present the entire set of 25 years of data recorded by this instrumentation. During this long interval, the Etna volcano was characterized by numerous major eruptions due to dyke intrusions. The long base tiltmeter recorded changes in the short term during the rapid intrusive phases. These signals contributed both to the modeling of eruptive processes and, in the most emblematic case of the 2002-2003 eruption, also to the real-time understanding of the ongoing eruptive phenomenon, supporting the correct hazard assessment. In the medium-long term (years to decades), we show that the PDN signal is mainly related to the marked sliding of the entire eastern sector of the volcano, and it is primarily affected by the dynamics of the unstable flank, cumulating monotonically tilt during this continuous and dominant process.

Vulcano Island and its activity reconstructed through the analysis of ground deformations recorded in the last 50 years, to better understand the 2021-2022 volcanic unrest

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Vulcano Island is the southernmost island of the Aeolian archipelago and, in perfect accord with what is the geodynamic environment in which it is framed, is characterized by volcanic activity ranging from phreatomagmatic to minor magmatic (namely, “Vulcanian” from this island where it was defined).

Its last eruption, in fact, occurred in the years 1888-90 and is remembered for its impressive sequence of intermittent explosions, with emission of dense ash clouds varying in height from a few to about 10 km and magma fragments of different sizes in a nearly solid state. This eruption later became the prototype event that led to the introduction of the term “Volcanian activity” into the international classification of eruptions.

Since then, volcanic activity on the island has been limited to fumarolic emanations of varying intensity and temperature, mainly concentrated in the area of “La Fossa” crater and its northern slope. Over the past fifty years, the situation has remained almost stationary, with the exception of very few cases.

The last crisis at Vulcano was recorded in 2021 starting in September: the La Fossa crater entered a new phase of unrest with a sudden and significant increase of degassing activity from the crater and with outstanding variations to fumarole gas composition, temperature, plume emissions, diffuse soil CO₂ degassing, local seismicity and ground deformation.

Observation of long-term geodetic data (EDM, GPS, leveling, and tilt) allowed us to identify changes as early as the second half of 2018 that, little by little, led to a major expansion of the La Fossa cone, culminating precisely in 2021, as a result of activity within the shallow hydrothermal system just below La Fossa, which was also confirmed later by SAR data.

Having such a large time window available, it was also possible to make an interesting comparison of such slow dynamics, looking for similarities and differences, with the hydrothermal unrests already observed by INGV in the late 1970s and early 1990s, with the aim of better defining the situation of the La Fossa cone.

S16 - MULTIDISCIPLINARY APPROACH FOR UNDERSTANDING
OF MAGMATIC SYSTEMS, VOLCANO-TECTONIC STRUCTURES
AND THEIR INTERPLAY IN VOLCANO DYNAMIC EVOLUTION

Conveners:

Roberto Isaia, Maria Giulia Di Giuseppe, Tommaso Pivetta, Stefano Carlino

3D interpretation and subsurface modelling of Meso-Cenozoic volcanic deposits in the Hyblean foreland (Sicily) by using wells and seismic reflection data

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The Hyblean Plateau represents the emergent foreland basin of the Apennine-Maghrebien Chain in Sicily (southern Italy). This domain is characterized by widespread Mesozoic volcanic deposits, from Triassic to Cretaceous time [Patacca et al., 1979]. The Upper Cretaceous volcanic rocks belong to Hybla (late Hauterivian-Albian p.p.) and Amerillo Formations (Albian p.p.-middle Lutetian). They are mainly known from subsurface deep well explorations, since they rarely crop out in the eastern coast of the Island [Carbone et al., 2016]. However, a detailed subsurface study of these deposits is still missing. This work provides quantitative 3D reconstructed volumes of these volcanic deposits, to better constrain their genesis and evolution through time. This research relies on the examination of open-source deep-wells, 2D offshore seismic reflection data, and documents from Oil & Gas exploration activities [e.g., ViDEPI repository] with a multidisciplinary approach. From composite logs, a full set of regional structural and thickness maps of Meso-Cenozoic Fms has been developed. Based on digitized electrical and lithological well logs, a new detailed lithological reconstruction and a velocity profile is here presented; petrophysical cross-plotting and well-seismic tie helped identifying volcanic facies. The link between well and seismic data led to: i) a new reference seismic-stratigraphic and facies scheme; ii) a 3D velocity model; iii) 3D geometry, thickness, and spatial distribution of the volcanic deposits at regional scale; iv) total volumes of the volcanic deposits; v) their relationship with the surrounding geological structures and the geodynamic evolution of the area.

