ID: 100

New trends on the use of HPC and cloud computing infrastructures for volcanic hazard assessments at multiple scales

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In Europe, an ecosystem of interrelated projects is boosting pre-exascale High Performance and cloud Computing infrastructures in geophysics (including volcanic hazards) for the next generation of data-informed early warning systems, forecasts, and probabilistic multi-hazard assessments. Three relevant on-going initiatives are:

1. The ChEESE-2P EuroHPC Center of Excellence (2023-2026, GA No 101093038), which is preparing community codes from different geoscience domains to perform on modern accellerated supercomputing systems. In volcanology, this includes demonstators and service enabling for ensemble-based volcanic dispersal and multiphase volcanic explosion modeling, oriented towards a new European tephra hazard map and to probabilistic hazard mapping for phreatic eruptions.

2. The DT-GEO project (2022-2025, GA No 101058129) is implementing 12 interdisciplinary Digital Twin Components (DTCs) for geophysical hazards. In volcanology, DT-GEO covers the modelling of magma and rock dynamics (DTC-V1), ensemble-based probabilistic forecasts of ash dispersal (DTC-V2), modelling of lava flow propagation and inundation areas (DTC-V3), and AI-based gas dispersal forecasts. This is a preliminary step before verifying these DTCs at different Site Demonstrators and starts a long-term community-driven effort towards a digital twin on Geophysical Extremes.

3. The Geo-INQUIRE project (2022-2024, GA No 101058518) is providing researchers with virtual and trans-national service access to data and state-of-the-art numerical models and workflows for monitoring and simulating the dynamic processes in the geosphere.

This contribution reviews the objectives and expectations from all these interrelated initiatives (with focus on probabilistic hazard assessments), which also liaise, align, and synergise with the European Plate Observing System (EPOS) and the long-term (2030) DestinE mission.

ID: 130

Forecasting the evolution of volcanic unrest

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The management of volcanic unrest near densely inhabited areas requires collaboration between scientists, who are required to provide near real-time information, and decision makers. The ambiguity of pre-eruptive patterns and the inaccessibility and the complexity of the system lead to large uncertainties, suggesting the preference for probabilistic approaches over deterministic ones. The divergence of scientists' opinions regarding pre-eruptive phenomena can lead to extreme confusion, which inevitably translates into the difficulty of reaching an agreement for the optimal management of an emergency. Expert elicitation is a procedure for extracting a collective opinion in a relatively short time despite the incomplete knowledge of the problem and is therefore an effective tool for managing forecasts during volcanic crises in near real-time. In this work we present the results of the latest elicitation sessions at the Campi Flegrei caldera, represented by a list of weighted parameters with their respective thresholds that define the anomalous values and their interpretation, to calibrate BET_EF eruption forecasting model. Our aim is to re-calibrate it using the most recent scientific evidence linked to the increase of the activity of Campi Flegrei which has been observed in the last few years, evaluating the probability that the mechanism underlying the current unrest is a rise of magma, and the probability that this could lead to an eruption. Finally, we demonstrate a practical application showing the variation of the probability of magmatic unrest and eruption as a function of the variation of the values of the monitoring parameters obtained through the elicitation.

ID: 172

Assessing volcanic hazards in the HPC era

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Decision-making and emergency planning for active volcanoes rely on understanding eruption probabilities and their potential impact areas. Probabilistic Volcanic Hazard Assessment is crucial for providing decision-makers with valuable information for both short-term crisis response and long-term planning.

