

Advances in volcano monitoring driven by the first decade of Sentinel-1 observations[☆]

Juliet Biggs^{a,*}, Nantheera Anantrasirichai^b, Kyle R. Anderson^c, Valerie Cayol^d,
Edna W. Dualah^a, Quentin Dumont^{e,m}, Susanna K. Ebmeier^f, Jean Luc Froger^g,
Matthew Gaddes^{f,i}, Federico Galetto^{h,i}, Pablo J. Gonzalez^j, Ian Hamling^k, Andrew Hooper^f,
Milan Lazecky^f, Camila Novoa Lizama^f, Matthew E. Pritchard^h

^a COMET, School of Earth Sciences, University of Bristol, UK

^b COMET, School of Computer Science, University of Bristol, UK

^c U.S. Geological Survey Volcano Science Center, Moffett Field, California, USA

^d Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, Clermont-Ferrand, France

^e Institute of Seismology and Volcanology, Faculty of Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan

^f COMET, School of Earth and Environment, University of Leeds, UK

^g Université Jean Monnet - Faculté des Sciences et Techniques, Laboratoire de géologie de Lyon: Terre, Planètes, Environnement, CNRS, Saint-Etienne, France

^h Department of Earth & Atmospheric Sciences, Cornell University, Ithaca, NY, USA

ⁱ Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

^j Estación Volcanológica de Canarias. Department of Life and Earth Sciences, Consejo Superior de Investigaciones Científicas (IPNA-CSIC), La Laguna, Canary Islands, Spain

^k GNS Science, Lower Hutt, New Zealand

^l JBA Risk Management, Skipton, BD23 3FD, United Kingdom

^m Solid Earth Physics Laboratory, Department of Geophysics, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan

ARTICLE INFO

Editor: Dr. Jing M. Chen

Keywords:

Sentinel-1
SAR
InSAR
Volcano
Magma
Deformation

ABSTRACT

Sentinel-1 has transformed how satellite radar data (SAR and InSAR) are used in volcanology. The systematic, long-term archive and open-access policy means that volcano observatories and research organisations have invested in integrating Sentinel-1 datasets into their monitoring systems. We identify 233 high priority volcanoes and estimate that Sentinel-1 data has been used in peer-reviewed publications for 90 of them. We examine a global archive of 3.3 million automatically processed Sentinel-1 interferograms of volcanoes and use machine learning methods to identify eruptions and periods of unrest. We then review the ways in which InSAR data are being used in different contexts. At frequently erupting basaltic systems in Iceland, Hawai'i, the Galápagos, and Piton de la Fournaise, InSAR has become an effective monitoring tool and is integrated with other datasets and models to forecast magma pathways. For large explosive eruptions, deformation measurements often remain challenging, but SAR backscatter is increasingly used to map damaging flows and measure the changing shape of ocean islands. Sentinel-1's long archive provides critical baseline measurements that are vital for measuring slow deformation, capturing new periods of unrest and providing fresh insights into subsurface dynamics. Understanding the drivers of deformation remains challenging and typically relies on integration with external datasets. Future European Space Agency missions have the potential to improve both resolution and coverage providing an even richer dataset to further enhance global volcano monitoring.

1. Introduction

Volcanic unrest can give warning of impending eruptions, thus

monitoring and appropriate emergency management can save lives. A good example is the 2010 eruption of Merapi, Indonesia, in which about 400 people were killed, but over 400,000 were evacuated and an

[☆] This article is part of a Special issue entitled: 'Ten years of Sentinel-1 in space (Invitation Only)' published in Remote Sensing of Environment.

* Corresponding author.

E-mail address: juliet.biggs@bristol.ac.uk (J. Biggs).

<https://doi.org/10.1016/j.rse.2026.115377>

Received 27 March 2025; Received in revised form 18 February 2026; Accepted 13 March 2026

Available online 26 March 2026

0034-4257/© 2026 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

estimated 10,000 to 20,000 were saved (Pallister et al., 2013). The signals of unrest (e.g., seismicity, deformation, changes in gas chemistry) can be measured and used to inform decisions such as defining exclusion zones and issuing evacuation alerts. (e.g., Sparks et al., 2012; Winson et al., 2014). However, less than half of the world's volcanoes have ground-based monitoring equipment and space-based methods are increasingly being used (Pritchard et al., 2018; Pritchard et al., 2022). Magma intrusions and subsurface pressure changes cause surface deformation and may lead to eruption; therefore, geodetic observations are key to understanding the structure and rheology of magmatic systems (Dumont et al., 2022; Le Mével et al., 2021; Weber et al., 2025) and forecasting volcanic eruptions (Galletto et al., 2022; Gregg et al., 2022).

In the past 30 years, satellite technology has revolutionised the coverage, resolution and frequency of geodetic observations of volcanoes (Pritchard et al., 2022). In 1997, deformation signals had been recorded at 44 volcanoes; by 2018, the number had risen to more than 300 (Biggs and Pritchard, 2017; Dvorak and Dzurisin, 1997; Ebmeier et al., 2018; Furtney et al., 2018). The nature of the observations has changed from infrequent ground-based point measurements using traditional surveying techniques to dense time series of high-resolution images. These new datasets have revealed complexity in spatial and temporal patterns that was not apparent during the earlier era of volcano geodesy (Biggs and Pritchard, 2017; Ebmeier et al., 2018).

The regular acquisition strategy and open data policy of Sentinel-1 has transformed the application of Synthetic Aperture Radar (SAR) to volcanoes from opportunistic research to a global monitoring tool (Biggs and Wright, 2020; Poland and Zebker, 2022). Since 2014, Sentinel-1 has acquired images every 6–12 days globally with a spatial resolution less than 30 m. Several groups have developed near-real-time processing systems that are robust enough for automated analysis (Agram et al., 2016; Casu et al., 2019; Meyer et al., 2019; Morishita et al., 2020) and have designed 'big data' tools to extract useful information from this enormous satellite archive (Biggs et al., 2022).

In this study, we review the use of Sentinel-1 for volcanology during its first decade of operation. In Section 2, we summarise the various ways in which SAR data can be used in volcanology and discuss the automated processing systems and machine learning approaches that have been and are being developed for Sentinel-1. In Section 3, we update global catalogues of volcano deformation using Sentinel-1 data, based on both traditional literature reviews and machine learning approaches. In Section 4, we review the use of Sentinel-1 for significant eruptions including effusive eruptions at ocean islands, large magnitude explosive eruptions and other societally important volcanic events. In Section 5, we consider non-eruptive activity at volcanoes including stalled intrusion, restless calderas, and flank motion. Finally, we discuss the lessons learned from the first decade of Sentinel-1 data and look forward to the opportunities presented by the upcoming European Space Agency (ESA) missions.

2. Methods

2.1. Sentinel-1

The Sentinel-1 constellation consists of two satellites in the same orbit acquiring data in a pre-programmed operation mode to produce a consistent long-term data archive. The first satellite, Sentinel-1 A, launched in April 2014, was followed by Sentinel-1B in 2016. Sentinel-1B stopped delivering radar data in December 2021 while Sentinel-1 A has been operational for more than a decade. Sentinel-1C was launched in December 2024 and Sentinel-1D in November 2025. The Sentinel High Level Operation Plan (Potin et al., 2021) states that while two satellites were operating, tectonically and volcanically active areas within Europe should be revisited every 6 days and areas outside of Europe should be revisited every 12 days, but this has not always been practical. Data from most continental volcanic areas were acquired using Interferometric Wide (IW) swath mode, which steers the beam in

both azimuth and range directions (TOPSAR) to acquire data with a 250 km swath at 5 m by 20 m resolution. A small fraction (~0.09%) of Sentinel-1 data has been acquired in Stripmap (SM) mode over isolated oceanic targets where the continuity of the IW background mission is not an issue, such as Piton de la Fournaise (La Reunion), and Fogo (Cape Verde). These products have an 80 km swath at slightly less than 5 m by 5 m spatial resolution.

Fig. 1 illustrates the different ways in which Sentinel-1 SAR data can be processed to provide information in volcanology, using the 2017 eruption of Erta `Ale (Ethiopia) as a case study. Changes in surface scattering properties (backscatter) and phase coherence can be used to map volcanic deposits, and in the case of Erta `Ale, show that the lava flows are smooth close to the vent and rougher at greater distance (Gosling et al., 2025; Moore et al., 2019). The interferogram (InSAR) and pixel offset tracking measurements can be used to measure the amount of surface displacement in the satellite line of sight and in the case of Erta `Ale show the intrusion of a dyke (Moore et al., 2019; Xu et al., 2017). Each of these methods can be used to produce a time series, providing detailed temporal as well as spatial information and reducing noise.

2.1.1. SAR backscatter

The amplitude, or backscatter, of the SAR signal represents the strength of the returned signal, providing information on the characteristics of the ground surface (Fig. 1a). The backscatter is a function of the known satellite observation parameters, including polarisation, wavelength and incidence angle, and also the surface scattering properties (i.e., surface roughness, local incidence angle and dielectric properties), which vary across the landscape (Pinel et al., 2014). Sentinel-1 SAR data includes both co-polarized (e.g., VV and HH) and cross-polarized (e.g., VH and HV) backscatter measurements. Cross-polarized backscatter is sensitive to volume scattering, allowing for better differentiation between forested and unvegetated areas, as well as the detection of volcanic material emplaced within these environments (Poland, 2022; Solikhin et al., 2015). However, it is currently underutilised in volcanic monitoring (Poland, 2022).

Volcanic activity can significantly alter the ground surface through the emplacement and removal of material and the development of deposits over time. The emplacement of lava flows (e.g., Ezquerro et al., 2023; Goitom et al., 2015), pyroclastic flow deposits (e.g., Dualeh et al., 2021), and ash (Goitom et al., 2015) dominantly cause changes to the surface roughness, which affects backscatter differently depending on radar wavelength. In contrast, lava dome growth and crack formation primarily affect the local topographic slope (e.g., Dualeh et al., 2023; Plank et al., 2019). Subtle temporal variations in backscatter can be caused by progressive weathering and compaction of deposits or vegetation decay caused by degassing (Dualeh et al., 2023). The interpretation of how the ground surface changes due to volcanic activity requires an understanding of the pre-eruption ground surface. The same deposit can cause either an increase or decrease in backscatter depending on the scattering properties prior to emplacement. The combined contributions to the surface scattering properties result in complex backscatter signals that can be challenging to interpret. However, radar images can provide insights when other sensors (e.g., optical or thermal) are limited by visibility due to cloud coverage.

SAR imagery can also be used to observe fluctuations in lava lake levels and lava flow thickness by calculating changes in the radar shadow widths (e.g., Barrière et al., 2022; Moore et al., 2019; Smittarello et al., 2023; Wadge et al., 2012). The accuracy of these measurements depends on the geometry of the volcanic feature with respect to the sensor's direction of travel and incidence angle. Continuous time series of lava lake fluctuations can provide insight about the connectivity of the system and potential about pressure changes in the shallow plumbing system (e.g., Moore et al., 2019).

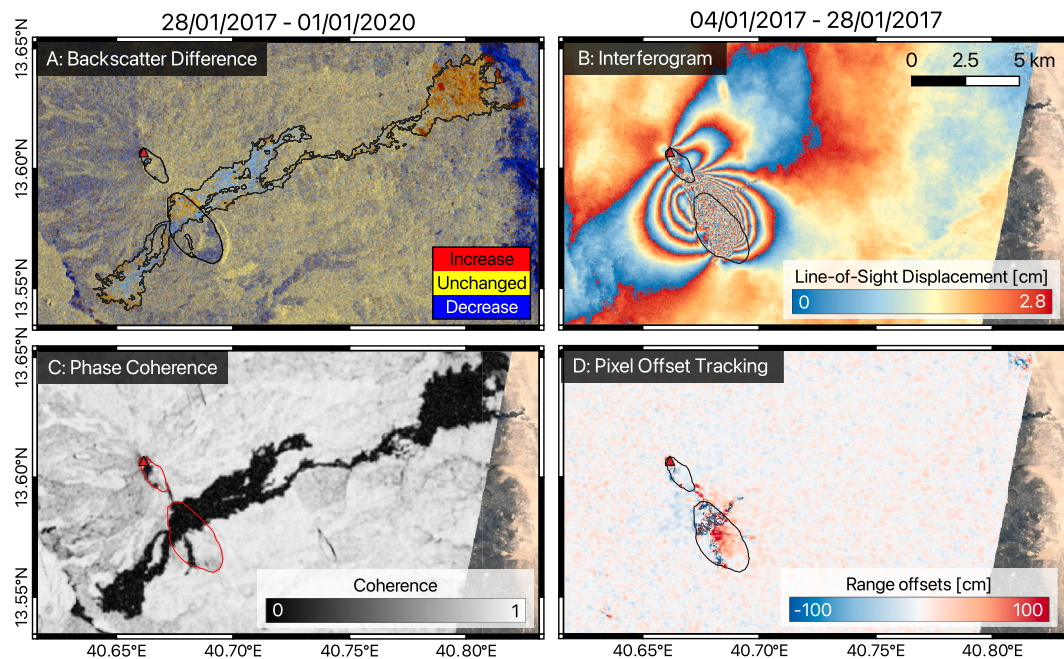


Fig. 1. Sentinel-1 Synthetic Aperture Radar (SAR) data over the 2017 eruption of Erta 'Ale (Ethiopia) showing (A) Backscatter RGB change difference (28/01/2017–01/01/2020), (B) Interferogram (04/01/2017–28/01/2017), (C) Phase Coherence (28/01/2017–01/01/2020), and (D) Range Pixel Offset Tracking (04/01/2017–28/01/2017). Erta 'Ale Crater outlined in black (red in C) and lava flow extent in (A). All images are from descending track. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1.2. SAR interferometry (InSAR)

The phase difference between two co-registered SAR images is determined primarily by the changes in distance between the satellite antenna and the ground targets, provided any changes in surface scattering properties are small (Fig. 1b). Once the topographic phase contribution has been removed using a digital elevation model (DEM), the remaining signal can be attributed to surface deformation and changes in atmospheric conditions. Many detailed reviews of this capability are available including (Bürgmann et al., 2000; Hooper et al., 2012; Pinel et al., 2014; Rosen et al., 2000).

The classic volcano deformation cycle suggests that volcanoes uplift prior to eruption as magma pressurises a chamber and then subside as magma is released during the eruption. Although this general pattern has been observed in some cases, dense time series of InSAR measurements reveal a much greater diversity of signal characteristics, compatible with the prevailing 'transcrustal mush' paradigm (Cashman et al., 2017). In reality, deformation signals at volcanoes are caused by a wide range of magmatic, hydrothermal and structural processes (Biggs and Pritchard, 2017; Ebmeier et al., 2018), and distinguishing between sources of deformation often remains challenging during periods of unrest (Pritchard et al., 2019). The characteristics of volcanic deformation that can be detected depend on the repeat interval of SAR acquisitions, resolution and wavelength of the instrument, rates of temporal and geometric decorrelation and noise (e.g., atmospheric contributions). Minimum detectable displacement rate or magnitude therefore differs from volcano to volcano, depending on radar wavelength, time span of observations, look direction of satellite, number of acquisitions in a time series, ability to reduce atmospheric noise, and level of coherence, but is typically on the order of a few centimeters.

Atmospheric effects, primarily due to water vapour in the troposphere, cause anomalies which can obscure or distort deformation or even lead to misinterpretation of signals (e.g., Beauducel et al., 2000; Yip et al., 2019). These effects are particularly challenging at high-relief volcanoes where the stratification of water vapour can lead to artefacts that correlate to topography, especially in humid, tropical environments (Albino et al., 2020; Ebmeier et al., 2013) and in arid continental environments, which are characterized by extreme seasonal variations in

tropospheric temperature and water vapour (Biggs et al., 2021; Dogru et al., 2023). Correction approaches can be divided into three categories: those based on empirical relationships, those based on external data sets, and those based on weather models. They can be used individually or in combination and have variable levels of success depending on the environment (e.g., Bekaert et al., 2015).

2.1.3. Phase coherence

The loss of phase coherence between SAR images (Fig. 1c) depends on both the technical specifications of the satellite system (signal wavelength, repeat interval, orbital tube) and the temporal stability of surface scattering properties (Kelndorfer et al., 2022). This provides opportunities for measuring volcanic processes that change surface scattering properties, including lava flows, pyroclastic flows, lahars and tephra fall (e.g., Poland, 2022; Udy et al., 2024). However, poor coherence limits the use of Sentinel-1 InSAR data in areas dominated by dense vegetation or snow cover.

2.1.4. Pixel offset tracking

Pixel offset tracking matches patterns between two backscatter images via image cross-correlation, producing displacement maps in across-track (range) and along-track (azimuth) directions (Fig. 1d). Pixel offset tracking is particularly useful for measuring displacement signals with gradients larger than 1 fringe per pixel, where InSAR cannot be used; however, the accuracy is significantly lower than that of InSAR, estimated to be 1/30th of the pixel dimension (Casu et al., 2011). This corresponds to roughly 8 cm in range and 47 cm in azimuth for Sentinel-1. Although pixel tracking has not been widely applied to Sentinel-1 studies of volcanoes, it has considerable potential for measuring displacement during dyke intrusions and caldera collapses (e.g., Hamling et al., 2019).

2.1.5. Time series analysis

InSAR time series combine multiple interferograms to track changes in displacement over time. This is particularly important in volcanology where transient behaviour may reflect sudden changes in the system. Time series analysis addresses two of the key limitations of InSAR: loss of

coherence due to changes in the scattering properties, and changes in radar path length not associated with surface deformation, such as atmospheric effects (Hooper et al., 2012). Time series algorithms fall into two broad categories, the first being persistent scatterer InSAR, which targets pixels with consistent scattering properties in time and viewing geometry (Ferretti et al., 2002; Hooper et al., 2007), and the second being the more general small baseline approach (Berardino et al., 2003; Doin et al., 2011; Morishita et al., 2020). The selection of interferograms for the time-series analysis must be carefully considered and adapted to suit particular volcanic environments (e.g., Smittarello et al., 2022a). For example, at high latitudes, processing strategies can be adapted to skip images collected during winter months (e.g., Wang et al., 2023) and in vegetated areas to overcome the 'fading signal' attributed to soil moisture variations (e.g., Bedón et al., 2024; De Zan et al., 2013).

2.2. Automatic processing systems

Automatic InSAR processing systems are crucial for volcano monitoring, leveraging satellite data to detect potential unrest, offer near real-time insights into volcanic activity and provide baseline measurements (Biggs et al., 2021; Tilling, 2008). While InSAR measurements have great potential for volcano monitoring in an observatory context, there are practical challenges to its uptake, especially in less-developed countries. In-house processing may be limited by the availability of suitable computers, reliable power and internet, as well as staff time required for training, radar processing and analysis (Watson et al., 2022).

The regular, open acquisition policy of Sentinel-1 makes it especially suited to automation, and several platforms have been developed to process and share data. Systems broadly fall into two categories: 1) those that automatically process new data over one or more target volcanoes as the data are acquired, such as COMET's LICsAR system (Lazecský et al., 2020), MOUNTS (Valade et al., 2019), AMSTer (d'Oreye et al., 2019), and the IREA system (Casu et al., 2019), and 2) on-demand services such as ESA's Geophysical Exploitation Platform (Foumelis et al., 2021), ASF's SARVIEWS project (Meyer et al., 2019), and Formater's Flatsim project (Thollard et al., 2021).

No global, automatic processing system specifically tailored for volcanoes is currently operational and volcanoes are a particularly challenging environment for multi-purpose processing systems. Default parameters designed for multiple applications and broad coverage may not always produce the best possible results at individual locations. Most detailed studies therefore rely on reprocessed datasets that have been optimised for a specific setting by making choices related to the interferogram selection, pixel dimensions in the final geocoded image, type of phase filtering, unwrapping strategy, etc. (Bedón et al., 2024). For example, in parts of the world where the scattering properties of the Earth's surface change rapidly, the best approach may be to make only the shortest possible time-span interferograms to maximise coherence. In contrast, where seasonal snow cover makes measurement during winter impossible, a better strategy is to make fewer one-year interferograms that span the snowy season.

Weather models are routinely available globally and therefore particularly suited for providing atmospheric corrections for automated Sentinel-1 processing systems. For example, the COMET LICsAR system provides corrections based on the Generic Atmospheric Correction Online Service for InSAR (GACOS), which uses the European Centre for Medium-Range Weather Forecasts (ECMWF) high resolution model (Yu et al., 2018). These, however, must be treated with caution for the many volcanoes where input data are sparse or orographic turbulence is significant, and the latency of data availability means that they cannot be used during emergency situations.

Several platforms have been developed to share the results of automatic processing systems without requiring local computing capacity beyond an internet browser. The Alaska Satellite Facility's cloud-based Hybrid Pluggable Processing Pipeline and OpenScienceLab platforms

allow on-demand InSAR processing capabilities and cloud-based Jupyter Notebook platforms that enable end-to-end research right next to the archive of large data volumes, without requiring data download (Meyer et al., 2025). The COMET Volcanic and Magmatic Deformation Portal (comet.nerc.ac.uk/comet-volcano-portal, referred to as COMET Volcano Portal) is a set of online tools designed to allow observatory scientists to critically interrogate automatically generated Sentinel-1 interferograms and identify deformation around active volcanoes (Watson et al., 2022). The tools are designed for volcano observatory scientists and researchers to get a first look at InSAR data around a volcano and to facilitate comparison with ground-based measurements (e.g., GNSS, levelling) or to motivate tasking/processing of data from other satellites (e.g., X-band radar satellites).

2.3. Machine learning approaches

Sentinel-1 provides a long-term, open-source data archive with systematic acquisition parameters, which is ideally suited to machine learning (e.g., Wassie and Milillo, 2025). For a more detailed discussion of the advantages and disadvantages of machine learning approaches in volcanology, the reader is referred to the recent review by Petrelli et al. (2025). Supervised-learning methods are designed for detecting signals whose characteristics are known and for which labelled datasets are available. For example, Convolutional Neural Networks (CNN) can be trained to identify deformation signals in InSAR images using labelled datasets (Anantrasirichai et al., 2018; Bountos et al., 2022) or synthetic images created from simple models of deformation processes and atmospheric artefacts (Anantrasirichai et al., 2019b; Valade et al., 2019). Although training the network is computationally expensive, application to large datasets is very quick and can rapidly identify images that need expert analysis. Combining with stacking or time-series approaches lowers the detection threshold, allowing for the detection of slow unrest as well as rapid events (Anantrasirichai et al., 2019a; Beker et al., 2023). CNNs are also used to improve the quality of signals through denoising approaches (Abdallah et al., 2025; Sun et al., 2020) and to classify the pattern of deformation (Gaddes et al., 2024).

Unsupervised methods have the advantage that they require no prior knowledge of the signal characteristics, instead learning the characteristics of 'normal' behaviour during a training period (Chandola et al., 2009). For example, time series of interferograms can be separated into component parts using blind signal separation methods, such as principal component analysis (PCA; Gaddes et al., 2018), independent component analysis (ICA; Ebmeier, 2016), and non-negative matrix factorisation (NMF; Gaddes et al., 2018). This can be used to detect changes in a component that was present during the training phase or the addition of new components that were not present during training (Gaddes et al., 2019). Deep learning techniques, including CNNs, Generative Adversarial Networks (GANs), and Variational Autoencoder (VAEs), can be trained in an unsupervised manner for anomaly detection (Popescu et al., 2025; Shakeel et al., 2022). Similarly, self-supervised contrastive learning does not require labelled data and instead learns meaningful representations of the data by contrasting similar and dissimilar data points (Bountos et al., 2021).