Therefore, the Meso-Cenozoic volcanic deposits result in a submarine volcanic succession of basaltic pillow lavas and hyaloclastites (called tuffs in the original description of the composite logs), interbedded with pelagic deposits. In particular, pillow lavas and massive lavas characterize the basal part of the Amerillo Fm, while hyaloclastites and subordinated basaltic lavas mark the upper part – both facies are interbedded with the pelagic deposits of the Amerillo Fm.

In the Early Cretaceous, during the deposition of the Hybla Fm (likely from Albian time), the area underwent the deposition of submarine volcanic rocks, with an average thickness of 100 m in more than 2000 km². From Albian to Later Cretaceous time, during the sedimentation of the pelagic facies of the Amerillo Fm., several significant volcanic structures developed: they have been here identified and well defined in the offshore, with an average thickness of 150-400 m, and a width from 400 m to 1500 m. At the same time, an almost 2-km thick volcanic succession took place in the southernmost corner of Sicily (Capo Passero district). Later, during the early Eocene, the pelagic deposits of the Amerillo Fm were able to fill up and compensate the volcanic submarine morphologies, showing onlap geometries. The last stage of volcanic deposition was recorded at the top of the Amerillo Fm, with offshore evidence of volcanism in the southern part of the Hyblean Plateau, onlapped by the Oligocene-Miocene Ragusa Fm.

The building of a 3D geocellular grid allowed the calculation of the volumes of volcanic deposits,

for both the Amerillo and Hybla Fms. These volumes appear comparable to the present-day Tyrrhenian Sea seamounts [Pensa et al., 2019].

The Amerillo volcanics show a preferred NE-SW alignment, which might be associated to elongated structural highs linked to local compressional tectonics. In the presented reconstruction, these extensive and thick volcanic successions could be related to the Cretaceous change in the geodynamic setting of the region, from a passive margin to a NNE-SSW oriented mega-hinge zone [Agip, 1992]. The magmatic fluids may have migrated along the main crustal discontinuities and fractures along hinge zones. Therefore, the observed volcanic structures may be a record of these regional events, that took place from Cretaceous to Eocene.

Exploring the Crustal Structure of Etna Volcano (Italy) through Anisotropic P-Wave Tomography

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Numerous seismic tomographic investigations have explored the intricate interplay between tectonic processes and magma uprising within Etna volcano. However, the majority of these studies rely on the assumption of a seismically isotropic crust. Here, we employ a pioneering methodology that incorporates the anisotropic nature of the crust, enabling simultaneous inversion for perturbations to P-wave isotropic velocity and three additional anisotropic parameters (i.e., magnitude of hexagonal anisotropy, azimuth, and dip of the symmetry axis). By analysing the seismicity recorded in the Mt. Etna area from 2006 to 2016, we have constructed 3D anisotropic P-wave tomography models to better constrain the crustal structure of Etna volcano within its local tectonic framework.

The revealed anisotropy patterns are consistent with the structural trends of Etna, unveiling the depth extent of fault segments. We have identified a high-velocity volume, deepening towards the northwest, attributed to collision-related subducting foreland units, that appear to confine a low velocity anomaly, interpreted as the expression of magmatic fluids within the crust. Furthermore, a discontinuity, likely tectonic in origin, affects the subducting units and allows magma transfer from depth to the surface. This structural configuration may explain the presence of such a very active basaltic strato-volcano within an atypical collisional geodynamic context. This research improves our understanding of the dynamics governing magma and fluid ascent beneath the volcanic edifice and emphasizes the importance of considering anisotropy in seismic investigations. It contributes to our framework for understanding volcanic processes and mitigating associated risks.

