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(Los Llanos de Aridane, noviembre de 2025)

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RESEARCHING A VOLCANIC ERUPTION IN REAL-TIME: THE TAJOGAITE VOLCANO (LA PALMA, CANARY ISLANDS)

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The Tajogaite eruption (2021) was the first terrestrial eruption in the Canary Islands since Teneguía (1971). Lasting 85 days, it became the longest fissural eruption on La Palma since historical records began. A simultaneous effusive, strombolian, and phreatomagmatic activity (Fig. 1), built an edifice with a volume of 34 Mm^3 and a height of ~200 m (PEVOLCA, 2021). It emitted approxi-

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mately 180 Mm^3 of lava flows, covering 12.41 km^2 (Copernicus, 2021), and affected the entire island with ashfall, accumulating more than 1.5 m thick in the vicinity of the cone (< 400 m). The eruption severely affected 4 % of the island's total surface area, damaging some 3,000 buildings and causing the evacuation of approximately 7,000 people (Carracedo *et al*., 2022). Furthermore, the emission of more than 180,000 tonnes of sulfur dioxide (SO_2) (Esse *et al*., 2025) caused significant stress to the island's natural ecosystems (Weiser *et al*., 2022).

Fig. 1. Early days of the Tajogaite eruption (La Palma, Canary Islands). Photograph taken on 22 September 2021

This eruption has been the best monitored of all those that have occurred in the Canary Islands (Carracedo *et al*., 2022). Not only during the eruptive event itself, but also long before, studies were carried out throughout the Cumbre Vieja ridge area. This ridge represents the most volcanically active area in historical times, in the Canary Islands, with seven eruptions documented to date (Carracedo, 2008). Due to this interest, the diffusion of gases such as helium and carbon dioxide (CO_2) has been studied since the early 2000s. Both the gasification processes, and the spatial distribution of these gases in the substrate are considered ideal geochemical tools for volcanic monitoring

(Padrón *et al*., 2012, 2015). Such is the case of the seismic activity that occurred in October 2017, which was related to episodes of magmatic intrusion and was preceded by the emission of gases, including hydrogen (Padrón *et al*., 2018, Pérez *et al*., 2018; Torres-González *et al*., 2020). Finally, the Tajogaite eruption, which began on 19 September 2021, was preceded by an increase in the intensity of seismic movements and ground deformation that had been detected since 2009 (see Torres-González *et al*., 2020; Fernández *et al*., 2021; Carracedo *et al*., 2022).

From the outset, this eruption attracted the attention of a large number of researchers and scientific institutions from around the world, bringing together up to 500 researchers from different disciplines of geology, vulcanology, oceanography, and biodiversity, all working in the field at the same time (Fig. 2). At the moment, close to 800 scientific publications can be found in Google Scholar (search conducted on September 13, 2025, a few days before the fourth anniversary of the eruption's onset).

The eruption caused an extensive damage to the population (homes, crops, and infrastructure (Carracedo *et al*., 2022)) and disturbed their daily lives. From an environmental perspective, although the eruption did not ultimately pose a direct threat to any endangered terrestrial species or habitats, its effects have also impacted the biodiversity (Nogales *et al*., 2022). However, on the coastline buried by the lava flows, there were populations of *Gelidium arbuscula* (Sangil *et al*., 2024), red algae classified as Vulnerable (*Ley 4/2010, de 4 de junio, del Catálogo Canario de Especies Protegidas*). Based on all the damage caused by the volcanic eruption, the Spanish Government enacted a Royal Decree-Law to provide urgent support for the economic and social reconstruction of the island of La Palma (*Real Decreto-ley 20/2021, de 5 de octubre, por el que se adoptan medidas urgentes de apoyo para la reparación de los daños ocasionados por las erupciones volcánicas y para la reconstrucción económica y social de la isla de La Palma. BOE-A-2021-16231*). This legislation also included a direct and specific subsidy to the Cabildo de La Palma, through the Ministry for Ecological Transition and Demographic Challenge, for the prevention and mitigation of damage to biodiversity and natural heritage caused by the 2021volcanic eruption.

The high degree of monitoring of the Tajogaite eruption, combined with the application of advanced surveillance techniques, enabled decision-making and civil protection measures based on the valuable scientific information obtained (Carracedo *et al*., 2022). However, much of the science applied at the time, as well as the results of published scientific research, has not adequately reached the general population. This is important because one of the primary concerns in such catastrophic events is ensuring the security and well-being of the citizens who are directly affected. It should be noted that scientists cannot conceive of science without society, and therefore their work must ultimately be reflected on it.

In this context, an international conference showing all the science and its transfer to society has been organised and will take place at the Benahoarita Archaeological Museum in Los Llanos de Aridane, from November 17 to 21, 2025. This event is an opportunity to involve science, society and governance in La Palma Island. The conference was organised under different topics to cover all the research fields investigated during the eruption. The first topics to be addressed are directly related to physical volcanology (Topic 1) and volcanotectonics (Topic 2), where aspects related to direct observations of

Fig. 2. Researchers collecting samples of ash emitted during the eruption of the Tajogaite volcano (La Palma, Canary Islands)

volcanic processes and associated deposits will be discussed, as well as the mapping and modelling of these processes (González, 2022; Mata *et al*., 2022; Mediato *et al*., 2023; Sanz-Mangas *et al*., 2024). On the other hand, the relationship between structural geology, topography, geophysical methods, and bathymetric sampling will be explored in order to understand magmatic emplacement, dyke propagation, and volcanic deformation (Romero *et al*., 2022; Plank *et al*., 2023).

Petrological studies (Topic 3) will show aspects related to the origin and evolution of the magma involved in volcanic eruptions (Day *et al*., 2022; Ubide *et al*., 2023; Frascerra *et al*., 2024; Scarrow *et al*., 2024; Andújar *et al*., 2025). Volcanic eruptions pose a serious risk to the population (Topic 4) due to the large amount of solid material of different sizes and characteristics (pyroclastic material and lava flows) that they expel. Therefore, their hazards must be continuously measured and assessed to minimize their effects (Bonadonna *et al*., 2023). This aspect will focus on the latest research and technological innovations (artificial intelligence, computational models, and satellite data) applied to risk assessment and prediction (Civico *et al*., 2022; Domínguez *et al*., 2025).

Special reference and emphasis will be made on these new geophysical and geodetic monitoring methods (high-resolution GPS, InSAR, seismic networks) (Topic 5), which are considered important for understanding the dynamics of volcanic and tectonic systems (Cabrera-Pérez *et al*., 2023). Geochemical monitoring (Topic 6) also plays a fundamental role in analysing changes in the composition of gases, thermal waters, and volcanic deposits, which are fundamental elements in the dynamics of eruptive processes and in mitigating the risks associated with them (Padrón *et al*., 2022; Sandoval-Velásquez *et al*., 2023; Asensio-Ramos *et al*., 2025). Other monitoring methods (Topic 7) include remote techniques, gravity and magnetotelluric surveys, drone-based campaigns, and thermal imaging, all of which were also applied during the Tajogaite eruption (for example, González de Vallejo *et al*., 2024).

In addition, the Tajogaite volcano also emitted significant amounts of gases into the atmosphere (Topic 8), which have a major impact on terrestrial ecosystems, the climate, air quality, and, consequently, human health (Rodríguez-Pérez *et al*., 2024). Studies on the estimation of gas and aerosol emissions and their chemical composition, as well as their impact on air quality and human health (Topic 9), are one of the most relevant aspects for the population affected by the Tajogaite eruption.

This eruption has expanded the frontiers of knowledge by enabling research into the formation of unique geological heritage (Topic 10) and its implications for recognition, legislation, and land use planning. This has presented scientists, administrations, and society with one of their most significant challenges: recognising the volcanic elements of greatest scientific value and proposing them for legal protection (Vegas *et al*., 2022).

The natural environment, both marine and terrestrial, was equally affected by this eruption. In the marine and coastal environments (Topic 11), when the lava reached the sea and formed lava deltas, it promoted impacts on the marine chemistry (González-Santana *et al*., 2022), biodiversity (Sangil *et al*., 2024), and other parameters (González-Vega *et al*., 2024). Terrestrial biodiversity (Topic 12) was also affected. The lava flows impacted various natural ecosystems, with the Canary pine forest suffering the most from the volcano's impact, but also areas of thermophilous and xerophytic ecosystems (Nogales *et al*., 2022). In the areas covered by the lava flows, re-colonisation processes will take place, forming new ecosystems, while the surrounding and more distant areas, affected by intense heat and gases, have been recovering over time (Fig. 3). These results demonstrate the resilience of Canary Islands

Fig. 3. The Canary Island pine (*Pinus canariensis*) has demonstrated an evolutionary adaptation to the destructive effect of volcanoes, being able to resprout several times just a few weeks after the end of the Tajogaite eruption (Photo: María Guerrero Campos)

ecosystems and their evolutionary adaptation to volcanic processes (Beierkuhnlein *et al*., 2023; Guerrero-Campos *et al*., 2023).

Volcanoes also provide valuable resources to the societies living near them, including geothermal energy, fertile soil, construction materials, geotourism, and tangible and intangible cultural heritage (Hernández *et al*., 2022; González de Vallejo *et al*., 2024). For this reason, research is needed to explore the potential of volcanic landscapes as a source of new resources (Topic 13).

The eruption of Tajogaite volcano had a severe impact on Aridane Valley, home to some 33,000 people, disrupting its social, economic, and territorial functions (Topic 14). This generated a strong community reaction, as well as the intervention of multiple external agents in relief, reconstruction, and strategic planning. Challenges included emergency management, the displacement of people, and governance in a context of multiple institutions and conflicting interests (Zapata Hernández, 2023; Zapata Hernández & del Rosario Martín, 2023). This stage also led to the development of original, highly participatory strategic planning initiatives (Fig. 4) in which people affected and their representative organisations played a prominent role (González Rodríguez

Fig. 4. Various informational meetings were held at different locations in the Aridane Valley throughout the volcanic process. These were organised by the 'Revivir El Valle' project and brought together local residents, authorities, and technical and scientific personnel (Photo: Vicente Zapata)

et al., 2024). The social mobilisation resulting from the eruption even culminated in the unanimous approval of an unprecedented Canary Islands Volcano Law in the regional Parliament in 2025.

Since one of the main objectives of this conference is to bring together the scientific work carried out around this historic event and to involve the citizens of the affected localities, the scientific presentations will be complemented by outreach activities. Talks, exhibitions, and debates will demonstrate the usefulness and importance of scientific knowledge in building a well-informed, healthy and developed society. We hope to achieve this objective, which is undoubtedly a task for everyone.

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Keynote talks

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ERUPTION DYNAMICS AND TEPHRA DEPOSITION OF THE 2021 TAJOGAITE EVENT: A CASE STUDY OF A LONG-LASTING HYBRID ERUPTION

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Abstract

The 2021 Tajogaite eruption of Cumbre Vieja (La Palma, Canary Islands) was a long-lasting (85-day) hybrid event characterized by the simultaneous emission of lava flows, tephra and volcanic gas from multiple vents along a 0.5 km fissure (Rodríguez *et al.*, 2024). Even though > 70 % of the erupted volume was associated with the effusive phase, explosive activity was continuous, with varying eruptive styles (ash-poor gas puffing, Strombolian and violent Strombolian activity, and lava fountaining) producing a widespread tephra blanket ($\sim 2 \times 10^7$ m^3) (Bonadonna *et al.*, 2022; 2023). This event exemplifies the complexity of hybrid basaltic eruptions, where eruptive styles vary over short spatial and temporal scales, posing significant challenges for hazard assessment and crisis management. In La Palma, impacts worsened as compound hazards hit interconnected, low-redundancy infrastructure typical of insular environments (e.g. Reyes-Hardy *et al.*, 2024; Domínguez *et al.*, 2025). Detailed analysis of the tephra deposits, combined with atmospheric wind data,

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volcanic seismic tremor, lava emission rates, and high-resolution field observations, has provided critical insights into the eruption dynamics. The tephra deposit was subdivided into three main units (Lower, Middle, and Upper Units: LU, MU, UU), 11 layers and 18 sub-layers (Fig. 1), which could be correlated across proximal to distal locations, also matching variations in seismic tremor and lava effusion rates along the eruption. The tephra blanket constitutes only 7-16 % of the total erupted volume (1-3 × 10^8 m^3 when including lava flows and the tephra cone), yet it remains a key archive for deciphering eruption dynamics (Bonadonna *et al*., 2022; Romero *et al*., 2022; Rodríguez *et al*., 2024).

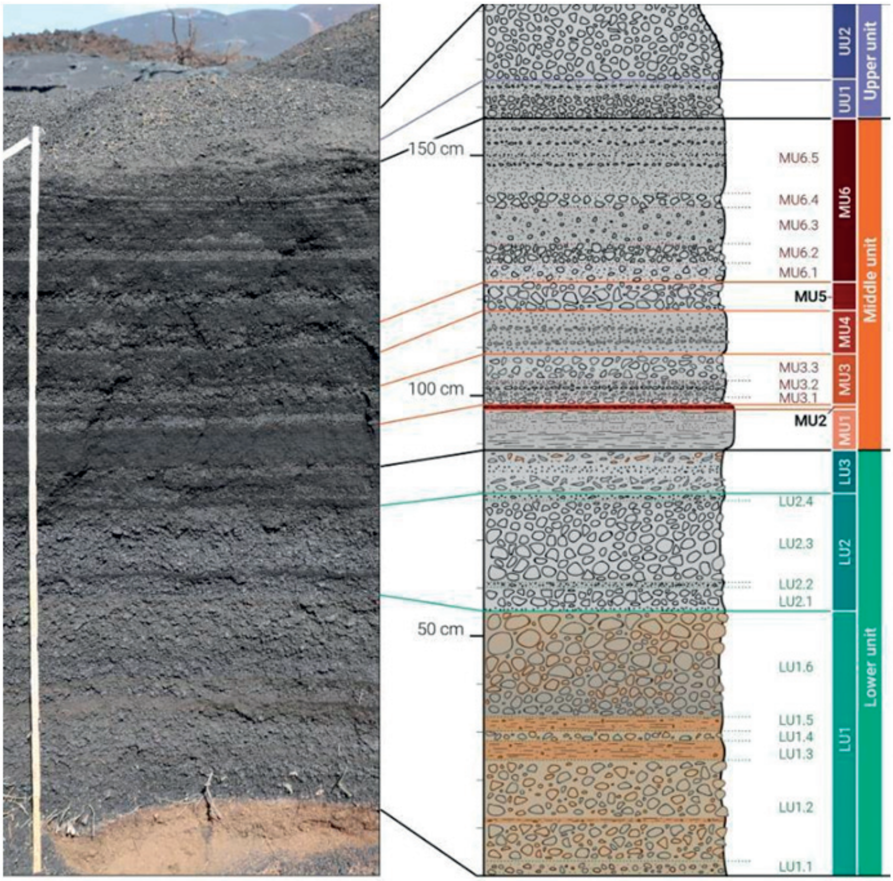

Fig. 1. Reference stratigraphic section ~1 km SW of vents showing: 3 different units (Lower, Middle, Upper), 11 layers (LU1, LU2, LU3, MU1, MU2, MU3, MU4, MU5, MU6, UU1, UU2), and 18 sublayers (LU1.1-6, LU2.1-4, MU3.1-3, MU6.1-5) (adapted from Bonadonna *et al*., 2022)

The mass eruption rate (MER) associated with tephra remained relatively constant (~3-4 × 10^3 kg/s), while lava effusion rates were an order of magnitude higher (~6 × 10^4 kg/s) and varied through time, peaking after a major cone collapse occurred after six days from eruption onset (Bonadonna *et al.*, 2022; Romero *et al.*, 2022). Although plume height fluctuated significantly on a daily scale, it was primarily modulated by wind intensity rather than MER variations. Strong trade winds inhibited plume rise, while weak or absent winds allowed for higher plume elevations (up to 7.5 km above the vent) even during phases dominated by effusive activity (Bonadonna *et al.*, 2022). This dynamic interplay between eruptive forcing and atmospheric conditions led to a tephra dispersal pattern elongated NE-SW, further influenced by land-sea breezes, local convection over the forming lava field, and orographic effects (Fig. 2).

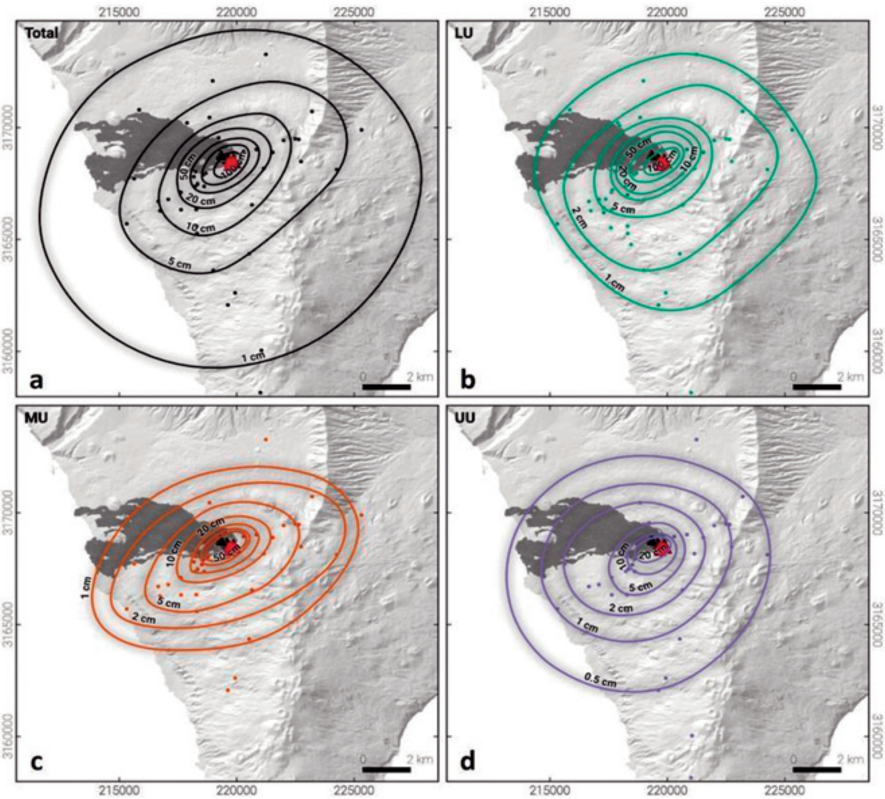

Fig. 2. Isopach maps of (a) total deposit, (b) Lower Unit (LU), (c) Middle Unit (MU), and (d) Upper Unit (UU) (adapted from Bonadonna *et al.*, 2022). Inundated area of lava flow (dark gray area) as well as eruptive vents (black and red triangles being the vents mostly producing lava and tephra, respectively) are shown. Thickness values (in cm) of each contour are indicated. Color of contours correlates with colors of Figure 1

Local and total grain-size distribution of tephra blanket associated with selected layers and the three units are unimodal, with Mdφ values ranging from -2.2 to 2.3 φ (4.6 to 0.2 mm) (Bonadonna *et al*., 2023). Aggregation processes, including the formation of coated particles and liquid pellets, were prevalent during rainfall events, while sedimentation features like lapilli waves and ash fingers were documented at varying distances from the vents. Notably, fine ash content (<63 μm) remained low and did not show correlation with distance, while the fraction of particles <1 mm increased distally. Despite the complex pulsatory activity and style transitions occurring over minutes to hours, the tephra blanket records an overall violent Strombolian character, as confirmed by classification schemes based on field data.