Nowadays HPC can be effectively used to produce quantitative hazard results, addressing the natural variability of volcanic phenomena, including eruption probability, eruption size, vent position, and meteorological conditions. Within the recent EU initiatives, interdisciplinary Digital Twins (DT) are emerging as powerful tools for replicating Earth system domains. In particular, the EU ChEESE (2018-2026) and DT-GEO (2022-2025) projects have developed a new generation of codes aimed to exploit modern HPC resources and a prototype DT for geophysical extremes, incorporating interconnected Digital Twin Components (DTCs) with simulation codes, artificial intelligence, real-time data streams, data assimilation, and workflows. These DTCs encompass geohazards related to earthquakes, volcanoes, and tsunamis, leveraging computational resources, data infrastructures, monitoring networks, and research collaborations. Among the 12 DTCs in DT-GEO, 4 focus on various volcanic hazards, vent opening, lava flows, tephra fallout, and gas dispersal. These advances in HPC-driven volcanic hazard assessment and DT technology promise to revolutionize our understanding and management of volcanic hazards in the HPC era.

For example, an application of these methodologies to tephra fallout allowed a more robust multi-volcano probabilistic hazard assessment over a large area, like those developed for seismic events and other natural disasters. This approach enables comparisons among various eruptive scenarios and with hazard assessments for seismic phenomena and other natural disasters.

ID: 326

Towards Developing a Probabilistic Eruption Forecasting Model for Redoubt Volcano, Alaska

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The multi-million-dollar losses produced by the 1989-1990 and 2009 eruptions of Redoubt Volcano resulting from aircraft damage and airspace closure illustrate the substantial threat that Alaska volcanoes pose to the aviation industry. The Alaska Volcano Observatory (AVO) combines ground-based instruments and remote sensing techniques to monitor 54 historically active volcanoes. Issuing warnings before eruptions at these remote and often inaccessible volcanoes is extremely challenging. In the presence of scarce data and large uncertainties, probabilistic forecasting models can help inform decisions and provide early warnings during a volcanic crisis, but have yet to be implemented at AVO. We present the first efforts to develop an eruption forecasting model for Redoubt volcano. To do this, we will use an event tree with nodes representing subsequent events to unrest, such as magmatic eruption and size. Geological and historical eruption records, theoretical models, and data from analogue volcanoes are used to estimate long-term eruption probabilities through Bayesian inference. In addition, we elicit expert opinions from those with extensive experience in monitoring and responding to volcanic crises in Alaska on what monitoring parameters should inform each node and what constitutes an anomaly based on critical thresholds. These anomalies are translated into probabilities via an entropy-based model to provide short-term eruption forecasts, which can be quickly updated in near-real time in the event of a crisis. The applicability of this approach for supporting future volcanic crises in Alaska will be tested by applying the forecasting model to past unrest episodes at Redoubt and Augustine (an analogue).

ID: 389

Satellite Data Synergy for Volcanic Monitoring: The Mauna Loa 2022 eruption

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The volume and diversity of both government and private satellite orbital data continues to increase. These data provide the volcanology community multiple tools to investigate an eruption and have distinct advantages and disadvantages; but used together, they enable synergistic options for volcanic monitoring at different temporal, spatial, and spectral scales. For this study, we present the use of multiple orbital datasets to investigate the 2022 Mauna Loa eruption. Thermal trends pre, syn and post eruption are investigated using the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) instrument. The flow front advance rates are calculated using very-high spatial and temporal resolution SkySat data from Planet. An average advance rate of 0.26 km^2/day was determined. High resolution digital elevation models (DEMs) were generated using stereo WorldView scenes to determine lava flow volume over time and geomorphological analysis. Individually each of these datasets provide useful information for hazard response, modeling, and/or mitigation. However, combining them provides a robust and more complete picture of the eruption.

ID: 465

Lava flow velocity in effusive contexts: a space-based approach using thermal data acquired by VIIRS

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Volcanic activity generates many hazardous phenomena that can damage and affect populations in terms of human lives, and infrastructures. Focusing on effusive contexts, the main risk is related to the flood from lava flows. The mitigation of this hazard is connected to the capability of predicting both the timing and the position of the active lava flows. Currently, different models can estimate the length and the path of the flows but there are still big uncertainties about the timing of this process. A significant enhancement in this sense could be represented by the measuring and monitoring of the velocity of lava flows, which is currently difficult.