3. Global deformation catalogues

3.1. Use of Sentinel-1

We assess the impact of the Sentinel-1 mission on the number of observations of volcano deformation on a global scale by reviewing published articles and observatory reports that contain Sentinel-1 imagery. This provides a preliminary impression of the coverage of Sentinel-1 observations, though heavily biased towards English-language literature and towards volcanoes where deformation is measurable (Fig. 2). We are also aware that Sentinel-1 is used by observatories and others to monitor volcanoes for which there have been

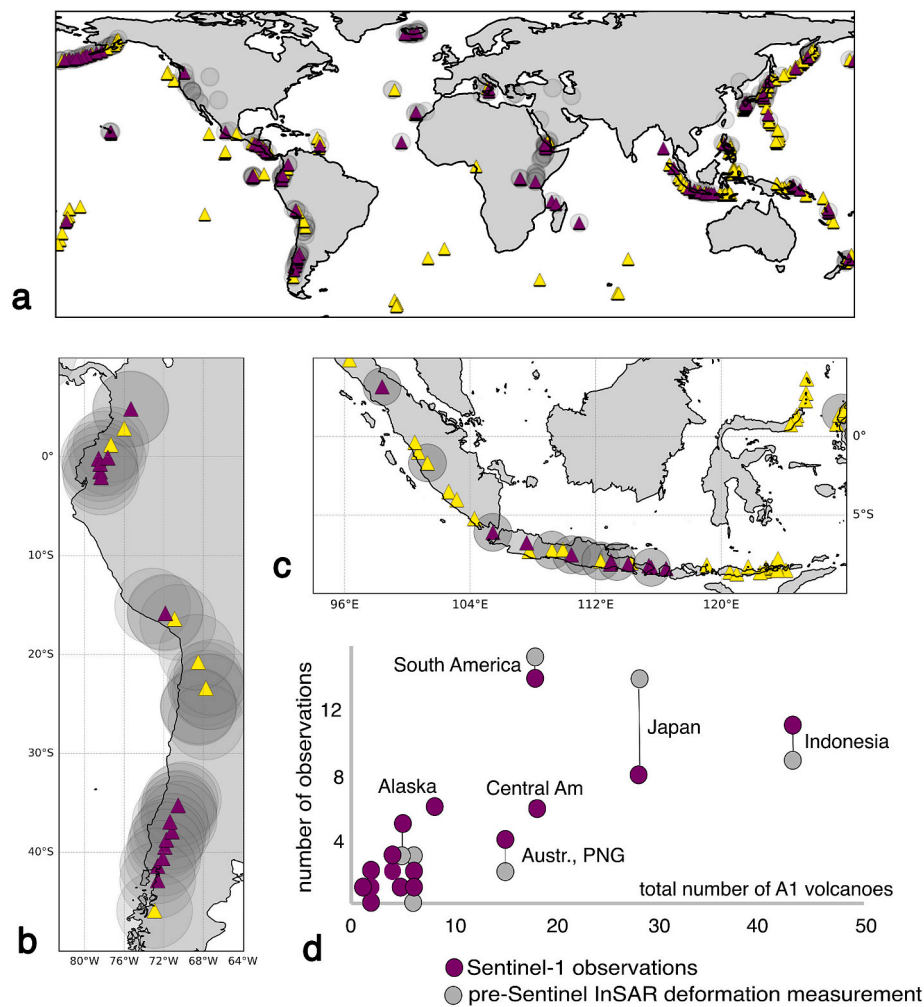


Fig. 2. (a) Global completeness of Sentinel-1 observations for volcanoes considered priorities for satellite remote sensing (categories ‘A1’ and ‘A2’). Purple triangles indicate A1 or A2 volcanoes where at least one Sentinel-1 interferogram has been published (volcanoes with only backscatter observations are not included), while yellow triangles are A1 or A2 volcanoes with no reports of Sentinel-1 observations. Grey circles indicate volcanoes where InSAR measurements of deformation pre-Sentinel (all activity categories). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

no publications. We frame our analysis using the system proposed by the USGS Powell Center Volcano Remote Sensing Working Group (Pritchard et al., 2022) to guide the frequency of satellite observations required for volcano monitoring. Volcanoes with recent eruptions and significant population exposure were categorised as ‘Active’ (A1 or A2, weekly to monthly SAR observations), those with reports of unrest as ‘Quiescent’ (B1 or B2, sufficient SAR observations to maintain InSAR coherence) and those with no evidence for unrest since 1990 as inactive (C, quarterly SAR observations, or as necessary to maintain InSAR coherence).

The eruption catalogue of the Global Volcanism Program lists 322 eruptions from 116 subaerial volcanoes with start dates in the first 10 years of Sentinel 1’s operations (April 2014–April 2024); however, we extend our analysis to the 264 (233 subaerial) volcanoes classified as ‘A1’ or ‘A2’ according to the approach of the USGS Powell Center Volcano Remote Sensing Working Group (Pritchard et al., 2022). Weekly SAR observations are recommended for ‘A1’ volcanoes, which are defined here as having erupted since 1900 in regions with a Population Exposure Index (PEI) ≥ 6 (Loughlin et al., 2015), since 1990 with PEI > 2 , or having had an eruption between 2019 and 2025. Monthly to weekly SAR images are recommended for ‘A2’ volcanoes, which include those with eruptions since 1990 with PEI < 2 . This classification of activity has been updated for this work (Supplementary Table) and aims to provide a basis for planning monitoring with SAR, optical and IR sensors. Since this classification exercise was last performed (Pritchard et al., 2022),

some volcanoes have erupted or had their first detection of unrest, leading to an increase in activity classification (e.g., Socompa, C – ‘inactive’, to B1 – ‘quiescent’, satellite observations of unrest since 1990). Others have entered phases of quiescence (e.g., Cerro Hudson, A1 to A2).

Of the 233 subaerial category ‘A’ volcanoes, 90 have reports using Sentinel-1 imagery (39%), with the global distribution illustrated in Fig. 2a. Sentinel-1 imagery has been used to study volcanoes in all of the world’s major volcanic regions, including tropical zones where C-band is commonly insufficient to penetrate dense vegetation. In Alaska, 75% of category A1 volcanoes have reports of Sentinel-1 observations, while in Indonesia only 26% have Sentinel-1 observations. In spite of the challenges of making useful measurements in tropical, highly vegetated regions, the number of Sentinel-1 observations that have been made in Indonesia, Australia and Papua New Guinea are higher than might have been expected relative to numbers of previously reported InSAR deformation measurements (Fig. 2d), perhaps due to the relative accessibility Sentinel-1 data. By contrast, there are lower numbers of Sentinel-1 observations reported at Japanese volcanoes, for which L-band ALOS-2 imagery is available.

Insets (b) and (c) show more detail of South America, where 70% of A1/A2 volcanoes have Sentinel-1 observations and Indonesia, where only 24% have observations. (d) Number of A1 volcanoes with reported Sentinel-1 observations and number with InSAR deformation

measurements from all satellites (L-, C- and X-band) in the 20 years prior to the launch of Sentinel-1. Note that Sentinel-1 has not increased the number of volcanoes with reported observations in Alaska. The unlabelled points in the lower left of the plot include regions where marginally more volcanoes have Sentinel-1 observations than reported InSAR measurements pre-2015 (New Zealand, Fiji and the Mediterranean), regions with no change (Africa, Iceland, Hawai'i, USA) and with fewer Sentinel-1 than pre-2015 observations (Philippines and West Indies).

3.2. Automatic detections

In this section, we analyse the first decade of Sentinel-1 observations using the LICsAR database, which contains 3.34 million InSAR images of

volcanoes (Lazecký et al., 2020). This is by far the largest dataset yet to be systematically analysed, surpassing the 600,000 interferograms reported in Biggs et al. (2022). However, the archive is heterogenous and incorporates interferograms generated for several purposes including routine background processing, detailed studies of individual volcanoes and applications outside of volcanology. Thus, the number and duration of interferograms varies significantly between volcanoes. For example, at Campi Flegrei (Italy) there are nearly 20,000 interferograms with timespans greater than 9 months, but at most volcanoes there are less than 1000 (Fig. 3e, Supplementary Table). However, due to differences in environmental conditions (e.g. snow and vegetation cover), it will never be possible to produce a completely uniform dataset and these heterogeneities must be accounted for during the analysis.

First, we use the supervised machine learning approach of

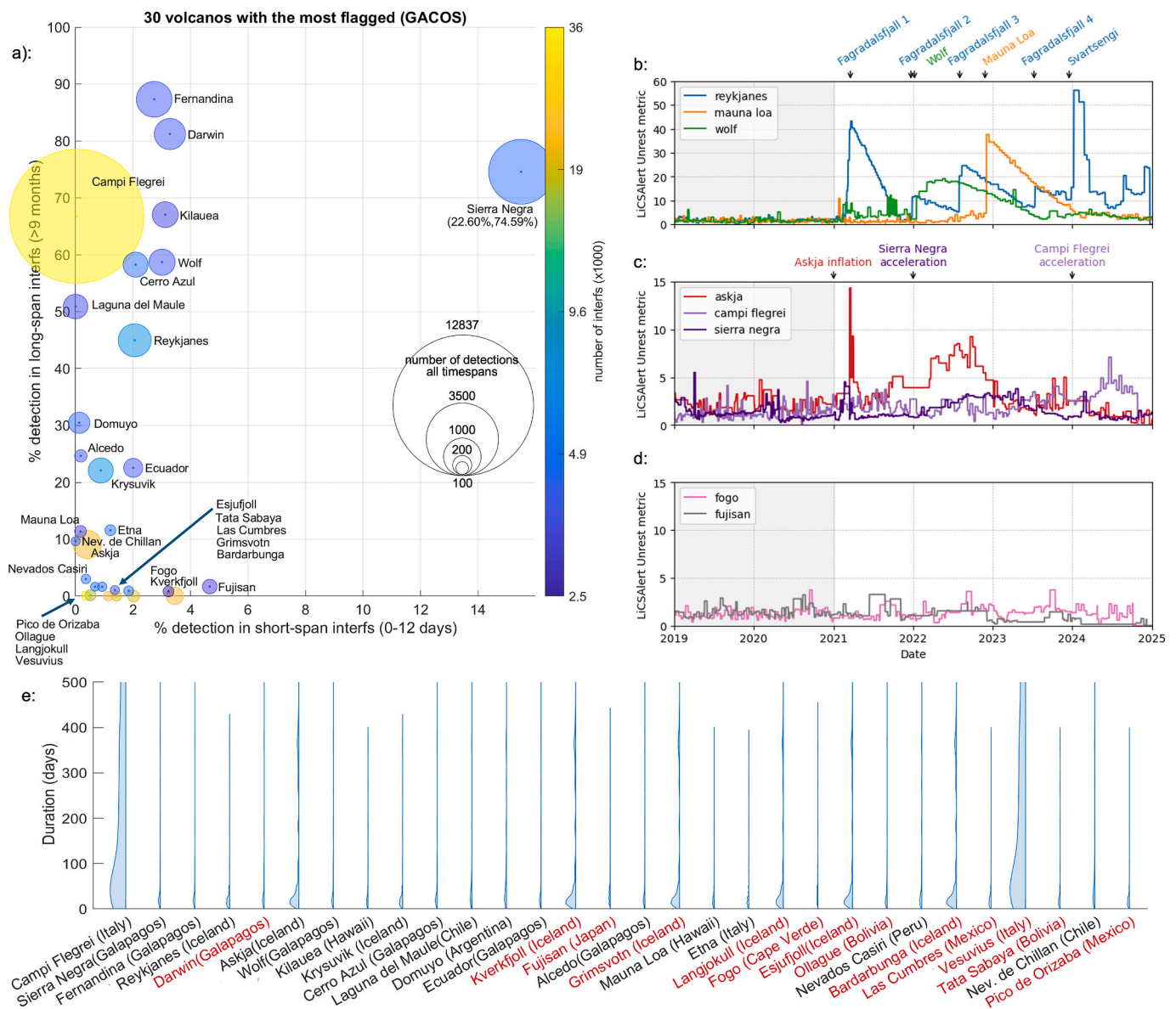


Fig. 3. Machine Learning approaches for detecting volcano deformation in Sentinel-1 datasets. a) Results of the CNN-detection algorithm applied to the 3.34 million interferograms in the LICsAR archive from the first decade of Sentinel-1 operations. The 30 volcanoes most frequently flagged following GACOS atmospheric corrections are displayed, with the percentage of short interferograms flagged on the x-axis and the percentage of long interferograms flagged on the y-axis. The red names correspond to false positives (Supplementary Table). b-d) Results of the LiCSAlert algorithm for eight of the volcanoes, with periods of volcanic unrest labelled. b) high unrest metrics associated with volcanoes that went on to erupt. c) moderate unrest metrics for volcanoes that experienced changes in deformation rate, but did not go on to erupt. d) low unrest metrics for volcanoes that did not change behaviour but are subject to large topographically correlated atmospheric signals. e) Violin plot showing the distribution of interferogram durations at each of the 30 volcanoes shown in panel a. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Anantrasirichai et al. (2019b), which uses a Convolutional Neural Network (CNN) for detecting volcano deformation in wrapped interferograms. Although more recent approaches such as transformers have been tested (Anantrasirichai et al., 2025) their performance has not yet been thoroughly investigated. We then apply the LiCSAlert algorithm to selected volcanoes at which the CNN flagged a large number of interferograms. LiCSAlert is a suite of machine learning methods for determining when the signals present in a time series of interferograms deviate from the previously exhibited behaviour (Gaddes et al., 2019). LiCSAlert is sensitive to new deformation entering a time series but, in contrast to the CNN method, only aims to detect existing deformation patterns if they change in rate (i.e., it will not alert a user to continued steady-state deformation).

3.2.1. CNN

Initially, the CNN described in Anantrasirichai et al. (2019b) flagged 61,235 of the 3.34 million interferograms (1.8%). The flagged images came from 621 different volcanoes, of which 39 had more than 100 flagged interferograms. To reduce the effect of atmospheric artefacts, we applied a GACOS correction to the unwrapped version of the flagged interferograms (Yu et al., 2018) and repeated the analysis. We then rewrapped the corrected interferograms to ensure compatibility with the same CNN-based model used above. Anantrasirichai et al. (2019b) reported a positive predictive value (PPV) of 82% without GACOS and 100% with GACOS. We introduced four different offsets to the unwrapped interferograms to generate variations in phase jump positions after wrapping following (Anantrasirichai et al., 2019a). This reduced the number of flagged interferograms to 26,934, which is 0.8% of the total.

Fig. 3a shows the detection results for the 30 volcanoes most frequently flagged as potentially deforming by the CNN-based framework after applying GACOS correction. As the dataset is heterogeneous, with different numbers and durations of interferograms at each volcano, we show the detection percentages (rather than total number of detections) and subdivide into short interferograms and long interferograms. The detection threshold varies between volcanoes thus there is no simple mapping function between detection threshold and displacement rate (Biggs et al., 2022; Anantrasirichai et al., 2019a). Nonetheless, to illustrate the typical values, we use a mid-range estimate of ~ 5 cm from Biggs et al. (2022). We define short interferograms as those less than or equal to 12 days (the repeat interval of Sentinel-1) and we would expect to detect discrete events with displacements above this threshold. We define long interferograms as those with timespans greater than 9 months and we would expect to be able to detect steady rates > 6.7 cm/yr.

This plot gives a first order approximation to the type of deformation detected: 1) continuous, rapid deformation will be detected in both long and short interferograms and plot in the top right quadrant (e.g., Sierra Negra); 2) continuous, slow deformation will be detected in long interferograms, but not short ones and will plot in the top left quadrant (e.g., Campi Flegrei); 3) atmospheric noise will be detected in equal numbers of short and long interferograms and will plot in the bottom right quadrant (noting the different scales for x- and y- axes); and 4) transient deformation will produce small numbers of detections with a slightly higher percentage in long interferograms than in short ones and will plot in the bottom left quadrant (e.g., Etna). More detailed analysis, including time-series approaches, source modelling and comparison with other monitoring data is required to fully understand the cause of deformation in each case.

Campi Flegrei (Italy), produced the largest number of flagged interferograms (13,122), of which 12,837 are long interferograms with time-spans greater than 9 months. The intense processing effort at this volcano means that a much larger number of interferograms (13,122) are available here in comparison to other volcanoes (Supplementary Table) and the overall detection percentage of 36% is similar to other restless caldera systems. This includes Laguna del Maule (Chile),

Domuyo (Argentina) and Askja (Iceland) which are flagged in many long term interferograms (51%, 30% and 9% respectively), but very few short-term ones, reflecting the slow, steady nature of the deformation at these systems (Le Mével et al., 2021; Lundgren et al., 2020; Parks et al., 2024). It is worth noting that the number of long interferograms available depends on the processing strategy for a given volcano and consequently some volcanoes may not be flagged despite relatively high rates of deformation. This includes restless caldera systems in the East African Rift (Albino and Biggs, 2021) and those in densely vegetated areas, including Indonesia.

The largest proportion of flagged interferograms (65%) are from Sierra Negra (Galápagos), which is flagged in both short- and long-term interferograms reflecting its status as the most rapidly and persistently deforming volcano globally (Section 4.1.3: Galápagos). Six other Galápagos volcanoes are ranked in the top 30 (Fernandina – 23%; Darwin – 18%, Wolf – 12%, Cerro Azul – 9.7%; Ecuador – 6.7%; Alcedo – 2.8%), although many of the flags at Darwin are artefacts caused by its proximity to Sierra Negra. In Hawai'i (Section 4.1.1), Kilauea is flagged in 67% of the long-term interferograms, while Mauna Loa's 2022 eruption also caused detections in over 3000 interferograms. Both the Rekjanes and Krysuvik tiles lie on the Reykjanes Peninsula of Iceland, where the ongoing dyke intrusion sequence is described in Section 4.1.2.

Fujisan (Japan), has a large number of detections, but is known to be a site of atmospheric artefacts that are challenging for the CNN to distinguish from real deformation (Biggs et al., 2022). The application of GACOS atmospheric corrections reduce the number of false positives but does not remove them entirely - the overall detections decrease from 14.7% to 4.9%. Similarly, the number of detections at Fogo (Cape Verde) decreases from 18% to 3.5% once GACOS has been applied. Other volcanoes in the top 30 whose detections appear to be caused by atmospheric artefacts include Las Cumbres and Pico de Orizaba (Mexico) and Tata Sabaya and Ollague (Bolivia), where the overall detection percentages are reduced from 2- 4% to 1.3–1.6% when GACOS is applied. Similarly, although Vesuvius has a large number of detections the percentage of detections is very small (0.2%). Some of these are likely atmospheric in origin, but longer timespan interferograms may record slow deformation at rates < 1 cm/yr. Interferograms from Kverkfjöll, Grimsvotn, Esjufjöll and Bardarbunga (all in Iceland) are mostly incoherent due to the icecap, but the small percentage of interferograms that are coherent ($< 1\%$) are affected by ice motion.

Etna (Italy), Nevados de Chillan (Chile) and Nevados Casiri (Peru) make up the remainder of the top 30 and have all experienced transient deformation signals (Astort et al., 2022; Biggs et al., 2022; Bonforte et al., 2019; De Novellis et al., 2019; Lizama et al., 2025). Biggs et al. (2022) also reported a large number of detections at Erte Ale (Ethiopia) and Rinjani (Indonesia) but as the transient deformation did not continue and no new detections were added, these volcanoes dropped to 44th and 39th respectively in the rankings. This highlights the dangers of ranking volcanoes based on the number of detections alone, because persistent atmospheric artefacts may produce a larger number of detections than transient deformation signals.

Overall, of the 30 most flagged volcanoes, we find that 17 are associated with real deformation signals (9 rapid persistent, 4 slow, continuous, and 4 transient) and 13 are false positives (5 ice-related deformation, 7 dominated by atmospheric signals, and 1 contaminated by the signal from a neighbouring volcano) as described in the supplementary table. Conversely, we cross-reference the flagged volcanoes against the list of 90 category A volcanoes which have reported deformation using Sentinel-1 InSAR data described in Section 3.1 and find that 46 have at least one flag and 18 have more than 25 flags. This suggests that although the current machine learning techniques show promise in automatically detecting deformation signals, they do not yet match the performance of expert analysis.

3.2.2. LiCSAlert

The basis of the LiCSAlert algorithm is described in Gaddes et al.

(2019), but we also provide a brief summary here. The algorithm uses a baseline time series of approximately three years to determine the background behaviour of each volcano. We first apply spatial independent component analysis (sICA) to recover the deformation and atmospheric signals that mix to form each interferogram, and then determine how each signal contributes over time by performing a least squares inversion to reconstruct each interferogram from the recovered sources. When used for volcano monitoring, the contribution of each signal to each new interferogram is recorded, allowing for any significant change in their level of contribution to be detected. Additionally, the residual signal in each interferogram that cannot be explained by a combination of the baseline signals is also recorded, allowing the algorithm to detect new deformation signals. If deformation that occurred during the baseline stage persists but slightly changes spatially, the residual when this is fit using the original (i.e., baseline) deformation signal would also increase and produce an increased unrest metric.

This approach produces a rich data set that details how each latent signal contributes in time, and also how the residual evolves. To condense this, we present here only the deviations of the most significant deformation signal (which we term the “existing deformation unrest metric”) and the deviations of the residual (which we term the “new deformation unrest metric”). As the Sentinel-1 acquisition strategy results in most volcanoes being imaged in at least two frames (i.e., ascending and descending), this analysis is repeated for each frame, with the maximum of either the new deformation unrest metric or the existing deformation metric across all frames being recorded as the unrest metric for each day.

Fig. 3b-d shows the results from our analysis of eight volcanoes selected from those that the CNN flagged when applied without GACOS corrections and which represent a range of processes. Fig. 3b shows three volcanoes that exhibited unrest and went on to erupt (Reykjanes Peninsula, Wolf Volcano, and Mauna Loa), each of which have a low unrest metric before eruption, which then jumps at the time of eruption. Following each eruption, the unrest metric gradually decays as the deformation associated with it recedes into the past, which allows the algorithm to reset in readiness to detect new episodes of unrest, as demonstrated through the detection of the multiple eruptions that occurred on the Reykjanes Peninsula. While this approach does not smooth the onset of unrest, it does smooth the end of unrest. This is a reasonable compromise to allow the algorithm to reset for future unrest.

Fig. 3c shows the results of our analysis of volcanoes that experienced unrest but did not go on to erupt. At Askja, the reversal from subsidence to uplift that occurred in early 2021 is clearly identified though a large increase in the unrest metric. At Campi Flegrei, acceleration in the uplift that occurred in 2024 is also identified, as well as acceleration in the uplift that occurred at Sierra Negra in early 2022. In both of these cases, the unrest metric reaches its peak 6–12 months after the onset of acceleration, and this time delay depends on the magnitude of the acceleration change. Fig. 3d shows the results of our analysis at volcanoes that did not experience unrest but were subject to strong topographically correlated atmospheric phase screens. The low unrest metric demonstrates that the LiCSAlert algorithm can detect these true negative cases, preventing interpretation of strong atmospheric signals as signs of volcanic unrest.