Pulsatory dynamics, driven by rapid gas segregation and high magma ascent rates, controlled fragmentation efficiency and the transition among bubbly (puffing), slug (Strombolian), churn (violent Strombolian), and annular (lava fountaining) gas flow regimes (Bonadonna *et al*., 2023). This variability led to significant short-term fluctuations in tephra accumulation and grain size at the ground, emphasizing the need for high-temporal-resolution observations during such eruptions. The Tajogaite eruption underscores the necessity of adopting multidisciplinary approaches to describe and classify hybrid eruptions. Relying solely on tephra volume-based metrics (e.g., Volcanic Explosivity Index, VEI) is insufficient; comprehensive assessments must integrate lava effusion trends, tephra cone evolution, and pulsatory dynamics. New strategies are also required for ash dispersal forecasting during long-lasting hybrid eruptions with highly variable winds and eruptive styles.

In conclusion, the Tajogaite eruption exemplifies how hybrid basaltic eruptions, even when predominantly effusive, can produce high plumes and widespread tephra impacts. Effective hazard assessment and crisis response for such events demand flexible, real-time integrative monitoring strategies capable of capturing rapid fluctuations in eruptive behaviour and tephra sedimentation processes

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MAGMA STORAGE AND MOVEMENT AT CUMBRE VIEJA (LA PALMA, CANARY ISLANDS)

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Abstract

With eight eruptions since the late 15th century, Cumbre Vieja is currently the most active volcano of the Canary Islands. Hence there is considerable interest in understanding the volcano's behavior, which is governed by magma composition, volatile contents, storage depths, and magma movements. Most historic eruptions of Cumbre Vieja were compositionally zoned, with earlier erupted tephrite being abruptly followed by more primitive basanite. Lavas from late eruption phases commonly carried abundant xenoliths, i.e., rock fragments from the crust and mantle that are messengers of deep-seated processes occurring before and during an eruption. The first mineral-based barometric investigations of xenoliths and their host lavas from Cumbre Vieja, using compositions of clinopyroxenes and densities of CO_2-rich fluid inclusions, showed a remarkable bimodality of pressures (Klügel *et al*., 2005). It was found that pre-eruptive storage of most magmas occurred in a complex reservoir system in the uppermost mantle, extending from about 14 to 26 km below sea-level (bsl). Storage at earlier stages of magma evolution also occurred at deeper levels (Barker *et al*., 2015). During an eruption, the magmas passed through a widespread magma accumulation zone in the lowermost crust, at around 7 to 13 km bsl, where the vertical ascent rates apparently slowed down. This short-term ponding can reflect a phase of lateral movement or slow passage through a plexus of magma pockets (Klügel *et al*., 2005, 2022). The accumulation zone hence receives fresh magma input at least with every eruption, and magmas remaining there after an eruption can differentiate to tephriphonolites and phonolites that commonly occur on Cumbre Vieja (Klügel *et al*., 2022). The existence of such an accumulation zone can explain the following observations: massive occurrences of gabbro fragments from the lower oceanic crust in some lavas; occurrence of mantle fragments that were tem-

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porarily deposited and embedded by magmatic cumulates within this zone; and intense magmatic overprinting of gabbro xenoliths (Klügel *et al*., 2005, 2022).

The 2021 Tajogaite eruption was a tragedy for the island but a stroke of luck for volcanologists and petrologists. Long-term volcano monitoring and daily sampling by Spanish scientists and international colleagues provided a base for unprecedented insights into magmatic processes and magma movement before, during, and after the eruption.

The combination of geophysical, geodetic, petrological and geochemical data principally confirmed and substantially expanded the earlier models of magma storage and transport. The first events associated with the eruption were injections of small magma volumes into the magma accumulation zone beneath the northeast of Cumbre Vieja in 2009-2010 and probably in 2011-2012 (Fig. 1A), causing minor surface deformation (Fernández *et al*., 2021). The first seismic swarms indicative of volcanic unrest were recorded in 2017-2018 mainly at 15 to 20 km bsl (Fig. 1B), within the main storage levels previously identified, coinciding with changes in helium and CO_2 emissions on La Palma (Fernández *et al*., 2021; Torres-González *et al*., 2021). Four more seismic swarms at similar depths followed, until magma began to intrude as shallow as 2 to 4 km beneath the west coast of La Palma in May 2021 (Fernández *et al*., 2022). This event was reflected in geodetic but not in seismic data. The intrusion may have stalled because of an older mechanically weak structure identified geophysically (Fernández *et al*., 2022). The intrusion subsequently grew in size, and eventually lead to shallow dike propagation and eruption.

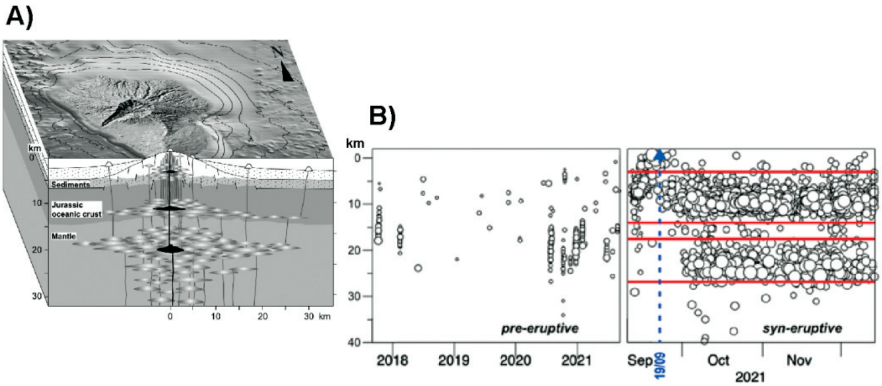

Fig. 1. A) Early model of magma storage beneath Cumbre Vieja showing the main reservoir system in the upper mantle and the magma accumulation zone in the lower oceanic crust (Barker *et al*., 2015). B) Pre- and syn-eruptive seismicity of the Tajogaite eruption, modified from Zanon *et al*. (2024) (License 4.0 CC BY)

Tajogaite lavas erupted during the first 8 days were amphibole-bearing tephrites that reflect remobilization and mixing of mush from an older, more evolved magma with ascending basanite magma (Day *et al*., 2022; Ubide *et al*., 2023). Mixing and recharge occurred in the uppermost mantle, at similar depth ranges as previous Cumbre Vieja eruptions (Klügel *et al*., 2005; Ubide *et al*., 2023). After 8 days the magma composition changed and the incoming basanite dominated. This was accompanied by intense seismicity at two depth ranges, about 7-12 km and 20-25 km (Zanon *et al*., 2024), which coincide with the magma accumulation zone in the lower crust and the main reservoir system in the upper mantle, respectively (Klügel *et al*., 2005).

This seismicity lasted until the end of the eruption and reflects coupled recharge and discharge of the two main storage systems. Distinct recharge pulses with fresh, undegassed magma from depth caused changes in eruptive behavior, and could be identified by subtle geochemical signatures in the lavas (Ubide *et al*., 2023). The combination of different interdisciplinary approaches in connection with the Tajogaite eruption has produced an unexpectedly clear picture of magma movement beneath Cumbre Vieja, but questions still remain.

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GEOPHYSICAL AND GEODETIC MONITORING OF VOLCANIC ACTIVITY

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ABSTRACT

Geophysical and geodetic monitoring are essential tools for understanding, forecasting, and mitigating volcanic hazards (Spica & Caudron, 2025). Effective volcano monitoring relies on multidisciplinary techniques including seismic networks, GNSS and InSAR, geochemical and petrological analysis, gravity measurements and recent innovations such as Distributed Acoustic Sensing (DAS) and artificial intelligence (AI)-driven approaches (Petrelli *et al*., 2024; Spica *et al*., 2025). These technologies, combined with integrative platforms, enable a near real-time multi-sensor framework that supports decision-making during volcanic crises (Spica & Caudron, 2025). Seismic monitoring provides critical information on volcanic tremor, earthquake swarms, subsurface structure, magma storage and magma migration. GNSS networks measure surface displacement with millimeter precision, while InSAR offers spatial comprehensive mapping of surface deformation related to magma ascent and eruptive dynamics. Additionally, gravity changes observed through terrestrial gravimetry, or satellite missions reveal subsurface mass redistribution (Spica & Caudron, 2025). Satellite and drone-based technologies are now indispensable in modern volcano monitoring. They enable the detection of subtle uplift, tracking plume dynamics, and identification of thermal anomalies across broad and often inaccessible areas. In parallel, aerial vehicles or drones offer high-resolution lava flow monitoring and close-range observations of active volcanic vents. This aerial instrumentation can be equipped with gas sensors, infrared cameras, and photogrammetry tools, and can safely collect data from hazardous zones, complementing satellite imagery and ground-based observations. The 2021 eruption of Cumbre Vieja (La Palma) (Suárez *et al*., 2021) provided an unprecedented opportunity to integrate seismic, geodetic, geochemical and petrological observations to interpret the dynamics and evolution of a volcanic unrest and eruption in an oceanic island context. Geophysical and geodetic monitoring throughout the pre-, syn-, and post-eruption phases provided a unique multidisciplinary dataset, advancing our understanding on eruptive dynamics, petrology, geophysics, and volcano hazard assessment.

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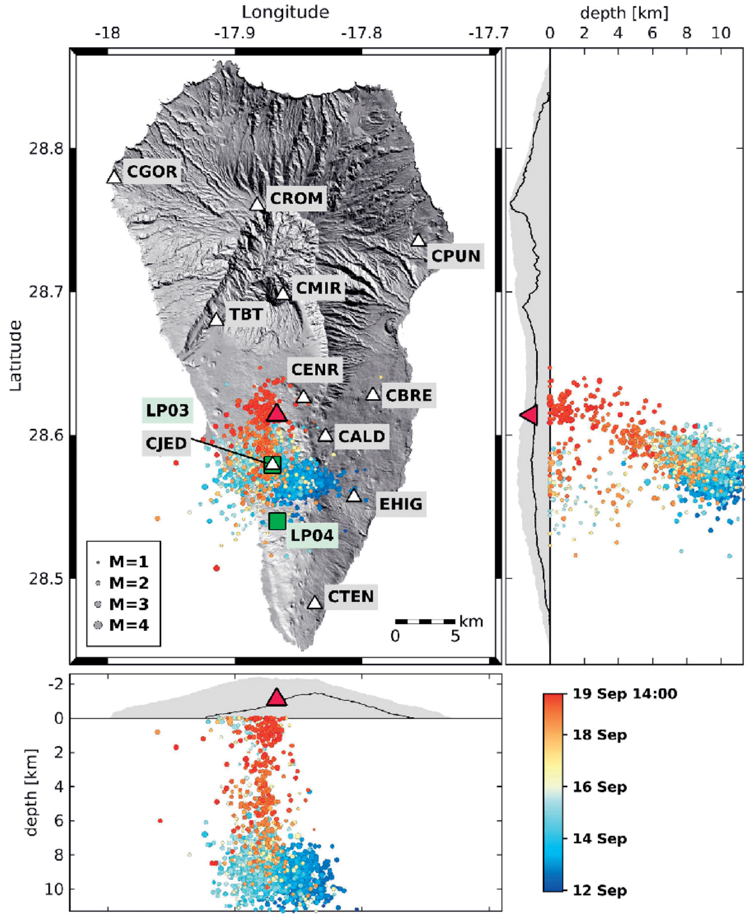

Fig. 1. Seismic and GNSS monitoring (IGN) during unrest phase preceding the 2021 eruption of Cumbre Vieja. Modified from Suarez *et al*. (2021)

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UNVEILING SILENT DEGASSING: KEY GEOCHEMICAL INDICATORS FOR EARLY WARNING OF CHANGES IN VOLCANIC ACTIVITY

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ABSTRACT

Traditionally, geochemical monitoring for volcanic surveillance focused on collecting and analyzing fumarole gases in evacuated flasks with NaOH 5N solution, enabling chemical characterization of volcanic gases and insights into magmatic processes. In the 1970s, the adaptation of the Correlation Spectrometer (COSPEC), originally for industrial pollution, revolutionized volcanic SO_2 measurements by enabling remote monitoring and time-series data collection. The 1980s brought two advances: helium-3 emission ($^3He/^4He$) measurements, a direct tracer of deep magmatic inputs, and the first satellite-based SO_2 monitoring via TOMS, capable of detecting large volcanic plumes. The 1990s introduced Open-Path Fourier Transform Infrared (OP-FTIR) Spectroscopy, allowing simultaneous quantification of multiple gases in volcanic plumes, and portable instruments for quick ground CO_2 efflux measurements, which advanced the study of diffuse degassing. These innovations transformed volcanic gas monitoring into a more precise, real-time, and multi-scale discipline, enhancing the ability to detect and interpret pre-eruptive magmatic processes. Ground CO_2 efflux measurements, particularly accumulation chamber techniques (Fig. 1), proved especially valuable (Chiodini *et al*., 1998) because (i) many active volcanoes lack visible volcanic degassing manifestations (e.g. fumarole, plume, etc.), (ii) CO_2 is the major gas species after water vapor in both volcanic fluids and magmas, (iii) it is an effective tracer of subsurface magma degassing due to its low solubility in silicate melts at low to moderate pressure favoring its early exsolution (Gerlach & Graeber, 1985) and (iv) it can easily escape through wide areas of the volcanic edifice via permeable features. As a result, diffuse ground degassing studies have become a

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cornerstone in the early detection of volcanic unrest, especially at volcanoes with limited or absent surface visible degassing. Together, these technological advancements have contributed to a more nuanced and comprehensive understanding of volcanic systems and remain fundamental to modern volcanic surveillance strategies.

Fig. 1. Permanent station for continuous monitoring of ground CO_2 efflux at the summit cone of Teide volcano (left), and INVOLCAN's staff performing a geochemical survey of quick ground CO_2 efflux measurements at the summit crater of Teide volcano (right)

The focus of this abstract is on the diffuse or «silent» degassing from volcanoes. Diffuse volcanic degassing disturbs the chemical and isotopic composition of the soil-air and water-air interfaces at the surface environment of the volcano, producing enrichments not only of CO_2 but also of He, H_2 and other tracer gases. During the last 30 years numerous gas geochemical studies have highlighted the importance of this type of degassing in volcanic systems and its great use to strengthen the geochemical monitoring program for volcanic surveillance, particularly at those volcanic areas where visible volcanic gas emissions (plume, fumaroles, etc.) either are scarce or do not exist. However, the detection of diffuse CO_2 degassing anomalies prior to volcanic eruptions reported are very scarce. The earliest scientific publications documenting significant variations in diffuse CO_2 degassing prior to volcanic eruptions were associated with the 2000 Usu and 2002 Stromboli eruptions. At Usu, diffuse CO_2 emission surveys revealed a notable increase leading up to the eruption, with emissions rising from approximately 120 $t \cdot d^{-1}$ in September 1998 to around 340 $t \cdot d^{-1}$ in September 1999. Following the 2000 eruption, diffuse CO_2 emissions declined sharply to ~39 $t \cdot d^{-1}$ by June 2000 (Hernández *et al.*, 2001). In the case of Stromboli, continuous monitoring of ground CO_2 efflux measurements revealed substantial increases in diffuse CO_2 degassing several months before the 2002 eruption, providing early evidence of heightened magmatic degassing (Carapezza *et al.*, 2024). In both cases, the observed pre-eruptive increases underscore the value of diffuse gas monitoring as a reliable tool for eruption forecasting. Chiodini *et al*. (2005) provide an essential framework for converting diffuse CO_2 degassing rates meaningful estimates of heat output. This enhances our understanding of volcanic-hydrothermal processes and supports more comprehensive monitoring of volcanic systems. Another important contribution came by Notsu *et al*. (2006) who developed a conceptual model illustrating the differences between diffuse and visible volcanic gas emissions prior to eruptions, showing that variations in diffuse emissions can be detected years before an eruption occurs (Fig. 2).

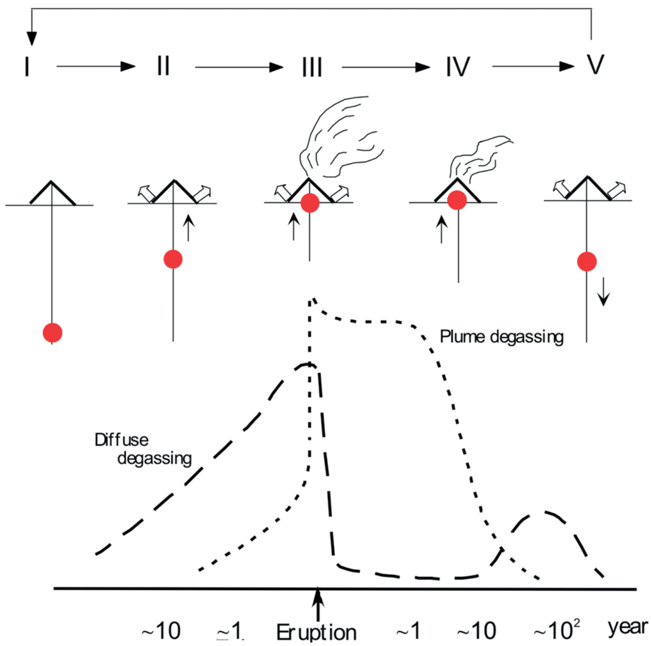

Fig. 2. Schematic illustration showing a simple conceptual model of the temporal evolution of gas emissions from volcanoes. The solid circle (red) represents magma rising and descending within the volcanic system. The patterns of both non-visible (diffuse) and visible (plumes) degassing are approximately illustrated as two broken lines. The time scale on the horizontal axis is qualitative. (Notsu *et al*., 2006).

The finding that anomalous diffuse CO_2 emissions can be detected in volcanic systems several years prior to the onset of unrest is supported by observations from the 2011-2012 Tagoro eruption (Melián *et al*., 2014), the 2021 Tajogaite eruption (Padrón *et al*., 2015), and the 2004-2005 seismic-volcanic crisis on Tenerife (Pérez *et al*., 2013). Research on diffuse He degassing is also of great scientific interest since both volatiles have low solubility in magmas (Padrón *et al*., 2013).

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ATMOSPHERIC AEROSOLS DURING THE ERUPTION OF TAJOGAITE

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ABSTRACT

Volcanoes are a natural source of atmospheric aerosols or particulate matter (PM), i.e. solid and liquid micrometer particles that blow in the air for weeks. Atmospheric aerosols are linked to a diversity of sources, including natural ones as desert-dust, marine or biogenic, and anthropogenic as urban, man-started fires and diverse industries. These aerosols may be directly emitted as particles (primary) or formed in the atmosphere by gas to particle conversion (secondary). When breathed-in, aerosols smaller than 10 microns (PM_{10}) may prompt inflammatory processes, oxidative stress and other adverse effects on human health. Aerosol particles are transported in the atmosphere across hundreds-to-thousands of kilometers, interacting with solar radiation and clouds, and supplying chemicals to ecosystems which may act as nutrients or toxics, affecting geochemical cycles. Thus, aerosols are key components of the Earth system that influence air quality, ecosystems and climate. Volcanic aerosols have a marked influence on weather and climate. Explosive eruptions lead to the injection of aerosols in the stratosphere, resulting in (months-to-few years) global decreases in temperature and promoting stratospheric ozone losses. Volcanic aerosols increase the number of cloud droplets and decrease the mean droplet size without substantial changes in liquid water content. Volcanic aerosols may reduce global mean precipitation in the years after major eruptions, yet the mechanisms that produce this response have not been rigorously identified (McGraw & Polvani, 2024). Many studies have used aerosols to characterize volcanic eruptions, by using their composition and ratios among elements to understand how eruption processes (e.g. degassing, melt composition, etc...) and/or eruption types (e.g. arc versus hot spot) influence on subaerial emissions (Edmonds *et al*., 2018). Despite these advances, the composition and physical properties of volcanic aerosols is still oversimpli-

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fied in many climate models, which just consider volcanic aerosols as sulphate and/or ashes as a whole without considering the specific elemental composition, salts speciation or trace elements.