Seismic response to volcanic processes at Mount Etna: coupling thermomechanical simulations with seismic wave-equation modelling

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Mount Etna, located in the central Mediterranean on the north-eastern coast of Sicily (Italy) is one of the most active and hazardous strato-volcanoes in the world whose south-eastern flank is sliding towards the Ionian Sea. Flank collapses can be caused by gravitational spreading and tectonic forces, leading to crustal fracturing and possible opening of magma pathways. To investigate their effect on the sliding flank at Etna, we created a 3D geodynamic model of the volcano, containing the primary geological parameters and produced ground deformation with the 3D thermomechanical finite differences code LaMEM (Lithosphere and Mantle Evolution Model) [Kaus et al. 2016]. The geometry of the model was built with the GeophysicalModelGenerator.jl package, also including real topography through the GMT.jl package by using the Julia programming language [<https://github.com/JuliaGeodynamics/GeophysicalModelGenerator.jl>]. Implemented geometries, which are based on geological maps and interpretation of seismic velocity data, were assigned rock parameters from laboratory-scale values and computational simplicity. The model includes most importantly an upper brittle crust with a south-eastern flank that is decoupled by surrounding objects of weak rock characteristics relative to the flank, represented by two bounding fault systems (Pernicana in the north and Mascalucia-Tremestieri, Fiandaca-Pennisi and Gravina in the south) and an underlying Apennine-Maghrebian Chain. Additionally, the effect of a visco-elastic basement, a solidified intrusive body and a supercritical fluid volume with strong and weak rock parameter values, respectively, were tested. Ground deformation was simulated from the simplest to the most complicated model and quantitatively compared to GPS data by calculating the misfit with the coefficient of determination to analyse the sensitivity of each implemented geometry. The greatest effect could be observed when adding the visco-elastic basement to the brittle upper part of the model, which also increased the fit to GPS observations. To achieve a sufficient model resolution, simulations were run in parallel on the Open Computing Cluster for Advanced data Manipulation (OCCAM), an HPC cluster operated by the Competence Centre for Scientific Computing (C3S), a collaboration of the University of Turin and the Istituto Nazionale di Fisica Nucleare - Sezione di Torino [Aldinucci et al. 2017].

The 2020-22 lava fountaining at Mt. Etna: one eruptive sequence, two magmatic stories

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From December 13, 2020 to February 21, 2022, Mt. Etna experienced an intense period characterized by 62 paroxysmal events. Our research utilized a comprehensive method, analyzing both tilt deformation and volcanic tremor RMS amplitude data over time. We explored the deflation events associated with lava fountains, the inflations that took place between events, the maximum values of volcanic tremor RMS amplitudes, and a gradient of each signal to assess the pace of change for each phase involved [cf. Cardone et al. 2024, JVGR]. The study delineated three distinct periods that illustrate the magma movement and storage behaviors. Initially, from February to April 2021, we detected generally medium to high values across all parameters, indicating the ascent of significant volumes of volatile-rich magma from deeper reservoirs to the higher segments of the plumbing system. During the next phase, from May to June 2021, the duration of lava fountains decreased, showing the lowest values, likely due to a decrease in the availability of undegassed magma in the topmost reservoirs. In the final period, from July to October 2021, we observed a clear increase in the measured parameters, which are accompanied by a slowdown of the inflation rates. Furthermore, our findings have been corroborated by a correlation analysis carried out between the geophysical parameters retrieved in this work and volcanological and petrological observations by other authors [Giuffrida et al., 2023, Earth-Sci.Rev.]. Among the most significant correlations, we found high values of Spearman correlation coefficients between deformations and SO₂ emissions during each paroxysmal event and between deflations and deflation rates, so that the larger the deflation amplitude during a lava fountain the faster the deformation occurs. Finally, detailed examination of tilt and volcanic tremor RMS amplitude during this period revealed unique patterns, namely inflations at the onset of eruptions and periodic RMS amplitude fluctuations. Our findings shed light on the complex processes governing the recent paroxysmal activity at Mt. Etna, highlighting how the wide heterogeneity of lava fountains-related geophysical and volcanological parameters can be due to different magma transfers and degassing mechanisms.

3D Electrical Resistivity Imaging of Transcrustal Magma System beneath the Campi Flegrei caldera

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Geophysical imaging is one of the fundamental tools to delineate the structure of the plumbing system of an active volcano, particularly for caldera systems. Among others, the magnetotelluric investigation provides remarkable information on the melting and fluid distribution of volcano-tectonic structures at various depths beneath the volcanoes. The deep features assume fundamental importance in reconstructing the mechanism of volcanic activity.