4. Sentinel-1 studies of significant eruptions

In this section, we focus on significant eruptions that have occurred during the first decade of Sentinel-1 data acquisitions. As demonstrated in Section 3, basaltic intraplate ocean island volcanoes are some of the most frequently deforming volcanoes globally, and these are discussed in Section 4.1. In contrast, large explosive eruptions are often more challenging to study using InSAR, and Section 4.2 reviews the use of Sentinel-1 at the large magnitude explosive eruptions (VEI4+) to have occurred between 2014 and 2024. Finally, we review additional eruptions that have had particular societal significance, either due to a large

number of fatalities or the scale of evacuations.

4.1. Effusive eruptions

4.1.1. Hawai'i

Ground deformation on the Island of Hawai'i – including Kilauea and Mauna Loa volcanoes – is measured by the U.S. Geological Survey's Hawai'i Volcano Observatory (HVO) using a network of in situ sensors (tiltmeters, GNSS sensors, and gravimeters) and SAR satellites. In addition to Sentinel-1, access to data from other radar satellites (e.g., TerraSAR-X, COSMO-SkyMed) is facilitated by Supersite designation for Hawai'i's volcanoes. The variety of data sets, combined with frequent volcanic activity, provides a unique ability to resolve magmatic processes (Fig. 4).

From 1983 to 2018, Kilauea erupted almost continuously from a rift zone vent at or near Pu'u'Ō'Ō some 20 km from the summit, and from 2008 to 2018 also from a summit lava lake. During the 1983–2018 eruption, changes in magma supply, vent elevation, tectonic stress, and other factors led to changes in magma pressure and intrusions in the summit and rift zones. Sentinel-1 data were used operationally by HVO to track unrest and to share changes with the public, and by the broader community for research purposes. An early application came in 2015, as heightened magma system pressurization led to an intrusion beneath Kilauea's summit. Combined with other geodetic data, a Sentinel-1 InSAR time series was used to model the geometry of two summit magma reservoirs and suggest that the event may have been caused by a short-term increase in magma supply to the volcano (Bemelmans et al., 2021).

In 2018, an intrusion into Kilauea's lower East Rift Zone 40 km from the summit triggered a series of destructive events, including an $M_w 6.9$ décollement earthquake, eruption of $>1 \text{ km}^3$ of magma from the lower East Rift Zone, and collapse of the summit caldera (Anderson et al., 2024; Neal et al., 2019). Operationally, interferograms and amplitude images from Sentinel-1 and other satellite SAR sensors were used by HVO during the eruption to monitor magma movement and the early stages of caldera collapse when the vent was obscured by tephra emissions. Subsequently, the data have contributed importantly to numerous research efforts (Fig. 4). Together with GNSS, tilt, and lava lake elevation data, Sentinel-1 interferograms were used to resolve the location, geometry, and total volume of the subcaldera magma reservoir in the days before collapse started, as well as the critical failure thresholds at which collapse began (Anderson et al., 2019). The data were also used to track and model the dike intrusion and magma extraction from the rift zone, suggesting that the décollement earthquake was triggered by stress change induced in part by the dike (Chen et al., 2019; Kundu et al., 2020). Other applications of Sentinel-1 data to the 2018 eruption included detecting surface fault slip (Wang et al., 2019), modelling caldera collapse processes (Roman and Lundgren, 2021), and mapping lava flows using SAR coherence (Lee et al., 2023).

HVO's extensive operational use of Sentinel-1 and other SAR data – which includes situational awareness, the internal development of explanatory models, and communications with the public and the observatory's partners continued in the years after 2018. Processes recorded at Kilauea during this time include multiple intrusions and eruptions as the volcano recovered from the 2018 activity, while data from Mauna Loa were used to track the buildup to its 2022 eruption, co-eruption dike intrusion and magma reservoir depressurization, and subsequent post-eruption repressurization. Research efforts include the development of an automated routine for integrating GNSS and InSAR time series data (Corsa et al., 2022) and mapping lava flows to investigate the potential for using InSAR correlation to track volcanic activity on Venus (Brandin et al., 2024).

4.1.2. Iceland

Automated processing of Sentinel-1 interferograms at the Iceland Meteorological Office (IMO) is used for routine monitoring of Iceland's

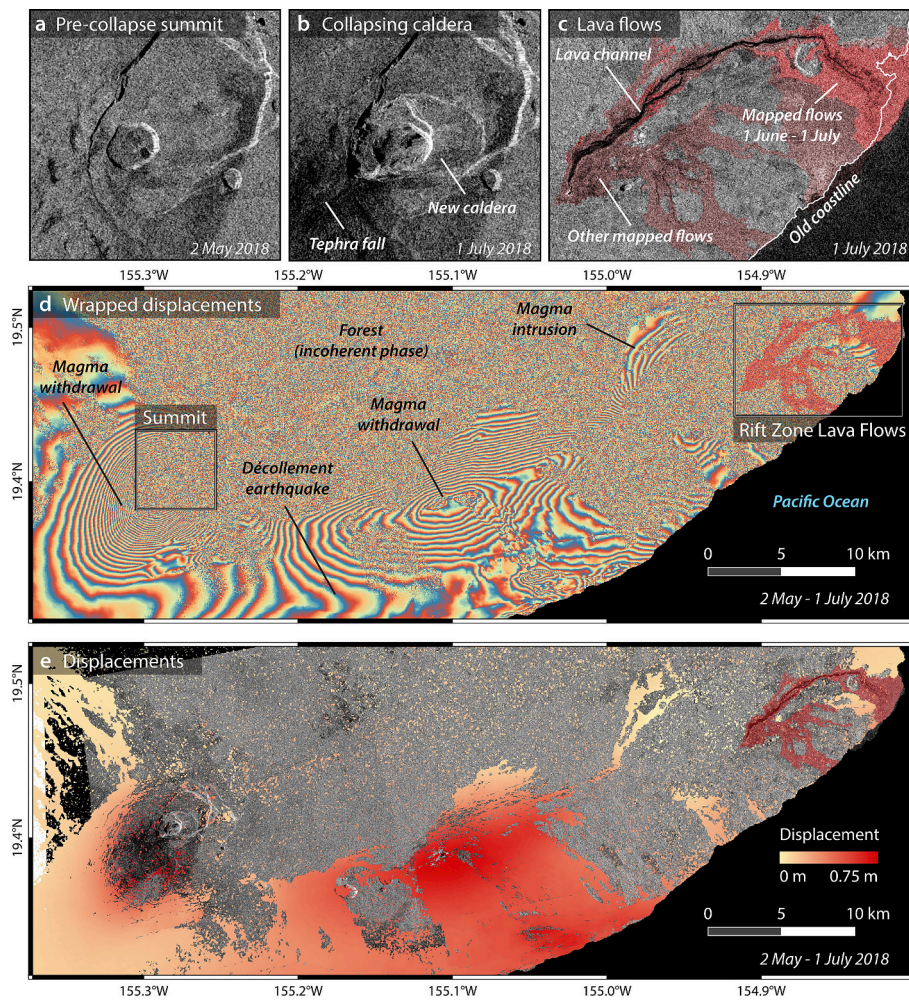


Fig. 4. Sentinel-1 images of Kilauea volcano during its 2018 lower East Rift Zone eruption and summit collapse. (a–b) Backscatter images from the summit showing the collapse of the caldera, which was ongoing when the second image was acquired. (c) Backscatter image of the lower East Rift Zone (ERZ) acquired on 1 July 2018 with pink indicating lava flows mapped by the Hawaiian Volcano Observatory. The backscatter imagery clearly shows the active lava channel and growth of the coastline due to lava emplacement. (d) Ascending-mode interferogram spanning 2 May to 1 July 2018 showing displacement in the range direction caused by magma evacuation from the summit and middle ERZ, intrusion into the lower ERZ, and the M_w 6.9 earthquake. Incoherent areas are caused mostly by forest and, in the lower ERZ, new lava flows (shown in pink). (e) Large magnitude displacements measured using pixel offset tracking in the range direction and refined using the interferometric phase. A mask is applied based on the offset cross-correlation coefficients and interferometric coherence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

34 active volcanoes. Reactivation of the Reykjanes Peninsula commenced in December 2019, with a week-long microearthquake swarm at the Fagradalsfjall volcanic system followed by inflation, detected by Sentinel-1 and GNSS, at the Svartsengi volcanic system the following month. A series of dike injections and eruptions then occurred at Fagradalsfjall between February 2021 and August 2023 (Parks et al., 2023; Sigmundsson et al., 2022) initially accompanied by a series of large earthquakes reaching greater than M_w 5. Sentinel-1 was used with GNSS and other radar satellites to constrain the location and volume of the dike injections and the slip for the largest earthquakes.

Meanwhile a series of uplift episodes, constrained by Sentinel-1 and GNSS, continued to occur at Svartsengi, eventually culminating in a major rifting event in November 2023, when a 15 km long dike was emplaced, with ultra-rapid initial magma flow rates of $7400 \text{ m}^3 \text{ s}^{-1}$ (Fig. 5, Sigmundsson et al., 2024). This event was also accompanied by earthquakes reaching greater than M_w 5. Since then, a series of dike intrusions and eruptions have occurred at Svartsengi (Parks et al., 2025), causing significant damage to houses, roads, hot water pipes, and power networks in and around the town of Grindavík. Inflation, constrained by Sentinel-1 and GNSS, has been almost continuous, punctuated only by periods of deflation during dike events and eruptions, and the

deformation rate and style is used to forecast when the events are likely to occur (Parks et al., 2025).

4.1.3. Galápagos

Six volcanoes in the Western Galápagos experienced unrest with significant deformation since the launch of Sentinel-1 A, of which three also had effusive eruptions: Wolf (2015, 2022), Sierra Negra (2018), and Fernandina (2017, 2018, 2020, 2024). Comparison of deformation measured using Sentinel-1 (Fig. 6a) to historical InSAR datasets show that locations of magma storage at these volcanoes (Fig. 6b) have been consistent, to within modelling uncertainty, for almost three decades (Reddin et al., 2024). Furthermore, correlations in displacements between all six active volcanoes (Alcedo, Cerro Azul, Darwin, Fernandina, Sierra Negra, and Wolf) between 2015 and 2022 are statistically significant, especially during periods of elevated magma flux into the shallow crust (Reddin et al., 2023). This has been attributed to pore pressure diffusion in sill complexes at the base of the crust, analogous to systems proposed to exist beneath Mauna Loa and Kilauea (Gonnermann et al., 2012), allowing changes in a magmatic zone beneath one volcano to affect neighbouring systems. Sentinel-1 has provided a much-increased temporal density of geodetic observations, allowing both

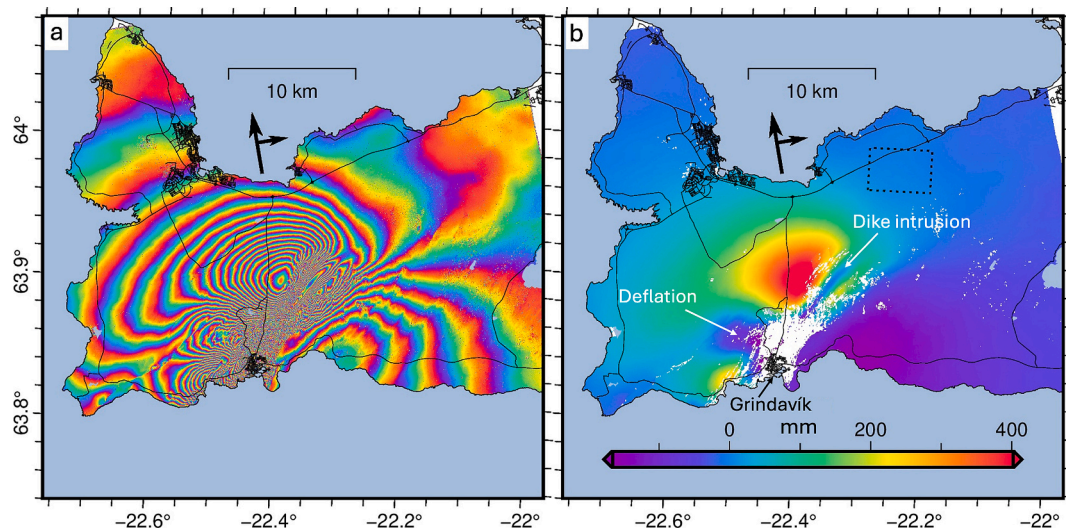


Fig. 5. Sentinel-1 interferogram spanning dike intrusion and deflation of a shallow magma reservoir occurring between 10 and 12 November 2023, at the Svartsengi volcanic system, Iceland. (a) wrapped and (b) unwrapped (modified from Sigmundsson et al., 2024).

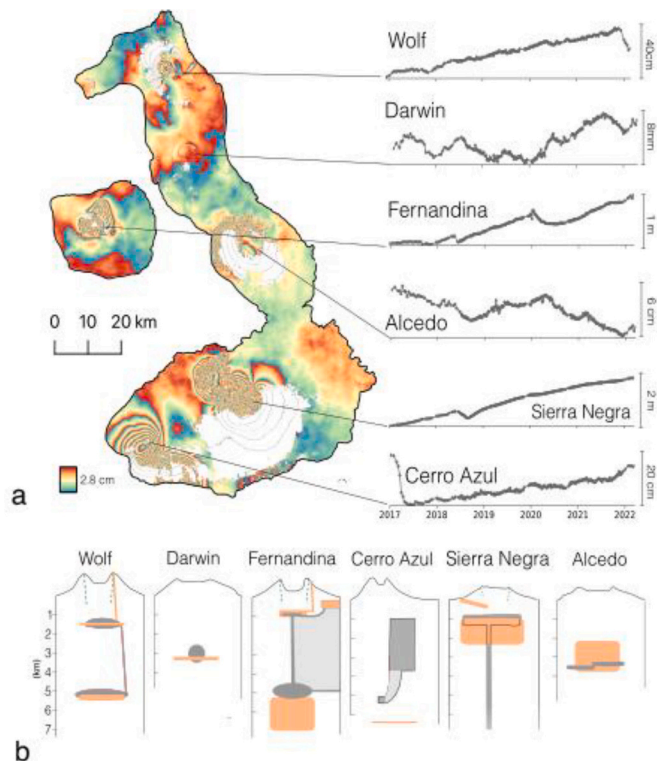


Fig. 6. (a) Map showing cumulative Sentinel-1 displacement of the Western Galápagos between January 2017 and July 2018 and spanning an intrusion at Cerro Azul and eruptions at Sierra Negra and Fernandina. Time series show representative displacements over a longer duration for each of the 6 active volcanoes (2017–22), after Reddin et al., 2023; note the different ranges of displacement amplitudes for each volcano and that positive values correspond to a reduction in range (generally indicative of inflation/uplift). (b) Diagrams showing magma storage areas adapted from Reddin et al. (2024), incorporating interpretations from Galetto, 2023, Xu et al., 2017 and others. Magmatic zone depths and geometries from inversion of Sentinel-1 imagery (2015–2024) in orange, for both co- and inter-eruptive displacements compared to previous interpretations of deformation in grey.

more granular analyses of eruption progression than previously possible (Davis et al., 2021), as well as applications of novel approaches to

comparing deformation time series (Reddin et al., 2023).

Deformation at Fernandina, the most frequently erupting of the Western Galápagos, has typically been characterized by inter-eruptive uplift lasting months to years and subsidence during eruptions. For example, Sentinel-1 interferograms showed that the eruption from a circumferential fissure in 2017 was supplied by connected reservoirs at ~1 km and 5 km depths below the surface, both of which recharged steadily until an eruption in 2018 that was oriented radially to the summit caldera and that was primarily supplied from the deeper reservoir (Galetto et al., 2023). In contrast, Sentinel-1 imagery showed that although the 2020 eruption was limited to a single day of lava flows from a fissure oriented circumferential to the caldera on the east flank, significant intrusion in the SW flank accompanied the eruption, which was also followed by three months of island-wide deformation. The volumes of magma involved in the intrusive event that accompanied the 2020 eruption were significantly larger than those intruded and erupted during each of the 2017 and 2018 eruptions (Galetto, 2023). Uplift during the 2020 eruption to the southwest of Fernandina Island, and extending offshore, is related to an offshore intrusion or eruption (Galetto, 2023; Reddin et al., 2024). Between the 2020 event and the February 2024 eruption, uplift was centred on the caldera and is consistent with increases in volume in the shallower (1 km depth) reservoir. Complex co-eruptive subsidence in February 2024 was related to *syn*-eruptive transport of magma to a circumferential fissure.

Sierra Negra uplifted over 6.5 m in at least 4 distinct phases between eruptions in 2005 and 2018, with a well-constrained magma accumulation depth of about 2 km below the surface (Bell et al., 2021). Sentinel-1 data were modelled in near real time using an Ensemble Kalman Filter (EnKF) to forecast the timing of reservoir failure, 5 months in advance of the 2018 eruption (Gregg et al., 2022). Sentinel-1 interferograms then captured the propagation of an unusual, highly curved sill, whose trajectory was controlled by the interaction of competing stresses, and that eventually surfaced to feed a fissure eruption (Davis et al., 2021).

Recent eruptions at Wolf in 2015 and 2022 provide a good example of Sentinel-1 imagery capturing a volcano's full eruptive cycle. Although regular Sentinel-1 acquisitions at Wolf did not begin until the end of 2015, there were a few descending acquisitions during the 2015 circumferential and intracaldera eruptions between May and July, and that contribute to a picture of hydraulically connected reservoirs at 1 and 5 km depths below surface (Xu et al., 2017), or alternatively to single reservoir interacting with a caldera bounding ring fault (Liu et al., 2019). Between 2017 and the 2022 eruption, Wolf caldera uplifted by more than 40 cm, with displacement data modelled plausibly by

interconnected stacked sills (Reddin et al., 2024) or by an asymmetrically opening ring fault that would have promoted the opening of the radial dyke that fed the 2022 fissure eruption (Xu et al., 2023).

4.1.4. Piton de la Fournaise, La Réunion

Since 1998, in addition to routine in situ monitoring carried out by the Observatoire Volcanologique du Piton de la Fournaise using seismic and GNSS networks, the volcanic activity of Piton de la Fournaise has been continuously monitored using InSAR data as part of a French national observation service (OI2/SNOV-ISDeform/INSU; Richter and Froger, 2020). A wide variety of SAR data have been employed for this purpose, provided by various sensors operating in X, C, or L bands. This monitoring has enabled the imaging of ground surface displacements associated with 61 magma intrusions (57 eruptions and 4 failed eruptions) that took place between March 1998 and July 2023.

For monitoring volcanic ground deformation using Sentinel-1, the higher spatial resolution of Stripmap (SM) mode is preferable to Interferometric Wide Swath (IW). Recognizing this advantage, ESA agreed in May 2015 to alternate Sentinel-1 acquisitions between IW and SM modes over La Réunion, with an average 24-day revisit interval for both ascending and descending passes. From October 2016, the launch of Sentinel-1B allowed the interval between successive acquisitions to be reduced to 12 days while maintaining the alternate acquisition of IW and SM images. This acquisition strategy, optimal for displacement characterization, continued until the failure of Sentinel-1B in December 2021. Subsequently, acquisitions were made in IW mode for both ascending and descending passes every 12 days until May 2022. From that point onward, IW data were acquired every 12 days for descending passes and SM data every 12 days for ascending passes. This acquisition scenario is significantly less favourable than the previous one for precise displacement characterization; however, during this period, Sentinel-1 data were supplemented with other datasets, particularly numerous ALOS-2 Spotlight-mode acquisitions, to continue monitoring the activity of Piton de la Fournaise.

Since the beginning of Sentinel-1 acquisitions over Piton de la Fournaise in July 2015, 26 intrusions (23 eruptions and 3 failed eruptions) have been imaged by at least one ascending and one descending

Sentinel-1 interferogram. Systematic inverse modelling of ground displacement associated with the 26 intrusions determined the location, geometry and stress changes for each. These analyses were complemented by inverse modelling of the 35 intrusions (34 eruptions and 1 failed intrusion) recorded prior to Sentinel-1 acquisitions between 1998 and July 2015, and measured by other InSAR sensors and by GNSS, leading to intrusion and fault models for a total of 61 displacement events (Dumont et al., 2022). This extensive analysis provided valuable insight into the structure and dynamics of the volcano's magma plumbing system, and major flank slip structure. For example, a spoon-shaped intrusion zone accommodating 45% of the intruded volume was imaged (Fig. 7a). This structure, suggestive of a rotational landslide, connects at the surface to the main NE-SE rift zone. The intrusion mechanism shows a continuum, transitioning from pure opening in the main rift zone to sheared intrusion and pure slip further east (Fig. 7b). On a geological time scale, it is likely that this structure is responsible for catastrophic flank failures, as evidenced from bathymetry. Four secondary rift zones were also imaged by the systematic modelling of intrusive events (Fig. 7a). Since 2015, Sentinel-1 acquisitions have contributed to understanding the link between stress inherited from intrusions and slip events and the location of subsequent events (Dumont et al., 2024). The increase in normal stress in the main rift zone explains the alternation of intrusions in the NE and SE rift zones, as well as the occurrence of intrusions in the secondary rift zones when normal stress in the NE-SE rift zones is too large to accommodate magma intrusion (Fig. 7c). It also explains that successive intrusions take place at increasing distances from the summit. Stress modelling also showed positive feedback where rift zone intrusions decrease normal stress, and increase Coulomb stress in the sill zone, explaining the occurrence of sills and sheared sills. Conversely, the intrusion of sills and sheared sills decreases normal stress in the rift zones, further allowing new rift zone intrusions. Since April 2021, normal stresses are at their maximum in the main rift-zone, and at their minimum in the sill zone, explaining the occurrence of sill intrusions in October 2021 and July 2023.

Sentinel-1 data were also used to test a new method for tracking the propagation of magma by joint inversion of InSAR and GNSS data (Smittarello et al., 2019). Indeed, in May 2016, Sentinel-1 acquired an

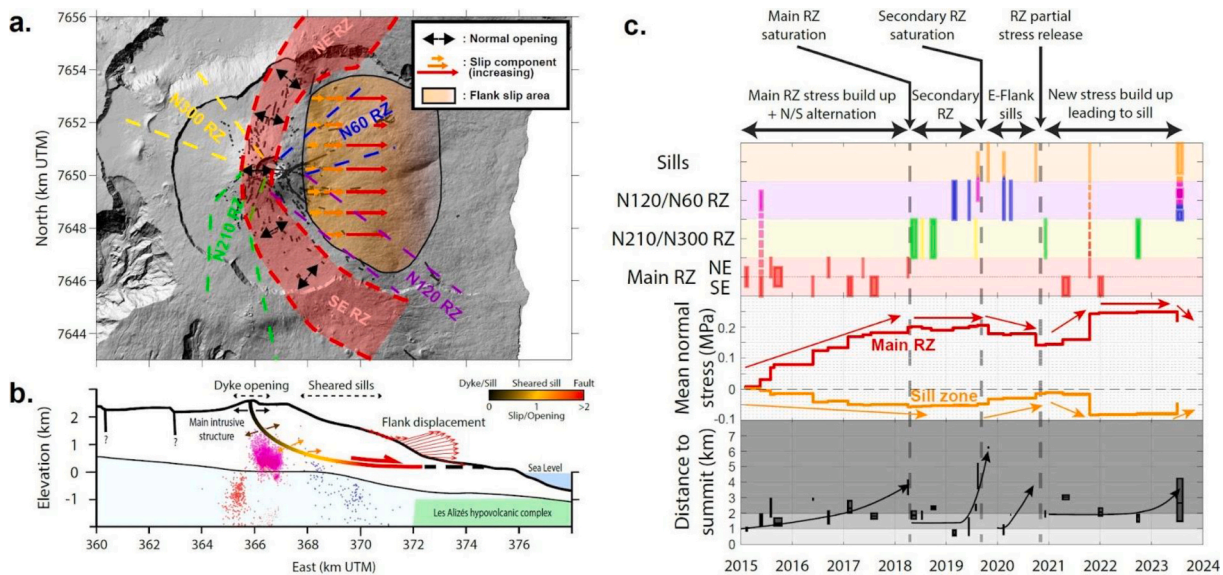


Fig. 7. Piton de la Fournaise intrusions. a) From systematic modelling of 61 magma intrusions (57 eruptions and 4 failed eruptions) in 1998–2023, a main rift zone (red) and four secondary rift zones (yellow, green, blue and purple) were identified. b) West-east cross-section showing the variation in fracture displacement when going towards the sea. c) Timeline of 2015–2023 intrusions. The top plot shows the location of each eruption along the rift zone (colors refer to the rift zone colors in a). The middle plot shows the mean normal stress increase in the main rift zone where dike opening takes place and in the sill zone where sills, sheared intrusions and slip take place. The bottom plot shows the distance of the eruptive fissures from the summit. Adapted from Dumont et al. (2022) and Dumont et al. (2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

image during magma propagation, separating the displacements induced by the beginning of the magma injection from those associated with the final opening of the eruptive fissures. The analysis showed that magma started to propagate in a sill that paused for 5 h before its final upward propagation in a dike that fed the eruption.