Currently, the climate modelling community is making an effort to include the atmospheric aerosols composition (including volcanic) in models, with some recent advances on molybdenum (Wong *et al*., 2021) and manganese (Lu *et al*., 2024). To advance with such improvement more observations are needed. During the eruption of Tajogaite, based on El Paso and Los Llanos de Aridane, we deployed a program for studying the formation mechanisms of volcanic aerosols, including the atmospheric chemistry beyond the immediate reactions during the emissions.

We performed (i) a continuous monitoring of number size distribution of aerosols (10 nanometers to 10 microns) based on nano Scanning-Mobility-Particle-Sizer and an Optical-Particle-Sizer and black carbon particles based on aethalometer online measurements, and (ii) continuous monitoring of aerosol chemistry based on the composition of bulk and size segregated PM_{10} samples, which included the elemental composition by total acid digestion and ICP-OES and ICP-MS, ions by ion chromatography and organic carbon and elemental carbon by TOR/TOT. These measurements were coordinated with other groups focused on tephra-falls and trace-gases. The number size distributions data shows that the concentrations of ultrafine particles (<100 nm) reached extremely high concentrations ($\sim 200 \cdot 10^3$ cm^{-3}). Evidence of nucleation processes (<20 nm particles) could only be directly detected in the second half of the eruption, associated with the decrease in the condensation sink favored by Aitken, accumulation and coarse particles. Primary volcanic aerosols, with a low compositional variability (quenched lava fragments), accounted for 61 % of PM_{10} whereas secondary aerosols (volcanic salt and acids) accounted for 26 % of PM_{10}, as average. Volcanic PM_{10} aerosols were enriched with respect to tephra in Bi, Tl, Mo and other trace-elements characteristic of volcanic emissions, associated with the condensation in the aerosol's accumulation and ultrafine ranges. The quantitative stoichiometric apportionment analysis we did for sulphate, chloride, fluoride and nitrate evidence that soil emission from crop-fields prompted by the coladas and atmospheric chemistry in aged-air influenced the formation of aerosol salts. The Saharan dust events occurred during the eruption allowed to perform a detailed compositional comparison between volcanic and dust aerosols, useful for modelling. The volcanic PM_{10} samples show an extraordinarily high oxidative potential, with implications on human health, that seems to be linked to soluble trace metals in the fresh volcanic aerosols. The conceptual model we propose contribute to improve the volcanic aerosols representation in health effects, air quality and climate models.

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FORECASTING THE EVOLUTION OF THE 2021 TAJOGAITE ERUPTION (LA PALMA) FROM TROPOMI/PLUMETRAJ SO_2 EMISSION RATES

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Abstract

Forecasting how an eruption evolves and when it will end is operationally critical yet often under quantified. We analyse the 2021 Tajogaite eruption using daily TROPOMI SO_2 imagery combined with a forward trajectory implementation of PlumeTraj to reconstruct injection time-altitude, correct vertical column densities for plume height, and derive robust daily SO_2 emission rates. Cumulative emissions exhibit an exponential trend after the initial fissure phase, enabling simple, testable forecasts. Total SO_2 released was 1.6 ± 0.3 Mt (upper limit 1.9 Mt) (Esse *et al*., 2025); emissions peaked near 80 kt day^{-1} on 20 Sep and again at ~70 kt day^{-1} on 29 Sep before decaying smoothly. Fitting the cumulative series from 29 September yields a characteristic time constant $\tau \approx 28$ days. The eruption ceased when SO_2 flux fell to ~6 % of the fitted maximum —an empirical threshold that closed the forecast loop. Fits stabilized from 20 Oct onward; using the 6 % criterion, forecast end dates were consistently within ±15 days of the true end. These results, produced and shared in near real time with the monitoring agencies, demonstrated actionable skill during the crisis.

To relate gas fluxes to subsurface drivers, we converted SO_2 to magma discharge using a melt sulphur content derived from melt inclusion studies of 3290 ± 390 ppm (Burton *et al*., 2023), then explored a 1-D steady magma ascent model (13 km conduit; inlet T ≈ 1160 °C; 3 wt % H_2O, 4.5 wt % CO_2).

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We highlight that the total volume of erupted magma is 212 Mm^3 (Plank *et al*., 2023) and derived SO_2 mass is 2.8 ± 0.7 Mt, comparable with observed upper limit of SO_2 gas emissions of 1.9 Mt.

The observed declining SO_2 flux was matched by a 20-30 MPa reservoir pressure drop together with an effective conduit radius of 1.3-1.6 m; a shrinking conduit alone (by ~0.3-0.5 m) can also reproduce the flux decrease if pressure is fixed. But we consider this unlikely as co evolution with GPS deflation (Charco *et al*., 2024) and independent lava volume estimates (Plank *et al*., 2023) supports simple reservoir drainage as the first order control, while short period departures (e.g., around 20 Oct and 1 Nov) likely reflect shallow process variability and episodic recharge (Ubide *et al*., 2023).

We highlight that the TROPOM/PlumeTraj approach coupled with magma ascent modelling permits: (i) global coverage and height aware flux quantification from space; (ii) a two parameter exponential model (ϕo, τ) that is transparent, testable mid crisis, and physically interpretable; and (iii) cross validation against independent deformation and thermal datasets. Limitations include: (i) near source under retrieval under ash/aerosol and cloud; (ii) reliance on coarse meteorological fields for trajectories; and (iii) the need to adopt an operational end threshold (here 6 %) that may vary by system, contributing tens of days of uncertainty late in an eruption. With the advent of Sentinel 4 (geostationary over Europe), higher cadence SO_2 will further tighten forecasts.

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Geological heritage, geodiversity
and new resources opportunities

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THE ROLE OF GEOHERITAGE AND GEODIVERSITY OF MONOGENETIC VOLCANIC FIELDS OF SAUDI ARABIA IN THE LIGHT OF SUSTAINABLE DEVELOPMENT WITHIN GEOSYSTEM SERVICES CONCEPT

KÁROLY NÉMETH[1,2,3,4]

ABSTRACT

Geoheritage is now established as an integral aspect of Earth science education, reinforcing connections between the planet and society through scientific, educational, and cultural perspectives (Brilha, 2020). It provides valuable insights into historical geologic events and acts as a conduit between natural phenomena and human comprehension of Earth's processes. The proposal to define geodiversity as the «numerical density» of abiotic elements within a particular area —akin to the approach used in biodiversity studies— introduces certain challenges (Brilha *et al*., 2018). Unlike biodiversity, which relies on quantifiable biotic parameters, geological features often present greater complexity and are less straightforward to assess (Gray, 2021). Abiotic components manifest in a variety of geoforms, each characterized by qualitative attributes such as rock types, minerals, and structural configurations. These qualitative factors also possess measurable relative abundances at global, regional, or local levels. Consequently, geodiversity encompasses both qualitative and quantitative aspects, though its practical application remains challenging (Zakharovskyi & Németh, 2021). Geoconservation endeavours to safeguard geoheritage —including geological specimens, archives, maps, artifacts, and sites— from deterioration caused by urban expansion, natural wea-

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thering, and other threats. The conservation of monogenetic volcanic fields in Saudi Arabia underscores the necessity of balancing resource development with preservation efforts (Moufti & Németh, 2016). The concept of geosystem services, analogous to ecosystem services, advocates for the sustainable utilization of abiotic natural resources through an integrated framework of geosystems, services, values, and governance (Gray, 2011). This approach fosters synergy between subsurface geosystem services and surface ecosystem services, supporting sustainable urban growth and efficient resource management.

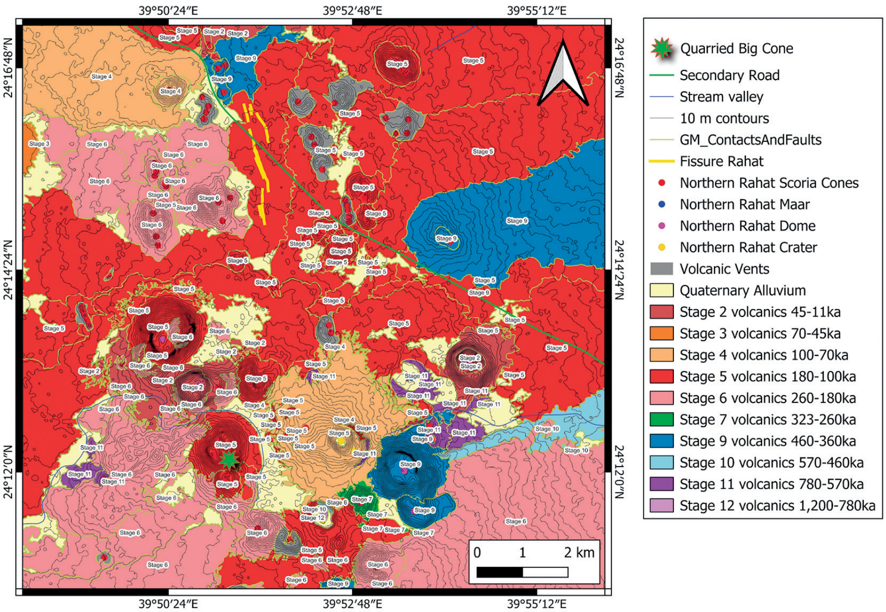

Fig. 1. High geodiversity region of the northern Harrat Rahat with various young monogenetic volcanoes. Scoria extraction removed a large part of one of the largest scoria cones of the region (green star). The mapped area documents around 1.1 million years of eruptive history, with lava flows forming a ridge about 500 meters high. Eruptions occurred roughly every thousand years, each producing about 0.1 km³ of dense rock. Older stages record fewer events as details are lost over time. In the highest ground, the field formed young silicic (trachytic, but still monogenetic style volcanoes with lava dome, block-and-ash fans, and collapsed craters visible as a light-coloured region in the bottom right corner of the image (Downs *et al.*, 2023).

Emphasis is placed on key exploration and future mining locations as part of Saudi Arabia's mineral resource strategy, targeting materials including scoria, alluvial sediments, and critical minerals such as lithium within major basins and volcanic systems. Notable scoria deposits have undergone partial exploitation at Harrat Al Rahat (Németh *et al.*, 2023) and Harrat Lunayyir, alongside maar volcanic complexes within Harrats Hutaymah and Kishb, components of western Saudi Arabia's Late Cenozoic volcanic provinces. Our research demonstrates that developments on highly vulnerable volcanic geosites such as those in the Harrat Lunayyir region (northwestern Saudi Arabia) would substantially impact the area's geoheritage integrity (Németh *et al.*, 2024). Harrat Lunayyir is recognized as one of the most unspoiled natural monogenetic volcanic environments within Saudi Arabia (Németh *et al.*, 2024). Such development poses risks, including potential loss of geodiversity and degradation of critical geoheritage properties. Such terrain is particularly sensitive from a geoheritage standpoint, encompassing zones with ash deposits and areas

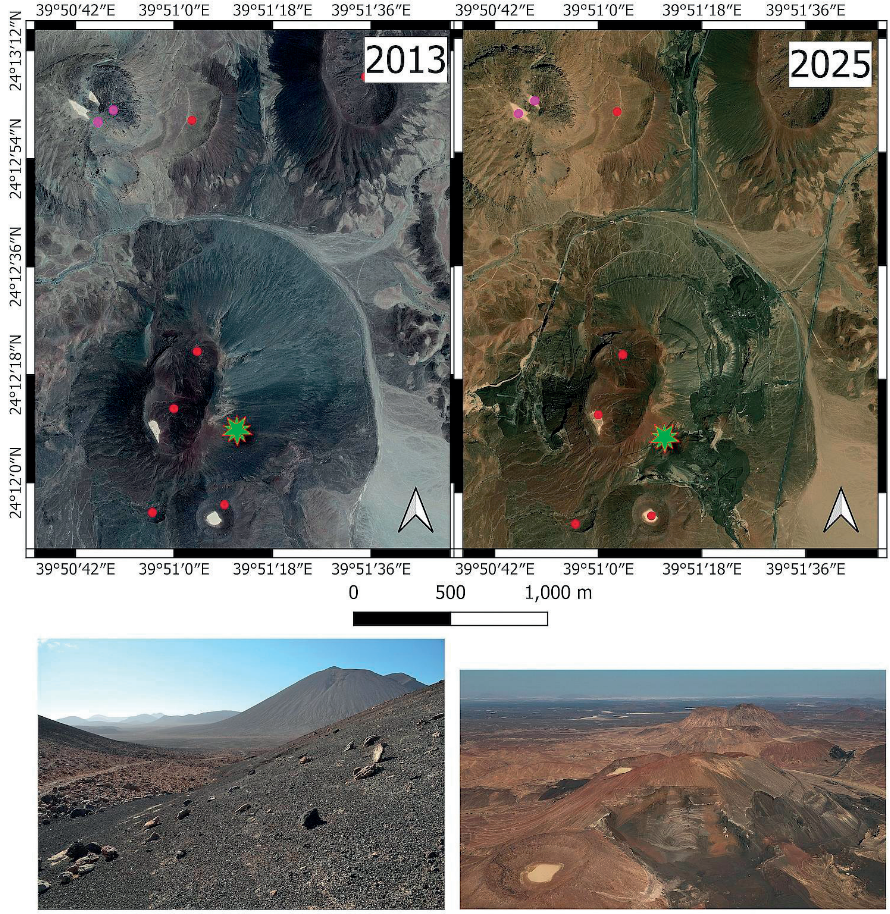

Fig. 2. Satellite imagery shows the impact of scoria extraction of one of the iconic large scoria cones near Al Madinah. The two images reflect a 12-year difference. Below, the large cone is shown from the ground (left bottom) and drone image (right bottom)

adjacent to well-preserved scoria cones; even carefully managed interventions may have adverse effects. While urbanization and immediate demand for raw materials have not been primary contributors to geoheritage decline in Harrat Lunayyir, the situation is more complex in the Harrat Rahat region (Fig. 1). There, urban expansion of Al Madinah city has resulted in the consumption or significant degradation of several notable volcanic geosites (Fig. 2), compromising their geoheritage integrity and diminishing their future value for geoeducation or geotourism. To address these challenges, implementing a geosystem conservation strategy can help mitigate geosite losses resulting from the exploitation of non-renewable resources. Accurate characterization and assessment of geodiversity are essential to support sustainable management. Employing scientifically robust methodologies for estimating geodiversity and selecting geosites supports comprehensive economic evaluations, which should incorporate feasibility studies and risk assessments using impact modelling. For instance, open-pit mining —such as the removal of scoria— has a pronounced effect on the landscape but also provides valuable geological insights into volcanic processes, exemplified by the volcanic fields of Saudi Arabia. This information is critical for both public education and expert analysis related to future volcanic hazards. In conclusion, a cost-benefit framework aligned with the concept of geosystem services offers a way to balance the economic advantages of resource extraction with the preservation of landscape integrity. Although mining operations can provide access to important geosites for hazard resilience education, this relationship is inherently non-linear; there are critical thresholds beyond which further resource extraction irreversibly compromises the landscape's value. Additionally, disused mining pits represent permanent losses unless they are incorporated into geoconservation and educational initiatives. Geoheritage values should be systematically monitored throughout exploitation activities, and abandoned quarry sites in volcanic regions should be repurposed for geoeducation as integral components of natural hazard resilience programs.

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THE CHEMISTRY AND GLOBAL IMPACT OF SUBMARINE ERUPTIONS AND HYDROTHERMAL ACTIVITY

JOSEPH RESING*

ABSTRACT

Most volcanic eruptions on Earth take place in the deep ocean where they may be recorded seismically but are otherwise generally unobserved and uncharacterized. As part of a NOAA-PMEL-University of Washington consortium we have observed the effects of recent and ongoing eruptions in a variety of environments, including eruptions along the Mariana Arc at NW Rota (Embley *et al*., 2006), Ahyi (Buck *et al*., 2018), and Daikoku seamounts, in the rear arc in the Lau Basin at West Mata (Fig. 1) (Resing *et al*., 2011) and Niuatahi Volcanoes, at hotspot volcanoes including El Hierro (Santana-Casiano *et al*., 2016), Loihi Seamount (Duennebier *et al*., 1997), and in back arc basins along the Mariana and Lau back arc spreading centers (Baumberger *et al*., 2020), and at mid-ocean ridge spreading centers e.g., Axial volcano (Resing *et al*., 1999), and along the Australian-Antarctic ridge crest. We find that the eruptive fluids are greatly altered and enriched in many elements and compounds including SO_2, H_2S, CO_2, CH_4, 3He, iron, manganese, and other chemical components of the lava (Resing *et al*., 1999, 2011; Butterfield *et al*., 2011; Chadwick *et al*., 2014; Baumberger *et al*., 2020). The enrichments in iron, manganese, and other components are driven by magmatic heat and the release of magmatic volatiles SO_2 and CO_2. The observed enrichments are ~10X or greater than those seen in steady state hydrothermal plumes, resulting in extremely large instantaneous chemical fluxes from submarine eruptions. The iron and manganese carried in fluids can potentially act as trace nutrients in the surface-ocean especially where biological productivity is limited by insufficient supply of these elements (e.g., Resing *et al*., 2015; Tagliabue & Resing, 2016). Submarine eruptions and their associated hydrothermal activity greatly impact the chemistry of the surrounding ocean, forming plumes of chemically altered fluids that rise in the water column and are carried by the currents to disperse throughout the ocean (Resing *et al*., 2015).

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Though originating in the deep ocean, these fluids ultimately reach the surface via thermohaline circulation. Eruptions also happen in the shallow ocean where their chemical impact is felt immediately in the surface ocean. In regions of favorable upwelling, direct transport to the surface ocean can occur even for much deeper eruptions. Hence these fluids play a direct role in the growth of phytoplankton in the sunlit surface ocean.

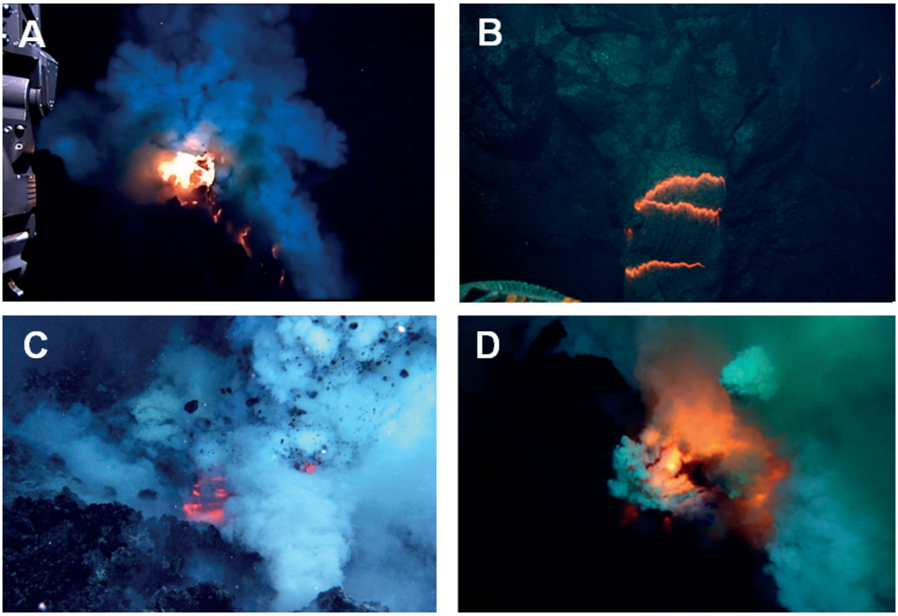

Fig. 1. Images from the Submarine eruption of West Mata Volcano in 2009. A. Magma bubble formation. B. Pillow Lava formation. C. explosive clast formation from pyro- and hyalo-clastic processes. D. Active effusion of molten lava

I will look at the impact of submarine eruptions on ocean chemistry. I will also look at the global impacts of submarine volcanism on ocean chemistry and biological productivity. I will discuss recent observations of an eruption in the Southern Ocean where eruption-altered fluids from 2000m reached the surface ocean in an area where a large phytoplankton has formed most years over the last 30 years of satellite observations.