We performed a 3D Resistivity Tomography up to 20 km depth beneath the Campi Flegrei caldera. The imaging has allowed the identification of the resistivity pattern of the investigated structure, highlighting various electrical resistivity anomalies attributable to distinct processes and physical conditions of the system. The configuration and properties of the anomalies indicate the presence of a transcrustal magmatic system beneath the caldera, including a low resistivity anomaly (LR) detected in the middle-lower crust at 8-20 km depth that can be associated with a main melt accumulation zone. Considering its electrical properties combined with a series of chemical-physical parameters of the magmas that have resided at those depths, it has been possible to estimate the average quantity of melt presently contained within the LR volume, corresponding to approximately 90 km³. This Cristal Mush zone is laterally confined by higher resistivity anomalies that can be associated with the basement rocks and bounded by regional tectonic and volcano-tectonic structures acting preferentially as magma/fluids pathways from depth. Due to such fluid transfer, intense hydrothermal rock alteration occurred at shallow depths, highlighted by conductive anomalies. On top of the LR, a mid-resistive body MR has been imaged, representing the upper crust zone where smaller magmatic reservoirs formed and partially or totally cooled. Notably, the larger part of the earthquake recorded in the last 15 years at Campi Flegrei is located along the upper edge of this anomaly.

The 3D MT tomography shows that a transcrustal, , crystal mush magma system represents the main source of the caldera volcanic activity in the past century. Geophysical imaging also constrains the geometry of the plumbing system, elucidating possible magmatic melt/fluid ascent zones and helping discern the possible pathways that can influence the unrest phenomena. In the end, the picture of the Campi Flegrei caldera obtained through our MT survey suggests a structural scheme for a transcrustal magma system, which appears layered in three distinct levels: (i) a more profound, spatially confined zone of magma storage where batches of crystals and melt coexist; (ii) a zone located at medium depth, acting as a transfer structure where the magma rising from the deep reservoir cumulates, undergoing partial cooling processes, whereas fluids flow toward the surface along channel-like structures following the main volcano-tectonic alignments; (iii) a shallower part where zones altered by the circulation of deep-sourced magmatic fluids (clay-caps) alternates with zones where highly-saline fluids cumulates (brine storage reservoirs) and with cooled or partially cooled magmatic bodies.

S16 - Oral Presentation

Magnetotelluric Imaging of Pantelleria Caldera: Implications for its Active Structures

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Pantelleria island is the emerged part of a volcanic structure extending in the NW-SE direction for nearly 135 km, with 31.7 km being the emerged portion [Mattia et al., 2007]. The main eruptive vents of Pantelleria develop along NW-SE structures, while another relevant structural system follows a NNE-SSW trend.

Pantelleria volcanic activity, characterized by peralkaline rhyolitic (pantelleritic) magmatism, generated large caldera forming explosive events and low-magnitude eruptions including lava flow. Recent submarine basaltic eruptions (Banco di Graham 1831; Foerstner volcano, 5 km NW of the island, in 1891), together with ongoing hydrothermal emissions and fumaroles field, indicate that Pantelleria's magmatic system is still active.

Fumaroles and diffused CO₂ emissions from the soil are widespread on the island with manifestations of rather high temperature [Granieri et al., 2014] concentrated in the central part of the island, and lower temperature manifestations (30°C) near the shore of Lago di Venere volcanic lake [Favara et al., 2001; Chiodini et al., 2005; D'Alessandro, 2007]. In particular, the most powerful fumaroles manifestation is located in the Favara area, where soils are deeply altered because of high temperatures (up to 100°C) and anomalous hydrothermal gas fluxes [Favara et al 2001; Granieri et al., 2014; Paz et al., 2016].

Despite this hydrothermal activity, no studies have been devoted to understand the structural framework of the Pantelleria caldera and the control exerted by the main structure on geothermal reservoirs and/or fluid circulation. The lack of geophysical tomographies represents a significant gap in reconstructing the subsurface of the caldera and its deep structures, including the geothermal system and volcano-tectonic features.

This study addresses this gap by employing a short-period magnetotelluric (MT) survey, a powerful tool for identifying the role and distribution of geothermal fluids and their interactions with main structural lineaments and surrounding rock volumes.

MT data, collected from seventy-eight on-shore soundings, allowed us to characterize the subsurface electrical resistivity, which was used to obtain a 3D model of electrical resistivity, revealing the main structures of Pantelleria down to a depth of 2.5 km. Integrating geological and geochemical datasets, the study delineates resistivity variations associated with volcanic structures, hydrothermal alterations, and possible magmatic signature.