4.1.5. Macaronesia (Canaries, Cape Verde and the Azores)

Ocean island volcanoes exhibit a wide range of eruptive recurrence times. At first order, eruption rates are proportional to magma flux rates and it is often more challenging to characterize the behaviour of low magma flux rate ocean islands due to their infrequent activity (González et al., 2013). Sentinel-1, with its high repeatability and operational capabilities, has enabled the tracking of a few of those elusive eruptive events that occur after decades of quiescence, for example, the November 2014 eruption of Fogo volcano (Cape Verde Islands) and the 2021 Tajogaite eruption in La Palma (Canary Islands).

The 2014–2015 Fogo eruption marked the first significant surface deformation event imaged by Sentinel-1's Terrain Observation by Progressive Scans (TOPS). The analysis of Sentinel-1 data revealed a multi-segmented dike system feeding the eruption, with magma ascending beneath the Pico do Fogo. This was the first demonstration that the geophysical parameters of magmatic intrusion models could be inferred from TOPS burst acquisitions (González et al., 2015).

For the 2021 Tajogaite eruption, multi-temporal Sentinel-1 interferograms from ascending and descending orbits captured pre- and co-eruptive deformation. Particularly relevant was modelling of Sentinel-1 displacement maps to reveal pre-eruptive sill-like magmatic intrusions evolving into a complex dike system (De Luca et al., 2022). During the co-eruptive phase, this complex network of interconnected sills and dikes modulated the eruptive activity as revealed by changes in crater arrangement, with at least three distinct phases of activity linked to pressure surges and increased seismic activity (Muñoz et al., 2022).

The lava flow fields generated during the Strombolian-style eruptions from Fogo and Tajogaite significantly impacted population centers, necessitating rapid post-eruptive reconstruction efforts. A key challenge arose from the urgent need to rehouse displaced populations and restore road connectivity on such small islands, leading to construction directly on actively cooling lava flows. Basaltic lava flows, characterized by variable thicknesses, undergo rapid initial contraction and compaction, followed by a gradual deceleration over longer timescales (Chaussard, 2016; Purcell et al., 2022). Consequently, severe damage to new housing in Chã das Caldeiras (Fogo) was concentrated in areas of rapid subsidence (Bagnardi et al., 2016), while by summer of 2024 newly paved roads in La Palma showed accumulated damage and cracking correlated with high-strain areas identified in post-eruption Sentinel-1 time series (González and Garmendia, 2024). Sentinel-1 data were pivotal to demonstrating such a link and offers a way to fully consider post-emplacment lava flow dynamics while planning infrastructure reconstruction following future eruptions.

4.2. Large explosive eruptions

Measuring the deformation associated with large explosive eruptions at stratovolcanoes is particularly challenging using InSAR. Many stratovolcanoes have snow or ice at their peaks and heavily vegetated flanks that, along with steep topography results in poor coherence and geometric distortions. Frequent height changes during eruptions mean that the DEMs required to correct topographic phase contributions are often out of date. Here we systematically report on the largest explosive eruptions that occurred during the first decade of Sentinel-1 operations. We rank the Global Volcanism Program list of eruptions for April 2014–April 2024 by Volcanic Explosivity Index (VEI; Newhall and Self, 1982) and find one VEI 5 eruption (the 2022 eruption of Hunga Tonga-Hunga Ha'apai in the Kingdom of Tonga) and twelve VEI 4 eruptions of which four occurred in Indonesia and three in Papua New Guinea. In this section, we review to what extent Sentinel-1 has been used at each of

these large explosive eruptions. We exclude the 2015 eruption of Wolf, which was described in Section 4.1.3 and the 2021 eruption of Fukutoku-Oka-no-Ba, which was submarine (Fauria et al., 2023).

4.2.1. Manam, Papua New Guinea 2015 & 2018

Manam is one of the most frequently active volcanoes in Papua New Guinea and is one of the world's largest emitters of SO₂ due to persistent open-vent degassing (Carn et al., 2017). During the first decade of Sentinel-1 observations, the Global Volcanism Program recorded VEI 4 eruptions on 31 July 2015 and 25 August 2018 as well as several VEI 2–3 events. Manam is a challenging target for InSAR measurements, however, as it sits on a densely vegetated island 10-km wide located approximately 19 km off the coast of the mainland. Although previous studies have demonstrated the potential of L- and P- band SAR to map volcanic flows at Manam (Weissel et al., 2004), we could not find any published analysis using Sentinel-1 or useful data via automated processing systems.

4.2.2. Calbuco, Chile, 2015

Calbuco volcano in Chile had an unexpected and large (VEI 4) eruption in April 2015. No precursory deformation was detected before the eruption by tiltmeters or InSAR (Delgado et al., 2017; Valderrama et al., 2015), but the number of local earthquakes increased about 3 h before the eruption (Valderrama et al., 2015). Co-eruptive ground subsidence, however, was well characterized by InSAR and provided unique information about the magma reservoir depth and volume change associated with the eruption (Delgado et al., 2017; Nikkhoo et al., 2016). Sentinel-1 was also used to map the changes to the crater morphology and eruption deposits (Pritchard et al., 2018).

4.2.3. Sinabung, Indonesia 2018–2019

Sinabung entered its current phase of eruption in 2010 after hundreds of years of quiescence. From late 2013 to 2021, activity was characterized by lava flows, explosive eruptions, and cycles of lava dome growth, collapse and resulting pyroclastic density currents (Gunawan et al., 2019). During the first decade of Sentinel-1 operations, there were three VEI 4 eruptions in Feb 2018, April 2018 and June 2019. While the repeated explosions and collapse events were short in duration, they resulted in fatalities and necessitated repeated relocations of more than 25,000 people. The pyroclastic deposits of the February 2018 eruption were mapped by Poland (2022) using cross-polarized amplitude imagery from two different dates combined with interferometric coherence across those same dates.

InSAR detection of deformation at Sinabung at all wavelengths is dominated by the subsidence of the flow deposits covering the southeast quadrant of the volcano (Hanif et al., 2024), which is also the only sector of the volcano with consistently good coherence at C-band. We note that the Sentinel-1 interferograms are almost always incoherent at the locations of continuous GNSS stations that detected phases of uplift prior to 2010 and 2013 eruptions (Hotta et al., 2019). Frequent explosive eruptions and high-rate changes in topography prevent InSAR measurements at Sinabung's summit crater, while tropical vegetation in the surrounding area cause rapid temporal incoherence at C-band. The VEI 4 explosion in Feb 2018 destroyed the existing lava dome, created a new summit crater and was followed quickly by another VEI 4 explosion in April. Although the summit lava dome regained some coherence in the year between the April 2018 event and the VEI 4 June 2019 eruption, it is not clear if true displacements are distinguishable from large atmospheric phase contributions and unwrapping errors without further work (Fattah et al., 2023). Sinabung is an exceptionally challenging target for monitoring with C-band InSAR; L-band imagery may have sufficient coherence to enable deformation measurements in the surrounding area.

4.2.4. Ulawun, Papua New Guinea. 2019

Over the past 70 years, the Ulawun volcano has erupted several

times. The most recent major eruption (VEI 4) began on 26 June 2019, with increased seismic activity and ash plumes rising more than 8 km. It was followed by lava flows and pyroclastic density currents that reached nearby villages, displacing around 11,000 people, although no fatalities were reported (Orynbaikyzy et al., 2023). No ground deformation was detected before or during the eruption, probably due to the low coherence of the volcanic edifice, which is heavily vegetated (Ebmeier et al., 2013; McKee et al., 2021). Despite challenges in tracking magma movement, Sentinel-1 was crucial in delineating areas impacted by eruptive activity and accurately mapping eruption deposits, with its polarimetric decomposition features notably improving ash deposit mapping (Orynbaikyzy et al., 2023).

4.2.5. Soufrière St. Vincent, St Vincent and the Grenadines, 2020–2021

La Soufrière, St Vincent, is the most active subaerial volcano in the Eastern Caribbean, and historical eruptions have caused significant fatalities. The 2020–2021 eruption did not cause any loss of life but ~16,000 people were evacuated during the explosive phase, which began on 9 April 2021 (Robertson et al., 2024). SAR imagery provided crucial observations of the evolution of the dome during the initial, effusive phase of the eruption (27 December 2020 to 8 April 2021) adding important information to ground-based observations that were hazardous to collect. The images recorded a change in growth direction from vertical to horizontal and could be used to observe structural changes (e.g., crack formation). Topographic extraction from SAR images provided a dense time series of dome volume and extrusion rates, resolving steady effusion during the majority of the eruption up until just before the onset of the explosive phase on April 9, 2021, when a rapid increase in effusion rate was noted (Dualeh et al., 2023). While sensor resolution, polarisation and incidence angle determined which sensors and tracks were most useful for the analysis, the 6 day repeat Sentinel-1 acquisitions allowed for a continuous timeseries of change, bridging gaps in other datasets.

4.2.6. Taal, Philippines, 2020

Taal volcano is located about 65 km south of Manila and has had several large historical eruptions. It experienced a VEI 4 eruption on January 12, 2020 directly affecting half a million individuals and causing ~\$69 M worth of damage to infrastructure and agriculture (Bato et al., 2021). Sentinel-1 detected co-eruptive deflation of a shallow reservoir and emplacement of a lateral dyke 20 km long (Fig. 8c), and a temporal incoherence model was used to map the distribution of ash fall to the northeast (Naranjo et al., 2023). Pre-eruptive inflation of a reservoir at 5 km depth was only detected retrospectively, although it had been tracked as it was occurring with ground-based GNSS stations (Bato et al., 2021).

4.2.7. Semeru, Indonesia 2021

Semeru has been continuously erupting since the beginning of Sentinel-1 acquisitions in October 2014. The activity has mostly been dominated by lava flows within a horseshoe-shaped scar on SE flank and small explosive eruptions, which cause poor coherence due to the rapid topographic changes. On 4 December 2021, a rainfall-induced dome collapse triggered a VEI 4 explosive eruption, producing block-and-ask-flows and lahars that caused fatalities (Thouret et al., 2023). These deposits could be accurately mapped by semi-automatic algorithms based on Sentinel-1 coherence, backscatter and polarimetric decomposition (Kurnianto et al., 2024; Orynbaikyzy et al., 2023). Time series of Sentinel-1 data show that negative line-of-sight displacements of up to 30 cm occurred continuously between October 2014 to 2023 on the SE flank around the horseshoe-shaped scar (Galetto et al., 2025), but there was no clear LOS displacement associated with the December 2021 VEI 4 eruption. Furthermore, the observed displacements seem related or to a shallow hydrothermal reservoir or to surface processes (e.g., gravitational spreading) and not to the main magma reservoir (Galetto et al., 2025).

4.2.8. Hunga Tonga-Hunga Ha'apai, Kingdom of Tonga, 2022

The January 15, 2022, eruption of Hunga Tonga–Hunga Ha'apai is

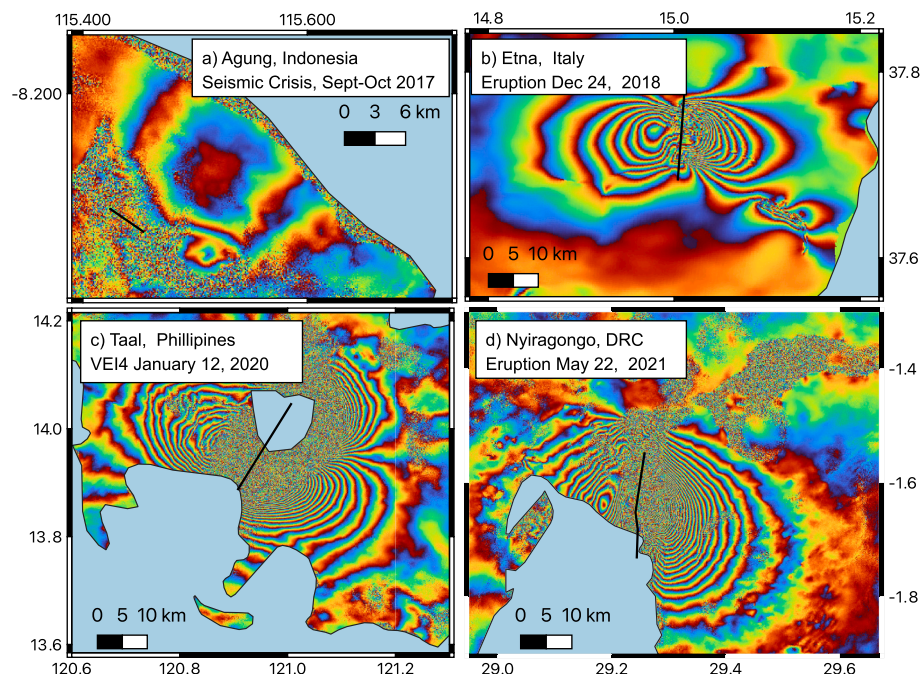


Fig. 8. Sentinel-1 interferograms showing dyke intrusions associated with significant eruptions. a) Agung (Indonesia). 24 day interferogram spanning 9 September–3 October 2017. b) Etna (Italy). 6-day interferogram spanning 22–28th December 2018. c) VEI 4 eruption Taal, (Philippines) on 12th January 2020. 6-day interferogram spanning 09-Jan-2020 to 15-Jan-2020. d) Nyiragongo (DRC). 12-day interferogram spanning 21-May-2021 to 2-June-2021. Interferograms automatically processed using the COMET LICS system (Lazecy et al., 2020). Each colour cycle represents 2.8 cm of displacement in the satellite line-of-sight. Black lines are model dyke locations from a) Albino et al. (2019), b) Bonforte et al. (2019), c) (Bato et al., 2021), d) Smittarello et al. (2022b).

thought to be the largest volcanic event since the 1991 eruption of Mt. Pinatubo in the Philippines. Following a period of vigorous shallow-water explosive activity beginning in mid-December 2021, the eruption culminated in a massive explosion generating unusual concentrically propagating atmospheric acoustic-gravity waves that traversed the globe multiple times (Matoza et al., 2022). This explosion also triggered an exceptionally fast-traveling global tsunami, recorded worldwide with minimal far-field dissipation, reaching Japan and Chile in under 7 and 10 h, respectively—significantly faster than a typical point-source tsunami (Omira et al., 2022). Total destruction of the two islands (Hunga Tonga and Hunga Ha'apai) prevented the application of satellite radar interferometry to study the eruption mechanism, but Sentinel-1 amplitude images were widely used to capture the change in land-masses (Fig. 9a-c; Wei et al., 2025).

4.3. Other societally significant eruptions

4.3.1. Fuego, Guatemala, 2018

The 3 June 2018 eruption at Volcan de Fuego was an atypical eruption for that volcano, producing rapid and far-reaching pyroclastic density currents (PDCs) that extended up to 12 km from the summit and destroyed the community of San Miguel Los Lotes. The eruption resulted in 332 officially reported missing people, with some reports suggesting up to 2900 fatalities (Naismith et al., 2020).

The dense vegetation and tropical environment of Fuego meant that InSAR measurements were not possible; however, Sentinel-1 and COSMO-SkyMed backscatter imagery were able to provide valuable insights into the extent and development of the deposits. Sentinel-1 imagery captured the full distribution of the PDCs within the drainages and where it overspilled drainage banks (Dualeh et al., 2021; Poland, 2022). The difference in viewing geometry allowed for the identification of a pyroclastic surge not previously reported and only partially visible in the COSMO-SkyMed imagery. These observations provided information on the extent of the fresh PDC deposit, identifying exactly which drainages were affected, where flows were channelised, where they overtopped drainages and flowed in different directions from previous eruptions - information that can be critical for understanding possible future flow paths. The high-resolution X-band COSMO-SkyMed imagery was able to observe complexity within the pyroclastic flows and small magnitude changes that were not visible in the Sentinel-1 imagery (Dualeh et al., 2021).

4.3.2. Anak Krakatau, Indonesia, 2018

On December 22, 2018, the southwestern flank of the Anak Krakatau collapsed into the sea after days of explosive eruptions, generating a tsunami that caused 437 fatalities and displaced almost 34,000 people. The island height was reduced by half and its coastline was transformed. Sentinel-1 imagery provided an early indication of the island's new morphology just 8 h after the eruption (Fig. 9d-f; Williams et al., 2019). The evolution of the new topography and ongoing processes (e.g., ocean waves and suspended sediments) are even clearer using SAR imagery from different sensors, with the higher spatial resolution of COSMO-SkyMed imagery being especially useful (Hunt et al., 2021). In conjunction with other available data, Sentinel-1 images were used to estimate the shape and volume range of the collapse and for tsunami simulations (Grilli et al., 2019). Retrospective analysis of Sentinel-1, ALOS-2 and COSMO-SkyMed imagery showed that the 2018 collapse was preceded by 15 m of slip on a detachment fault since 2012. Sentinel-1 data show a rate of about 1.1 m/yr between 2014 and 2018, with a notable acceleration prior to the 2018 collapse (Kim et al., 2024),

4.3.3. Whakaari/White Island, New Zealand, 2019

The 9 December 2019 eruption at Whakaari in New Zealand caused 22 fatalities. The short-lived event occurred after a few weeks of heightened unrest had been observed with increased seismicity and visual observations of geysering in the crater lake. Due to its small aerial footprint ($\sim 2 \times 2$ km), steep crater walls and frequent re-working of the vent area and crater lake, moderate resolution SAR data has had limited success in detecting precursory changes. Typically, the underlying processes driving the eruptive behaviour at Whakaari are shallow, limited to the area around the vent and have only been routinely detected with high resolution SAR datasets (e.g., TerraSAR-X, Hamling, 2017); however, full-resolution Sentinel-1 persistent scatterer datasets are able to provide long-term observations of deformation over the wider island edifice and crater floor, complementing data from the higher-resolution sensors (Fig. 10). Furthermore, with a revisit time of only 6 days when two satellites are operating, reliable acquisition scheduling and a low latency between acquisition and availability, Sentinel-1 data provides useful support for monitoring.

4.3.4. Nyiragongo, Democratic Republic of the Congo, 2021

On 22 May 2021, Nyiragongo experienced a flank eruption that lasted 6 h and produced a lava flow that destroyed schools, health centres and churches, and that damaged critical infrastructure including

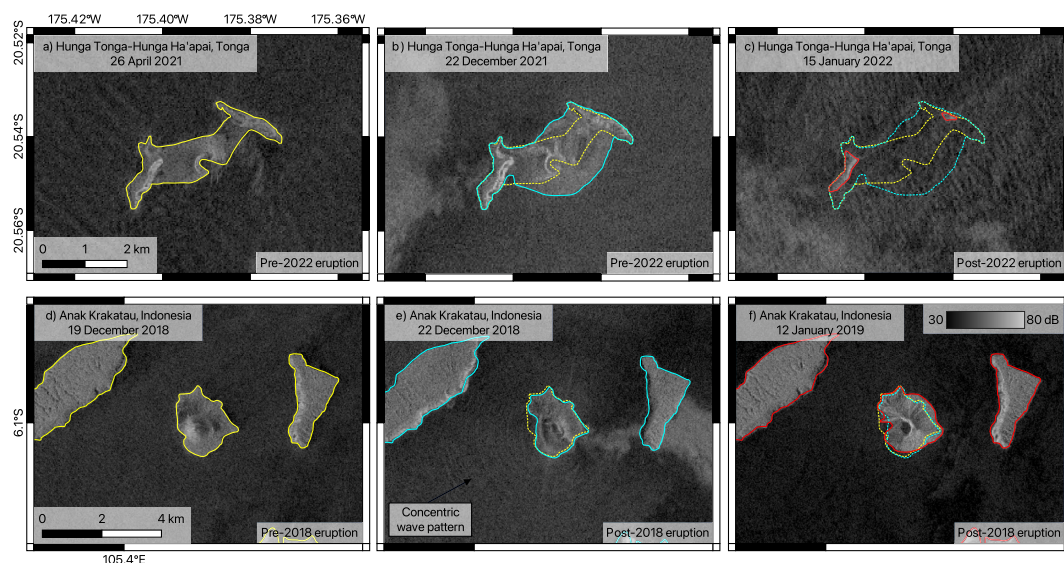


Fig. 9. Sentinel-1 backscatter images showing change in island morphology associated with recent eruptions. a-c) 2022 Hunga Tonga-Hunga Ha'apai VEI5 2021–2022, d-f) Anak Krakatau, Indonesia, 2018–2019. Solid and dashed lines indicate island shape in backscatter images and previous acquisitions respectively.

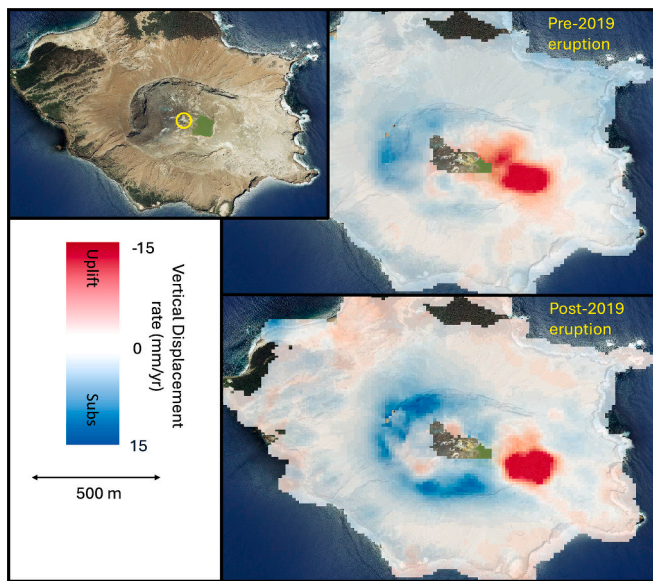


Fig. 10. Vertical deformation rates from before and after the 2019 eruption of White Island/Whakaari derived from ascending and descending Sentinel-1 data. Inset in the top left shows an aerial photo from 2022 with the location of the 2019 vent highlighted by the yellow circle. Long term uplift, which is uninterrupted by the eruption, is observed within the crater floor along with increased subsidence around most of the crater walls. Data provided by Sat-Sense Ltd. (<https://satsense.com/>). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the water supply for half a million people. Field surveys found that 220 people died or were reported missing, over 750 people were reported injured and 4000–6000 homes were destroyed (Smitarello et al., 2022b). Despite the dense and continuous deformation and seismic monitoring networks operating since 2015, this eruption was unexpected, as none of the precursors seen before previous eruptions occurred (Smitarello et al., 2023). Sentinel-1 images spanning the event show a deformation pattern consistent with the propagation of a 25 km long dyke and in places forming a 450 m wide graben (Fig. 8d; Smitarello et al., 2022b). The dyke propagated southward for 10 days beneath the cities of Goma (Democratic Republic of the Congo) and Gisenyi (Rwanda) finally arresting beneath Lake Kivu, which contains large amount of dissolved methane and CO₂. The intrusion fully drained the lava lake within the volcano's summit crater, which had been the largest lava lake in the world at that time.