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EFFECTS OF EXTREME EVENTS ON ECOSYSTEMS – A THEORY ON PULE DYNAMICS AND DISTURBANCE IN ECOLOGY

ANKE JENTSCH*

ABSTRACT

The biomes of the world are characterized by typical disturbance regimes (White & Jentsch, 2001). Disturbance ecology includes vegetation ecology, ecosystem dynamics, and biogeochemistry of nutrient cycles (Fig. 1). Here, I will present contents and topics of disturbance ecology, definitions of disturbance events and regimes, descriptors of disturbance regimes, and methods for the quantitative characterization of disturbance. Extreme events, such as the Tajogaite volcanic eruption on La Palma, can cause abrupt change in ecosystems (Turner *et al*., 2022) and drive long term changes in biodiversity and ecosystem functioning. Thus, this talk addresses fundamental elements of disturbance ecology, such as drivers of disturbances, adaptations of plants to disturbance, disturbance effects on biodiversity and resilience.

The new theory of pulse dynamics and disturbance in ecology (Jentsch & White, 2019) is based on four postulates:

1) 'Resource Dynamics' characterizes the magnitude, rate, and duration of resource change caused by pulse events, including the continuing changes in resources that are the result of abiotic and biotic processes;

2) 'Energy Flux' characterizes the energy flow that controls the variation in the rates of resource assimilation across ecosystems;

3) 'Patch Dynamics' characterizes the distribution of resource patches over space and time, and the resulting patterns of biotic diversity, ecosystem structure, and cross-scale feedbacks of pulses processes; and

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4) 'Biotic Trait Diversity' characterizes the evolutionary responses to pulse dynamics and, in turn, the way trait diversity affects ecosystem dynamics during and after pulse events.

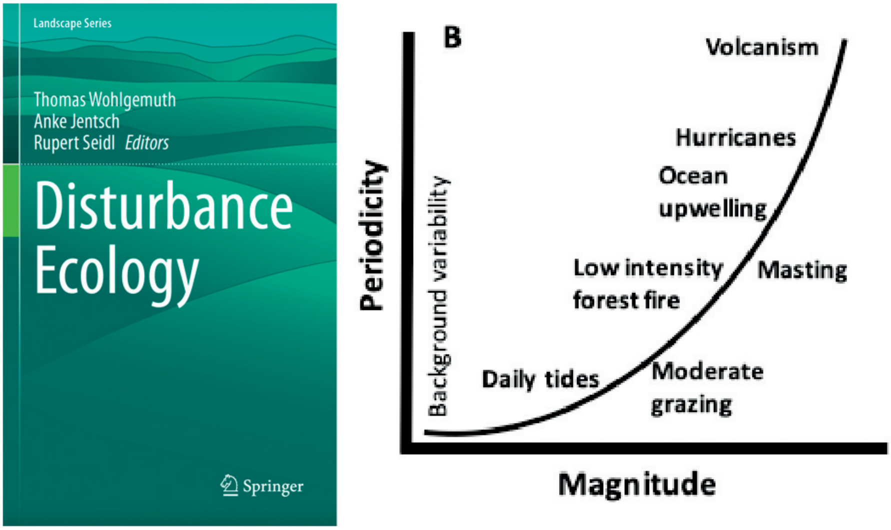

Fig. 1. The scientific textbook on «Disturbance Ecology» (Wohlgemuth *et al*., 2022) covering elements of ecosystem dynamics such as disturbance interactions (Burton *et al*., 2020), disturbance cycles, and disturbance cascades, discuss important attributes of disturbance ecology such as frequency and magnitude, classify successional processes depending on disturbances, touch at niche differentiation, the Intermediate Disturbance Hypothesis, and the role of disturbances for biodiversity and productivity

I will apply the four postulates to biomass-altering disturbances and derive generalizations that predict disturbance magnitude, resource trajectory, rate of resource change, disturbance probability, biotic trait diversification at evolutionary scales, biotic diversity at ecological scales, and functional resilience.

Ultimately, we aim at better understanding community dynamics, comprising resistance, recovery, resilience and adaptation to disturbance and extreme weather events. Let's discuss and be inspired!

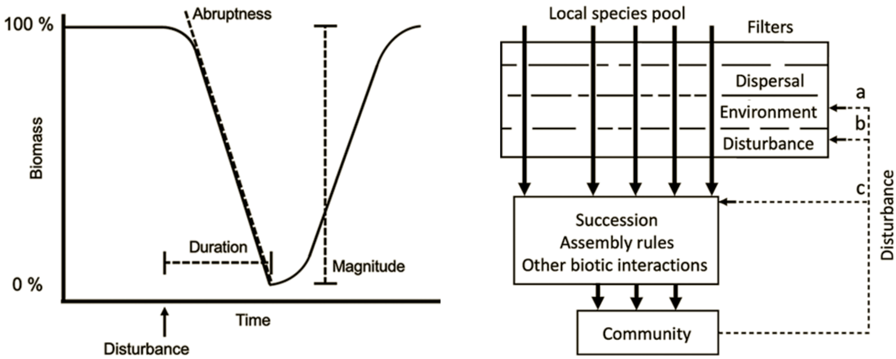

Fig. 2. Left) Three criteria for the definition of a disturbance event: (1) discrete beginning and duration (abruptness), (2) short duration relative to the lifespan of the dominant organisms or ecosystems, and (3) strength/magnitude as a proportionate change in a measurement variable, such as biomass (White & Jentsch, 2001). Right) The threefold role of disturbances in community assembly: (a) disturbances influence abiotic filters, e.g. nitrogen release after fire; (b) disturbances act directly as selective filters according to their properties, e.g. by mowing height, fire temperature, or wind energy; and (c) disturbances influence biotic interactions within a community, e.g. by selective feeding and shifting of competitive equilibria (White & Jentsch, 2004)

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THE FASCINATING ECOLOGY OF YOUNG OCEANIC ISLANDS

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ABSTRACT

Oceanic islands such as La Palma, Hawaii, Azores, Galápagos, Réunion and many others are of outstanding importance for global biodiversity. Every single island is specific in its ecosystems and the high number of endemic species. Altogether, these islands provide the same number of plant species to the global heritage as the entire tropical rainforest. Individual islands are not extremely rich in species, but every island contributes different species to global biodiversity. The Canary Islands are a hotspot of biodiversity (Beierkuhnlein *et al.*, 2021). This unique biodiversity is even more threatened by climate change than the tropical rain forest because populations of endemic species are small and very sensitive to extinction (Harter *et al.*, 2015).

All volcanic islands on the oceanic Earth crust are geologically rather young but this type of island has always existed in Earth history. Together with spatial and ecological isolation, dynamic physical and chemical processes deliver specific conditions for organisms and ecosystems. Their substrates are very comparable, but species assemblages are highly individual across the globe. This even applies to tephra fields formed by volcanic ash deposits within individual oceanic islands.

Oceanic islands arise through volcanism from the oceanic crust, reach the sea surface, grow to high mountains, and are eroded when volcanism ends (Fig. 1). This has been constantly repeated since the development of terrestrial ecosystems. This Earth System's contribution to global biodiversity can only be understood when biosciences (phylogeny, ecology) and geosciences (geochemistry, tephra dating, soil science) are combined.

Elevational gradients on islands such as La Palma are classic sites to stu-

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dy endemism and isolation (Steinbauer *et al.*, 2017). However, it is surprising that speciation, the development of new species on an island, is highest not towards the mature end of the existence of an island, but during the early phase of island development with ongoing impacts such as lava flows, gas emission, and pyroclastic ejections (Fig. 2). This indicates that the phase of volcanic activity is important for originating new species.

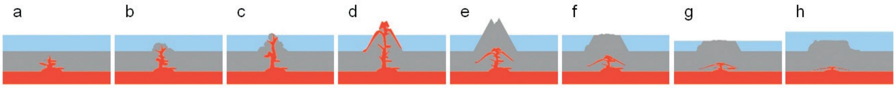

Fig. 1. Development of oceanic islands. a) intrusion, b) seamount, c) pillows, d) shield volcano with lava flows and tephra, e) end of volcanic activity and increasing topographic differentiation, f) erosion down to sea level, g) sea level fluctuation and erosion to new sea level, h) submarine guyot. Species can establish as soon as the island emerges above sea level, then biodiversity increases and is maintained until islands decay through erosion. With sea level fluctuations they will disappear from the sea surface

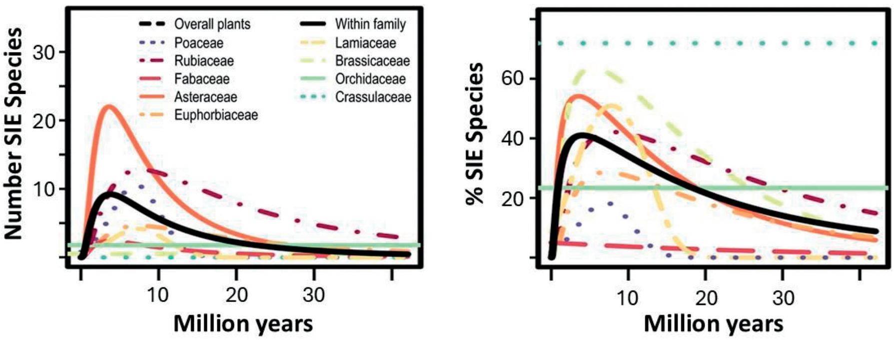

Fig. 2. Temporal trends of plant species richness and endemism (SIE = Single Island Endemics) for abundant families on 101 oceanic islands in 14 archipelagos (Lenzner *et al.*, 2017). The peak of endemism in young islands indicates that speciation takes mainly place during the initial phase of island formation, which is the phase of volcanic activity

Lava flows provide new terrestrial surfaces, but they destroy the vegetation underneath completely. The emission of toxic gases during the eruption has a strong impact on the health of ecosystems, but this impact is transient and not long-term effective (Weiser *et al.*, 2022, 2023). The impact that is most important for the selection of new species is the deposition of volcanic ashes (Nogales *et al.*, 2022; Beierkuhnlein *et al.*, 2023). The immense amount of volcanic ash produced by the Tajogaite eruption (Shatto *et al.*, 2024) allows us to study many processes such as the survival of seed banks under the tephra (Medina *et al.*, 2025).

The consequences of the Tajogaite eruption in 2021 provide a unique opportunity for basic research that is relevant at the global scale, because the processes that can be investigated now are also relevant for the understanding of biodiversity on all oceanic islands. Nevertheless, they can only be investigated during and after a recent volcanic eruption.

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ON THE NECESSARY REINTERPRETATION OF THE CONCEPT OF DEVELOPMENT AND ITS APPLICATION TO THE ARIDANE VALLEY AFTER THE ERUPTION

Carlos Giménez Romero*

Abstract

Taking into account the criticism of the concept of development, but not agreeing that it is best not to use it, we advocate its redefinition as shared wealth and employment, a stronger and better social fabric and active citizenship, greater local autonomy and environmental sustainability, all of which are highly relevant to the current and future development of the Aridane Valley, taking advantage of the changes that the volcanic eruption has brought about.

The contribution is structured in two parts. The first section is theoretical and conceptual in nature and is divided into two sections: a) an analysis of the criticisms of the concept of development that have been formulated internationally and from different disciplines and schools of thought; b) the author's position on the notion of development itself and his proposal to understand it in a multidimensional way that is compatible with a just eco-social transition. The second section is practical and operational in nature, suggesting a series of five implications that can be inferred for the current and future development of the Aridane Valley.

I. Towards a reinterpretation of the notion of development

The term 'development' is ubiquitous and has been used extensively for a long time. Although it was mentioned in English in the 16th century (Robertson, 1984; Williams, 1985), it was in the early decades of the 20th century, in the context of Soviet planning and the New Deal in the United States, that it took centre stage in economics and planning.

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Consider its endless adjectives: national, regional or local development; social, urban, rural or territorial development; participatory and community development, business and corporate development; top-down or bottom-up; human and sustainable development, ethno-development or development with identity, co-development and mutual development, etc.

Although present in planning, institutional and civil discourse, the world of cooperation, etc., it is by no means a consensual category. Throughout the 20th century and so far in the 21st century, there has been discussion not only about how each person understands it, but also a whole series of criticisms of what it actually entails: economic growth at all costs and damage to society and the environment.

After analysing this set of criticisms and classifying the positions into three groups —continuity, reinterpretation, overcoming— the following notion is proposed: «a set of multidimensional and induced/planned change processes which, based on specific techno-economic, infrastructure and connectivity actions: 1) generate wealth and employment and 2) incorporate operational lines of action to improve: a) the quality of life of the population; b) the equitable distribution of goods and services; c) the civic fabric, local democracy and social cohesion; d) the capacity and opportunities of territories, communities and individuals; e) ecological sustainability» (Giménez Romero, 2024).

II. Application to the Aridane Valley after the eruption

This section explains what this approach implies in terms of local, territorial and participatory development actions, referring to the reality of the Aridane Valley, its historical background, structural characteristics and post-eruption situation.

These references to the western region of the island do not constitute a detailed description —which is already covered in other contributions— but rather some key data and examples, based mainly on the work and contributions of the Revivir el Valle project, promoted by the University of La Laguna together with the Cabildo de La Palma, as well as a review of publications (García Rodríguez, 2021; Zapata Hernández, 2023; Zapata Hernández & Del Rosario Martín, 2023) and various official reports (CES, 2021; Comisión mixta para la reconstrucción, recuperación y apoyo a la isla de La Palma, 2022; Parlamento de Canarias, 2022; Revivir El Valle, 2021, 2022a, 2022b, 2023).

These points for reflection are organised into the following series of implications:

1) The need to understand and study the processes of change before and after the eruption, taking into account their multidimensional nature and whether or not there is shared knowledge among all stakeholders.

2) Identification of agreements and disagreements regarding the nature, scope and means of induced and planned change and recovery strategies.

3) Specification of priorities in infrastructure, techno-economics and connectivity: those that are de facto priorities and whether or not they correspond to those that are claimed.

4) Examination of the objectives and whether they reflect the different dimensions of development, whether they have been formulated in a participatory manner and whether three frequent errors studied in development sociology and anthropology have been avoided: over-innovation, social under-design and socio-cultural incompatibility of the plan.

5) With regard to the generation of wealth and employment, analyse why and how it will generate improvements both for the local population and beyond the territory, specifying: a) quality of life of the population; b) equitable distribution of goods and services; c) strengthening of the civic fabric, local democracy and social cohesion; d) increase in the capacities and opportunities of the territory, municipalities, communities and individuals; and e) ecological sustainability.

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CONTRIBUTIONS

Topic 1

Physical volcanology

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POST-ERUPTIVE SUBSIDENCE OF TAJOGAITE: QUANTIFYING THE ROLE OF COMPACTION IN VOLCANICLASTIC CLASTIC MATERIALS

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Abstract

The 2021 Tajogaite eruption has deposited large volumes of lava and tephra on the western flank of La Palma. Satellite geodetic and in-situ data show that many of these deposits are subject to subsidence. Concentric fractures around the craters have increased in number and existing fractures have widened in the 4 years since the end of the eruption, supporting a considerable volume reduction within the cone. While the effects of cooling contraction in lavas are well-known, mechanical compaction of unconsolidated volcaniclastic materials (ash, lapilli, bombs) are poorly quantified. The proximal spattercone of Tajogaite consists largely of volcaniclastics and therefore presents an ideal site to investigate the magnitudes and timescales of compaction-induced post-eruptive subsidence. We present high-resolution UAS-derived surface models of the cone, tracking morphological evolution, structural changes and quantifying surface subsidence. We find that some parts of the cone have subsided for more than 10 m in the first two years since the end of the eruption (from January 2022). We compare subsidence measurements from Tajogaite to laboratory compaction experiments of volcaniclastic materials, where compaction is experimentally induced via a uniaxial press of cup-confined samples and the measured deformation is scaled to field size. Preliminary results suggest that surface subsidence on the order of a few meters can be expected from mechanical clast compaction within a few weeks to months. These results showcase the significance of compaction in post-eruptive volcano deformation. We will further quantify the changes in frictional properties and shear strength of volcaniclastic lithologies under compaction conditions, enabling a better understanding of the evolution of volcano slope stability and potentially catastrophic collapse events.

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STRATIGRAPHIC COLUMNS FROM BOREHOLES IN LA PALMA LAVA FLOWS (LP-213)

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Ana Castro[1], David Sanz-Mangas[1], Inés Galindo[1]

Abstract

The 2021 Cumbre Vieja volcanic eruption on La Palma generated an extensive and complex lava flow field, fundamentally reshaping the island's landscape. A comprehensive understanding of its internal structure is crucial not only for reconstructing its geological evolution but also for assessing geotechnical properties essential for future infrastructure development and hazard management. This study presents the detailed stratigraphic columns obtained from a series of mechanical boreholes. These boreholes were strategically drilled along the route of the new LP-213 road (Fig. 1), a vital infrastructure project connecting the neighbourhoods of La Laguna and Las Norias, directly traversing the recently emplaced volcanic material (García-Davalillo *et al.*, 2024). A total of 17 boreholes were drilled specifically for this investigation, conducted over an approximate nine-month period, between 25 July 2022 and 20 April 2023. These boreholes ranged significantly in depth, from a shallow 3 metres to a maximum of 23.5 metres, allowing for a substantial vertical sampling of the lava field. The depth of investigation was limited by extreme working conditions, primarily due to high temperatures. To ensure comprehensive characterisation of the subsurface materials, six of these boreholes were executed with continuous core recovery. This method provided intact rock samples, allowing for detailed direct analysis of lithological variations, textures, and structural features. The remaining eleven boreholes were conducted using destructive drilling techniques, which, while not yielding core samples, effectively complemented the dataset by providing information on the broader lithological variability and internal structures of the lava flows across a wider spatial extent. The meticulous reconstruction of these stratigraphic columns offers invaluable insight into several key aspects of the lava field. They clearly delineate the internal structure of the flows, reveal instances of flow superposition, highlight the presence of lava tubes, and illustrate the tex-

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tural and compositional variations within the different lava units. This robust dataset is not merely academic; it is essential for understanding the complex emplacement and cooling processes of these recent volcanic deposits. Moreover, this information is critical for planning future infrastructure interventions, such as road construction and utility routing, and for guiding recovery efforts in the areas significantly affected by the eruption, ensuring long-term safety and resilience.

Fig. 1. Borehole drilling machine after operation in LP-213 road

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PRELIMINARY RESULTS OF THE SAN BERNARDINO FUMAROLES: IMPLICATIONS FOR TAJOGAITE ERUPTIVE BEHAVIOUR AND VEGETATION RECOVERY

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Abstract

This study investigates localized gas and thermal anomalies in the San Bernardino volcano area, southeast of the Tajogaite volcano. In September 2024, environmental rangers reported unexplained drying of pine trees in the area, prompting field surveys in early October 2024 and May 2025. Fumaroles in the area were reported during the eruption and these surveys confirmed that they remained active. Gas emissions seems to be primarily water vapor, with negligible content of volcanic gases. However, geochemical sampling and analysis are needed to characterize the detailed composition. Soil radon (Rn) values in the area showed relatively high levels (^{222}Rn>5,000 Bq/m^3; ^{220}Rn>15,000 Bq/m^3). Fumarole temperatures range from 45.7 °C to 50.6 °C. Most fumaroles located along a small ravine's northern margin showing an ENE-WSW alignment. Others were at the Bernardino volcano's crater rim. The thermal anomalies might be related with the shallow feeding system of the Tajogaite volcano that heats meteoric waters or groundwaters from a perched aquifer. Water vapor rise through high-permeability zones like the San Bernardino crater rim or fractures resulting in fumaroles. The westward extension of this fracture zone reaches Tajogaite volcano's upper vents, which exhibited phreatomagmatic episodes during the eruption. This suggest that the fracture zone probably played a crucial role enhancing water-magma interaction during the eruption.