In this work, we present an approach that uses the infrared thermal anomalies detected by the Visible Infrared Imaging Radiometer Suite (VIIRS) imaging bands (I-bands) to measure the advancement of the thermally active lava flow of several eruptions that occurred at Piton de la Fournaise (La Reunion, France) in the last decade. Through the analysis of satellite thermal data processed by the MIROVA algorithm, we estimate the length of the active lava flow, providing the first estimate of the initial velocity of the observed eruptions.

We consider challenging perspectives for the future of this work extending this approach to different effusive volcanoes, thereby providing a multiparametric and more comprehensive assessment of the risks associated with effusive volcanic activity.

ID: 534

Democratizing and Advancing Eruption Modeling Through a Cloud-based Open Software Cyber-Infrastructure

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Effective hazard assessment relies on access to robust modeling tools that are tested, documented, simple to use, and, critically, accessible to the community. In many cases, the codes for volcano modeling tools are not open-source, only tested on a limited set of examples, difficult to install, and require more computing power than is available to many users.

The Volcanology Infrastructure for Computational Tools and Resources (VICTOR) is a new platform that makes modeling tools for simulating eruption processes accessible, user-friendly, and open-source. Through VICTOR, models focused on lava flows, tephra fallout, lahars, pyroclastic density currents, and more are actively supported. Modern geoscience-focused programming libraries and cloud-based tools assure a convenient experience for all users. Interactive programming notebooks allow even those with limited coding experience to have detailed, informative outputs, resulting in seamless workflows. Using a standardized platform allows an easy flow of information between users, removing the need for any tool configuration, setup, and formatting while retaining modularity. Being cloud-based, access to processing power is no longer an obstacle, and only a basic internet connection is required. Importantly, utilities for benchmarking models are available on VICTOR and help users assess existing tools and test new ones. As the platform grows, workflows for data inversions and for linking models of the different components of the volcanic system will become available. VICTOR aims to serve the hazard assessment community by harnessing the power of cloud computing to support the rapid execution of probabilistic model ensembles and integrating cloud-ready monitoring data.

ID: 660

SISTEMATIZACIÓN DE LA CLASIFICACIÓN DE SEÑALES SISMO-VOLCÁNICAS DEL VOLCÁN UBINAS BASADO EN MODELOS OCULTOS DE MARKOV

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Los eventos sismo-volcánicos nos dan información del estado de un volcán dentro de su ciclo eruptivo. Algunos tipos de eventos pueden ser precursores de erupciones, mientras otros - como explosiones y emisiones de ceniza - implican un riesgo inminente para la población. Los sistemas de reconocimiento automático de eventos sismo-volcánicos (VSR, Volcano-Seismic Recognition) son una herramienta indispensable, sobre todo en periodos de crisis eruptiva, cuando cientos de eventos pueden ser registrados en pocas horas y es necesario un rápido análisis del riesgo existente. En esta situación, se hace casi imposible detectar y clasificar eventos manualmente, por lo que la implementación de un sistema VSR en tiempo cuasi-real (RT, Real Time) que genere continuamente un catálogo de eventos se hace clave para la evaluación del peligro.

Este trabajo detalla el diseño e implementación de un sistema VSR-RT automático basado en Modelos Ocultos de Markov. El sistema fue entrenado con eventos del volcán Ubinas (estación UBN02 ubicada a 3.1 km del cráter) clasificados manualmente para crear un modelo estadístico para cada clase o tipo de evento. Los modelos entrenados se integran junto a un servidor de datos sísmicos en tiempo-real. La evaluación del sistema muestra que esta siendo de gran utilidad durante el último proceso eruptivo del volcán Ubinas, posibilitando clasificar cientos de eventos en pocos minutos y detectando instantáneamente las explosiones volcánicas para así poder alertar a las autoridades encargadas de la gestión de riesgos.