5. Non-eruptive deformation

Sentinel-1's long-term, systematic archive is well suited to providing baseline measurements of slow steady deformation that occurs during non-eruptive periods. This is particularly important for volcanoes at which ground-based monitoring is limited or intermittent, such as those in remote locations or developing countries where resources are limited. In this section, we review three categories of non-eruptive deformation: stalled intrusions, restless caldera systems, and flank motion.

5.1. Stalled intrusions

Magma intrusion does not always result in eruption, but may still have significant societal impact especially if an evacuation is called (Barclay et al., 2019; Woo, 2008). Previous metadata studies have shown that about half of all deformation signals are associated with eruption (Biggs et al., 2014; Furtney et al., 2018). Here we discuss two examples of stalled magma ascent where Sentinel-1 data helped inform critical decisions about evacuations.

5.1.1. Agung, Indonesia 2017

In September 2017, a rapid increase in seismicity near Agung volcano on the island of Bali caused the volcano alert level to be raised to the maximum level. A VEI5 eruption in 1963 caused over 1000 fatalities, and the 2017 earthquakes could be felt by the local population and tourists causing intense social media interest and prompting a significant self-evacuation. The seismicity remained high for 4 weeks and at the peak over 140,000 people were officially evacuated (Syahbana et al., 2019). Sentinel-1 interferograms from September 2017 showed several fringes of deformation correlated with topography, which weather models demonstrated to be an atmospheric artefact rather than volcanic deformation (Albino et al., 2020). Several images were shared on social media, however, and inaccurately attributed to ground deformation, with a negative impact on the management of the crisis (Syahbana et al., 2019).

Retrospectively, Sentinel-1 images with atmospheric corrections applied showed a deformation signal on the NE flank of Agung volcano (Fig. 8a), interpreted as a dike intrusion between Agung and neighbouring Batur volcano (Albino et al., 2019). Although the seismicity dropped in late October and alert levels were reduced, an eruption at Agung began on 21 November 2017 lasting until June 13, 2019 (Andaru et al., 2022). Subsequent analysis of high resolution datasets (COSMO-SkyMed and TerraSAR-X) showed a very localised signal within the crater of Agung, which was poorly visible in Sentinel-1 imagery (Bemelmans et al., 2023).

5.1.2. São Jorge Island, Azores, Portugal, 2022

In March 2022, seismo-volcanic unrest started on São Jorge Island. The origin of the seismicity was uncertain due to the possibility of being tectonic or magmatic. The near real-time availability of Sentinel-1 InSAR data proved essential to evaluate the situation, and analysis of interferograms was done by a national and international group of academic scientists in close collaboration with the Portuguese Institute for Sea and Atmosphere (IPMA), Centro de Informação e Vigilância Sismovulcânica dos Açores (CIVISA), and the Azores Islands government. Early interpretation of Sentinel-1 interferograms suggested that surface deformation was related to magma accumulation and ruled out major tectonic fault slip. This rapid assessment, enabled by Sentinel-1, provided crucial information for decision-making during the crisis, contributing to the decision to relocate 85 vulnerable residents and influencing the voluntary departure of around 2500 people from the island. While no official evacuation order was issued, this significant population movement was facilitated by the government, which reinforced transport services to allow people to leave.

Although the unrest ultimately ended without an eruption, the Sentinel-1 data were essential to retrospectively revealing the complex processes governing the interplay between magma ascent and fault zone dynamics. Sentinel-1 interferograms combined with seismic observations and seismic autocorrelation imaging show evidence for a rapid magma ascent from the upper mantle along the pre-existing Pico do Carvão Fault Zone (PdC-FZ), followed by magma stalling beneath the island at a depth of around 2 km beneath the surface. The magma may have stalled due to lateral migration of devolatilized fluids within the fault zone, leading to increased magma viscosity (Hicks et al., 2024).

5.2. Restless calderas

Unrest at calderas can last from weeks to decades, with dramatic changes in the rate and pattern of surface deformation (e.g., Acocella et al., 2015; Biggs et al., 2014; Gottsmann and Battaglia, 2008; Newhall and Dzurisin, 1988) but without resulting in eruption. In Fig. 11, we compile InSAR observations from 8 different caldera systems that demonstrate the variability of temporal and spatial deformation patterns (Biggs et al., 2011; Foulmelis et al., 2013; Garthwaite et al., 2019; Polcari et al., 2022; Riddick and Schmidt, 2011; Tizzani et al., 2009). The temporal pattern of these time series can be categorised as follows. (1)

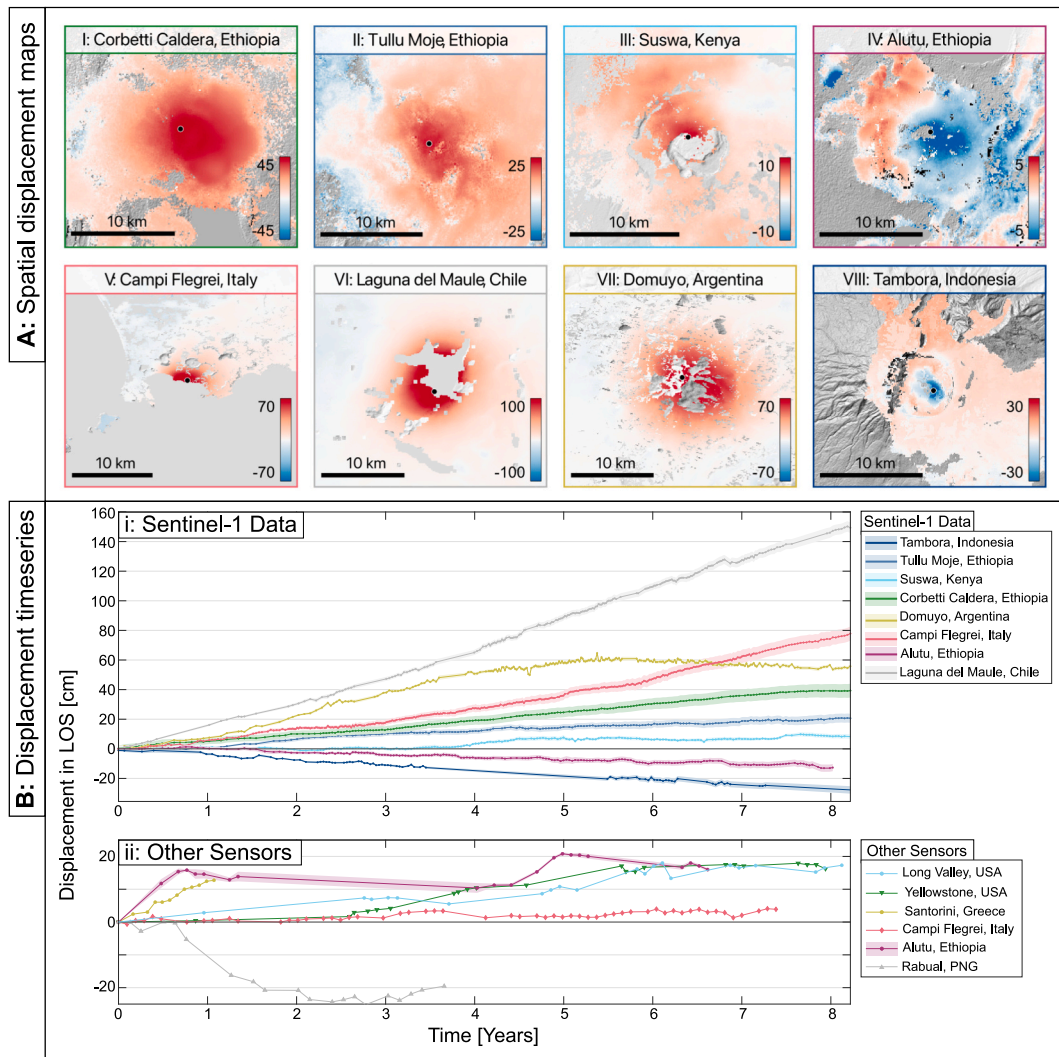


Fig. 11. Line-of-Sight (LOS) displacement (A) Sentinel-1 mean displacement maps for 8 large silicic caldera systems from 2014 to 2023. (B) Corresponding displacement timeseries. The upper panel shows Sentinel-1 data from 2014 to 2023 and the lower panel show InSAR observations from earlier missions: Long Valley (USA) (ERS, 1992–2008, [Riddick and Schmidt, 2011](#)), Yellowstone (USA) (ERS-ENVISAT, 1992–2010, (ERS-ENVISAT, 1992–2010, [Tizzani et al., 2015](#)), Santorini (Greece) (ENVISAT, 2011–2012, [Foumelis et al., 2013](#)), Campi Flegrei (Italy) (ENVISAT, 2003–2011, [Polcari et al., 2022](#)), Alutu (Ethiopia) (ENVISAT, 2004–2010, [Biggs et al., 2011](#)), and Rabual (Papua New Guinea) (ALOS, 2007–2011, [Garthwaite et al., 2019](#)).

steady long-term uplift (e.g., Laguna del Maule (Chile), and Corbetti caldera (Ethiopia)); (2) continuous subsidence (e.g., Tambora (Indonesia)); (3) transient deformation - either uplift or subsidence occurring over timescales of 1–2 years (e.g., Tulle Moje (Ethiopia), Suswa (Kenya), and Long Valley, (USA)); and (4) a mixture of uplift and subsidence (e.g., Domuyo (Argentina), and Aluto, (Ethiopia)). With InSAR observations spanning three decades at some calderas, we can observe systems entering new periods of unrest (e.g., Campi Flegrei) or changes in ongoing unrest patterns (e.g., Aluto).

This compilation illustrates the improvement in the temporal density of observations provided by the Sentinel-1 satellite system. Acquisition for satellites prior to Sentinel-1 were infrequent and non-systematic, with on average an image every ~ 167 days. This varied greatly between volcanoes and sensors, however, ranging from 36 to 426 days for the subset shown in [Fig. 11 Bii](#), with year-long gaps in some timeseries (e.g., Aluto). In comparison, Sentinel-1 usually provides 6–12 days between images globally, allowing for more detailed timeseries that can be used to examine rapid changes (e.g., fluctuating rates at Campi Flegrei; [Fig. 11 Bi](#)), as well as long-term deformation trends that may have been missed with longer intervals between images (e.g., seasonal signal at Aluto; [Fig. 11 Bi](#)).

Despite the improvements in data quality, understanding the dynamics of the processes at depth remains challenging. The diversity of signals likely reflects the complex, poro-viscoelastic rheology of the subsurface systems within which magma, hydrothermal fluids and gases are all stored (e.g., [Alshembari et al., 2023](#); [Weber et al., 2025](#)). The dense sampling of the Sentinel-1 time series shows some promise for disentangling processes with different spatial and temporal patterns ([Dualeh and Biggs, 2025](#)), but in most cases, it is necessary to include external datasets and apply sophisticated models. For example, finite element method models of Sentinel-1 data and dynamic gravity surveys at the inflating Corbetti caldera showed that the uplift was dominated by magmatic rather than hydrothermal processes ([Gottsmann et al., 2020](#)). At Campi Flegrei, in contrast, isotopic analysis of the fumarole gases is consistent with decompression-driven degassing of mafic magma at ≥ 6 km depth, suggesting a slightly different magmatic process driving uplift at that caldera ([Caliro et al., 2025](#)). Interpreting the source of the deformation signal in real time thus remains challenging, even at well-monitored systems.

5.3. Flank motion

Geophysical, geological, and bathymetric data show ubiquitous evidence of flank motion at volcanoes worldwide. These flank motions are steady most of the time, but they sometimes accelerate in association with eruptions and fault ruptures (e.g., Neal et al., 2019; Walter et al., 2019) and they may culminate in catastrophic flank collapses, causing tsunamis or cascades of other hazardous events. The consistency of Sentinel-1 acquisitions enable measurements of both steady flank motions and large amplitude transients associated with flank failure.

At ocean island volcanoes, Sentinel-1 has proven especially useful at detecting and characterizing flank motion. For example, at Piton de la Fournaise, seaward flank displacements were found to be induced by sheared intrusions (September 2020 and October 2021) and slip on a detachment fault (in October 2019) located beneath the eastern flank of the volcano (Dumont et al., 2022). At La Palma during its 2021 Tajogaite eruption, analysis of Sentinel-1 amplitude images tracked the opening of eccentric fractures and lava flows far from the main effusion vents, pointing to a potential relation with flank instability processes acting during the late phases of an eruption (González, 2022; Walter et al., 2023). Sentinel-1 interferograms also captured the previously elusive kinematics of the Hilina and Koa'e normal fault systems at Kīlauea—especially the relation between secular strain accumulation and major magmatic and decollement slip events along the mobile south flank of the volcano (Wang et al., 2019).

Sentinel-1 has similarly facilitated progress in understanding flank instability in arc settings. At Sangay (Ecuador), Sentinel-1 captured the movement of $\sim 5 \text{ km}^2$ of young volcanic deposits moving downslope at $\sim 5 \text{ cm/yr}$ between 2019 and 2022, and persistent flank uplift related to the inflation of a dike beneath the western flank (Bedón et al., 2024). At Mount Etna, inverse modelling of Sentinel-1 data (Iozzia et al., 2024) demonstrated that the December 2018 summit eruption was associated with a sheared intrusion that accelerated slip of the mobile flank towards the sea and triggered a M.5 earthquake on a fault (Fig. 8b). On the other hand, at Pacaya (Guatemala) Sentinel-1 documented the slowing of flank slip following transient motion initiated by major eruptions in 2010 and 2014 (Gonzalez-Santana et al., 2022). The largest flank failure event documented by Sentinel-1 took place at Anak Krakatau (Indonesia), where the flank collapse triggered a deadly tsunami in 2018. Sentinel-1 amplitude images provided the first estimate of the collapse area (Ye et al., 2020) and retrospectively showed that the 2018 collapse was preceded by 15 m of slip on a detachment fault, with a notable acceleration prior to the collapse (Kim et al., 2024).

6. Discussion

6.1. Lessons learned from a decade of Sentinel-1 observations

6.1.1. Advantages of Sentinel-1

Sentinel-1's data policy has transformed the utility of SAR data in volcanology (e.g., Biggs and Wright, 2020; Poland and Zebker, 2022). The systematic, long-term archive combined with an open-access policy means that volcano observatories and research organisations have invested in integrating Sentinel-1 SAR datasets into their monitoring systems. This has enabled SAR data to be used for baseline monitoring and in real-time crisis response, driven an increase in the number of volcanoes where SAR data are used and identified deformation at many volcanoes considered to be quiescent. In turn, this has increased the variety of deformation signals that have been observed at volcanoes at different stages of the eruptive cycle, providing new insights into the architecture and dynamics of magmatic systems and volcanic eruptions. In addition, Sentinel-1 SAR backscatter is increasingly being used to map eruptive products, including tracking lava flows and mapping damage areas associated with lahars and pyroclastic flows (e.g., Poland, 2022). The large, systematic Sentinel-1 datasets are ideally suited to machine learning approaches, with promising applications in detection,

denoising, modelling and forecasting (e.g., Petrelli et al., 2025).

In this review, we have demonstrated how Sentinel-1 InSAR has become an effective monitoring tool at volcanoes worldwide. In combination with other monitoring techniques, Sentinel-1 has already produced new understanding of major eruptions that occurred during the mission's first decade. The reduction in repeat interval from 6 days to 12 days caused by the loss of Sentinel 1B significantly degraded the utility of Sentinel-1 data during crises, and the loss of both satellites would have a serious impact on operations. For example, it is fortunate that Sentinel-1 A could continue operating until Sentinel-1C and Sentinel-1D were launched.

A significant proportion of historically active volcanoes do not have any ground-based monitoring (Loughlin et al., 2015), and for many of these, satellite data are increasingly being used as the primary tool for volcano surveillance. Open-access data portals, such as the one operated by COMET, allow users in developing countries the opportunity to analyse Sentinel-1 data from a web browser, and to download processed images for integration with their own monitoring data (Watson et al., 2022). This has democratized the use of SAR data, fostering a wider user community. Although GACOS corrections are integrated into the automated system, atmospheric noise remains a major challenge, especially at tropical island volcanoes where corrections based on weather models are only partially effective (e.g., Albino et al., 2020).

6.1.2. Limitations

A major limitation of Sentinel-1 imagery for volcano monitoring is the rapid decorrelation of C-band imagery over dense vegetation, especially in the tropics. This in practice limits measurements at many volcanoes to unvegetated summit areas or to recent flow deposits, making deeper magmatic processes unobservable. This is apparent in our assessment of the completeness of Sentinel-1 observations at recently active (A1 or A2) volcanoes (Fig. 2, Section 3.1). Sentinel-1 measurements have been made that capture 80% of Africa's category 'A' volcanoes and 70% of South America's. However, in Indonesia and Japan, where most volcanoes are vegetated, only 22% and 24% respectively have been observed with Sentinel-1. The category A volcanoes in these two regions together make up 25% of all category A volcanoes globally. L-band imagery performs significantly better than C-band in tropical forests and ecosystems, and with a systematic acquisitions strategy and open data would transform the utility of InSAR for monitoring volcanoes in tropical regions.

Despite the bold ambition of the Sentinel-1 acquisition plan, the global volcano dataset is still incomplete. Although the Sentinel High Level Operation Plan aims for a repeat interval of less than 12 days in all volcanically active areas (Potin et al., 2021), this has not been possible in practice, especially when only one satellite was operational. Even where long time-series of 12-day acquisitions are available, systematic InSAR processing of such a large dataset remains challenging. For example, Albino et al. (2022) found that $\sim 8\%$ of the interferograms processed by the LICsAR system for volcanoes in the East African Rift system did not pass quality tests based on average coherence and fraction of unwrapped pixels, and the proportion is likely much higher in other regions. The low resolution of Sentinel-1 IW mode compared to other SAR sensors means monitoring small-island volcanoes is especially challenging. This includes Manam, which has had several large explosive eruptions in the 20th century. Small-footprint signals associated with shallow processes may also be missed (e.g., Bemelmans et al., 2023; Hamling, 2017). The higher resolution of the stripmap mode (SM) acquisitions at isolated volcanic islands has been particularly useful in this respect (e.g., Dumont et al., 2022).

6.1.3. Application to volcano monitoring

At frequently erupting basaltic systems, the long, systematic Sentinel-1 time series has captured the full deformation-eruption cycle, allowing the monitoring of stress within the crust and the forecasting of magma pathways and future vent locations (e.g., Davis et al., 2021;

Dumont et al., 2024; Gregg et al., 2022; Rivalta et al., 2019). The large spatial extent of the IW mode acquisitions has facilitated exploration of the connections between different magmatic reservoirs and their relations to flank instability (e.g., González, 2022; Reddin et al., 2023). The global, systematic acquisition policy of Sentinel-1 has allowed the identification and measurement of deformation from a much larger number of volcanic systems at high temporal resolution than previously possible. Understanding the drivers of unrest within the complex magmatic plumbing systems, however, remains challenging and typically relies on integration with external datasets (e.g., Caliro et al., 2025; Gottsmann et al., 2020).

Sentinel-1 SAR backscatter is increasingly being used to map damage associated with pyroclastic flows and lahars and the changing shape of volcanic islands for large explosive eruptions (Dualet et al., 2021; Orynbaikyzy et al., 2023; Poland, 2022; Williams et al., 2019). Of the 10 volcanoes with VEI4+ explosive eruptions occurring in the first decade that Sentinel-1 was operational, backscatter data were used at 7 and InSAR at just 4 because interferometric coherence was poor at several of these volcanoes. The only VEI4+ eruptions for which Sentinel-1 data were not used at all were the submarine eruption of Fukutoku-Oka-no-Ba and those on the small island of Manam.

A major challenge in volcano monitoring is to determine in real time whether a particular deformation signal is precursory. In several examples, Sentinel-1 has been used to monitor magma accumulating and moving underground for several weeks prior to eruption, providing critical information for civil defence (e.g. Hawai'i, Iceland). For many other eruptions, however, precursory deformation was present but only detected after the eruption (e.g., Taal, Anak Krakatau), or no precursory signals could be identified even by detailed retrospective analysis (e.g., Calbuco, Nyiragongo). In other cases, challenging environmental conditions (e.g., vegetation and snow/ice cover, steep topography) prevented detection of surface displacements, and it is unknown if any precursory deformation occurred (e.g., Manam, Sinabung, White Island/Whakaari).

The examples described in Sections 4 and 5 highlight the diversity of volcanic behaviour and environments, and the different ways in which Sentinel-1 SAR and InSAR data are being used. Given the complexity of volcanic systems, the lack of a unified approach is not surprising and reflects an emerging challenge in modern volcanology: the apparent contradiction between the perception that every volcano is unique, and classification systems based on commonalities among volcano morphology and eruptive style (Cashman and Biggs, 2014). The examples described in Sections 4 and 5 demonstrate that volcanological insights typically arise from tailored, expert analysis that integrates data from multiple sensors. This represents a significant challenge for the design of automated analysis systems and highlights the need for international collaborations and intercomparison exercises to ensure that data from future missions and analysis systems achieve their full potential (e.g., Crozier et al., 2023; Pritchard et al., 2018; Pritchard et al., 2022; Sadeghi et al., 2021).

6.2. Looking ahead

Over the next decade, several planned ESA missions offer the potential for another step-change improvement in volcano monitoring capabilities, including both Copernicus missions, which are committed to providing long-term, consistent datasets for operational purposes, and Earth Explorer missions, which are designed for scientific research. The next generation of Sentinel-1 satellites (Sentinel-1 NG) are currently in development and will have a repeat interval of 12 days, but a wider swath and a higher spatial resolution (25 m²). The wider swath will mean that each volcano will appear in more tracks, thus providing more frequent images and the higher resolution will improve the ability to measure more localised signals. This is particularly important for detecting eruption precursors caused by shallow processes (e.g., Bemelmans et al., 2023; Hamling, 2017) and identification of smaller

features in backscatter images such as the opening and development of fractures and cracks and variations across flow deposits. The Copernicus expansion mission Rose-L will operate an L-band SAR satellite in the same orbit and spatial resolution as Sentinel-1 NG, expanding coherent InSAR coverage to volcanoes in densely vegetated areas such as Indonesia and Central America. The longer wavelength will also have advantages for measuring rapid or high magnitude signals that may be aliased in C-band data. These Copernicus missions, along with those planned by other space agencies, including NASA and ISRO's NISAR and JAXA's ALOS-4, mean the use of SAR data for volcano monitoring is set to grow over the decade ahead.