Regarding vegetation impact, the area shows many dry pine trees (*Pinus canariensis*) (Fig. 1), in contrast with the surrounding forest that is actively

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recovering from the ash fallout and gases of the 2021 eruption. The deep root system of the Canary Pines makes them particularly vulnerable to subterranean heat. Some affected trunks were dry and broken at the base.

However, younger pines and the undergrowth seem to be recovering more effectively and, at the fumaroles, there is abundant vegetation, including lichens and flower plants. This growth might be primarily fostered by the high-water content derived from steam emissions and thermal anomalies. This finding highlights how the volcanic system's structural permeability creates microclimatic contrasts that controls local vegetation's resilience and distribution.

Fig. 1. Fumarole in the San Bernardino volcano area. Note the dry pine tree behind and the proliferation of small vegetation associated to the fumarole

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LAVA DELTA EVOLUTION DURING THE 2021 TAJOGAITE VOLCANO ERUPTION

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Abstract

The 2021 eruption of the Tajogaite volcano on La Palma Island led to the formation of two significant lava deltas as lava flows reached the sea, favoured by the slope of the western side of Cumbre Vieja. The first delta (south) began to form 10 days after the eruption, when lava flows cascaded down an approximately 85 m-high cliff. It evolved through several growth phases, remaining active until the end of the eruption and beyond, as lava-flow continued discharging from lava tube drainages. It covered an area of approximately 88 ha, overlying part of a pre-existing delta from the 1949 San Juan eruption. The second delta (north), smaller in size, formed 64 days into the eruption, 1.3 km north of the first. It expanded to cover an area of 5 ha in just 4 days. Digital elevation models and drone observations were fundamental in documenting the morphological evolution of deltas. These tools allowed researchers to analyse topographic profiles, revealing the growth processes and structural characteristics of lava delta formation in oceanic islands. Moreover, fumarolic activity observed on the delta surface after the eruption, suggests the presence of lava tubes beneath the surface associated with the delta's formation. During the eruption, the interaction of lava with seawater (Fig. 1) was sometimes explosive, generating gas clouds and scattered hyaloclastites deposits over surrounding areas (González-Vega *et al*., 2024), influenced by wind conditions and forcing people to evacuate. These findings underscore the scientific importance of studying lava deltas for volcanic hazard assessment and the need for preserving them as part of La Palma's geological heritage.

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Fig. 1. Formation of the northern lava delta, producing a gas plume potentially loaded with hyaloclastites on 22th November of 2021 (image acquired using the IGME drone).

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LAVA MORPHOLOGICAL TYPES ALONG THE TAJOGAITE LAVA FLOW FIELD

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Abstract

The 2021 Tajogaite eruption on La Palma generated a complex lava flow field that covers approximately 1,175 km^2 and extends up to 6 km from the main cone to the coastline. The eruption culminated in the formation of two prominent lava deltas, contributing 88 ha of new land to the island (Sáez-Gabarrón *et al*., 2024). This study presents a typological characterization of the lava flow morphologies to better understand both the newly formed terrain and the eruptive dynamics that produce it.

The Tajogaite lava flow field exhibits a wide variety of effusive morphologies:

1. ʻAʻā lavas: These are the dominant type, typically less than 3 metres thick, forming broad channels tens of metres wide. Their rubbly texture includes diverse clasts, such as accretionary lava balls and anthropogenic lithics. Minor ʻaʻā-blocky lavas, which can contain large erratic blocks, are also present.
2. Pāhoehoe lavas: Prevalent in lower-lying central areas, these result from short, thin advances from individual front-lobes, forming narrow channels that accumulate into thicker units. They are often highly vesiculated and associated with eccentric vents (Sanz-Mangas *et al*., 2024), tumuli, and lava tubes (Sanz-Mangas *et al*., 2023), displaying textures like ropy or sharkskin.
3. Blocky lavas: Scarce but significantly thick (up to 10 metres), these are rich in megablocks, mainly from cone-flank collapses. They dominate the southern sector and cone margins, forming the widest channels, and show stratification with overlying squeeze-out structures.

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4. Pillow lavas: Found in the lava deltas at depths around 50 metres, these adapted to seabed morphology within submarine canyons. They are up to 4.5 metres in diameter and 5.2 metres long, displaying typical «Tortoise Shell» structures and transverse fracturing.

Although largely continuous, the lava flow field notably includes over 150 kipukas, untouched land areas surrounded by new lava, ranging from a few to thousands of square metres, providing unique insights into pre-eruption topography.

This morphological analysis provides crucial insights into the eruption's effusive processes, lava rheology, and interactions with the pre-existing topography. Understanding these diverse forms is essential for volcano hazard assessment, modelling, reconstruction efforts, hydrological studies, and ecological recovery in this complex volcanic landscape.

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LAVA VISCOSITIES DURING THE 2021 TAJOGAITE ERUPTION

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ABSTRACT

Magma viscosity is a major factor controlling volcanic eruptions and lava runout distances. An accurate characterization at a given volcano or volcanic field is therefore fundamental for realistic forecasting of the impact of ongoing or future volcanic events. We have evaluated the potential viscosity at the vent of effusive lavas emitted during the 2021 Tajogaite eruption by employing the numerical models by Giordano *et al*. (2008) and Maron *et al*. (1956), and melt compositions derived from glass in tephra compositions reported in Castro & Feisel (2022). Lava viscosity was estimated by initially calculating dry melt viscosity and subsequently considering the effect of water in melt and of the crystal cargo in lava. The low end of lava viscosities was first estimated. At 1150 °C (high end of the likely eruption temperatures) dry melt viscosities are 142-212 Pa·s. At this temperature, water in the melt reduces viscosity by a factor of 1.5 at 0.1 wt. % H_2O (maximum water content at surface pressures), resulting in viscosities of 97-145 Pa·s. If the effect of crystal content on effective viscosity is then calculated —using a maximum packing fraction of 0.62—, estimated lava viscosities increase by a factor of 1.7 at 15 vol. % crystals (minimum value for the effusive lavas at the vent), resulting in effective lava viscosities of 168-253 Pa·s. The most likely characteristics

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of effusive lavas at the vent during the Tajogaite eruption were estimated considering a melt based on glass in sample T1-3 of Castro & Feisel (2022), at 1140 °C, 0.085 wt. % H_2O in the melt, and 20 vol. % crystal content. This calculation results in a lava effective viscosity of 400 Pa·s, which is similar to other oceanic island basaltic eruptions. For instance, it overlaps the range of viscosities estimated for the 2018 flank eruption of Kilauea (250-1150 Pa·s) (Gansecki *et al*., 2019).

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SHATTER RING EVOLUTION IN LA PALMA 2021 ERUPTION AND LAVA TUBE DEVELOPMENT

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ABSTRACT

The most recent eruption on La Palma occurred in 2021, lasting 85 days and 8 hours. It resulted in the construction of the Tajogaite volcano, a pyroclastic edifice approximately 185 m high and 900 m wide at its base, with eruptive vents aligned along a NW-SE structural orientation. The evolution of the lava flow field, erupted from the base of the Tajogaite cone, was characterized by the emplacement of channel-fed arterial flows that constructed a complex lava flow field on the western flank of the Cumbre Vieja rift incorporating an extensive network of lava tubes (Sanz-Mangas *et al*., 2024; Calvari *et al*., 2025). As observed during effusive eruptions of Mount Etna (Kilburn & Lopes, 1988), variation in magma supply rate at the vents, obstructions within lava tubes, overflows or the opening of ephemeral vent can induce pressure fluctuations within the tubes system, leading to the formation of structures such as tumuli, skylights and shatter rings. Shatter rings are circular to elliptical surface features observed on lava flow field at several worldwide volcanoes, including Hallmundarhraun in Iceland, Fogo in Cape Verde, Kilauea in Hawaii or Etna in Italy (Orr, 2011; Calvari *et al*., 2024). On La Palma island, a shatter ring developed during November 2021 (Fig. 1), starting as a stacked lava flow that evolved from a ~30 m-width channel to a <10 m-width lava tube in less than 5 days. The shatter ring structure formation was favored by the previous channel-shaped topography and by the variable discharge rate during that period which promoted the development of a lava pond (Calvari *et al*., 2025).

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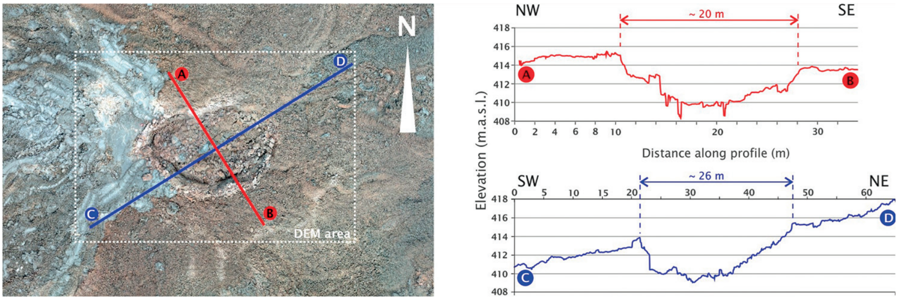

Fig. 1. Shatter ring photogrammetric image with NW-SE and NE-SW topographic profiles

The cycles of overpressure within the lava tube produced first an uplift whilst later drainage caused subsidence of the roof that eventually lead to the formation of a shatter ring comprising brecciated basalt forming the outer ring. The shatter ring was active for several days intermittently discharging pâhoehoe lava flows downslope. The shatter ring facilitated the transport of lava far from the main eruptive fissure, increasing the volcanic risk of lava flood.

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LAVA TUBES AND ASSOCIATED GEOMORPHOLOGICAL STRUCTURES IN THE TAJOGAITE LAVA FLOW FIELD

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Abstract

On 19 September 2021 the Tajogaite volcano erupted on the western flank of the Cumbre Vieja ridge (La Palma) with multiple vents emitting lava flows that advanced toward the western side of the island covering a distance of 700 m in less than one hour. The dense rock equivalent (DRE) (Harris *et al*., 2007) was estimated in more than 240 m^3 of material (Calvari *et al*., 2025) with lava temperatures ranging between 1125 and 1140°C. The flows predominantly affected urbanized areas. Four distinct lava flow morphologies were identified in the field: ‘a’ā, pāhoehoe, ‘a’ā - blocky and blocky. Preliminary results allowed us to evaluate the lava flow invasion hazard which was enhanced by the continuous evolution of volcanic dynamics and the development of lava tubes. Processes such as lava channel overflows leading to levee growth, upwelling lava in skylights or inflation-deflation cycles of the forming lava tube roofs were observed during the eruption (Sanz-Mangas *et al*., 2024) (Fig. 1). Fieldwork conducted after the eruption led to the identification of over 150 structures including narrow channels, lava breakouts, hornitos, tumuli, collapses, degassing vents with fumarolic activity, lava tube drainages and skylights (Sanz-Mangas *et al*., 2025). Moreover, complex distributary features such as shatter rings and tumuli-like structures related with the lava tubes have been found. These structures favored lava flows discharges at high temperature far from the Tajogaite cinder cone, increasing the risk of new breakouts along the

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margins of the lava flow field. The associated geomorphological features are still visible on the lava field surface, indicating the presence of lava tubes. Only a small portion of these tubes has been explored, as most remain inaccessible due to internal temperatures exceeding 200ºC.

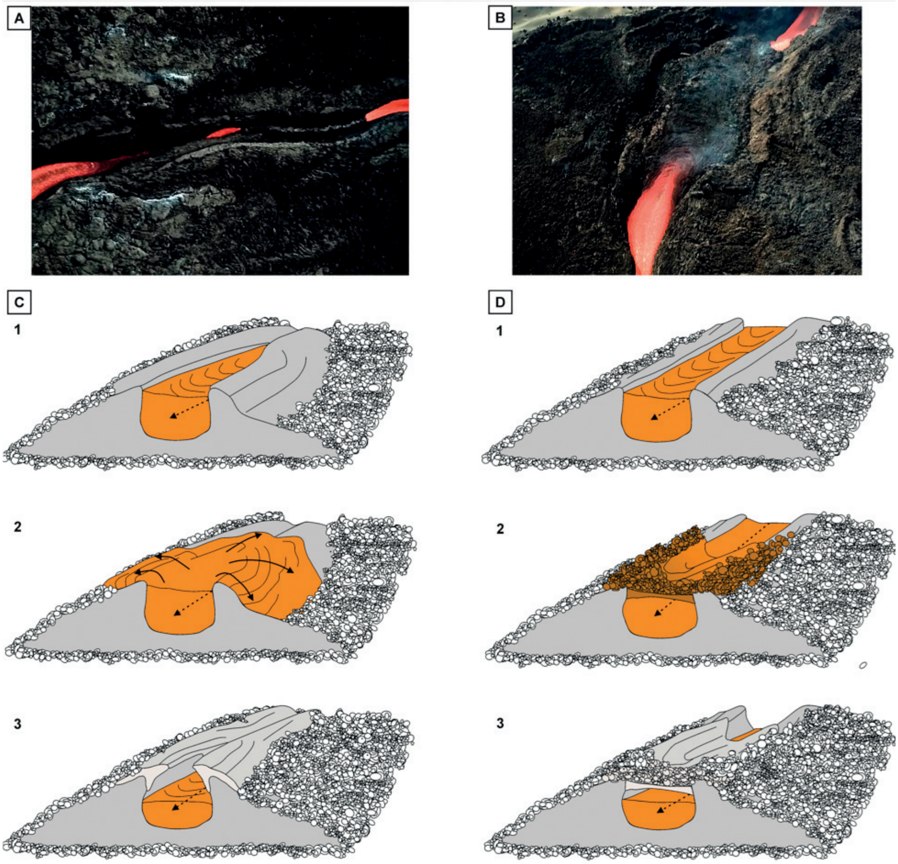

Fig. 1. RPA images and conceptual schemes showing lava tube formation during the 2021 eruption at La Palma island. A: Type 1 section, showing the formation of a stable crust along an active lava channel during unsteady flow. B: Steady lava flowage forming a cool roof developed during the advance of a lava flow due the surface cooling and later emptying of the lava tube. C: Stages of unsteady lava flowage within the channel building up a tube roof by (1) flowing within the channel, (2) overflowing during lava surges, and (3) draining during lava waning. D: Steady lava flowage within a channel forming a stable crust by (1) sustained flowage within the channel, (2) roofing and crusting over by ‘a’ā rubble accumulation, and (3) drainage of the channel leaving a lava tube cave with a stable roof.

The entire cumulated length of each identified lava tube system may exceed 17 km beneath the surface. Assessment of geological hazard for possible collapses of the affected zone and geo-heritage evaluation highlight the fragility and scientific value of these features and the need of establishing an organized protection.

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EMPLACEMENT AND GROWTH OF A TUBE-FED COMPLEX LAVA FLOW FIELD AT TAJOGAITE VOLCANO

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Abstract

After 50 years of latent activity, the Cumbre Vieja volcano erupted on 19 September 2021. The eruptive fissure opened on the western side of the Cumbre Vieja rift in the half south of the island producing explosive and effusive activity that lasted until 13 December (Birbaum *et al*., 2023). A new cinder cone built up, named Tajogaite, which discharged from its base a low viscosity and high temperature tephrite-basanite magma (Ubide *et al*., 2023) forming a complex lava flow field with several lava flows and lava tube pathways. The eruption emitted ~200 Mm^3 of lava and ~45 Mm^3 of tephra that covered more than 12 km^2 of surface comprising buildings and farmland (Copernicus, 2021; D'Auria *et al*., 2022; De Luca *et al*., 2022). This work presents an account of the lava flow field expansion and lava tube development using images gathered during and after the eruption from satellite and fieldwork. Combining daily time-averaged discharge rates (TADR) with the development of the lava flows and the growth of lava tubes, we have reconstructed the processes of lava tube formation and the speed of lava tube growth. During the initial phase of the eruption the lava flow field was characterized by the emplacement of four arterial 'a'â lava flows that expanded in a caterpillar-like motion, alternating slowing down and inflation of the lava flow front and lava overflows along the proximal lava channel with fast spreading of the inflated lava flow front and proximal lava channel drainage. In early November the decrease in TADR resulted in the emplacement of mainly pâhoehoe lava flows in the central part of the lava flow field that resulted in a very

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braided and well-developed lava tube system. We have reconstructed the extent and timing of the complex lava tube systems (Fig. 1) in order to provide information useful for hazard assessment during future eruptions at Cumbre Vieja and analogous volcanoes.

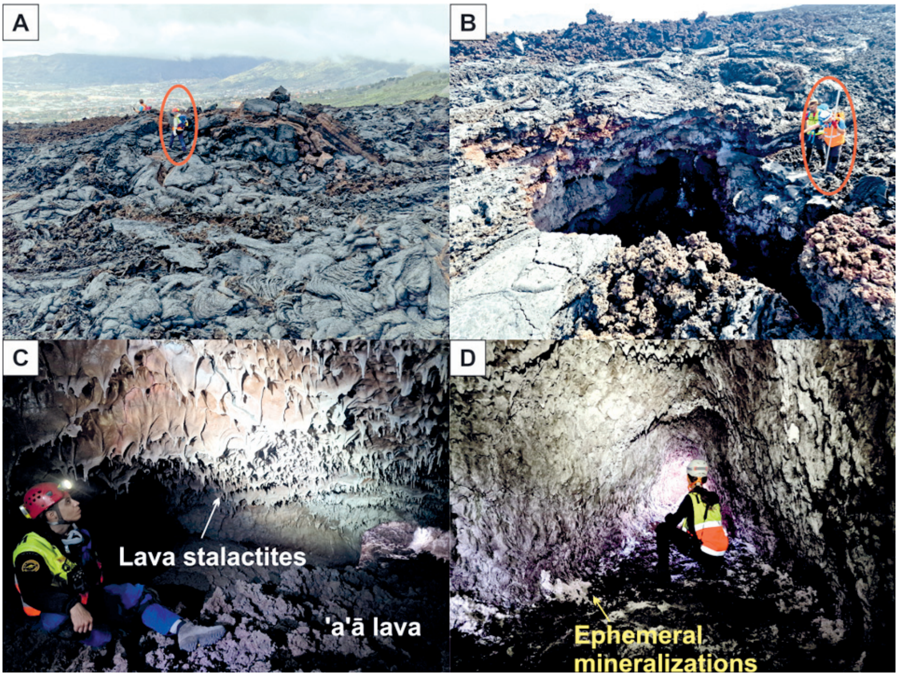

Fig. 1. Photos taken during the field surveys, showing: (A) image from the south of a tumuli-like structure with pāhoehoe lava flow morphologies and ropy texture, located in the mid-northern part of the lava flow field; (B) skylight cutting pāhoehoe flows and offering access to the lava tube cave underneath close by to a new road; (C) inside of a lava tube cave located in the central part of the lava flow field and developed during mid-Nov. with stalactites on the roof and ʻaʻā rubble on the floor; (D) superficial lava tube cave formed during the end of Nov. with ephemeral mineralization on the wall, lava stalactites on the ceiling and multiple coatings (above the person). The person in the images is less than 1.8 m high, and is marked with the red oval in A and B.