ID: 733

Modeling Eruptive Activity at Fuego on Multiple Time Scales

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Over the last several centuries, eruptive activity at Fuego has been documented (often by newspapers), and it is available in the Smithsonian Institute (SI) Global Volcanism Catalog. This record is a valuable asset for constructing long-term (decades to centuries) predictive models for eruptive activity at Fuego. Yet, the record is imperfect -- missing eruptions, mis-attributed eruptions. Our goal is to both reduce and quantify uncertainties in the data by updating the SI catalog with first-hand accounts of historical eruptions and by considering Bayesian models of eruption frequency that can account for missing data and data of varying quality.

Details of individual paroxysms over the current eruptive phase at Fuego, roughly the last 25 years, are well documented. Paroxsyms seem to occur regularly for periods of time (we will call these a paroxysmal phases) with pauses of months to years in between phases. We will use this data to build models of paroxysmal phase frequency and duration. Such models are useful for predicting the occurrence of paroxysms and hence pyroclastic density currents (PDCs) on a moderate time scale (months to years).

Our final objective is to combine these efforts into a multi-scale model for making defensible predictions of the frequency of PDCs at Fuego, and we will lay out the framework to do so in this talk.

ID: 404

Bayesian Inference applied to hazard assessment for Pyroclastic Density Currents and Lahars in Planchón-Peteroa Chilean volcano

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Bayesian Inference has been demonstrated to be a powerful tool to perform and enhance the Volcanic Hazard Assessment (VHA), especially under poor or limited data scenarios. The application of these tools combined with numerical simulations and field data allow to develop a joint VHA. In general, Bayesian Inference methods are applied to forecast eruptions recurrence times. This project is focused on designing a joint methodology that allows to perform probabilistic hazard maps for Pyroclastic Density Currents (PDCs) and lahars in Planchón-Peteroa volcanic complex. Planchón-Peteroa is classified as type II (i.e. high risk) under the specific risk ranking for Chilean volcanoes. Their PDCs and lahars are between the main hazards occurring during (both) and after (lahars) volcanic activity. Currently, Planchón-Peteroa does not count with detailed hazard maps or proper volcanic hazard studies. To mitigate the lack of data and to study the behavior of the current events, a multi-parametric lahar monitoring station is being built along the main drainage Teno river where lahars have historically affected the infrastructure, communications and tourism. The results of this research will encompass the selection of main input parameters that represent the physical behavior of the phenomena and detailed probabilistic hazard maps for each process.

ID: 174

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 stand-alone 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 being remarked: 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.

ID: 405

Challenges in block-and-ash flow hazard assessment: the July 10-11, 2015 eruption of Volcán de Colima, Mexico

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On July 10 and 11, 2015, Volcán de Colima, one of the most active Mexican volcanoes, underwent its largest eruption since the 1913 Plinian event. Highly mobile block-and-ash flows (BAF) were originated from the dome collapse and subsequent extrusion of degassed magma from the conduit. The TITAN2D code was used to understand the factors controlling the mobility of the dense BAF undercurrent emplaced during the 2015 eruption. The selection of different input parameters was based on field data, on the seismic signal of the BAFs recorded by a broadband station located a few meters away from the channel, and by considering the different eruptive mechanisms of the July 10 eruptive phase (collapsing dome) with respect to the July 11 event (boiling over). Both events were simulated using the same topography, neglecting the significant changes in the morphology of the Montegrande ravine after the emplacement of the July 10 BAF. To analyze this effect, simulations in a synthetic flume with variable widths were conducted, evidencing the importance of the change in channel capacity (width) on the granular flow mobility. The emplacement of the July 10 BAF reduced the channel's capacity, increasing its width and decreasing its depth; this new morphology enhanced the July 11 BAF mobility by reducing clast to clast interaction, and between the flow and the channel walls. The results presented here set the basis to improve the hazard zonation for pyroclastic density currents at Volcán de Colima, which should be based on a multifactor, probabilistic analysis.