ESA's Earth Explorer programme also provides several opportunities for volcanology. The 10th Earth Explorer Mission, Harmony, will consist of two receive-only SAR systems operating in constellation with Sentinel-1D to provide multi-static SAR measurements (Prats et al., 2023). The along-track component of deformation can be combined with Sentinel-1 data to enable the retrieval of a full 3-dimensional deformation field, and, in the across-track interferometry configuration, Harmony will produce time series of topographic change, improving estimates of effusion rates and providing up-to-date DEMs for InSAR processing (Pappas et al., 2025). Hydroterra+ is currently a candidate for ESA's 12th Earth Explorer mission, which if selected, would be the first SAR mission in a geostationary orbit (Jonas et al., 2021). Harmony and potentially Hydroterra+ could also serve as a proof of concept for future Copernicus missions.

The operational nature of Sentinel-1 has provided a backbone of observations that have been used to motivate more detailed data collection, and during a crisis Sentinel-1 is often used with a variety of other remote sensing resources (Pritchard et al., 2022). ESA's third party mission programme (TPM) currently comprises over 50 missions owned by commercial providers and public organisations worldwide, while the Committee on Earth Observation Satellites (CEOS) Volcano Projects have provided access to SAR data from a variety of missions including COSMO-SkyMed, TerraSAR-X, and RADARSAT-1&2 (Galletto et al., 2024; Pritchard et al., 2018). Several commercial SAR satellites (e.g., ICEYE, Umbra, and Capella) now acquire high-resolution SAR backscatter images, and in some cases can produce interferograms. At present, these typically do not make systematic acquisitions over all volcanoes or have mechanisms designed to routinely respond during crises, however, these sensors have enormous potential in volcanology and developing partnerships with commercial providers will be key to their uptake by the volcanology community.

7. Conclusions

Sentinel-1 is the first satellite of the Copernicus programme, which is aimed to provide accurate, timely and easily accessible information to improve monitoring of the environment. This service-driven data policy has facilitated widespread use of Sentinel-1 SAR data and the resource has become integral to volcano monitoring efforts globally. In 2019, the USGS Powell Center working group categorised global volcanoes according to their need for satellite-based deformation measurement (Pritchard et al., 2022). This list is used to drive automated processing systems such as COMET LICsAR, but it is already outdated. In this study, we updated the original Powell Center list to include recent behaviour, categorising 233 volcanoes as highest priority subaerial volcanoes (A1/A2) requiring weekly observations. Based on the published literature, we estimate that Sentinel-1 has been used at 90 of 233 A1/A2 volcanoes globally (57%). We applied machine learning algorithms to retrospectively identify signals in the automatically processed LICsAR archive of Sentinel-1 interferograms which contains 3.34 million images from the first decade of the Sentinel-1 mission. Although these algorithms can identify deformation signals retrospectively, they have yet to be routinely applied in real-time.

We review the ways in which Sentinel-1 data are being used at different volcanoes. At frequently erupting basaltic volcanoes in Iceland,

Hawai'i, and Galápagos, Sentinel-1 InSAR is integrated into routine monitoring and used to identify magma pathways and forecast the outcomes of unrest. In contrast, InSAR measurements could not be made, or were not useful, at several of the large explosive eruptions that occurred during the first decade, but Sentinel-1 SAR backscatter is increasingly being used to map damage associated with eruptive deposits and flank collapses.

The long-term, systematic archive of Sentinel-1 data is particularly critical for detecting and understanding deformation when a volcano first enters a phase of unrest, especially given that roughly half of unrest episodes do not culminate in an eruption. Long-term baseline monitoring has proven especially useful for mapping deformation at restless calderas and associated with flank instability, providing new insights into the complex dynamic interactions within magmatic plumbing systems and between magmatic and tectonic systems. Understanding the drivers of deformation within complex magmatic plumbing systems, however, remains challenging and typically relies on integration with external datasets.

CRedit authorship contribution statement

Juliet Biggs: Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **Nantheera Anantrasirchai:** Visualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft. **Kyle R. Anderson:** Visualization, Investigation, Formal analysis, Data curation, Writing – review & editing, Writing – original draft. **Valerie Cayol:** Visualization, Investigation, Writing – review & editing, Writing – original draft. **Edna W. Dualeh:** Visualization, Investigation, Funding acquisition, Formal analysis, Writing – review & editing, Writing – original draft. **Quentin Dumont:** Visualization, Investigation, Writing – review & editing, Writing – original draft. **Susanna K. Ebmeier:** Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **Matthew Gaddes:** Visualization, Investigation, Formal analysis, Writing – review & editing, Writing – original draft. **Federico Galetto:** Investigation, Writing – review & editing, Writing – original draft. **Pablo J. Gonzalez:** Investigation, Funding acquisition, Writing – review & editing, Writing – original draft. **Ian Hamling:** Visualization, Investigation, Funding acquisition, Writing – review & editing, Writing – original draft. **Andrew Hooper:** Visualization, Supervision, Investigation, Funding acquisition, Conceptualization, Writing – review & editing, Writing – original draft. **Milan Lazecky:** Visualization, Software, Resources, Methodology. **Camila Novoa Lizama:** Investigation, Writing – original draft. **Matthew E. Pritchard:** Writing – review & editing, Writing – original draft. **Jean Luc Froger:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the editor, three reviewers and a USGS internal reviewer. N.A., J.B., E.W.D., S.K.E., M.G., A.H., M.L. and C.N. were supported by the NERC Centre for the Observation and Modelling of Earthquakes, Volcanoes, and Tectonics (COMET, <http://comet.nerc.ac.uk>) a partnership between UK Universities and the British Geological Survey. J.B., N.A., E.W.D. and M.L. received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (MAST; Grant No. 101003173). J.B., S.E., M.G.,

A.H., M.L. and C.N. were supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (DEEPVOLC; Grant No. 866085). S.K.E. is supported by a NERC Independent Research Fellowship (NE/R015546/1). E.W.D. is supported by a European Space Agency (ESA) Living Planet Fellowship (VolcScatter). M.G. was supported by an (ESA) Living Planet Fellowship. P.J.G. thanks the Spanish Agencia Estatal de Investigación project PID2022-139159NB-I00 (Volca-Motion) funded by MCIN/AEI/10.13039/501100011033 and 'FEDER Una manera de hacer Europa'. F.G. and M.E.P. were supported by 80NSSC21K0842 and 80NSSC20K1674 issued through NASA's Science Mission Directorate's Earth Science Division. This work was supported by the TelluS program of CNRS/INSU, by the EUROVOLC project, under the EU Horizon 2020 Research and Innovation Action, grant No. 731070. InSAR data were acquired within the framework of the Indian Ocean InSAR Observatory (OI/ISDeform/INSU). Deformation modelling benefited from the infrastructure and assistance of the Mésocentre from the University of Clermont Auvergne, from funds from French Government Laboratory of Excellence initiative no. ANR-10-LABX-0006. This is a Laboratory of Excellence Clervolc contribution number 753. I. J.H. was supported by public research funding from the Government of New Zealand. InSAR data over Whakaari was provided by SatSense Ltd. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rse.2026.115377>.

Data availability

Most data is open access. There is one supplementary file.

References

- Abdallah, M., Xiaoli, D., Younis, S., Songbo, W., 2025. A novel lightweight 3D CNN for accurate deformation time series retrieval in MT-InSAR. *Sci. Remote Sens.*, 100206 <https://doi.org/10.1016/j.srs.2025.100206>.
- Accocella, V., Di Lorenzo, R., Newhall, C., Scandone, R., 2015. An overview of recent (1988 to 2014) caldera unrest: knowledge and perspectives. *Rev. Geophys.* 53, 896–955. <https://doi.org/10.1002/2015RG000492>.
- Agram, P.S., Owen, S.E., Hua, H., Manipon, G., Sacco, G.F., Bue, B., Fielding, E.J., Yun, S.-H., Simons, M., Webb, F., 2016. ARIA: Delivering state-of-the-art InSAR products to end users. In: *AGU Fall Meeting Abstracts* (pp. G33C-02), 2016AGUFM.G33C..02A.
- Albino, F., Biggs, J., 2021. Magmatic processes in the East African Rift System: insights from a 2015–2020 Sentinel-1 InSAR survey. *Geochem. Geophys. Geosyst.* 22, e2020GC009488. <https://doi.org/10.1029/2020GC009488>.
- Albino, F., Biggs, J., Syahbana, D.K., 2019. Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung. *Nat. Commun.* 10, 748. <https://doi.org/10.1038/s41467-019-08564-9>.
- Albino, F., Biggs, J., Yu, C., Li, Z., 2020. Automated methods for detecting volcanic deformation using Sentinel-1 InSAR time series illustrated by the 2017–2018 unrest at Agung, Indonesia. *J. Geophys. Res. Solid Earth* 125, e2019JB017908. <https://doi.org/10.1029/2019JB017908>.
- Albino, F., Biggs, J., Lazecký, M., Maghsoudi, Y., 2022. Routine processing and automatic detection of volcanic ground deformation using Sentinel-1 InSAR data: insights from African volcanoes. *Remote Sens.* 14, 5703. <https://doi.org/10.3390/rs14225703>.
- Alshembari, R., Hickey, J., Williamson, B.J., Cashman, K., 2023. Unveiling the rheological control of magmatic systems on volcano deformation: the interplay of poroviscoelastic magma-mush and thermo-viscoelastic crust. *J. Geophys. Res. Solid Earth* 128, e2023JB026625. <https://doi.org/10.1029/2023JB026625>.
- Anantrasirchai, N., Biggs, J., Albino, F., Hill, P., Bull, D., 2018. Application of machine learning to classification of volcanic deformation in routinely generated InSAR data. *J. Geophys. Res. Solid Earth* 123, 6592–6606. <https://doi.org/10.1029/2018JB015911>.
- Anantrasirchai, N., Biggs, J., Albino, F., Bull, D., 2019a. The application of convolutional neural networks to detect slow, sustained deformation in InSAR time series. *Geophys. Res. Lett.* 46, 11850–11858. <https://doi.org/10.1029/2019GL084993>.
- Anantrasirchai, N., Biggs, J., Albino, F., Bull, D., 2019b. A deep learning approach to detecting volcano deformation from satellite imagery using synthetic datasets. *Remote Sens. Environ.* 230, 111179. <https://doi.org/10.1016/j.rse.2019.04.032>.

- Anantrasirichai, N., Biggs, J., Popescu, R.G., Xuan Wern, J.K., Yang, T., 2025. Modern deep learning techniques for volcanic unrest monitoring using InSAR data. In: *EGU General Assembly 2025*. Vienna, Austria. <https://doi.org/10.5194/egusphere-egu25-6355>.
- Andaru, R., Rau, J.Y., Syahbana, D.K., Purnamasari, H.D., 2022. Post-eruption lava dome emplacement measured by UAV photogrammetry: an investigation one year after the 2017–2019 Mt. Agung eruptions. In: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLIII-B2-2022*, 517–522. <https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-517-2022>.
- Anderson, K.R., Johanson, I.A., Patrick, M.R., Gu, M., Segall, P., Poland, M.P., Montgomery-Brown, E.K., Miklius, A., 2019. Magma reservoir failure and the onset of caldera collapse at Kilauea volcano in 2018. *Science* 366, eaaz1822. <https://doi.org/10.1126/science.aaz1822>.
- Anderson, K.R., Shea, T., Lynn, K.J., Montgomery-Brown, E.K., Swanson, D.A., Patrick, M.R., Shiro, B.R., Neal, C.A., 2024. The 2018 eruption of Kilauea: insights, puzzles, and opportunities for volcano science. *Annu. Rev. Earth Planet. Sci.* 52. <https://doi.org/10.1146/annurev-earth-031621-075925>.
- Astori, A., Boixart, G., Folguera, A., Battaglia, M., 2022. Volcanic unrest at Nevados de Chillán (southern Andean volcanic zone) from January 2019 to November 2020, imaged by DInSAR. *J. Volcanol. Geotherm. Res.* 427, 107568. <https://doi.org/10.1016/j.jvolgeores.2022.107568>.
- Bagnardi, M., González, P.J., Hooper, A., 2016. High-resolution digital elevation model from tri-stereo Pleiades-1 satellite imagery for lava flow volume estimates at Fogo Volcano. *Geophys. Res. Lett.* 43 (12), 6267–6275.
- Barclay, J., Few, R., Armijos, M.T., Phillips, J.C., Pyle, D.M., Hicks, A., Brown, S.K., Robertson, R.E., 2019. Livelihoods, wellbeing and the risk to life during volcanic eruptions. *Front. Earth Sci.* 7, 205. <https://doi.org/10.3389/feart.2019.00205>.
- Barrière, J., d'Oreye, N., Smets, B., Oth, A., Delhaye, L., Subira, J., Mashagiro, N., Derauw, D., Smittarello, D., Syavulisebo, A.M., 2022. Intra-crater eruption dynamics at Nyiragongo (DR Congo), 2002–2021. *J. Geophys. Res. Solid Earth* 127, e2021JB023858. <https://doi.org/10.1029/2021JB023858>.
- Bato, M., Lundgren, P., Pintel, V., Solidum Jr., R., Daag, A., Cahulogan, M., 2021. The 2020 eruption and large lateral dike emplacement at Taal volcano, Philippines: insights from satellite radar data. *Geophys. Res. Lett.* 48. <https://doi.org/10.1029/2021GL092803>.
- Beauducel, F., Briole, P., Froger, J.L., 2000. Volcano-wide fringes in ERS synthetic aperture radar interferograms of Etna (1992–1998): deformation or tropospheric effect? *J. Geophys. Res. Solid Earth* 105, 16391–16402. <https://doi.org/10.1029/2000JB900095>.
- Bedón, P.A.E., Ebmeier, S.K., Elliott, J.R., Wright, T.J., Mothes, P., Cayol, V., Maghsoudi, Y., Lazecký, M., Andrade, D., 2024. Co-eruptive, endogenous edifice growth, uplift during 4 years of eruption at Sangay volcano, Ecuador. *J. Volcanol. Geotherm. Res.* 454, 108147. <https://doi.org/10.1016/j.jvolgeores.2024.108147>.
- Bekaert, D., Walters, R., Wright, T., Hooper, A., Parker, D., 2015. Statistical comparison of InSAR tropospheric correction techniques. *Remote Sens. Environ.* 170, 40–47. <https://doi.org/10.1016/j.rse.2015.08.035>.
- Beker, T., Ansari, H., Montazeri, S., Song, Q., Zhu, X.X., 2023. Deep learning for subtle volcanic deformation detection with InSAR data in central volcanic zone. *IEEE Trans. Geosci. Remote Sens.* 61, 1–20. <https://doi.org/10.1109/TGRS.2023.3318469>.
- Bell, A.F., La Femina, P.C., Ruiz, M., Amelung, F., Bagnardi, M., Bean, C.J., Bernard, B., Ebinger, C., Gleeson, M., Grannell, J., 2021. Caldera resurgence during the 2018 eruption of Sierra Negra volcano, Galápagos Islands. *Nat. Commun.* 12, 1397. <https://doi.org/10.1038/s41467-021-21596-4>.
- Bemelmans, M.J., de Zeeuw-van Dalsen, E., Poland, M.P., Johanson, I.A., 2021. Insight into the may 2015 summit inflation event at Kilauea volcano, Hawai'i. *J. Volcanol. Geotherm. Res.* 415, 107250. <https://doi.org/10.1016/j.jvolgeores.2021.107250>.
- Bemelmans, M.J., Biggs, J., Poland, M., Wookey, J., Ebmeier, S., Diefenbach, A.K., Syahbana, D., 2023. High-resolution InSAR reveals localized pre-eruptive deformation inside the crater of Agung volcano, Indonesia. *J. Geophys. Res. Solid Earth* 128. <https://doi.org/10.1029/2022JB025669> e2022JB025669.
- Berardino, P., Fornaro, G., Lanari, R., Sansosti, E., 2003. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Trans. Geosci. Remote Sens.* 40, 2375–2383. <https://doi.org/10.1109/TGRS.2002.803792>.
- Biggs, J., Pritchard, M.E., 2017. Global volcano monitoring: what does it mean when volcanoes deform? *Elements* 13, 17–22. <https://doi.org/10.2113/gselements.13.1.17>.
- Biggs, J., Wright, T.J., 2020. How satellite InSAR has grown from opportunistic science to routine monitoring over the last decade. *Nat. Commun.* 11, 3863. <https://doi.org/10.1038/s41467-020-17587-6>.
- Biggs, J., Bastow, I., Keir, D., Lewi, E., 2011. Pulses of deformation reveal frequently recurring shallow magmatic activity beneath the main Ethiopian rift. *Geochem. Geophys. Geosyst.* 12. <https://doi.org/10.1029/2011GC003662>.
- Biggs, J., Ebmeier, S., Aspinall, W., Lu, Z., Pritchard, M., Sparks, R., Mather, T., 2014. Global link between deformation and volcanic eruption quantified by satellite imagery. *Nat. Commun.* 5, 3471. <https://doi.org/10.1038/ncomms4471>.
- Biggs, J., Dogru, F., Dagliyar, A., Albino, F., Yip, S., Brown, S., Anantrasirichai, N., Atici, G., 2021. Baseline monitoring of volcanic regions with little recent activity: application of Sentinel-1 InSAR to Turkish volcanoes. *J. Appl. Volcanol.* 10, 1–14. <https://doi.org/10.1186/s13617-021-00102-x>.
- Biggs, J., Anantrasirichai, N., Albino, F., Lazecky, M., Maghsoudi, Y., 2022. Large-scale demonstration of machine learning for the detection of volcanic deformation in Sentinel-1 satellite imagery. *Bull. Volcanol.* 84, 100. <https://doi.org/10.1007/s00445-022-01608-x>.
- Bonforte, A., Guglielmino, F., Puglisi, G., 2019. Large dyke intrusion and small eruption: the December 24, 2018 Mt. Etna eruption imaged by Sentinel-1 data. *Terra Nova* 31, 405–412. <https://doi.org/10.1111/ter.12403>.
- Bountos, N.I., Papoutsis, I., Michail, D., Anantrasirichai, N., 2021. Self-supervised contrastive learning for volcanic unrest detection. *IEEE Geosci. Remote Sens. Lett.* 19, 1–5. <https://doi.org/10.1109/LGRS.2021.3104506>.
- Bountos, N.I., Papoutsis, I., Michail, D., Karavias, A., Elias, P., Parcharidis, I., 2022. Hephæstus: a large scale multitask dataset towards InSAR understanding. In: *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 1453–1462.
- Brandin, M., Sandwell, D.T., Johnson, C.L., Russell, M., 2024. Mapping lava flows on Venus using SAR and InSAR: Hawai'i case study. *Earth Space Sci.* 11, e2024EA003510. <https://doi.org/10.1029/2024EA003510>.
- Bürgmann, R., Rosen, P.A., Fielding, E.J., 2000. Synthetic Aperture Radar interferometry to measure Earth's surface topography and its deformation. *Annu. Rev. Earth Planet. Sci.* 28, 169–209. <https://doi.org/10.1146/annurev.earth.28.1.169>.
- Caliro, S., Chiodini, G., Avino, R., Carandente, A., Cuoco, E., Di Vito, M., Minopoli, C., Rufino, F., Santi, A., Lages, J., 2025. Escalation of caldera unrest indicated by increasing emission of isotopically light sulfur. *Nat. Geosci.* 1–8. <https://doi.org/10.1038/s41561-024-01632-w>.
- Carn, S., Fioletov, V., McLinden, C., Li, C., Krotkov, N., 2017. A decade of global volcanic SO₂ emissions measured from space. *Sci. Rep.* 7, 44095. <https://doi.org/10.1038/srep44095>.
- Cashman, K., Biggs, J., 2014. Common processes at unique volcanoes—a volcanological conundrum. *Front. Earth Sci.* 2, 28. <https://doi.org/10.3389/feart.2014.00028>.
- Cashman, K.V., Sparks, R.S.J., Blundy, J.D., 2017. Vertically extensive and unstable magmatic systems: a unified view of igneous processes. *Science* 355, eaag3055. <https://doi.org/10.1126/science.aag3055>.
- Casu, F., Manconi, A., Pepe, A., Lanari, R., 2011. Deformation time-series generation in areas characterized by large displacement dynamics: the SAR amplitude pixel-offset SBAS technique. *IEEE Trans. Geosci. Remote Sens.* 49, 2752–2763. <https://doi.org/10.1109/TGRS.2010.2104325>.
- Casu, F., Bonano, M., Castaldo, R., De Luca, C., De Novellis, V., Lanari, R., Manunta, M., Manzo, M., Onorato, G., Pepe, S., 2019. Monitoring volcano deformation from space with Sentinel-1 Data for Civil Protection. In: *IGARSS 2019–2019 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, pp. 9303–9306. <https://doi.org/10.1109/IGARSS.2019.8897804>.
- Chandola, V., Banerjee, A., Kumar, V., 2009. Anomaly detection: a survey. *ACM Comput. Surv. (CSUR)* 41, 1–58. <https://doi.org/10.1145/1541880.1541882>.
- Chaussard, E., 2016. Subsidence in the Parícutin lava field: causes and implications for interpretation of deformation fields at volcanoes. *J. Volcanol. Geotherm. Res.* 320, 1–11.
- Chen, K., Smith, J.D., Avouac, J.P., Liu, Z., Song, Y.T., Gualandri, A., 2019. Triggering of the Mw 7.2 Hawaii earthquake of 4 may 2018 by a dike intrusion. *Geophys. Res. Lett.* 46, 2503–2510. <https://doi.org/10.1029/2018GL081428>.
- Corsa, B., Barba-Sevilla, M., Tiampo, K., Meertens, C., 2022. Integration of DInSAR time series and GNSS data for continuous volcanic deformation monitoring and eruption early warning applications. *Remote Sens.* 14, 784. <https://doi.org/10.3390/rs14030784>.
- Crozier, J., Karlstrom, L., Montgomery-Brown, E., Angarita, M., Cayol, V., Bato, M.G., Wang, T.A., Grapenthin, R., Shreve, T., Anderson, K., 2023. Understanding the drivers of volcano deformation through geodetic model verification and validation. *Bull. Volcanol.* 85, 74. <https://doi.org/10.1007/s00445-023-01687-4>.
- Davis, T., Bagnardi, M., Lundgren, P., Rivalta, E., 2021. Extreme curvature of shallow magma pathways controlled by competing stresses: insights from the 2018 Sierra Negra eruption. *Geophys. Res. Lett.* 48, e2021GL093038. <https://doi.org/10.1029/2021GL093038>.
- De Luca, C., Valerio, E., Giudicepietro, F., Macedonio, G., Casu, F., Lanari, R., 2022. Pre- and co-eruptive analysis of the September 2021 eruption at Cumbre Vieja volcano (La Palma, Canary Islands) through DInSAR measurements and analytical modeling. *Geophys. Res. Lett.* 49, e2021GL097293. <https://doi.org/10.1029/2021GL097293>.
- De Novellis, V., Atzori, S., De Luca, C., Manzo, M., Valerio, E., Bonano, M., Cardaci, C., Castaldo, R., Di Bucci, D., Manunta, M., 2019. DInSAR analysis and analytical modeling of Mount Etna displacements: the December 2018 volcano-tectonic crisis. *Geophys. Res. Lett.* 46, 5817–5827. <https://doi.org/10.1029/2019GL082467>.
- De Zan, F., Parizzi, A., Prats-Iraola, P., López-Dekker, P., 2013. A SAR interferometric model for soil moisture. *IEEE Trans. Geosci. Remote Sens.* 52, 418–425. <https://doi.org/10.1109/TGRS.2013.2241069>.
- Delgado, F., Pritchard, M.E., Ebmeier, S., González, P., Lara, L., 2017. Recent unrest (2002–2015) imaged by space geodesy at the highest risk Chilean volcanoes: Villarrica, Llaima, and Calbuco (southern Andes). *J. Volcanol. Geotherm. Res.* 344, 270–288. <https://doi.org/10.1016/j.jvolgeores.2017.05.020>.
- Dogru, F., Albino, F., Biggs, J., 2023. Weather model based atmospheric corrections of Sentinel-1 InSAR deformation data at Turkish volcanoes. *Geophys. J. Int.* 234, 280–296. <https://doi.org/10.1093/gji/ggad070>.
- Doin, M.-P., Lodge, F., Guillas, S., Jolivet, R., Lasserre, C., Ducret, G., Grandin, R., Pathier, E., Pintel, V., 2011. Presentation of the small baseline NSBAS processing chain on a case example: the Etna deformation monitoring from 2003 to 2010 using Envisat data. In: *Fringe Symposium*.
- d'Oreye, N., Derauw, D., Libert, L., Samsonov, S., Dille, A., Nobile, A., Monsieurs, E., Dewitte, O., Kervyn, F., 2019. Automation of InSAR mass processing using CSL InSAR suite (CIS) software for multidimensional small baseline subset (MSBAS) analysis: example combining Sentinel-1 and Cosmo-SkyMed SAR data for landslides monitoring in south Kivu, DR Congo. In: *ESA Living Planet Symposium*, pp. 13–17.