The imaging of the deep sector of the Island shows different resistivity anomalies that provide fundamental information on the geometry and volume of possible geothermal reservoirs, as well as insights into the interaction between lithostratigraphic setting, fluid circulation, and current hydrothermal activity. Vertical and lateral resistivity contrasts also highlight the main volcano-tectonic features such as the caldera boundary. Low resistivity anomalies dominate within the caldera, while a more resistive environment characterizes the external zones of the island.

The 3D resistivity model significantly improves the understanding of Pantelleria's volcanic and geothermal processes and supports further research aimed at estimating the geothermal potential of the island.

Fault reactivation and growth at rift-related calderas

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Caldera collapses are paramount volcano-tectonic features because they form during hazardous explosive volcanic eruptions, they are ideal sites for geothermal development and mineral resources exploitation, and also because they preserve the evidence of the interaction between caldera magmatism and the regional tectonic processes. Despite this, many aspects of the caldera collapse process remain unclear, particularly concerning the interaction between caldera and tectonic related fault systems. We therefore used analogue models 1) to quantify the effect of regional strain on caldera elongation in extensional settings, such as the Main Ethiopian and the Kenya rifts, 2) to describe the effect of regional strain on caldera structures and, vice-versa 3) to document, for the first time, “the other side of the coin”, that is how caldera structures affect the formation of newly forming regional extensional faults. Our models showed that tectonic extension only explains a small proportion (e.g. 13% for the Main Ethiopian Rift) of the elongation of most rift calderas. Furthermore, we showed how specific segments of caldera faults may accommodate regional extension by reactivating, therefore precluding caldera elongation. Finally, we showed how the presence of caldera structures may influence the geometry of newly forming regional normal faults, that display a marked curvature, “faking” caldera ring faults. We have suggested that these “fake” curved caldera ring faults may lead to incorrect estimations of caldera elongation in nature. In addition, such faults may also mislead geothermal fluid exploration, as they are likely disconnected from the caldera structures or the caldera plumbing system, and less likely the locus of hydrothermal fluid flow.

Reconstructing the plumbing system feeding the Auckland Volcanic Field by magma pathways retrogression

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The Auckland Volcanic Field (AVF) consists of ~53 volcanoes, distributed over an area of ~ 360 km² comprising the City of Auckland, New Zealand's largest population centre (~1.7M people). The last eruption at the AVF occurred over 500 years ago: since pre-eruptive observations are lacking, modelling pre-eruption scenarios may be a key tool for enhanced preparedness. Geological evidence shows that past eruptions were variably explosive and formed maars, lava shields, and tuff rings. Any future eruption from a new vent location within the AVF would cause significant socio-economic impacts, extensive evacuations, and national-scale impacts. Our work aims to constrain the next probable vent location using a novel modelling approach based on physical understanding of dyke propagation. We employ newly developed 3D numerical codes that consider crustal stresses as the main controls on the orientation of dyke pathways. We estimate regional stresses based on GNSS data and consider surface mass redistributions at the Hauraki Rift and other volcano-tectonic structures in the wider area to constrain the overall elastic stress field. We backtrack magma pathways from known vent locations downward through the crust. Pathways are oblique and reach below the Hauraki Gulf or Firth of Thames (~30 km E of Auckland City) at the inferred depth of magma dyke release (35-80 km). We infer a common magma source is physically plausible in that location. Further work will improve the robustness of the model, constrain the spatial spread of vents over time, dyke propagation velocity, and implications for early identification of future volcanic unrest.

Volcanic activity on Vulcano Island (Aeolian Islands, Sicily, Italy) and its connection with deformation patterns in northern Sicily (Italy): GNSS and seismic evidence

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We analysed Global Navigation Satellite System (GNSS) and seismic data collected during the last 12 years in North-eastern Sicily and the Aeolian Islands (Italy). Since September 2021, the La Fossa caldera at Vulcano showed a significant phase of unrest. By examining GNSS time series and velocity fields, we found evidence of changes in the deformation pattern of the Peloritani area, located about 40 km South of the island of Vulcano in North-eastern Sicily. The changes in deformation patterns occurred about seven months before the Vulcano unrest and were accompanied by a release of seismic strain, which was released at increasingly shallower depths. Our results suggest a temporal correlation between deformation measured in the Peloritani area and volcanic activity on the Vulcano island, which was further investigated by analyzing another phase characterized by an increase in the areal variation measured at La Fossa Caldera in 2018. This study presents a new perspective for understanding the geodynamic, volcanic, and seismic phenomena in the investigated area, with particular attention to the Vulcano unrest between September and November 2021.