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TAJOGAITE ERUPTION HYALOCLASTITES STUDIES FROM GEOCHEMICAL ANALYSIS: SEA-WATER INTERACTION INSIGHTS

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Javier Martínez-Martínez[1], José F. Mediato[1], Inés Galindo[1]

Abstract

The eruption of La Palma began to develop a cinder cone since the first day of eruption emitting between 215 to 240 Mm^3 of volcanic materials, forming a pyroclastic cone, an extensive ash deposit of variable thickness across the island and a lava flow field (Copernicus, 2021; Mediato *et al*., 2023; Calvari *et al*., 2025). Previous studies on volcanoclastic deposits (Mediato *et al*., 2023) identified tephra particles composed mainly by lithics, tachylites, sideromelane and crystals (Mata *et al*., 2022). The Volcanic Explosivity Index (VEI) was a total of 3, with violent explosive Strombolian activity (PEVOLCA 25/12/2021). Monitoring assessment for this eruption presented a methodological challenge to the scientific Spanish community. The formation of a lava delta showed lava-sea interaction forming a significant steam column. Observations from the delta progression showed explosive activity that was confirmed as hydromagmatic activity, forming hyaloclastites particles that were transported 1.5 km onshore (Coello *et al*., 2024). On November 11, samples of hyaloclastites produced by the lava-sea interaction at the lava delta and transported by the steam plume were collected. The deposit was sampled using sediment traps, avoiding contact with the substrate and potential contamination from previous pyroclastic deposits. Pyroclastic deposits sampled show a majority population of gray-black tachylite-type particles very homogeneous in size, identified as hyaloclastites (Fig. 1). Morphometric studies via digital images analysis (DIA) on stereomicroscope images show diameters with mean of 450 to 637 μm in diameter. Hyaloclastites exhibit uniform grain size distribution. Scanning electron microscopy on studies allows to identify phenocrysts of plagioclases, pyroxene, amphibole and iron oxides with variable titanium content. On the surface, sodium chloride and calcium carbonates and

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sulfates are observed. This study shows some significantly different characteristics if we compare them with aerial ash populations from the Tajogaite eruption, probably due to the interaction with the sea water. Potential health harm of the hyaloclastites released to the atmosphere by accidental ingestion makes imperative the study of these types of particles.

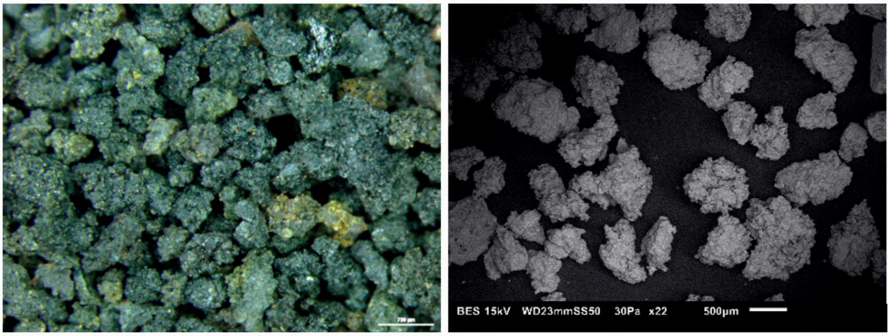

Fig. 1. Right image showing photomicrographs showing hialoclastites studied, under Leica stereomicroscope and left image sample of selected hialoclastites done with scanning electron microscope (Jeol JSM 6010 PLUS/La) backscatter.

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ERUPTIVE DYNAMICS OF THE 2021 TAJOGAITE ERUPTION (LA PALMA, CANARY ISLANDS) AS REVEALED BY THE PHYSICAL AND TEXTURAL CHARACTERIZATION OF TEPHRA

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Abstract

Hybrid eruptions are characterized by mixed effusive-explosive behavior and are often difficult to classify due to their complex, variable dynamics. During these events, several magmatic and conduit parameters can change, producing a wide range of juvenile material having different physical, morphological, textural, and compositional characteristics. The 2021 Tajogaite eruption on La Palma lasted for about 86 days and the eruptive activity comprised effusive activity from the base of the newly-formed cone as well as contemporaneous explosive activity from the summit vents. In this contribution, we present a multidisciplinary study of the associated tephra sequence, investigating the spatial and temporal variability of the juvenile material. The main results can be summarized as follows: (i) four main groups of juvenile fragments distributed with different proportions along the stratigraphic sequence were identified, that show wide variations in terms of morphology, vesicularity and and glass matrix composition; (ii) the three main stratigraphic units, previously identified by Bonadonna *et al*. (2022), were correlated with three main eruptive phases. The high intensity Phase I contains highly vesicular clasts of irregular to spongy morphology showing a wide range in vesicularity (~ 55-68 %), while volume-normalised vesicle numbers N_V^m show limited variability (11.4-16.6×10^6 cm^{-3}). The subsequent Phase II marks an overall decrease in

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eruption intensity towards more intermittent activity. The associated juvenile material shows a lower vesicularity with a narrow range between 60.3 and 61.2 %, while N_V^m are more variable with values between 14.6 and 42.0 × 10^6 cm^{-3}. Finally, Phase III was marked by a new increase in eruption intensity with clasts that show high N_V^m values (24-85.2 × 10^6 cm^{-3}), ~ 60 % of vesicularity and predominantly variable morphology

(Fig. 1a, b); (iii) tephra clasts are compositionally grouped in the tephrite-basanite field, with a decreasing degree of magma evolution as the eruption progressed but during which observed variations could be associated with repeated (more primitive) magmatic inputs that fuelled the eruption over time

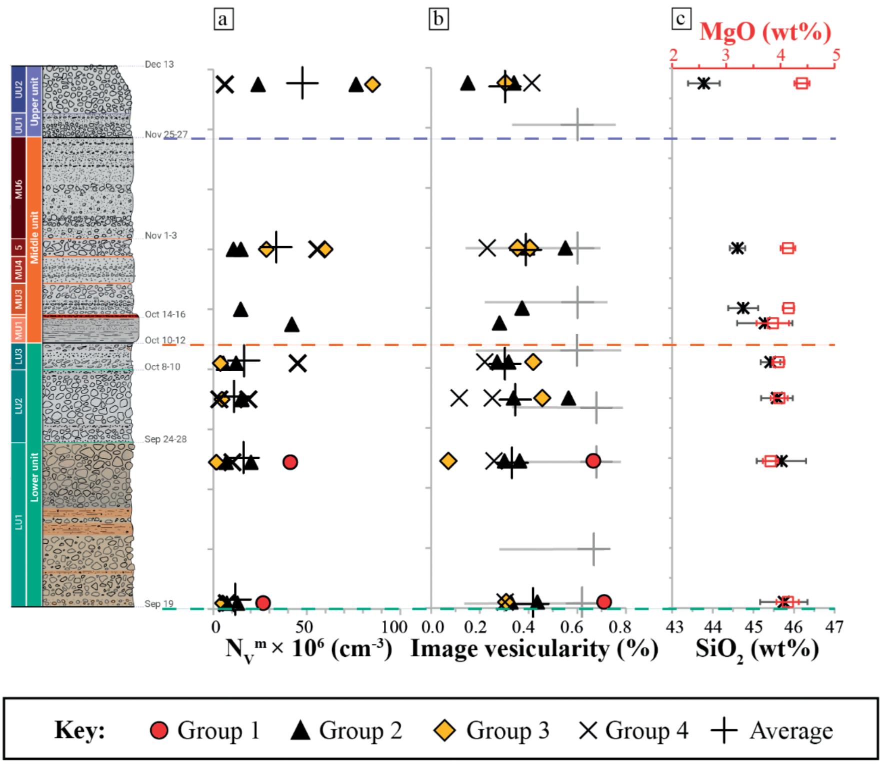

Fig. 1. (a) N_V^m, number of bubbles per unit volume (cm^{-3}) for different componentry groups; layer average indicated by a plus sign. (b) Image vesicularity (%) for the same groups; layer average is marked by plus sign. Vesicularity from density analysis is shown in grey: the primary mode is marked by plus signs, while the distribution range is marked by the grey line. (c) SiO_2 and MgO compositions of analyzed clasts in each layer and sublayer, marked by black stars and red squares, respectively. From Da Mommio *et al*. (2025)

(Fig. 1c). The variability of juvenile material, both along the stratigraphic sequence and within individual layers, provided crucial information on degassing, fragmentation, and crystallization of magma during pre-eruptive ascent and within the conduit.

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VOLCANOLOGICAL SIMILARITIES OF OCEANIC VOLCANIC ISLANDS AND MATURE VOLCANIC FIELDS IN INTRACONTINENTAL SETTINGS

KÁROLY NÉMETH*

ABSTRACT

Small-volume volcanoes commonly form dispersed volcanic fields within intracontinental environments (Németh & Kereszturi, 2015). Volcanic fields in continental regions such as those in western Arabia (Fig. 1) are often related to large-scale geotectonic elements, particularly rifting events that create conditions conducive to the ascent of magma and the formation of small, typically monogenetic, volcanoes at the surface. In oceanic intraplate settings, volcanic systems are often linked to persistent melt sources within a structurally regulated network of vents, also frequently associated with rifting. This stable melting anomaly and elevated magma flux rate may lead to the development of amalgamated volcanic systems characterised by lava shields with vents aligned along primary structural trends. Such patterns are observed on volcanic islands near subduction zones, including mafic arc volcanoes like those in the Vanuatu Volcanic Arc, such Ambrym, and ocean island basalt-dominated lava shields such as those found in Samoa in the southwest Pacific. Most of these volcanic systems exhibit predominantly mafic volcanism with largely effusive and moderately explosive eruptions. Over geological timescales, some islands develop into mature magmatic systems capable of producing highly evolved and explosive, often alkaline, volcanic eruptions. These evolutionary trends show notable similarities to mature distributed volcanic systems present within continental plates. In Saudi Arabia, intracontinental volcanism has produced at least 19 volcanic fields since the Miocene (Németh & Moufti, 2024). The most mature volcanic fields exhibit dome-shaped, shield-like lava-dominated volcanic systems fed by vents distributed within aligned zones, along with defined centres at silicic volcanic systems such as northern Harrat Rahat or Khaybar in central dispersed volcanic regions.

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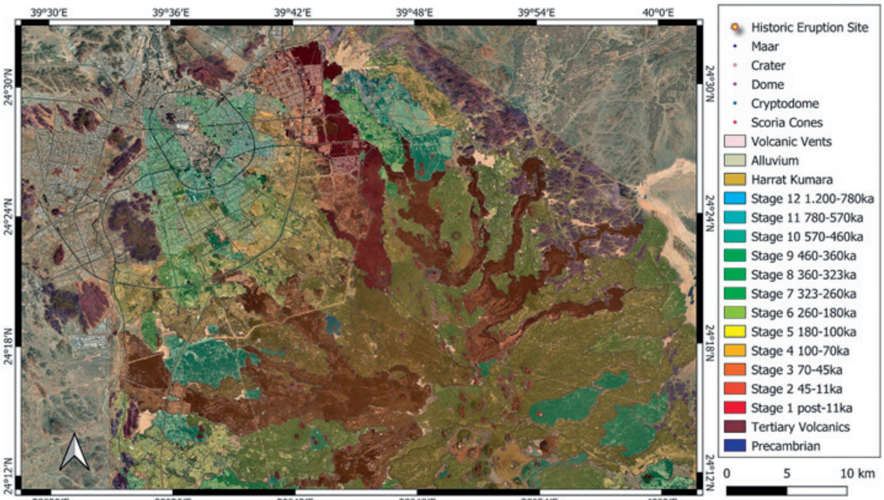

Fig. 1. Geological map of northern Harrat Rahat near Al Madinah (Downs *et al*., 2023). The mapped area documents around 1.1 million years of eruptive history, with lava flows forming a ridge about 500 meters high. Eruptions occurred roughly every thousand years, each producing about 0.1 km³ of dense rock. Older stages record fewer events as details are lost over time. In the highest ground, the field formed young silicic (trachytic, but still monogenetic style volcanoes with lava dome, block-and-ash fans, and collapsed craters visible as light-coloured region in the bottom right corner of the image.

Within these areas, trachytic lava domes, tuff rings, and block-and-ash shields create differentiated volcanic zones, displaying volcanic hazards commonly found in both monogenetic and polygenetic systems in oceanic and continental environments. These shield-like volcanoes, corresponding to elevated magma flux stages, continuously emit lava, a behaviour comparable to that observed in oceanic lava shields (such as those in the Canary Islands), but typically do not develop into systems of similar size or definition.

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AGE-CLUSTERED ERUPTIVE ACTIVITY AT LA PALMA (CANARY ISLANDS) DURING THE LAST 4000 YEARS: EVIDENCE FROM PALEOMAGNETIC DATING

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Abstract

The detailed knowledge of timing and dynamics of pre-historic eruptions is pivotal for volcanic hazard assessment (Speranza *et al*., 2006). This is most relevant for inhabited lower slopes of active basaltic volcanoes such as La Palma (Canary Islands), where the 2021 Tajogaite eruption caused severe destruction. We paleomagnetically investigated eight La Palma Holocene eruptions which are currently loosely constrained either by few radiometric (K/Ar and 14C), ages (Soler *et al*., 1984; Carracedo *et al*., 2001), or by stratigraphic/archaeological evidence. The paleomagnetic directions gathered from 28 sites (300 oriented cores) were compared with updated reference models of the paleo-secular variation of the geomagnetic field direction during the Holocene (Pavón-Carrasco *et al*., 2014). Overlapping paleomagnetic directions from the Fuego and La Fajana lava flows, along with geologic and geochemical evidence, imply that the two flows were emplaced during the same eruptive event falling within the 2000-1730 BC time window. Single paleomagnetic age windows —consistent with and narrower than available 14C age intervals— were obtained for the Malforada-Nambroque, Montaña Quemada, and Fuego-La Fajana lava flows. Conversely, the Martín, Birigoyo-La Barquita, and La Caldereta flows yielded multiple age solutions. Moreover, our data show that the flanks of the pre-historic San Antonio scoria cone are almost totally covered by pyroclastic products of the nearby AD 1677 Fuencaliente

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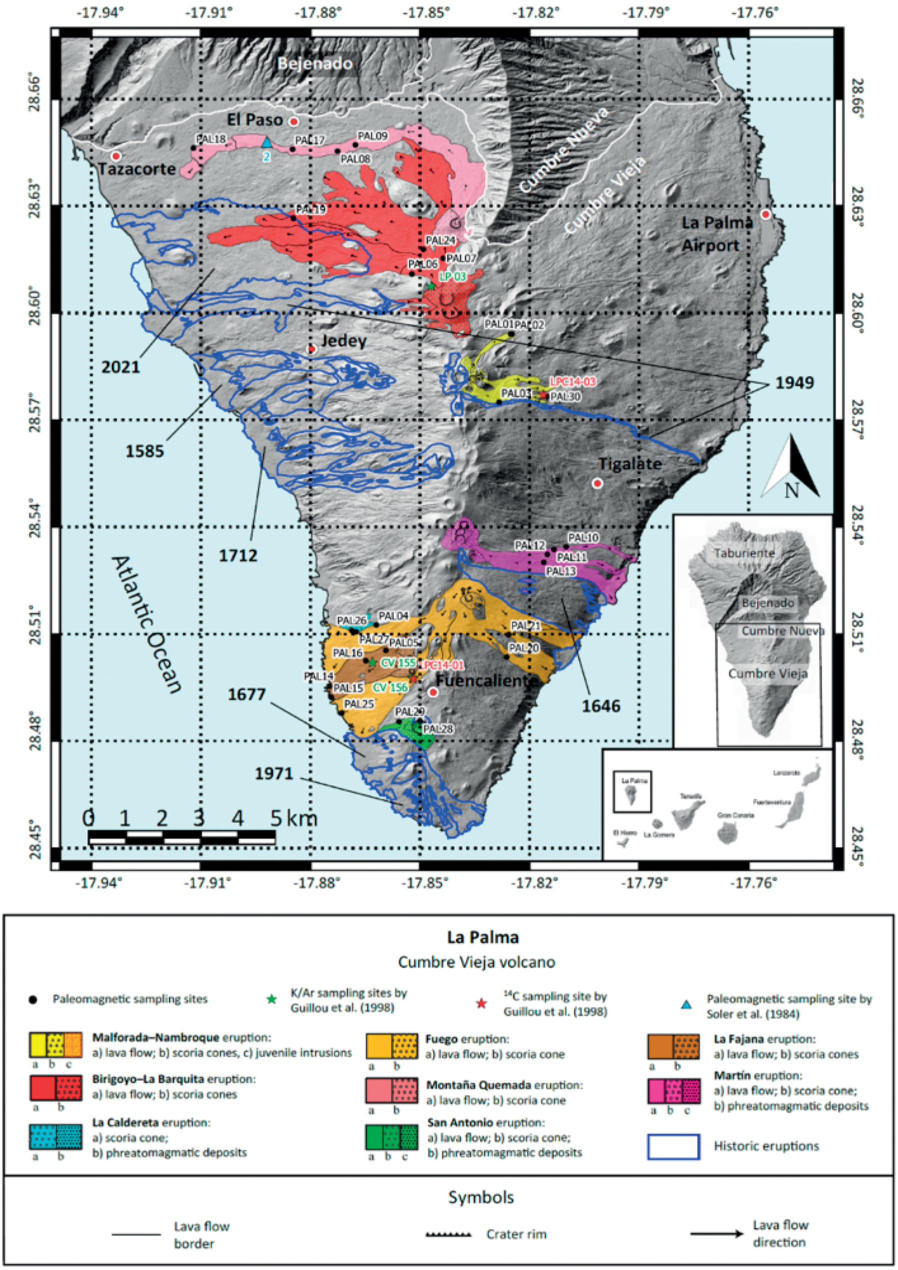

Fig. 1. Simplified map of the Cumbre Vieja volcano, La Palma showing the location of the studied lava flows, paleomagnetic sampling sites from this work (black circles), and the historic eruptions (blue contours)

eruption. The updated chronologic framework of the pre-historic volcanic activity at La Palma demonstrates that the past four kyr are characterized by an early period with low-frequency eruptions (three lava flow eruptions between ca. 2000 BC and 300 BC), followed by a ca. 1000 yr-long quiescence period, and by a subsequent clustering of nine events during the last 1100 yr (about one eruption per century).

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APPLICATION OF GEOSPATIAL TECHNIQUES TO THE MAPPING OF LAVA TUBES FORMED DURING THE CUMBRE VIEJA VOLCANIC ERUPTION (SEPTEMBER-DECEMBER 2021, LA PALMA, SPAIN)

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Abstract

The 2021 eruption is the longest on La Palma since historical records began. The drone flights carried out during the eruption and subsequent work have allowed us to formulate the hypothesis that the largest volcanic tube system in the Canary Islands may have formed on La Palma. To confirm this hypothesis, science will need years of research, initially slowed down by high temperatures and gas emissions, which make access difficult. In order to select the most appropriate technologies for the recording of this vast geological heritage, a multidisciplinary team has begun the exploration of the new lava tubes and their mapping, using geospatial techniques based on terrestrial photogrammetry and LiDAR scans, in a series of field work coordinated by technicians from the Volcanic Speleology Team of the Canary Islands Speleology Federation. This work presents the results of the first topographic surveys of the new cavities (December 2022-March 2024), seeking the greatest resolution and versatility. To achieve this, terrestrial photogrammetry techniques have been used with iPhone Pro equipment, stationary laser scanners (FARO Focus S150) and portable scanners with SLAM technology (Leica BLK2GO). Thanks to the combined use of these technologies, it has been possible to carry

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out the initial 3D mapping of the accessible segments (temperatures below 40 °C) of the new lava tube system. The results obtained are very satisfactory and have allowed different techniques to be tested, which leads to an efficient design of future exploration and mapping work of the new tube system formed after the eruption of 2021 on the island of La Palma.