- Dualeh, E., Biggs, J., 2025. Separating magmatic and hydrothermal deformation using InSAR timeseries: independent component analysis at Corbetti caldera, Ethiopia. *J. Geophys. Res. Solid Earth*. <https://doi.org/10.1029/2024JB030974>.
- Dualeh, E.W., Ebmeier, S.K., Wright, T.J., Albino, F., Naismith, A., Biggs, J., Ordoñez, P. A., Boogher, R.M., Roca, A., 2021. Analyzing explosive volcanic deposits from satellite-based radar backscatter, Volcán de Fuego, 2018. *J. Geophys. Res. Solid Earth* 126, e2021JB022250. <https://doi.org/10.1029/2021JB022250>.
- Dualeh, E., Ebmeier, S., Wright, T.J., Poland, M., Grandin, R., Stinton, A., Camejo-Harry, M., Esse, B., Burton, M., 2023. Rapid pre-explosion increase in dome extrusion rate at La Soufrière, St. Vincent quantified from synthetic aperture radar backscatter. *Earth Planet. Sci. Lett.* 603, 117980. <https://doi.org/10.1016/j.epsl.2022.117980>.
- Dumont, Q., Cayol, V., Froger, J.-L., Peltier, A., 2022. 22 years of satellite imagery reveal a major destabilization structure at Piton de la Fournaise. *Nat. Commun.* 13, 2649. <https://doi.org/10.1038/s41467-022-30109-w>.
- Dumont, Q., Cayol, V., Froger, J.-L., 2024. Is stress modeling able to forecast intrusions and slip events at piton de la Fournaise volcano? *Earth Planet. Sci. Lett.* 626, 118494. <https://doi.org/10.1016/j.epsl.2023.118494>.
- Dvorak, J.J., Dzurisin, D., 1997. Volcano geodesy: the search for magma reservoirs and the formation of eruptive vents. *Rev. Geophys.* 35, 343–384. <https://doi.org/10.1029/97RG00070>.
- Ebmeier, S., 2016. Application of independent component analysis to multitemporal InSAR data with volcanic case studies. *J. Geophys. Res. Solid Earth* 121, 8970–8986. <https://doi.org/10.1002/2016JB013765>.
- Ebmeier, S.K., Biggs, J., Mather, T.A., Amelung, F., 2013. Applicability of InSAR to tropical volcanoes: insights from Central America. *Geol. Soc. Lond. Spec. Publ.* 380, 15–37. <https://doi.org/10.1144/SP380.2>.
- Ebmeier, S., Andrews, B., Araya, M., Arnold, D., Biggs, J., Cooper, C., Cottrell, E., Furtney, M., Hickey, J., Jay, J., 2018. Synthesis of global satellite observations of magmatic and volcanic deformation: implications for volcano monitoring & the lateral extent of magmatic domains. *J. Appl. Volcanol.* 7, 2. <https://doi.org/10.1186/s13617-018-0071-3>.
- Ezquerro, P., Bru, G., Galindo, I., Monserrat, O., García-Davalillo, J., Sánchez, N., Montoya, I., Palamà, R., Mateos, R., Pérez-López, R., 2023. Analysis of SAR-derived products to support emergency management during volcanic crisis: La Palma case study. *Remote Sens. Environ.* 295, 113668. <https://doi.org/10.1016/j.rse.2023.113668>.
- Fattah, E.I., Saepuloh, A., Nugraha, A.D., 2023. Observing near-real-time volcanoes deformation using InSAR–time series of LiCSBAS in Indonesia. In: *IOP Conference Series: Earth and Environmental Science*. IOP Publishing. <https://doi.org/10.1088/1755-1315/1227/1/012026>, 012026.
- Fauria, K.E., Jutzeler, M., Mittal, T., Gupta, A.K., Kelly, L.J., Rausch, J., Bennartz, R., Delbridge, B., Retailleau, L., 2023. Simultaneous creation of a large vapor plume and pumice raft by the 2021 Fukutoku-Oka-no-Ba shallow submarine eruption. *Earth Planet. Sci. Lett.* 609, 118076. <https://doi.org/10.1016/j.epsl.2023.118076>.
- Ferretti, A., Prati, C., Rocca, F., 2002. Permanent scatterers in SAR interferometry. *IEEE Trans. Geosci. Remote Sens.* 39, 8–20. <https://doi.org/10.1109/36.988661>.
- Foumelis, M., Trasatti, E., Papageorgiou, E., Stramondo, S., Parcharidis, I., 2013. Monitoring Santorini volcano (Greece) breathing from space. *Geophys. J. Int.* 193, 161–170. <https://doi.org/10.1093/gji/ggs135>.
- Foumelis, M., Blasco, J.M.D., Brito, F., Pacini, F., Pishevar, P., 2021. SNAPPING for Sentinel-1 mission on geohazards exploitation platform: an online medium resolution surface motion mapping service. In: *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*. IEEE, pp. 3991–3994. <https://doi.org/10.1109/IGARSS47720.2021.9553893>.
- Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., Kilbride, B. T.M., Reath, K.A., 2018. Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. *J. Volcanol. Geotherm. Res.* 365, 38–56. <https://doi.org/10.1016/j.jvolgeores.2018.10.002>.
- Gaddes, M., Hooper, A., Bagnardi, M., 2019. Using machine learning to automatically detect volcanic unrest in a time series of interferograms. *J. Geophys. Res. Solid Earth* 124, 12304–12322. <https://doi.org/10.1029/2019JB017519>.
- Gaddes, M., Hooper, A., Albino, F., 2024. Simultaneous classification and location of volcanic deformation in SAR interferograms using a convolutional neural network. *Earth Space Sci.* 11, e2024EA003679. <https://doi.org/10.1029/2024EA003679>.
- Gaddes, M.E., Hooper, A., Bagnardi, M., Inman, H., Albino, F., 2018. Blind signal separation methods for InSAR: The potential to automatically detect and monitor signals of volcanic deformation. *J. Geophys. Res. Solid Earth* 123 (11), 10–226.
- Galettto, F., 2023. Complex paths of magma propagation at Fernandina (Galápagos): the coexistence of circumferential and radial dike intrusion during the January 2020 eruption. *Bull. Volcanol.* 85, 71. <https://doi.org/10.1007/s00445-023-01688-3>.
- Galettto, F., Accolla, V., Hooper, A., Bagnardi, M., 2022. Eruption at basaltic calderas forecast by magma flow rate. *Nat. Geosci.* 15, 580–584. <https://doi.org/10.1038/s41561-022-00960-z>.
- Galettto, F., Reale, D., Sansosti, E., Accolla, V., 2023. Implications for shallow magma transfer during the 2017 and 2018 eruptions at Fernandina (Galápagos) inferred from InSAR data. *J. Geophys. Res. Solid Earth* 128, e2022JB026174. <https://doi.org/10.1029/2022JB026174>.
- Galettto, F., Dualeh, E., Delgado, F., Pritchard, M., Poland, M., Ebmeier, S., Shreve, T., Biggs, J., Hamling, I., Wauthier, C., 2024. The utility of TerraSAR-X, TanDEM-X, and PAZ for studying global volcanic activity: successes, challenges, and future prospects. *Volcanica* 7, 273–301. <https://doi.org/10.30909/vol.07.01.273301>.
- Galettto, F., Reale, D., Coppola, D., Sansosti, E., Pritchard, M.E., 2025. The application of remote sensing data (SAR, thermal and optical) and geodetic modelling to investigate the volcanic activity at Semeru volcano (Indonesia). *J. Geophys. Res. Solid Earth* 130. <https://doi.org/10.1029/2025JB031428>.
- Garthwaite, M.C., Miller, V.L., Saunders, S., Parks, M.M., Hu, G., Parker, A.L., 2019. A simplified approach to operational InSAR monitoring of volcano deformation in low-and middle-income countries: case study of Rabaul caldera, Papua New Guinea. *Front. Earth Sci.* 6, 240. <https://doi.org/10.3389/feart.2018.00240>.
- Goitom, B., Oppenheimer, C., Hammond, J.O., Grandin, R., Barnie, T., Donovan, A., Ogbuzghi, G., Yohannes, E., Kibrom, G., Kendall, J.-M., 2015. First recorded eruption of Nabro volcano, Eritrea, 2011. *Bull. Volcanol.* 77, 1–21. <https://doi.org/10.1007/s00445-015-0966-3>.
- Gonnermann, H.M., Foster, J.H., Poland, M., Wolfe, C.J., Brooks, B.A., Miklius, A., 2012. Coupling at Mauna Loa and Kilauea by stress transfer in an asthenospheric melt layer. *Nat. Geosci.* 5, 826–829. <https://doi.org/10.1038/ngeo1612>.
- González, P.J., 2022. Volcano-tectonic control of cumbre Vieja. *Science* 375, 1348–1349. <https://doi.org/10.1126/science.abn5148>.
- González, P.J., Samsonov, S.V., Pepe, S., Tiampo, K.F., Tizzani, P., Casu, F., Fernández, J., Camacho, A.G., Sansosti, E., 2013. Magma storage and migration associated with the 2011–2012 El Hierro eruption: implications for crustal magmatic systems at oceanic island volcanoes. *J. Geophys. Res. Solid Earth* 118, 4361–4377. <https://doi.org/10.1002/jgrb.50289>.
- González, P.J., Bagnardi, M., Hooper, A.J., Larsen, Y., Marinkovic, P., Samsonov, S.V., Wright, T.J., 2015. The 2014–2015 eruption of Fogo volcano: geodetic modeling of Sentinel-1 TOPS interferometry. *Geophys. Res. Lett.* 42, 9239–9246. <https://doi.org/10.1002/2015GL066003>.
- Gonzalez-Santana, J., Wauthier, C., Burns, M., 2022. Links between volcanic activity and flank creep behavior at Pacaya volcano, Guatemala. *Bull. Volcanol.* 84, 84. <https://doi.org/10.1007/s00445-022-01592-2>.
- Gosling, J., Dualeh, E.W., Biggs, J., 2025. Analysis and automatic detection of lava flows using SAR backscatter applied to the 2017 eruption of Erta'ale volcano, Ethiopia. *Res. Sq.* <https://doi.org/10.21203/rs.3.rs-5003481/v1>.
- Gottsmann, J., Battaglia, M., 2008. Deciphering causes of unrest at explosive collapse calderas: recent advances and future challenges of joint time-lapse gravimetric and ground deformation studies. *Dev. Volcanol.* 10, 417–446. [https://doi.org/10.1016/S1871-644X\(07\)00012-5](https://doi.org/10.1016/S1871-644X(07)00012-5).
- Gottsmann, J., Biggs, J., Lloyd, R., Biranhu, Y., Lewi, E., 2020. Ductility and compressibility accommodate high magma flux beneath a silicic continental rift caldera: insights from Corbetti caldera (Ethiopia). *Geochim. Geophys. Geosyst.* 21, e2020GC008952. <https://doi.org/10.1029/2020GC008952>.
- Gregg, P.M., Zhan, Y., Amelung, F., Geist, D., Mothes, P., Koric, S., Yunjun, Z., 2022. Forecasting mechanical failure and the 26 June 2018 eruption of Sierra Negra volcano, Galápagos, Ecuador. *Sci. Adv.* 8, eabm4261. <https://doi.org/10.1126/sciadv.abm4261>.
- Grilli, S.T., Tappin, D.R., Carey, S., Watt, S.F., Ward, S.N., Grilli, A.R., Engwell, S.L., Zhang, C., Kirby, J.T., Schambach, L., 2019. Modelling of the tsunami in the December 22, 2018 lateral collapse of Anak Krakatau volcano in the Sunda Straits, Indonesia. *Sci. Rep.* 9, 11946. <https://doi.org/10.1038/s41598-019-48327-6>.
- González, P.J., Garmendia, A., 2024. Pre-, co-, and post-eruptive deformation at Cumbre Vieja, La Palma (2021–2024). In *Vulcania III symposium*. Santa Cruz de Tenerife, 18 October 2024.
- Gunawan, H., Budianto, A., Prambada, O., McCausland, W., Pallister, J., Iguchi, M., 2019. Overview of the eruptions of Sinabung volcano, 2010 and 2013–present and details of the 2013 phreatomagmatic phase. *J. Volcanol. Geotherm. Res.* 382, 103–119. <https://doi.org/10.1016/j.jvolgeores.2017.08.005>.
- Hamling, I.J., 2017. Crater lake controls on volcano stability: insights from White Island, New Zealand. *Geophys. Res. Lett.* 44. <https://doi.org/10.1002/2017GL075572>, 11,311–311,319.
- Hamling, I.J., Cevuar, S., Garaebiti, E., 2019. Large-scale drainage of a complex magmatic system: observations from the 2018 eruption of Ambrym volcano, Vanuatu. *Geophys. Res. Lett.* 46, 4609–4617. <https://doi.org/10.1029/2019GL082606>.
- Hicks, S.P., González, P.J., Lomax, A., Ferreira, A., Ramalho, R.S., Mitchell, N., Silveira, G., Dias, N.A., Fontiela, J., Fernandes, R., 2024. Leaky Faults Modulated Magma Ascent and Seismicity during the 2022 São Jorge (Azores) Volcanic Unrest. <https://doi.org/10.31223/X5HT4V>.
- Hanif, M., Apichontrakul, S., Razi, P., 2024. *Asia-Pacific Journal of Science and Technology*, 5.
- Hooper, A., Segall, P., Zebker, H., 2007. Persistent scatterer interferometric synthetic aperture radar for crustal deformation analysis, with application to Volcán Alcedo, Galápagos. *J. Geophys. Res. Solid Earth* 112. <https://doi.org/10.1029/2006JB004763>.
- Hooper, A., Bekaert, D., Spaans, K., Arkan, M., 2012. Recent advances in SAR interferometry time series analysis for measuring crustal deformation. *Tectonophysics* 514, 1–13. <https://doi.org/10.1016/j.tecto.2011.10.013>.
- Hotta, K., Iguchi, M., Ohkura, T., Hendrasto, M., Gunawan, H., Rosadi, U., Kriswati, E., 2019. Magma intrusion and effusion at Sinabung volcano, Indonesia, from 2013 to 2016, as revealed by continuous GPS observation. *J. Volcanol. Geotherm. Res.* 382, 173–183. <https://doi.org/10.1016/j.jvolgeores.2017.12.015>.
- Hunt, J., Tappin, D., Watt, S., Susilohadi, S., Novellino, A., Ebmeier, S., Cassidy, M., Engwell, S., Grilli, S., Hanif, M., 2021. Submarine landslide megablocks show half of Anak Krakatau island failed on December 22nd, 2018. *Nat. Commun.* 12, 2827. <https://doi.org/10.1038/s41467-021-22610-5>.
- Iozzia, A., Currenti, G., Cayol, V., Bonforte, A., Cannata, A., Froger, J., 2024. Mechanically consistent model of the 2018 Christmas volcano-tectonic event at Etna. *Geophys. Res. Lett.* 51, e2023GL108017. <https://doi.org/10.1029/2023GL108017>.
- Jonas, C., Velarde, C., Gabrielli, S., Imre, E., Schulz, A.-T., 2021. Geo-SAR orbit characteristics derived from the hydroterra mission performance model. In: *EUSAR 2021; 13th European Conference on Synthetic Aperture Radar*. VDE, pp. 1–6.