Characterization of the Vulcano's active geothermal system: an integrated approach based on geophysical models and numerical simulations

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The island of Vulcano belongs to the Aeolian Archipelago (Italy), and throughout its history, it has experienced many eruptions, including at least three phreatic events. After its last eruption (1888-1890 AD), Vulcano has been the site of various volcanic unrest crises, and a continuous fumarolic activity mainly concentrated within La Fossa crater and Baia Levante beach. In September 2021, Vulcano entered a new phase of unrest characterized by rising fumarole temperatures and changes in gas composition, as well as ground deformation and microseismicity, indicating an increased input of magmatic fluids in the geothermal system [Federico et al., 2023].

We conducted a comprehensive study integrating geophysical models with numerical simulations to understand the fluid dynamics and mechanisms driving Vulcano's active geothermal system. Specifically, a petrophysical model for the La Fossa Caldera area was derived from evidence gained through a magnetotelluric tomography (MT) carried out in 2022 [Di Giuseppe et al., 2023]. This provided fundamental information for characterizing the volcanic tectonic structures and geothermal fluid pathways down to 2.5 km depth. The geophysical highlights were also integrated with additional geochemical and geological constraints.

To further investigate the thermodynamic state of the system, we employed the TOUGH2 numerical code [Pruess et al., 1999] to simulate fluid and heat flow in porous and fractured media. This powerful tool allowed us to model the complex dynamics of the Vulcano geothermal system, including its temporal evolution. The simulations provided estimates of the fluid distribution in terms of pressure, temperature, and gas saturation, ultimately elucidating the current state of the Vulcano's geothermal system.

Characterizing the shallow hydrothermal system of Vulcano Island (Aeolian Islands, Italy) using geoelectrical survey: implications for the eruptive scenario

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Vulcano island is situated in the southern part of the Salina-Lipari-Vulcano ridge and, together with these two islands, forms the central sector of the Aeolian archipelago. Vulcano is an active volcanic system whose last eruption occurred between 1888 and 1890. Since then, intense fumarolic activity has accompanied various phases of unrest of the associated hydrothermal system, making Vulcano the subject of numerous geophysical, geochemical and hydrogeological studies.

The aim of this study was to investigate the shallow hydrothermal system of the 'La Fossa' caldera, and particularly the northern sector of Vulcano island, which hosts a degassing area very active also during the last period of unrest, started in 2021. The survey was carried out using geoelectrical methods due to their proven effectiveness in studying active geothermal systems [e.g. Di Maio et al., 1997; Revil et al., 2008; Troiano et al., 2021]. This approach enables to identify changes in subsurface structural features and to assess the presence of discontinuities, such as faults, which play a fundamental role in fluid circulation.

Our survey consisted of 2D electrical resistivity and induced polarization tomographies, and self-potential measurements along four profiles located at the base of the La Fossa cone in the northern part of the island, which allowed an investigation depth of about 200 m below the ground level. The reconstruction of the spatial distribution of the electrical properties, in terms of resistivity, chargeability and natural polarization, facilitated the identification of various structures associated with the activity manifestations of the shallow hydrothermal system of Vulcano.

Specifically, the observed anomalies revealed a discontinuous layer between 40 m and 140 m below sea level composed of lavas overlying a saturated hyaloclastite layer that is supposed to be the main reservoir of high-temperature hydrothermal fluids. The results obtained, integrated with those of previous studies carried out on the island, have highlighted areas characterized by the presence of hydrothermal fluids in the liquid state (low resistivity and low chargeability anomalies) and in the gaseous state (high resistivity and low chargeability anomalies), upwelling along structural discontinuities, as testified by the fumarolic manifestations observed on the surface.

Identifying the island's main fault system and understanding its effect on fluid circulation in the areas adjacent to the La Fossa caldera represent fundamental information for assessing the establishment of conditions favourable to fluid overpressure or decompression, which can lead to phreatic/hydrothermal-type explosive events [Isaia et al., 2021].