ACKNOWLEDGEMENTS

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Topic 2

Volcanotectonics

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COMBINING THERMAL, TRI-STEREO OPTICAL AND BI-STATIC INSAR SATELLITE IMAGERY TO ESTIMATE LAVA EFFUSION RATES AND VOLUME OF THE 2021 TAJOGAITE ERUPTION, LA PALMA

Simon Plank[1], Alina V. Shevchenko[2], Pablo d'Angelo[1], Veronika Gstaiger[1], Pablo J. González[3], Simone Cesca[2], Sandro Martinis[1], Thomas R. Walter[2]

Abstract

Up-to-date information on the outline, volume and effusion rate during an effusive volcanic eruption is crucial as it is a major controlling factor of the lava flow lengths, the prospective duration and hence the associated hazards. Here, we present a multi-sensor approach combining thermal and topographic satellite data for estimating lava effusion rates and volume. We investigated the 2021 Tajogaite eruption of Cumbre Vieja (La Palma, Canary Islands) by combining MODIS and VIIRS thermal data-based effusion rate estimates with digital surface model (DSM) analysis derived from bi-static TanDEM-X synthetic aperture radar (SAR) and optical-tri-stereo Pléiades data (Fig. 1). Advantage of this multi-sensor approach is to achieve both, high-frequent observation of the relative short-term effusion rate trends and precise total volume estimates. Our results show a final subaerial lava volume of $212\times10^6 \pm 13\times10^6$ m^3 with a mean output rate (MOR) of 28.8 ± 1.4 m^3/s. The 2021 Tajogaite eruption was characterized by an initially sharp eruption rate peak, followed by a gradually decreasing trend, and interrupted by two short-lived peaks in mid and late November. Comparison with independent seismic observations show a high eruption rate accompanied by weak seismicity during the early stages of the eruption, while during later stages the lava effusion trend coincides with seismicity. We demonstrate that the geophysical monitoring of erup-

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tion rate fluctuations allows us to speculate about changes of an underlying pathway during the 2021 Tajogaite eruption. For more details see Plank *et al*. (2023).

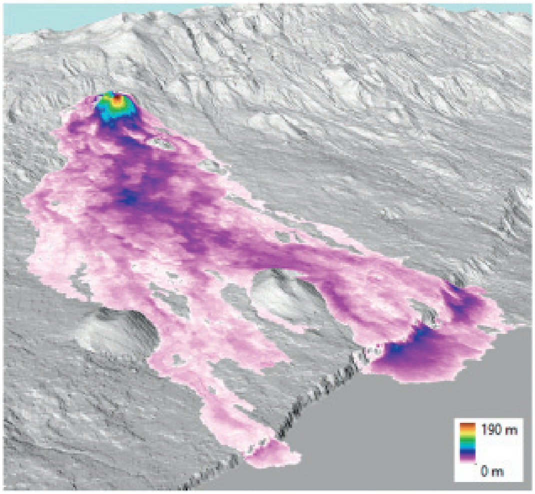

Fig. 1. Lava flow thickness derived from Pléiades tri-stereo data acquired on December 31, 2021. Modified after Plank *et al.* (2023)

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TOPOGRAPHIC INFLUENCE ON TERMINAL TENSILE FRACTURING DURING THE 2021 CUMBRE VIEJA ERUPTION

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Abstract

Volcanic eruptions are frequently preceded by magma intrusion and associated surface deformation, typically manifested as inflation and the propagation of magma along tensile fractures. In this study, we investigate the 2021 Tajogaite-Cumbre Vieja eruption on La Palma, Canary Islands, with a focus on the development of tensile fractures that transected the newly formed cone during the waning phase of the eruption. Utilizing synthetic aperture radar (SAR) data in conjunction with drone-based photogrammetry and time-lapse imagery, we constrain the timing, spatial extent, and structural complexity of a prominent fracturing episode that exhibited divergence at a topographic ridge. By integrating these field observations with scaled analogue experiments, we analyze the formation of lens-shaped tensile fractures typical of fault systems that diverge at topographic highs and converge at lows. Our findings are summarized in Walter *et al*. (2023) and demonstrate that the geometry and evolution of such fracture systems are strongly influenced by local topographic gradients (Fig. 1). These results provide broader insights into how surface topography governs the architecture of subsurface magma pathways, fracture network development, and eruption site localization in volcanic terrains.

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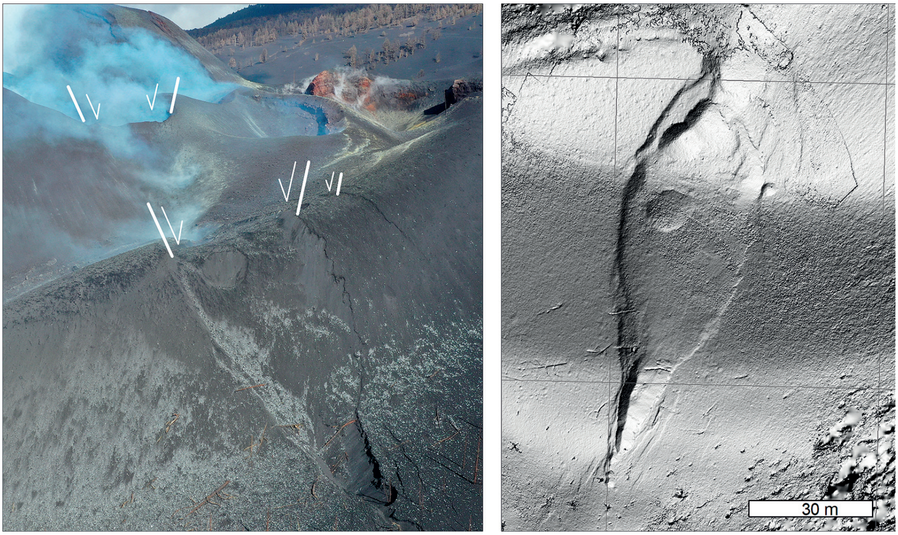

Fig. 1. A divergent graben was established during the late Tajogaite eruption, 2021. Left: Drone image, view to the North. Right: Hillshade map of graben complexity

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SYN-ERUPTIVE DIKING DURING THE 2021 TAJOGAITE ERUPTION, LA PALMA: INSIGHTS INTO MECHANISMS OF LATERAL DIKE PROPAGATION AND LONG-TERM DEFORMATION OF THE WESTERN FLANK OF CUMBRE VIEJA

Mikel Díez[1], Andrew Hogg[1], Robert Constantinescu[2]

Abstract

Accumulating field observations at eroded and active volcanoes reveal that near-surface dike propagation is often lateral, and occasionally even downwards. Dikes resulting from lateral propagation are referred to as blade dikes. A large body of evidence, mostly from Hawaiian and Icelandic volcanic rift zones, reveals that these dikes can be tens of kilometers long and a few kilometers tall, with orientations subparallel to the rift axis. Two conditions are required for their lateral propagation: (*i*) first, a level of neutral buoyancy trapping the dike, and (*ii*) second, the stress intensity at the upper and lower tips of the blade dike is equal to or lower than the fracture toughness of the host-rocks. Lateral propagation is driven by horizontal head gradients caused by lateral variations in dike height and topography, though it is worth noting that some aspects of dike propagation, such as the empirical value of fracture toughness, remain debated. Two months into the 2021 Tajogaite eruption a series of vents, fissures, secondary cracks, and associated small-volume lava flows emerged from the southern tip of the main eruptive fissure. The first set of structures appeared on November 25th, and the second on December 3rd with the last identified vents still active on December 5th (Fig. 1). Here, we describe and analyze these structures, and interpret them as resulting from the downslope lateral propagation and eruption of shallow, blade-like dikes emerging from the main fissure. We investigate their geometrical properties using physical models of dike emplacement and scaling arguments, and find

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them rather short compared to commonly reported lateral dikes. We also estimate a minimum average rate of propagation and, based on mechanical considerations, determine that lateral propagation was driven by topographic gradients.

Finally, we estimate fracture toughness. The orientation of these dikes is unusual —perpendicular to the rift axis— and we explain it as the result of a stress field arising from the coordinated interplay between lateral expansion of the of Cumbre Vieja rift, westward displacement of its western flank, and its anticlockwise bending driven by an underlying overpressured magmatic reservoir.

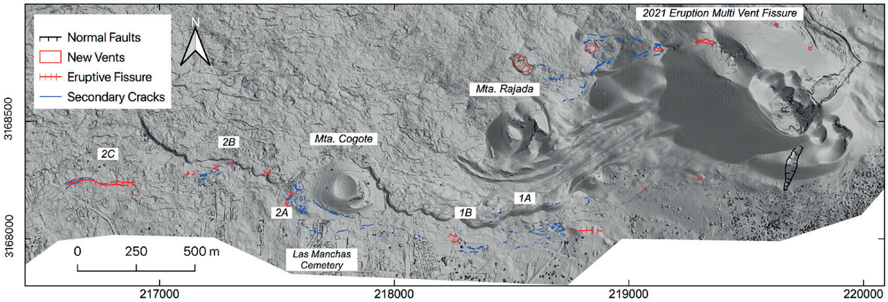

Fig. 1. Digital elevation map of the study area. While volcano-structural features are present at both ends of the 2021 main eruptive fissure, this analysis focuses on those emerging from the southern tip (subsectors 1A, B; 2 A, B, C)

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THE FRACTURE SYSTEM ASSOCIATED WITH THE LATE DISTAL VENTS OF TAJOGAITE ERUPTION

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Benoit Smets[2,3], Thomas R. Walter[4]

Abstract

The eccentric fissure system that emerged during the late phase of the 2021 Tajogaite eruption presented a unique opportunity to investigate ephemeral volcano-tectonic features. Unlike the main eruptive fissure which followed a northwest-southeast orientation, associated with a westerly dipping magmatic dike and the continuation of the 1949 normal faulting system, these later vents exhibited an unexpected orientation and opened at remarkably low magmastatic pressures, often producing extremely short lava flows (González, 2022). To characterize these structures, we integrate high-resolution optical and thermal drone imagery, detailed topographic maps, and advanced image pattern recognition algorithms. Specifically, drone imagery captured at a 2-cm resolution orthomosaic provided an unprecedented level of detail, allowing for the precise mapping of surface expressions of the fracture field that rapidly disappeared due to degradation by later December 2021 (Fig. 1). Integration with other datasets allow for a deeper understanding the relationship between the fractures and the surrounding topography, especially considering the observed complex set of fractures that broke the northeastern flank of the active cone in late November and early December, coinciding with appearance of a graben-like structure (Walter *et al*., 2023). Image pattern recognition algorithms were subsequently applied to analyze the spatial density, branching patterns, and lengths of the fractures, which were fragile as they developed predominantly affecting fresh soft volcanic ash deposits. The puzzling aspect of this late fissure system, including its roughly 100 m width and variable orienta-

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tions of eruptive fissures, underscores the importance of such high-resolution, rapid mapping data acquisition. By documenting and characterizing these ephemeral features, this study aims to contribute to a deeper understanding of complex volcano-tectonic stress fields and their influence on eruptive activity and/or volcano flank instability hazards.

Fig. 1. (Top) 2-cm orthomoscaic of the fracture systems associated with the late distal vent locations (white stars) of Tajogaite eruption. (Bottom) Corresponding interpreted map illustrating fractures (red lines), distal lava flows (dark gray areas), and the location of late distal vents (white stars)

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EVIDENCE OF RECENT TECTONIC ACTIVITY ON THE WESTERN FLANK OF LA PALMA (CANARY ISLANDS, SPAIN)

Ricardo León[1], Luisa Rollwage[2,3], Jacob Geersen[2,4], Olga Sánchez-Guillamón[5], Morelia Urlaub[1,6], Sebastian Krastel[2], Juan-Tomás Vázquez[5]

Abstract

Seafloor mapping was conducted during the MSM113 expedition aboard the R/V Maria S. Merian (January 7-12, 2023). High-resolution multibeam bathymetry and backscatter data were acquired using an EM122 system, focusing on the western submarine slope of La Palma Island, including the Cumbre Vieja volcanic edifice. The surveyed area spans water depths ranging from approximately 1,500 m to 4,200 m. Parametric echosounder data were collected along the multibeam profiles running mostly parallel to seafloor contours. Based on the bathymetric data, two families of lineaments have been identified on the debris avalanche (DA) deposits associated with the Cumbre Nueva and Playa de la Veta flank collapse events (Fig. 1). These lineaments are grouped into two systems: one with a dominant WNW-ESE trend, and a secondary one with a NNE-SSW orientation. In the parametric echosounder profiles acquired from the southern sector of the Cumbre Nueva DA, these lineaments appear to correspond to vertical faults cutting through continuous sub-seafloor reflections. This observation indicates that the faults are younger than the flank collapse event associated with the Cumbre Nueva DA, which has been dated between 125 and 536 ka (Masson *et al*., 2002). Moreover, the identified lineaments are consistent with onshore fault structures in the Cumbre Vieja region, particularly those near Puerto Naos and those related to the eruption of the Tajogaite volcano (Fernández *et al*., 2022; Rodríguez-Pascua *et al*., 2024).

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In this context, we propose that the system of lineaments identified on the Cumbre Nueva DA, along the western flank of La Palma, is associated with a network of deep-seated crustal fractures related to the regional intraplate tectonics of the Nubian Plate (León *et al.*, 2022; Anguita *et al.*, 2025).

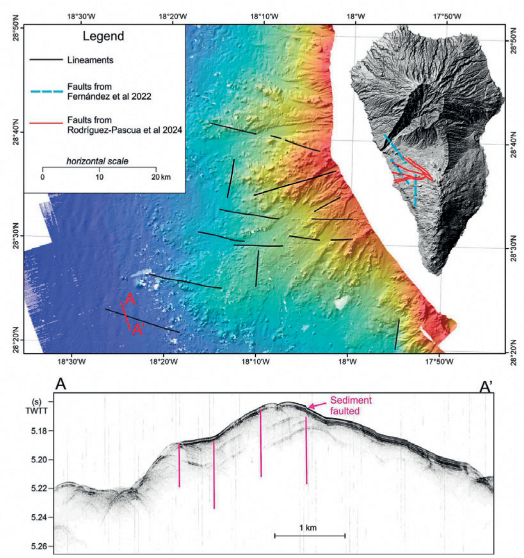

Fig. 1. WNW-ESE and NNE-SSW lineaments interpreted from the multibeam mosaic acquired during the MSM113 expedition aboard the R/V Maria S. Merian (January 7-12, 2023)

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HIGH-DENSITY MHVSR MODEL OF THE TAJOGAITE VOLCANO

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Abstract

As part of the IMAGMA-SEIS project, which aims to investigate the internal structure of La Palma using passive seismic methods following the 2021 eruption of Tajogaite volcano on the Cumbre Vieja ridge, a dense temporary seismic network was deployed near the volcano by the Andalusian Institute of Geophysics. This network consisted of 33 three-component short-period stations installed around the Tajogaite cone and remained in operation from February to October 2024. The stations continuously recorded ambient seismic noise and low-magnitude seismicity in the post-eruptive phase, offering a unique opportunity to study the volcano during its transition back to a dormant state. This deployment enables the use of passive seismic techniques such as the microtremor Horizontal-to-Vertical Spectral Ratio (mHVSR) method. The mHVSR analysis was performed using the *hvsrpy* software (Vantassel, 2024) on all available data per station. To isolate ambient noise from seismic events, contaminated windows were removed following the method of Cox *et al*. (2020), and mHVSR curves were computed hourly to track temporal evolution. For velocity model inversion, the OpenHVSR software was used (Bignardi *et al*., 2016). Results show stable mHVSR curves throughout the recording period, and average curves were used for model characterization. Resonance frequencies exhibit a clear spatial gradient, ranging from ~20 Hz in distal areas to ~2 Hz near the volcanic cone. This pattern is attributed to the greater accumulation of volcanic ejecta near the cone, enabling estimations of sediment thickness. Moreover, the inverted seismic velocity model reveals lateral heterogeneities and structural variability within the volcanic edi-

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fice. These findings represent a key advancement in understanding the internal structure of Tajogaite volcano using passive seismic data from a dense network deployed near the eruption site.

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CHARACTERIZATION OF SHALLOW SEISMICITY AT TAJOGAITE VOLCANO USING A DENSE SEISMIC DEPLOYMENT

JAVIER FERNÁNDEZ-CARABANTES[1, 2], JAVIER TORTOSA[1,2], MIGUEL DENGRA[1], JAVIER ALMENDROS[1,2]

ABSTRACT

As part of the IMAGMA-SEIS project, which aims to investigate the internal structure of La Palma using passive seismic methods following the 2021 eruption of the Tajogaite volcano on the Cumbre Vieja ridge, the Andalusian Institute of Geophysics deployed a dense temporary seismic network. This network included broadband stations distributed across the island and short-period stations densely installed near the volcano, with continuous recordings between February and October 2024. This configuration provides a unique opportunity to detect low-magnitude seismicity that would otherwise go unnoticed by more distant stations, especially during the post-eruptive phase as the volcanic system transitions back to a dormant state. To analyze the seismicity, we employed the Qseek software (Isken *et al*., 2025), which allowed us to perform automated event detection and phase picking using machine learning-based models, as well as to determine the hypocentral locations and estimate the magnitudes of the detected events. For this purpose, we applied a 3D velocity model derived from ambient noise tomography to compute ray paths, achieving a high spatial resolution in the generated seismic catalog. The results reveal hundreds of low-magnitude, shallow seismic events associated with the ongoing post-eruptive evolution of the volcano, along with deeper events related to the internal magmatic system. These findings are critical for understanding the tectonic and structural evolution of the Tajogaite volcano, offering new insights into its internal stress regime and volcano-tectonic architecture during the post-eruptive phase.

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ERUPTION ENDING FORECAST THROUGH MAGMA PRESSURE DROP: LA PALMA, 2021

María Charco[1], Pablo J. González[2], José Luís García Pallero[3], Laura García-Cañada[4] , Carmen Del Fresno[4]

Abstract

Forecasting the end of volcanic eruptions is one of the major challenges in volcanology, yet it has been scarcely addressed in the literature despite its crucial role in risk mitigation. The 2021 eruption of Cumbre Vieja (La Palma, Canary Islands) —the largest in over 50 years— lasted 85 days and 9 hours, caused significant damage, and highlighted the need for improved forecasting tools. In this study, we used continuous GNSS deformation data to assess the temporal evolution of the magmatic reservoir, located near the Moho discontinuity, and its associated pressure drop. Under the assumption of a closed magmatic system and pressure decay controlling the eruption, a model estimated its end date within 86 ± 7 days, achieving a realistic prediction well before its halfway point. Although the lack of a priori constraints on reservoir overpressure limited its operational usefulness, retrospective analysis confirmed that pressure loss governed the eruption's duration via mass conservation dynamics (Fig. 1). Nevertheless, the model should consider a detectable offset in the GNSS time series. This offset temporally correlates with a change of lava effusion rate and some additional geophysical and geochemical changes occurred around this time. These results demonstrate that a combined near real-time geodetic, lava effusion rates and geochemical and geophysical monitoring can enable credible forecasts for an eruption duration for basaltic Strombolian eruptions in La Palma (Charco *et al*., 2024). This approach could have potential applicability to other volcanoes of the Canary Islands and other volcanoes worldwide.