- Kellndorfer, J., Cartus, O., Lavallo, M., Magnard, C., Milillo, P., Oveisgharan, S., Osmanoglu, B., Rosen, P.A., Wegmüller, U., 2022. Global seasonal Sentinel-1 interferometric coherence and backscatter data set. *Sci. Data* 9, 73. <https://doi.org/10.1038/s41597-022-01189-6>.
- Kim, Y.C., Wauthier, C., Walter, T.R., 2024. Satellite geodesy uncovers 15 m of slip on a detachment fault prior to the 2018 collapse at Anak Krakatau, Indonesia. *Geophys. Res. Lett.* 51, e2024GL112296. <https://doi.org/10.1029/2024GL112296>.
- Kundu, B., Yadav, R.K., Bürgmann, R., Wang, K., Panda, D., Gahalaut, V.K., 2020. Triggering relationships between magmatic and faulting processes in the May 2018 eruptive sequence at Kilauea volcano, Hawaii. *Geophys. J. Int.* 222, 461–473. <https://doi.org/10.1093/gji/ggaa178>.
- Kurnianto, F.A., Naim, M., Susiati, A., Susanti, D.A.J., 2024. Insight into the 2021 Semeru volcano eruption from rapid monitoring of its pyroclastic deposits using Google Earth engine and multi-sensor data. *Remote Sens. Appl.: Soc. Environ.* 36, 101380. <https://doi.org/10.1016/j.rsase.2024.101380>.
- Lazecký, M., Spaans, K., González, P.J., Maghsoudi, Y., Morishita, Y., Albino, F., Elliott, J., Greenall, N., Hatton, E., Hooper, A., 2020. LiCSAR: an automatic InSAR tool for measuring and monitoring tectonic and volcanic activity. *Remote Sens.* 12, 2430. <https://doi.org/10.3390/rs12152430>.
- Le Mével, H., Córdova, L., Cardona, C., Feigl, K., 2021. Unrest at the Laguna del Maule volcanic field 2005–2020: renewed acceleration of deformation. *Bull. Volcanol.* 83, 39. <https://doi.org/10.1007/s00445-021-01457-0>.
- Lee, J.-Y., Jung, S.-W., Hong, S.-H., 2023. Mapping lava flow from the Kilauea eruption of 2018 in the east rift zone using space-based synthetic aperture radar. *GIScience & Rem. Sens.* 60, 2176275. <https://doi.org/10.1080/15481603.2023.2176275>.
- Liu, Y.K., Ruch, J., Vasyura-Bathke, H., Jónsson, S., 2019. Influence of ring faulting in localizing surface deformation at subsiding calderas. *Earth Planet. Sci. Lett.* 526, 115784.
- Lizama, C.N., Remy, D., Baez, J., Oyarzun, A., Bonvalot, S., Hooper, A., 2025. Modeling magma recharge dynamics during the 2016 Nevados de Chillan eruption: an interacting two-chamber system evidenced by petrology and geodesy. *J. Volcanol. Geotherm. Res.* 458, 108253. <https://doi.org/10.1016/j.jvolgeores.2024.108253>.
- Loughlin, S.C., Sparks, R.S.J., Brown, S.K., Jenkins, S.F., Vye-Brown, C., 2015. *Global Volcanic Hazards and Risk*. Cambridge University Press, 1107111757.
- Lundgren, P., Girona, T., Bato, M.G., Realmuto, V.J., Samsonov, S., Cardona, C., Franco, L., Gurrola, E., Aivazis, M., 2020. The dynamics of large silicic systems from satellite remote sensing observations: the intriguing case of Domuyo volcano, Argentina. *Sci. Rep.* 10, 11642. <https://doi.org/10.1038/s41598-020-67982-8>.
- Matoza, R.S., Fee, D., Assink, J.D., Iezzi, A.M., Green, D.N., Kim, K., Toney, L., Lecocq, T., Krishnamoorthy, S., Lalande, J.-M., 2022. Atmospheric waves and global seismoacoustic observations of the January 2022 Hunga eruption, Tonga. *Science* 377, 95–100. <https://doi.org/10.1126/science.abc706>.
- McKee, K., Smith, C.M., Reath, K., Snee, E., Maher, S., Matoza, R.S., Carn, S., Roman, D. C., Mastin, L., Anderson, K., 2021. Evaluating the state-of-the-art in remote volcanic eruption characterization part II: Ulawun volcano, Papua New Guinea. *J. Volcanol. Geotherm. Res.* 420, 107381. <https://doi.org/10.1016/j.jvolgeores.2021.107381>.
- Meyer, F.J., Whitley, M., Logan, T., McAlpin, D.B., Hogenson, K., Nicoll, J.B., 2019. The SARVIEWS project: Automated processing of Sentinel-1 SAR data for geoscience and hazard response. In: *IGARSS 2019–2019 IEEE International Geoscience and Remote Sensing Symposium. IEEE*, pp. 5468–5471. <https://doi.org/10.1109/IGARSS.2019.8898957>.
- Meyer, F.J., Hogenson, K., Kennedy, J.H., Lewandowski, A.F., Albright, R.W., Short, G., Flores-Anderson, A.L., Rosen, P.A., 2025. Facilitating the golden age of synthetic aperture radar: new tools, services, and training to make synthetic aperture radar data more accessible. *IEEE Geosci. Rem. Sens. Magazine* 13, 198–209. <https://doi.org/10.1109/MGRS.2025.3526588>.
- Moore, C., Wright, T., Hooper, A., Biggs, J., 2019. The 2017 eruption of Erta' Ale volcano, Ethiopia: insights into the shallow axial plumbing system of an incipient Mid-Ocean ridge. *Geochim. Geophys. Geosyst.* 20, 5727–5743. <https://doi.org/10.1029/2019GC008692>.
- Morishita, Y., Lazecký, M., Wright, T.J., Weiss, J.R., Elliott, J.R., Hooper, A., 2020. LiCSBAS: an open-source InSAR time series analysis package integrated with the LiCSAR automated Sentinel-1 InSAR processor. *Remote Sens.* 12, 424. <https://doi.org/10.3390/rs12030424>.
- Muñoz, V., Walter, T.R., Zorn, E.U., Shevchenko, A.V., González, P.J., Reale, D., Sansosti, E., 2022. Satellite radar and camera time series reveal transition from aligned to distributed crater arrangement during the 2021 eruption of Cumbre Vieja, La Palma (Spain). *Remote Sens.* 14, 6168. <https://doi.org/10.3390/rs14236168>.
- Naismith, A., Armijos, M.T., Escobar, E.A.B., Chigna, W., Watson, I.M., 2020. Fireside tales: understanding experiences of previous eruptions and factors influencing the decision to evacuate from activity of Volcán de Fuego. *Volcanica* 3, 205–226. <https://doi.org/10.30909/vol.03.02.205226>.
- Naranjo, C., Euillades, P., Toyos, G., Euillades, L., Villarosa, G., 2023. Application of a temporal decorrelation model using Sentinel-1 SAR data to detect volcanic ash deposits related to the 2020 Taal volcano eruption. *Rem. Sens. Appl.: Soc. Environ.* 31, 100991. <https://doi.org/10.1016/j.rsase.2023.100991>.
- Neal, C.A., Brantley, S., Antolik, L., Babb, J., Burgess, M., Calles, K., Capps, M., Chang, J., Conway, S., Desmither, L., 2019. The 2018 rift eruption and summit collapse of Kilauea volcano. *Science* 363, 367–374. <https://doi.org/10.1126/science.aav7046>.
- Newhall, C., Dzurisin, D., 1988. Historical Unrest at Large Calderas of the World. In: *Bulletin of the U. S. Geological Survey*. <https://doi.org/10.3133/b1855>.
- Newhall, C.G., Self, S., 1982. The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism. *J. Geophys. Res. Oceans* 87, 1231–1238. <https://doi.org/10.1029/JC087iC02p01231>.
- Nikkhoo, M., Walter, T.R., Lundgren, P.R., Prats-Iraola, P., 2016. Compound dislocation models (CDMs) for volcano deformation analyses. *Geophys. J. Int.* <https://doi.org/10.1093/gji/ggw427>.
- Omira, R., Ramalho, R., Kim, J., González, P.J., Kadri, U., Miranda, J., Carrilho, F., Baptista, M., 2022. Global Tonga tsunami explained by a fast-moving atmospheric source. *Nature* 609, 734–740. <https://doi.org/10.1038/s41586-022-04926-4>.
- Orynbaikyzy, A., Plank, S., Vetrina, Y., Martinis, S., Santoso, I., Ismanto, R.D., Chusnayay, F., Tjahjaningsih, A., Genzano, N., Marchese, F., 2023. Joint use of Sentinel-2 and Sentinel-1 data for rapid mapping of volcanic eruption deposits in Southeast Asia. *Int. J. Appl. Earth Obs. Geoinf.* 116, 103166. <https://doi.org/10.1016/j.jag.2022.103166>.
- Pallister, J.S., Schneider, D.J., Griswold, J.P., Keeler, R.H., Burton, W.C., Noyles, C., Newhall, C.G., Ratdomopurbo, A., 2013. Merapi 2010 eruption—chronology and extrusion rates monitored with satellite radar and used in eruption forecasting. *J. Volcanol. Geotherm. Res.* 261, 144–152. <https://doi.org/10.1016/j.jvolgeores.2012.07.012>.
- Pappas, O., Biggs, J., Prats-Iraola, P., Pulella, A., Stinton, A., Achim, A., 2025. Measuring topographic change after volcanic eruptions using multistatic SAR satellites: simulations in preparation for ESA's harmony mission. *Remote Sens. Environ.* 317, 114528. <https://doi.org/10.1016/j.rse.2024.114528>.
- Parks, M., Sigmundsson, F., Drouin, V., Hjartardóttir, Á.R., Geirsson, H., Hooper, A., Vogfjörð, C., Ófeigsson, B.G., Hreinsdóttir, S., Jensen, E.H., 2023. Deformation, seismicity, and monitoring response preceding and during the 2022 Fagradalsfjall eruption, Iceland. *Bull. Volcanol.* 85, 60. <https://doi.org/10.1007/s00445-023-01671-y>.
- Parks, M.M., Sigmundsson, F., Drouin, V., Hreinsdóttir, S., Hooper, A., Yang, Y., Ófeigsson, B.G., Sturkell, E., Hjartardóttir, Á.R., Grapenthin, R., 2024. 2021–2023 unrest and geodetic observations at Askja volcano, Iceland. *Geophys. Res. Lett.* 51, e2023GL106730. <https://doi.org/10.1029/2023GL106730>.
- Parks, M., Drouin, V., Sigmundsson, F., Hjartardóttir, Á., Geirsson, H., Pedersen, G., Belart, J., Barsotti, S., Lanzì, C., Vogfjörð, K., Hooper, A., Ófeigsson, B., Hreinsdóttir, S., Gestsson, E., Prastarson, R., Einarsson, P., Tolpekin, V., Rotherham-Clarke, D., Gunnarsson, S., Óskarsson, B., Pinel, V., 2025. 2023–2024 inflation-deflation cycles at Svartsengi and repeated dike injections and eruptions at the Sundhnúkur crater row, Reykjanes peninsula, Iceland. *Earth Planet. Sci. Lett.* 658. <https://doi.org/10.1016/j.epsl.2025.119324>.
- Petrelli, M., Anantrasirichai, N., Bean, C.J., Biggs, J., Malfante, M., Wilding, J.D., Zhu, W., 2025. Methodological advances in volcanology: the role of artificial intelligence in volcano monitoring, modelling, and hazard assessment. In: Bonadonna, C. (Ed.), *The Encyclopedia of Volcanoes*. Elsevier. <https://doi.org/10.31223/X5043X>.
- Pinel, V., Poland, M.P., Hooper, A., 2014. Volcanology: lessons learned from synthetic aperture radar imagery. *J. Volcanol. Geotherm. Res.* 289, 81–113. <https://doi.org/10.1016/j.jvolgeores.2014.10.010>.
- Plank, S., Walter, T.R., Martinis, S., Cesca, S., 2019. Growth and collapse of a littoral lava dome during the 2018/19 eruption of Kadovar volcano, Papua New Guinea, analyzed by multi-sensor satellite imagery. *J. Volcanol. Geotherm. Res.* 388, 106704. <https://doi.org/10.1016/j.jvolgeores.2019.106704>.
- Poland, M.P., 2022. Synthetic aperture radar volcanic flow maps (SAR VFM): a simple method for rapid identification and mapping of volcanic mass flows. *Bull. Volcanol.* 84, 32. <https://doi.org/10.1007/s00445-022-01539-7>.
- Poland, M.P., Zebker, H.A., 2022. Volcano geodesy using InSAR in 2020: the past and next decades. *Bull. Volcanol.* 84, 27. <https://doi.org/10.1007/s00445-022-01531-1>.
- Polcarì, M., Borgstrom, S., Del Gaudio, C., De Martino, P., Ricco, C., Siniscalchi, V., Trasatti, E., 2022. Thirty years of volcano geodesy from space at Campi Flegrei caldera (Italy). *Sci. Data* 9, 728. <https://doi.org/10.1038/s41597-022-01849-7>.
- Popescu, R., Anantrasirichai, N., Biggs, J., 2025. Unsupervised anomaly detection for volcanic deformation in InSAR Imagery. *Earth Space Sci.* 12, e2024EA003892.
- Potin, P., Gascon, F., Stromme, A., Zehner, C., Wilson, H., Figa, J., Obligis, E., Lindström, R., 2021. Sentinel high level operations plan; ESA technical note. In: COPE-S1OP-EOPG-PL-15-0020.
- Prats, P., Pulella, A., Benedikter, A., Hooper, A., Biggs, J., Kääb, A., Rabus, B., Nagler, T., Rott, H., Pappas, O., 2023. Performance analysis of the harmony mission for land applications: results from the phase a study. *FRINGE Online Abstracts* 1–4.
- Pritchard, M., Biggs, J., Wauthier, C., Sansosti, E., Arnold, D.W., Delgado, F., Ebmeier, S., Henderson, S., Stephens, K., Cooper, C., 2018. Towards coordinated regional multi-satellite InSAR volcano observations: results from the Latin America pilot project. *J. Appl. Volcanol.* 7, 1–28. <https://doi.org/10.1186/s13617-018-0074-0>.
- Pritchard, M., Mather, T., McNutt, S.R., Delgado, F., Reath, K., 2019. Thoughts on the criteria to determine the origin of volcanic unrest as magmatic or non-magmatic. *Phil. Trans. R. Soc. A* 377. <https://doi.org/10.1098/rsta.2018.0008>, 20180008.
- Pritchard, M., Poland, M., Reath, K., Andrews, B., Bagnardi, M., Biggs, J., Carn, S., Coppola, D., Ebmeier, S., Furtney, M., 2022. Optimizing satellite resources for the global assessment and mitigation of volcanic hazards—Suggestions from the USGS Powell Center Volcano Remote Sensing Working Group. In: *Scientific Investigations Report*. US Geological Survey. <https://doi.org/10.3133/sir20225116>.
- Purcell, V., Reddin, E., Ebmeier, S., González, P.J., Watson, A., Morishita, Y., Elliott, J., 2022. Nearly three centuries of lava flow subsidence at Timanfaya, Lanzarote. *Geochem. Geophys. Geosyst.* 23 (10), e2022GC010576.
- Reddin, E., Ebmeier, S.K., Rivalta, E., Bagnardi, M., Baker, S., Bell, A.F., Mothes, P., Aguaiza, S., 2023. Magmatic connectivity among six Galápagos volcanoes revealed by satellite geodesy. *Nat. Commun.* 14, 6614. <https://doi.org/10.1038/s41467-023-42157-x>.
- Reddin, E., Ebmeier, S., Bagnardi, M., Bell, A.F., 2024. Craters of habit: patterns of deformation in the western Galápagos. *Volcanica* 7, 181–227. <https://doi.org/10.30909/vol.07.01.181227>.

- Richter, N., Froger, J.-L., 2020. The role of interferometric synthetic aperture radar in detecting, mapping, monitoring, and modelling the volcanic activity of Piton de la Fournaise, La Réunion: a review. *Remote Sens.* 12, 1019. <https://doi.org/10.3390/rs12061019>.
- Riddick, S., Schmidt, D., 2011. Time-dependent changes in volcanic inflation rate near Three Sisters, Oregon, revealed by InSAR. *Geochem. Geophys. Geosyst.* 12. <https://doi.org/10.1029/2011GC003826>.
- Rivalta, E., Corbi, F., Passarelli, L., Acocella, V., Davis, T., Di Vito, M.A., 2019. Stress inversions to forecast magma pathways and eruptive vent location. *Sci. Adv.* 5, eaau9784. <https://doi.org/10.1126/sciadv.aau9784>.
- Robertson, R.E., Barclay, J., Joseph, E., Sparks, R., 2024. An overview of the eruption of La Soufrière volcano, St Vincent 2020–21. *Geol. Soc. Lond. Spec. Publ.* 539, 1–24. <https://doi.org/10.1144/SP539-2023-95>.
- Roman, A., Lundgren, P., 2021. Dynamics of large effusive eruptions driven by caldera collapse. *Nature* 592, 392–396. <https://doi.org/10.1038/s41586-021-03414-5>.
- Rosen, P.A., Hensley, S., Joughin, I.R., Li, F.K., Madsen, S.N., Rodriguez, E., Goldstein, R. M., 2000. Synthetic aperture radar interferometry. *Proc. IEEE* 88, 333–382. <https://doi.org/10.1109/5.838084>.
- Sadeghi, Z., Wright, T.J., Hooper, A.J., Jordan, C., Novellino, A., Bateson, L., Biggs, J., 2021. Benchmarking and inter-comparison of Sentinel-1 InSAR velocities and time series. *Remote Sens. Environ.* 256, 112306. <https://doi.org/10.1016/j.rse.2021.112306>.
- Shakeel, A., Walters, R.J., Ebmeier, S.K., Al Moubayed, N., 2022. ALADDIn: autoencoder-LSTM-based anomaly detector of deformation in InSAR. *IEEE Trans. Geosci. Remote Sens.* 60, 1–12. <https://doi.org/10.1109/TGRS.2022.3169455>.
- Sigmundsson, F., Parks, M., Hooper, A., Geirsson, H., Vogfjörð, K.S., Drouin, V., Ófeigsson, B.G., Hreinsdóttir, S., Hjaltadóttir, S., Jónsdóttir, K., 2022. Deformation and seismicity decline before the 2021 Fagradalsfjall eruption. *Nature* 609, 523–528. <https://doi.org/10.1038/s41586-022-05083-4>.
- Sigmundsson, F., Parks, M., Geirsson, H., Hooper, A., Drouin, V., Vogfjörð, K.S., Ófeigsson, B.G., Greiner, S.H., Yang, Y., Lanzi, C., 2024. Fracturing and tectonic stress drive ultrarapid magma flow into dikes. *Science* 383, 1228–1235. <https://doi.org/10.1126/science.adn2838>.
- Smittarello, D., Cayol, V., Pinel, V., Peltier, A., Froger, J.L., Ferrazzini, V., 2019. Magma propagation at Piton de la Fournaise from joint inversion of InSAR and GNSS. *J. Geophys. Res. Solid Earth* 124 (2), 1361–1387.
- Smittarello, D., d'Oreye, N., Jaspard, M., Derauw, D., Samsonov, S., 2022a. Pair selection optimization for InSAR time series processing. *J. Geophys. Res. Solid Earth* 127, e2021JB022825. <https://doi.org/10.1029/2021JB022825>.
- Smittarello, D., Smets, B., Barrière, J., Michellier, C., Oth, A., Shreve, T., Grandin, R., Theys, N., Brenot, H., Cayol, V., 2022b. Precursor-free eruption triggered by edifice rupture at Nyiragongo volcano. *Nature* 609, 83–88. <https://doi.org/10.1038/s41586-022-05047-8>.
- Smittarello, D., Grandin, R., Jaspard, M., Derauw, D., d'Oreye, N., Shreve, T., Debret, M., Theys, N., Brenot, H., 2023. Nyiragongo crater collapses measured by multi-sensor SAR amplitude time series. *J. Geophys. Res. Solid Earth* 128, e2023JB026683. <https://doi.org/10.1029/2023JB026683>.
- Solikhin, A., Pinel, V., Vandemeulebrouck, J., Thouret, J.-C., Hendrasto, M., 2015. Mapping the 2010 Merapi pyroclastic deposits using dual-polarization synthetic aperture radar (SAR) data. *Remote Sens. Environ.* 158, 180–192. <https://doi.org/10.1016/j.rse.2014.11.002>.
- Sparks, R.S.J., Biggs, J., Neuberg, J.W., 2012. Monitoring Volcanoes. *Science* 335, 1310–1311. <https://doi.org/10.1126/science.1219485>.
- Sun, J., Wauthier, C., Stephens, K., Gervais, M., Cervone, G., La Femina, P., Higgins, M., 2020. Automatic detection of volcanic surface deformation using deep learning. *J. Geophys. Res. Solid Earth* 125, e2020JB019840. <https://doi.org/10.1029/2020JB019840>.
- Syahbana, D., Kasbani, K., Suantika, G., Prambada, O., Andreas, A., Saing, U., Kunrat, S., Andreastuti, S., Martanto, M., Kriswati, E., 2019. The 2017–19 activity at mount Agung in Bali (Indonesia): intense unrest, monitoring, crisis response, evacuation, and eruption. *Sci. Rep.* 9, 8848. <https://doi.org/10.1038/s41598-019-45295-9>.
- Thollard, F., Clesse, D., Doin, M.-P., Donadieu, J., Durand, P., Grandin, R., Lasserre, C., Laurent, C., Deschamps-Ostanciaux, E., Pathier, E., 2021. Flatsim: the form@ter large-scale multi-temporal sentinel-1 interferometry service. *Remote Sens.* 13, 3734. <https://doi.org/10.3390/rs13183734>.
- Thouret, J.-C., Taillandier, M., Wavelet, E., Azzaoui, N., Santoni, O., Tjahjono, B., 2023. Semeru volcano, Indonesia: measuring hazard, exposure and response of densely populated neighbourhoods facing persistent volcanic threats. *Nat. Hazards* 117, 1405–1453. <https://doi.org/10.1007/s11069-023-05910-5>.
- Tilling, R., 2008. The critical role of volcano monitoring in risk reduction. *Adv. Geosci.* 14, 3–11. <https://doi.org/10.5194/adgeo-14-3-2008>.
- Tizzani, P., Battaglia, M., Zeni, G., Atzori, S., Berardino, P., Lanari, R., 2009. Uplift and magma intrusion at Long Valley caldera from InSAR and gravity measurements. *Geology* 37, 63–66. <https://doi.org/10.1130/G25318A.1>.
- Tizzani, P., Battaglia, M., Castaldo, R., Pepe, A., Zeni, G., Lanari, R., 2015. Magma and fluid migration at Yellowstone caldera in the last three decades inferred from InSAR, leveling, and gravity measurements. *J. Geophys. Res. Solid Earth* 120, 2627–2647. <https://doi.org/10.1002/2014JB011502>.
- Udy, M., Ebmeier, S., Watt, S., Hooper, A., Paredes, A., 2024. Satellite measurement of forest disturbance, recovery and deposit distribution following explosive volcanic eruptions. *J. Volcanol. Geotherm. Res.* 455, 108204. <https://doi.org/10.1016/j.jvolgeores.2024.108204>.
- Valade, S., Ley, A., Massimetti, F., D'Hondt, O., Laiolo, M., Coppola, D., Loibl, D., Hellwich, O., Walter, T.R., 2019. Towards global volcano monitoring using multisensor sentinel missions and artificial intelligence: the MOUNTS monitoring system. *Remote Sens.* 11, 1528. <https://doi.org/10.3390/rs11131528>.
- Valderrama, O., Franco, L., Gil-Cruz, F., 2015. Erupción intempestiva del volcán Calbuco, Abril 2015. In: *Congreso Geológico Chileno*. LA Serena, Chile repositorio.sernageomin.cl/handle/0104/22505.
- Wadge, G., Saunders, S., Itikarai, I., 2012. Pulsatory andesite lava flow at Bagana volcano. *Geochem. Geophys. Geosyst.* 13. <https://doi.org/10.1029/2012GC004336>.
- Walter, T.R., Haghsheenas Haghighi, M., Schneider, F.M., Coppola, D., Motagh, M., Saul, J., Babeyko, A., Dahm, T., Troll, V.R., Tilmann, F., 2019. Complex hazard cascade culminating in the Anak Krakatau sector collapse. *Nat. Commun.* 10, 4339. <https://doi.org/10.1038/s41467-019-12284-5>.
- Walter, T.R., Zorn, E.U., González, P.J., Sansosti, E., Muñoz, V., Shevchenko, A.V., Plank, S.M., Reale, D., Richter, N., 2023. Late complex tensile fracturing interacts with topography at Cumbre Vieja, La Palma. *Volcanica* 6, 1–17. <https://doi.org/10.30909/vol.06.01.0117>.
- Wang, K., MacArthur, H., Johanson, I., Montgomery-Brown, E., Poland, M.P., Cannon, E., d'Alessio, M., Bürgmann, R., 2019. Interseismic quiescence and triggered slip of active normal faults of Kilauea volcano's south flank during 2001–2018. *J. Geophys. Res. Solid Earth* 124, 9780–9794. <https://doi.org/10.1029/2019JB017419>.
- Wang, J., Lu, Z., Bekaert, D., Marshak, C., Govorcina, M., Sangha, S., Kennedy, J., Gregg, P., 2023. Along-arc volcanism in the western and central Aleutian from 2015 to 2021 revealed by cloud-based InSAR processing. *Geophys. Res. Lett.* 50, e2023GL106323. <https://doi.org/10.1029/2023GL106323>.
- Wassie, Y., Millilo, P., 2025. Interferometric synthetic aperture radar multitemporal deformation monitoring: a review of machine learning techniques. *IEEE Geosci. Rem. Sens. Magazine*. <https://doi.org/10.1109/MGRS.2025.3538667>.
- Watson, C.S., Elliott, J.R., Ebmeier, S.K., Biggs, J., Albino, F., Brown, S.K., Burns, H., Hooper, A., Lazecky, M., Maghsoudi, Y., 2022. Strategies for improving the communication of satellite-derived InSAR ground displacements. *Geosci. Commun. Discuss.* 2022, 1–39. <https://doi.org/10.5194/gc-6-75-2023>.
- Weber, G., Biggs, J., Annen, C., 2025. Distinct patterns of volcano deformation for hot and cold magmatic systems. *Nat. Commun.* 16, 532. <https://doi.org/10.1038/s41467-024-55443-z>.
- Wei, L., Pan, X., Trasatti, E., Ao, M., Liu, S., Tolomei, C., Liu, G., Ventura, G., 2025. Deformation and morphological changes before the 2021–2022 explosive eruption at Hunga Tonga-Hunga Ha'apai submarine caldera revealed by satellite remote sensing. *Bull. Volcanol.* 87, 17. <https://doi.org/10.1007/s00445-025-01804-5>.
- Weissel, J., Czuchlewski, K., Kim, Y., 2004. Synthetic aperture radar (SAR)-based mapping of volcanic flows: Manam Island, Papua New Guinea. *Nat. Hazards Earth Syst. Sci.* 4, 339–346. <https://doi.org/10.5194/nhess-4-339-2004>.
- Williams, R., Rowley, P., Garthwaite, M.C., 2019. Reconstructing the Anak Krakatau flank collapse that caused the December 2018 Indonesian tsunami. *Geology* 47, 973–976. <https://doi.org/10.1130/G46517.1>.
- Winson, A.E., Costa, F., Newhall, C.G., Woo, G., 2014. An analysis of the issuance of volcanic alert levels during volcanic crises. *J. Appl. Volcanol.* 3, 14. <https://doi.org/10.1186/s13617-014-0014-6>.
- Woo, G., 2008. Probabilistic criteria for volcano evacuation decisions. *Nat. Hazards* 45, 87–97. <https://doi.org/10.1007/s11069-007-9171-9>.
- Xu, W., Rivalta, E., Li, X., 2017. Magmatic architecture within a rift segment: articulate axial magma storage at Erta Ale volcano, Ethiopia. *Earth Planet. Sci. Lett.* 476, 79–86. <https://doi.org/10.1016/j.epsl.2017.07.051>.
- Xu, W., Xie, L., Bürgmann, R., Liu, X., Wang, J., 2023. The 2022 eruption of Wolf volcano, Galápagos: The role of caldera ring-faults during magma transfer from InSAR deformation data. *Geophys. Res. Lett.* 50, e2023GL103704. <https://doi.org/10.1029/2023GL103704>.
- Ye, L., Kanamori, H., Rivera, L., Lay, T., Zhou, Y., Sianipar, D., Satake, K., 2020. The 22 December 2018 tsunami from flank collapse of Anak Krakatau volcano during eruption. *Sci. Adv.* 6, eaaz1377. <https://doi.org/10.1126/sciadv.aaz1377>.
- Yip, S.T.H., Biggs, J., Albino, F., 2019. Reevaluating volcanic deformation using atmospheric corrections: implications for the magmatic system of Agung volcano, Indonesia. *Geophys. Res. Lett.* 46, 13704–13711. <https://doi.org/10.1029/2019GL085233>.
- Yu, C., Li, Z., Penna, N.T., Crippa, P., 2018. Generic atmospheric correction model for interferometric synthetic aperture radar observations. *J. Geophys. Res. Solid Earth* 123, 9202–9222. <https://doi.org/10.1029/2017JB015305>.