Integration of geophysical images and thermo-fluid dynamic modelling to understand the current dynamics of the Pisciarelli Fumarole Field (Campi Flegrei Caldera, Italy)

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The Pisciarelli fumarolic-hydrothermal area, in the Campi Flegrei caldera (southern Italy), along with the adjacent Solfatara maar-diatreme, is currently considered the most concerning site due to the recent increase in volcanic activity. This ongoing activity includes very high CO₂ fluxes (over 600 tons/day), continuous evolution of its morphological elements, and a large portion of the seismic events recorded in the entire caldera.

Here, we present the first comprehensive interdisciplinary study aimed at reconstructing the architecture and the fluid dynamics of the Pisciarelli Fumarole Field area. Our study integrates geophysical imaging and thermo-fluid dynamic numerical modelling to understand the hydrothermal processes occurring in the shallow feeding system of Pisciarelli.

The main pathways (i.e. faults and/or fracture networks) for fluid and gas migration from deep sources to the Earth's surface have been identified by utilizing 3D electrical resistivity and time-domain induced polarization tomographies of the very shallow hydrothermal system of Pisciarelli. Also, the mapping of the spontaneous potential has been realized in the area.

Based on these data, numerical modelling has been developed to understand the current system dynamics (i.e. temperature, gas pressure, gas saturation and fluid flow distributions) and the physical processes likely occurring within the system.

For this purpose, the numerical simulator TOUGH2 was employed to solve the thermodynamic equation for an H₂O+CO₂ mixture flowing in the system of interest, considered a porous and fractured medium.

An accurate 3D petrophysical model of the explored hydrothermal system was built using the geophysical tomographies. Subsequently, by imposing constraints derived from different data (i.e. volcanological and geochemical analyses available in the literature), the natural state of the system in its current conditions has been estimated. This includes reconstructing the water and CO₂ pressure distribution, as well as the temperature, the CO₂ flow, the gas saturation degree, and other relevant variables.

The thermo-dynamical modelling provided valuable insights into the role played by the main fault system and the highly permeable channel identified by the geophysical survey in the dynamics of the hot fluid mixture rising to the surface. Furthermore, a simulated map of the CO₂ flux was produced, clarifying the mechanisms at the base of the intense degassing activity of Pisciarelli. These results contribute significantly to a better understanding of the current dynamics of the Pisciarelli Fumarole Field. This knowledge provides a basis for improved hazard assessment and risk mitigation strategies in this highly active volcano-hydrothermal system.

Control of gravitational potential energy on the distribution of off-axis volcanic activity in the Turkana Depression, East African Rift

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Several studies have shown that magma migration, emplacement and final eruption, and the consequent alignment of fissures and vents in continental rifts are controlled by regional extensional stresses modulated by several factors, such as structural inheritance, loading by volcanic edifices, rift architecture, etc. This interaction gives rise to complex characteristics of rift-related volcanic features, which may be therefore difficult to reconcile with the different controlling processes. The Turkana Depression in East Africa exemplifies these complexities, showing an anomalous distribution of volcanism with several important volcanic fields located outside the area of focused, ongoing extension and showing variable orientation of vents. In this paper we analyse vent distribution in the different volcanic fields and calculate the stresses resulting from gravitational potential energy (GPE) in the Turkana Depression by using geophysical data available for the area. Our results show that West to East variations in topography and crustal thickness give rise to dominant extensional GPE-related stresses East of Lake Turkana. This in turn causes recent off-axis volcanism to be localised in this area, where GPE allows magma to ascend to the surface and emplace in major volcanic fields (e.g., Hurri Hills, Marsabit) whose alignments are perpendicular to the local, GPE-controlled least compressive stress.

Gravity survey of Pantelleria Island (Southern Italy) for geothermal exploration

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Although the Italian peninsula has a large potential for the development of geothermal energy, this renewable resource is still largely underexploited. The potential use of geothermal heat is very wide and spans from agriculture and breeding farm to electric production, in the range of temperatures between 20 °C to >150 °C (low to high enthalpy, respectively). All projects for geothermal energy exploitation, from low enthalpy at a local scale to high enthalpy at a national scale, need the development of a preliminary and fundamental phase aimed at the assessment of the resource. This phase aims at identifying the geothermal resource in terms of surface extent, volume, rock and fluid properties, and collects all necessary information for making investment decisions regarding geothermal use.