ID: 478

Developing a Catastrophe Bond for effusive eruptions

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Recent effusive eruptions have caused hundreds of millions of US$ of losses. Yet, the insurance gap for volcanic eruptions is up to 100% and it therefore often falls to governments and humanitarian organizations to stem the massive financial burden that comes with a volcanic crisis and the rebuilding. Even if insurance policies do exist for homeowners and businesses, claims are complicated, and a natural disaster can quickly exhaust the insurance and reinsurance system.

Catastrophe (Cat) Bonds are innovative financial tools that transfer the risk of natural disasters to the capital market and provide cover similar to insurance. The first Volcano Cat Bond, covering explosive eruptions and resulting ash-induced losses, was successfully brought to market in 2021 by Mitiga Solutions and their partners and is presented in an accompanying presentation. We are now developing a methodology to structure Cat Bonds for effusive eruptions, which necessitates a catastrophe / loss model for lava flows. The loss models are based on statistical analyses of the target volcano and probabilistic simulations of lava flows with varying vent locations and eruptive volumes. The probabilistic simulations make use of high-performance computing to account for statistical variability and computational effort of lava flow simulations. The hazard footprints are combined with exposure data and vulnerability to produce a stochastic loss event catalogue – the basis for parametric insurance products and Cat Bonds.

This presentation will demonstrate our developed methodology with Hawaiian volcanoes as a case study and invites active discussion with the community.

ID: 571

Evaluation of long-term volcanic activity and the first hazard map of Sumaco volcano, Ecuador

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Volcano hazard maps are essential tools for understanding and mitigating the potential risks associated with volcanic activity. These maps provide critical information about the potential hazards that can arise during a volcanic eruption, helping governments, emergency responders, and communities prepare for and respond to volcanic events. A principal responsibility of the Instituto Geofísico de la Escuela Politécnica Nacional is evaluating volcanic hazards.

We recently developed the first Hazard Map of Sumaco Volcano. This stratovolcano stands as an impressive natural landmark in the northern Subandean zone. The map shows the three most probable eruptive scenarios that reflect the eruptive activity that Sumaco has experienced: I) smaller scenario (every 100-300 years), II) intermediate scenario (every 2,000 years), and III) larger scenario (every 10,000 years).

Sumaco has produced at least five major ash falls during the last 4,400 years, with thicknesses of 1.50m in areas close to the edifice. Heavy rains have been one of the main triggers of lahars on the volcano’s slopes in several streams. These flows are the more dangerous phenomena that can reach distal communities. Deposits of remobilized pyroclastic flow crop out on the east flank of the volcano and in proximal areas. Lava flows are a common phenomenon in Sumaco´s geological evolution. Both in historical times and especially in prehistoric times, they have descended along the southwestern and southern flank of the volcano. As for debris avalanches, three events have occurred in the past ~40,000 years, giving rise to its current configuration, although these events are very rare.

ID: 579

Hybrid modeling of volcanic hazards: blending machine-learning approaches and physics-based simulations

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Simulating the evolution of lava flows is a primary focus in volcano hazards modeling. Lava flows are inherently complex fluids exhibiting phenomena like canalization, and accurate numerical simulation can play a crucial role for their understanding. However, traditional CFD models often necessitate extensive run times and computational resources, which can make their application impractical. In this context, Artificial Intelligence (AI) techniques can be combined with CFD approaches to develop hybrid models, able to deliver improved performances and functionalities. Here, we present a hybrid model that utilizes an Artificial Neural Network (ANN) to emulate the most computationally challenging parts of a CFD model by learning from its simulated data. Such a hybrid model, obtained through this process, is referred to as an *emulator*. We apply this concept to the Smoothed Particle Hydrodynamics (SPH) numerical method, a Lagrangian, mesh-free approach with well-established advantages for simulating lava flows, and renown computational challenges. We validate the results obtained by the SPH emulator with respect to some benchmark tests representative for lava flows, discussing the reliability and performance of this kind of approach.