Pantelleria Island, located in Southern Italy, represents an attractive target area for geothermal energy exploitation. The island is characterized by a high-temperature geothermal system (>150 °C/km, as detected from deep borehole measurements), hot fluids, CO₂ diffuse degassing, and past active resurgent volcanism. Pantelleria has already been the subject of several studies assessing its geothermal potential. To further increase knowledge about the geometry and physical properties of the main structures of the geothermal system, a new gravity survey has been carried out. The gravimetric survey involved supplementing existing data from previous studies, which included marine and terrestrial stations, with a new survey of approximately 130 additional stations. This effort has produced updated and more detailed Free-Air and Bouguer anomaly maps with a spatial resolution of about 3 stations per km². These maps highlight anomalies showing significant horizontal density variations corresponding to subsurface geological structures. Gravity data have been enhanced by a multiscale derivative technique to obtain the horizontal location of the density contrast, helping to identify both stratigraphic and structural boundaries between contiguous rock units. Additionally, the characterization of the main sources of gravity anomaly was carried out using 3D imaging techniques based on a multiscale analysis of potential fields (DEXP – Depth to EXtreme Points), providing a picture of the main density distribution at depth.

The preliminary results of this research seem promising in better assessing Pantelleria's geothermal potential. By revealing the geological features of the island and resource distribution, this research not only enriches our understanding of geothermal systems but also highlights the essential role of geophysical surveys in guiding decision-making and promoting the transition to renewable energy.

Multiparametric clustering of synchronous seismic, acoustic, and thermal events at Mt. Etna in 2023

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This work explores the behavior of a magma degassing system via a multi-parametric approach. A dataset of continuous thermal, acoustic, and seismic signals has been obtained at Mt Etna's Bocca Nuova crater. During the recording period, two vents from Bocca Nova; named "Sboffer" and "Ringer", showed active degassing.. Studying the type of activity exhibited in active magma degassing systems such as this is important to increase our understanding of shallow volcanic plumbing systems. The use of multi-parametric instrumentation allows for inner processes to be better constrained and increases the reliability of interpretations. Multi-parametric clustering of magma degassing events is performed to examine the behavior of the system and gain insight into the inner dynamics.

Time periods of degassing activity are identified from the thermal signal, and used to identify time periods of degassing events in the seismic and acoustic datasets. An analysis of the power spectrum of the acoustic events and the spectral content of stacked seismic traces reveals different degassing types between events occurring at the two vents. 'Sboffer' displays impulsive signals easily detectable, while 'Ringer' exhibits smaller amplitude signals. The events are grouped based on acoustic and seismic signals, separately, before relationships between these signals are explored. Events from each vent are processed separately due to the difference in the frequency signature. Two methods are explored for grouping the events: waveform similarity, where different families generated from acoustic and seismic data are used; and feature extraction coupled with machine learning clustering methods. The feature extraction methods include independent component analysis, variational mode decomposition, and classical feature extraction using the time series feature extraction library (TSFEL). The implemented clustering methods employ common techniques such as K-means, agglomerative methods, and HDBscan. The objective is to discern degassing patterns during the stable observation period and elucidate shallow magma behavior.

Analysis of the seismo-volcanic signals during the 2021-2022 volcanic unrest at Vulcano island

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Starting from September 2021, Vulcano Island, the southernmost island in the Aeolian archipelago, was interested by a phase of volcanic unrest. Various geochemical and geophysical parameters exhibited significant alterations, such as an increase in fumarolic activity, variations in the gas composition, and an increase in the temperature, along with considerable ground deformation. Vulcano island is characterized by a broad spectrum of seismo-volcanic signals, whose source has been related to the fluid dynamics within the shallow hydrothermal system. Beginning on September 5th, 2021, a significant increase in the daily number of signals, spanning both the 1-30 Hz and 1 Hz frequency bands, occurred. Events characterized by a very long period (VLP) component, with dominant frequencies below 1 Hz, were clustered predominantly northward of the Vulcano crater, at shallow depth. The presence of the seismo-volcanic signals may indicate fluid movement, conduit pressurization, resonance phenomena, the interaction between magma and water within the plumbing system, or vaporization and expansion phenomena in the hydrothermal system.

In this work, we analyzed the seismo-volcanic events with a frequency higher than 1 Hz spanning from September 2021 to December 2022, which include long-period events, high-frequency events, tornillos, and monochromatic events, as well as VLP events recorded in the same period. The generation of these events seems to be associated with the rapid release of fluids from the hydrothermal system, due to the interaction with magmatic fluids.

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