ID: 688

Towards improved forecasting of volcanic hazards using Artificial Intelligence applied to multispectral satellite imagery

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Lava flow emplacement is one of the main phenomena associated with volcanic eruptions that represent serious threats to the community in terms of volcanic hazards. Machine learning (ML), a type of Artificial Intelligence (AI) in which computers learn from data, is gaining importance in volcanology. Here, we explore the possibility of monitoring and nowcasting the lava flow eruption using a variety of satellite sensors (e.g. Sentinel-2 MSI, Landsat 8 OLI-TIR, MSG-SEVIRI) and ML algorithms, including Deep Learning (DL) techniques. The real-time monitoring of an ongoing volcanic eruption is achieved by using both ML image classifiers with high spatial resolution satellite sensors to characterize the emplaced lava flow (e.g. localization, areal coverage, length), and analytical approaches with high temporal resolution sensors to retrieve relevant eruptive parameters (e.g., volcanic radiative power, effusive rate, volume). As for the hazard analysis, we show the potentiality of combining the spatio-temporal correlation between different satellite data with advanced DL algorithms (e.g., CNN, LSTM) to nowcast the evolution of the lava flow. The main DL input features are the spatial distribution and eruptive parameters of the lava flow coming from real-time monitoring, and the topographic information, i.e. Digital Elevation Model, accounting for the surface morphology. The model is trained by using previous long-lasting lava flow eruptions in different targeted volcanoes.

ID: 777

Machine learning for data-driven discovery in volcanology

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The Operational monitoring centers, like the Etna Volcano Observatory (EVO) are poised for a revolution centered around the application of existing and rapidly emerging Artificial Intelligence (AI) techniques to large and complex data sets being collected. These techniques have great potential to help volcanologist address some of the most urgent challenges and questions about the dynamics of volcanic eruptions.

At the EVO, a variety of geophysical and volcanological data are continuously acquired and used to improve our understanding of volcanic processes and our ability to identify renewed volcanic activity, forecast eruptions, and assess hazards. However, extracting meaningful information and gaining new insights from such a large volume of data is a challenging task. Under this perspective, Machine Learning (ML), a type of AI in which computers learn from data, plays a key role. From one hand, ML is used to automate the analysis of geophysical and volcanological data performing complex tasks that cannot easily be described by a set of explicit commands. On the other hand, ML can be used to discover new patterns, and relationships between geophysical and geological variables, otherwise partially or totally unknown, that are not easily revealed using traditional approaches. Thus, we have developed a ML-based algorithm to extract knowledge and draw inference from our geophysical and volcanological datasets collected at Mt. Etna revealing hidden dynamics of the volcanic system.

ID: 770

Machine learning for volcano deformation: moving beyond detection and classification to forecasting

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Ground deformation is a key indicator of volcanic activity and routine acquisition by the Sentinel-1 satellite mission now allows us to monitor volcano deformation globally. We have developed a system to routinely apply radar interferometry (InSAR), whenever a new Sentinel-1 image is acquired, and extract the deformation. As there are too many images to inspect individually, we have developed an automated machine-learning approach, based on independent component analysis, to identify new deformation patterns and also any changes in rate of existing deformation patterns, both of which are key indicators of changes in activity. In addition, we have developed a deep-learning based algorithm to classify the potential source of the deformation.
Our current goal is to forecast how a volcano might deform in the future, based on a time series of interferograms up to the present day. To this end, we have tested various deep-learning algorithms from the field of video prediction. Training of these networks requires a large data set of deformation time series so, in addition to processing all available SAR data acquired over volcanoes, we are simulating data using physical models of various deformation processes that occur at volcanoes.

We aim for our forecasts to be a useful tool for volcano observatories and we also expect the resulting forecasts to highlight common deformation sequences operating at volcanoes, leading to deeper understanding of the underlying processes. Already, characterising how deformation develops in time, has led us to new discoveries about generalisable underlying processes operating at volcanoes undergoing uplift.