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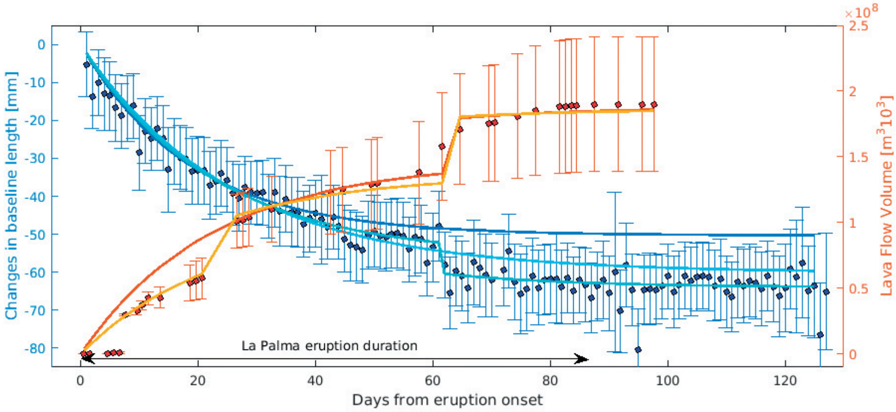

Fig. 1. Changes in GNSS baseline length (blue diamonds with error bars) since the eruption onset vs. modeled changes in GNSS baseline length (solid blue lines). Cumulated lava flow volume (red diamonds with error bars) since the eruption onset vs. modeled cumulated lava flow volume (solid orange lines).

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LOCALIZING DEFORMATION ALONG UNSTABLE VOLCANIC FLANKS IN THE CANARY ISLANDS THROUGH SEMI-AUTOMATED GEOMORPHOLOGICAL MAPPING

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Abstract

Ocean island volcanoes are among the fastest-growing edifices on Earth, and their potential collapse poses a significant hazard —not only due to mass wasting, but also due to the tsunami risk (Paris, 2015). The Canary Island volcanoes have a history of frequent mass wasting due to their steep flanks and unstable pyroclastic deposits (Krastel *et al*., 2001). All islands, except La Gomera, are considered volcanically active and are actively deforming. It is difficult to identify whether, and which parts of their flanks are mobile and might pose a hazard because far more than 90 % of the edifice is under water (Klein *et al*., 2023). Here, we apply a semi-automated GIS workflow to combined topographic and bathymetric digital elevation data of the Canary Islands to identify potentially unstable regions. We aim to trace morphological changes that result from long-term movement along faults that decouple moving and stable sectors of volcanic flanks. The workflow generates an artificial drainage network whose divides align with spatially continuous, downslope-trending ridges —features that can result from transpressional deformation along the boundaries of moving sectors. This workflow has been successfully tested against the well-constrained boundaries of Kilauea's mobile southern flank and Mt. Etna's moving southeastern flank, and the potentially moving

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western flank of Cumbre Vieja volcano on La Palma (Fig. 1) (Rollwage *et al.*, 2024). We propose that some of the delineated topographic ridges indicate areas of long-term transpressional deformation and therefore may outline the boundaries of potentially unstable volcanic flanks at the Canary Islands. In the offshore realm, the identified regions are considered prime candidates for collecting multibeam bathymetric and marine seismic data that can help locate shallow crustal faults and target future monitoring networks.

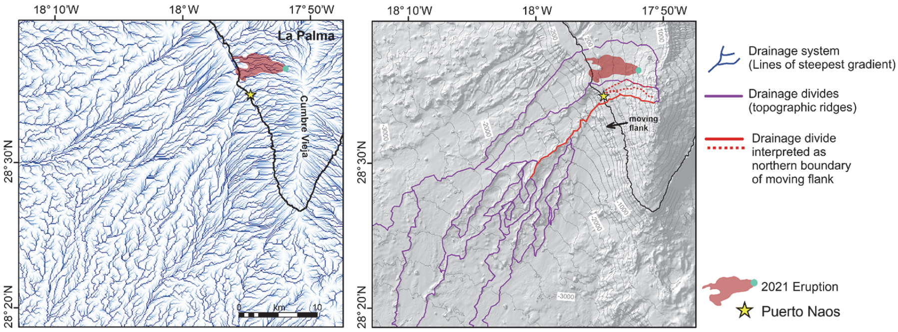

Fig. 1. Example of a drainage system and derived downslope trending topographic ridges (drainage divides) for La Palma island (modified from Rollwage *et al*., 2024). One drainage divide was interpreted as resulting from transpressional surface deformation from seaward movement of Cumbre Vieja's western flank.

This semi-automated mapping approach is a straight-forward method that can be applied to trace deformation within various tectonic settings, including volcanoes, continental margins, and mountain ranges.

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IMAGING THE MOHO AND AN UNDERPLATING LAYER BELOW LA PALMA ISLAND USING RECEIVER FUNCTION ANALYSIS

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Abstract

As part of the IMAGMASEIS project, a dense broadband seismic network was deployed across La Palma Island to investigate its lithospheric structure. The temporary network comprises 37 broadband seismometers provided by GFZ and the University of Granada, in addition to 20 permanent stations operated by the Spanish National Geographic Institute (IGN) and the Volcanological Institute of the Canary Islands (INVOLCAN). With an average inter-station spacing of approximately 5 km, the array offers high density full island coverage. The network operated from September 2023 to October 2024. A key objective of this deployment is to refine our understanding of crustal architecture using teleseismic data. We calculate P-wave receiver functions and apply the Common Conversion Point (CCP) stacking method to generate 2D seismic profiles, enabling detailed imaging of the crust–mantle boundary (Moho). Our results reveal a shallow oceanic Moho in the southern sector of the island, at depths near 10 km, in agreement with prior studies. In contrast, the northern region exhibits a more complex and thicker crustal structure, reaching up to 20 km. This could be explained by the flexure of the oceanic crust due to the overlaying volcanic seamount. We also found a discontinuous underplating layer at approximately 30 km depth, which implies the creation of a new deeper Moho below the oceanic crust.

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HIGH-RESOLUTION AMBIENT NOISE TOMOGRAPHY OF LA PALMA ISLAND: REVEALING THE SHALLOW CRUSTAL STRUCTURE

Javier Tortosa[1,2], Iván Cabrera-Pérez[3], Douglas Stumpp[3], Luca D'Auria[4,5], Benjamin Heit[6], Xiaohui Yuan[6], Rafael Abella[7], Javier Almendros[1,2]

Abstract

We study the shallow velocity structure of La Palma Island using continuous ambient seismic noise recorded by a temporary dense broadband network. As part of the IMAGMASEIS project, multiple dense seismic deployments were established to improve our understanding of the uppermost crustal structure of the island. We use 37 broadband stations, provided by GFZ and the University of Granada, complemented by 11 permanent stations operated by IGN and 10 by INVOLCAN. With average inter-station distances of approximately 5 km and maximum separations of up to 40 km, the network ensures dense coverage across the island. In addition, we used 200 short-period sensors distributed around the island in 299 different positions provided by GFZ. This study focuses on data collected over a period of 13 months, from September 2023 to October 2024. Cross-correlation of ambient noise waveforms allows us to retrieve empirical Green's functions and derive surface-wave dispersion curves. These are used in a tomographic inversion to produce a high-resolution S-wave velocity model of the shallow structure beneath the island. Our results align with previous studies, indicating higher S-wave velocities in the northern part of the island, associated with older geological formations and plutonic intrusions, and lower velocities in the southern sector, where more recent volcanic activity has occurred and possibly related to hydrothermal systems.

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IMAGMASEIS PROJECT: A LARGE SEISMOLOGICAL EXPERIMENT IN LA PALMA TO INVESTIGATE THE SUBSURFACE STRUCTURE OF THE ISLAND

Javier Tortosa[1,2], Enrique Carmona[2], Benito Martín[2], Javier Fernández-Carabantes[1, 2], Benjamin Heit[3], Xiaohui Yuan[3], Rafael Abella[4], Javier Almendros[1,2]

Abstract

IMAGMASEIS is the most extensive seismological experiment ever conducted on La Palma, designed to investigate the island's internal structure after the 2021 Tajogaite eruption. The project deployed a dense temporary network of 35 broadband seismometers across the island, in addition to 21 permanent stations operated by IGN and INVOLCAN. Complementary high-density arrays included ~200 short-period sensors rotated across multiple configurations including a very dense 32-station grid near Tajogaite volcano. These deployments operated from September 2023 to October 2024. This network configuration enabled the application of diverse passive seismic methods. Ambient noise tomography has revealed significant lateral heterogeneities in the shallow crust, with lower S-wave velocities in the younger volcanic southern sector and higher velocities in the north, associated with older, intrusive bodies. Receiver function analysis shows a shallow oceanic Moho at ~10 km depth in the south, deepening to ~20 km in the north, along with a discontinuous underplating layer near 30 km. HVSR results around Tajogaite indicate strong spatial variation in resonance frequencies, reflecting sediment distribution and structural complexity of the edifice. Additionally, high-resolution seismicity analysis using machine learning tools has uncovered hundreds of low-magnitude, shallow events during the volcano's post-eruptive phase. These preliminary results highlight the potential of dense, multi-scale passive seismic deployments to illuminate both deep and shallow structures in volcanic oceanic islands. Further details on each method and dataset are presented in dedicated posters.

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Topic 3

Petrology

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THERMOCHROMISM OF SULFATES OF Cu^{2+} AND Pb^{2+} IN HOT FUMAROLE AT THE TAJOGAITE CINDER CONE

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Abstract

An active high-temperature fumarole, with temperatures ranging from 796-810 °C, has been detected recently at the summit crater of Tajogaite, four years after the 2021 eruption. Gas analysis revealed concentrations of H, S at 17.4 μg/g, SO, at 18.4 μg/g, and HCl at 30 μg/g. Within the fumarole, emerald-green efflorescent mineral clusters were observed, forming flat-sheet structures that decorated the upper section of the vent (Fig. 1). These minerals exhibited a gradient of habits and colors, suggesting mineralogical zonation. Samples from the hottest part of the fumarole were collected for further analysis using Scanning Electron Microscopy (SEM, Fig. 1). Sampling within this temperature range was carried out by the Military Emergency Unit of Spain (UME) using a borosilicate vessel, which was inserted directly into the fumarole. Within seconds, the color of the collected material changed from emerald-green to a light turquoise-blue (Fig. 1). A few minutes later, a spatial gradient of colors developed, ranging from bluish to white-translucent tones. Preliminary analyses indicate that anhydrous alkali copper and lead sulfates represent the most abundant group of mineral species present at the Tajogaite cinder cone. The mineral paragenesis identified by EDS analysis is consistent with the presence of euchlorine, $KNaCu_3(SO_4)_3O$, occurring in association with kristjánite $KNa_2H(SO_4)_2$, belomarinaite $KNa(SO_4)$, aphthitalite $(K,Na)_3Na(SO_4)_2$, and palmierite $K_2Pb(SO_4)_2$. This assemblage is characteristic of high-temperature fumarolic environments (≥796 °C, up to 810 °C). These high-temperature minerals have previously been described at the Tobalchik secondary cinder cone (Siidra *et al.*, 2018) and in Iceland (Balić-Žunić *et al.*, 2024), where they are associated with active hot fumaroles exceeding 600 °C.

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The observed thermochromic behavior of the minerals can be attributed to rapid cooling from the original temperature of 810 °C to ambient conditions (24 °C), combined with hydration-dehydration cycles. Further analyses using X-ray diffraction (XRD) and Raman spectroscopy are currently underway.

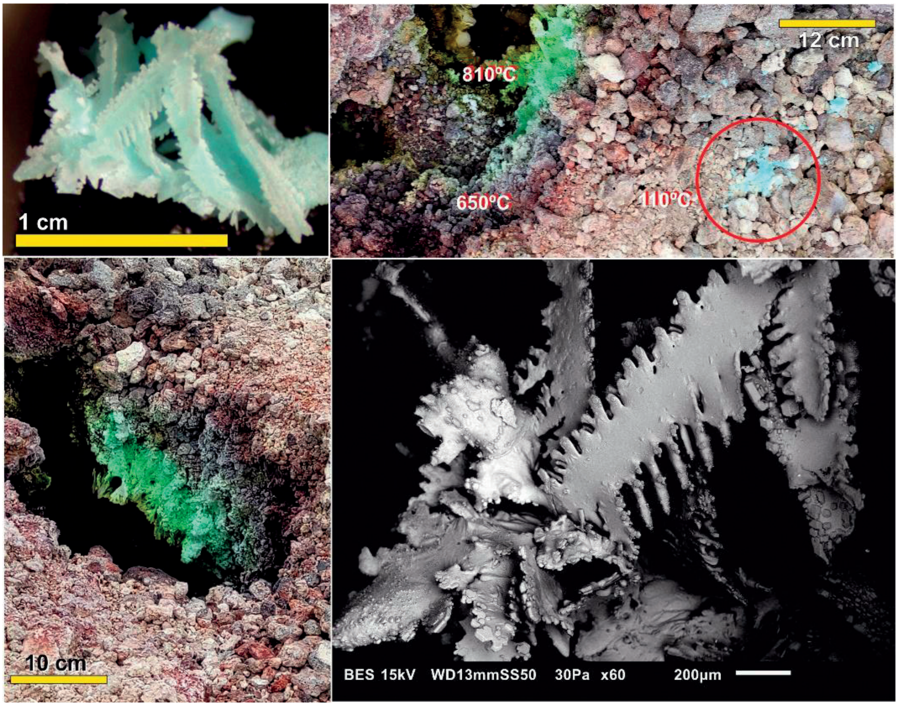

Fig. 1. Anhydrous alkali sulfates of Cu^{2+} and Pb^{2+} found in a very hot fumarole (~810 °C) at the top of the Tajogaite cinder cone. Upper right, color difference between «in situ anhydrous alkali sulfate (greenish) and the cooler sample (bluish).

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PETROLOGIC EVOLUTION OF EL CHARCO ERUPTION (1712, CUMBRE VIEJA, LA PALMA)

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ABSTRACT

The 1712 El Charco eruption is one of the eight historical eruptions occurred in La Palma (Canary Islands). The eruption was a monogenetic, long-lasting, hybrid event, forming a large scoria cone with hydromagmatic phases, and producing lava effusion from multiple vents more than 3 km apart. The mainly *«aa»* lava flows are more than 5 km long and reached the sea forming a 2.8 km wide coastal lava platform. Two petrological types were emitted during the eruption: pyroxene-amphibole tephrites and pyroxene-olivine basanites (Chicharro *et al.*, 2025). The main petrographical difference between both types is the proportion of olivine, which is a main component of basanites and accessory in the tephrites, and amphibole, which is the second most abundant phase in tephrites and accessory in the basanites. El Charco's olivine is forsterite-rich, amphibole is always kaersutite, clinopyroxene is dioposide, and plagioclase is labradorite, with a few andesine macrocrysts as exceptions. Normal and reverse zoning are common in clinopyroxene and can also be seen in olivine and amphibole. Olivine is characterized by the abundance of disequilibrium textures, especially frequent in tephrites. Amphibole often displays Fe-Ti oxides, Cpx and plagioclase reaction rims, which can completely replace original crystals in some basanites. The tephrites (TF) and basanites (BSN) also show chemical differences, basanites are richer in MgO, CaO, Ni and Cr. On the contrary, tephrites are richer in incompatible elements such as alkali, P_2O_5, Sr, Ba and REE. El Charco's basanites and tephrites do not define a continuous compositional spectrum. Instead, there is a gap, particularly conspicuous in MgO content. Basanites contain around 8 % MgO, while tephrites

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concentrate near 6 % MgO, with no intermediate compositions. This gap is also apparent in alkali, Cr, Ni, P_2O_5 and other trace elements (Fig. 1).

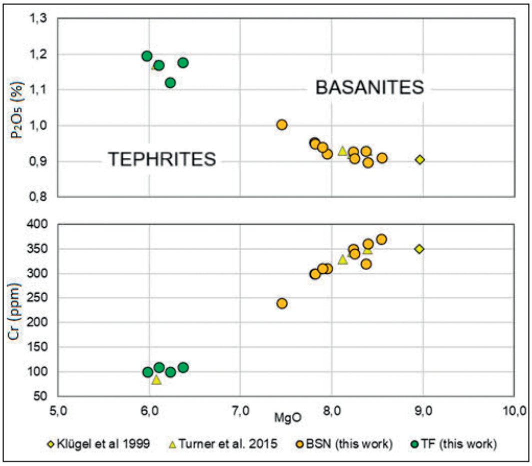

Fig. 1 Geochemical variation in El Charco's lava flows. Data represented in yellow rhombus and triangles are from Klügel *et al*., 1999 and Turner *et al*., 2015 respectively

Our field observations reveal that basanitic lava flows always overlay the tephritic flows, suggesting the latter were emitted first. The same compositional pattern has been recognized in the most recent eruptions in La Palma (1971 Teneguía and 2021 Tajogaite: Ibarrola, 1974; Ubide *et al*., 2023). The petrological evolution of El Charco eruption is compared with these well-monitored events and with the previous eruptions.

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MELT/FLUID-ROCK REACTIONS IN THE LITHOSPHERE BENEATH LA PALMA (CANARY ISLANDS): CLUES FROM MINERAL AND FLUID INCLUSION CHEMISTRY IN ULTRAMAFIC XENOLITHS

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Abstract

Combining the chemistry of minerals with that of mineral-hosted fluid inclusions in mantle-derived xenoliths from active volcanic areas is a powerful tool to investigate both the long-term geodynamic evolution of the lithospheric mantle and the short-term variations associated to volcanic unrests. Here, we present mineral major and trace element chemistry and fluid inclusions chemistry data on a suite of ultramafic xenoliths from La Palma (Canary Islands), which also includes n. 1 cm-sized xenolith brought to the surface by the 2021 Tajogaite eruption. The studied xenoliths are spinel-bearing, and vary in composition from harzburgites to dunites, with subordinated lherzolites, modally metasomatized amphibole- and phlogopite-bearing varieties, and pyroxenites. The composition of primary olivine in harzburgites and dunites is $Fo_{90\text{-}91}$ and NiO = 0.3-0.4 wt%, while the most metasomatized and cumulate rocks bear relatively Fe-rich olivine ($Fo_{80\text{-}82}$ and NiO < 0.2 wt %). Fluid inclusions are abundant in the dunites, where they occur either as trails or isolated. In the harzburgite xenoliths, orthopyroxene is rich while olivine is relatively poor in primary fluid inclusions, albeit secondary fluid inclusion trails propagating through olivine grains are frequently associated to the reaction forming secondary amphibole, clinopyroxene and glass. All fluid inclusions are dominated by CO_2, whose concentration reaches 1.64×10^{-6} mol/g. Their $CO_2/^3He$ ratios

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ranges between 3.37×10^9 and 1.06×10^{10}, while $\delta^{13}C$ values vary from -4.5 to -2 ‰.

Corroborated by thermobarometric modelling, our results show that peridotite xenoliths equilibrated in the lithospheric mantle beneath La Palma, and were first overprinted by melt/fluid-rock reactions caused by the infiltration of C-rich metasomatic agents at mantle depth. Subsequent melt/fluid-rock reactions took place during ascent to the surface and/or magma ponding at the Moho. The bulk Fe-Mg diffusion of olivine and the occurrence of a well-developed clinopyroxene + spinel reaction corona around the cm-sized xenolith from the Tajogaite eruption testifies for the arrival of mantle-derived pulses in the plumbing system beneath La Palma long before the eruption onset.

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UNRAVELLING THE INNER STRUCTURE AND TEMPORAL REACTIVATION OF THE CRUSTAL RESERVOIR FEEDING LA PALMA 2021 ERUPTION

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ABSTRACT

In order to shed light on the pre-eruptive architecture and temporal evolution of the crustal reservoir that fed the magmas of the first month of La Palma 2021 eruption, we performed High-pressure and High-temperature crystallization experiments on three representative products emitted during this period. Our results confirm that the reservoir was initially located at 10 km depth with a top to bottom thermal zonation, from a colder-wetter (1065 °C-2.5 wt. % H_2O_{melt}) Amp-bearing tephritic top magma to a hotter and driest (1090-1115 °C, 1-2 wt. % H_2O_{melt}) underlying basanites (Fig. 1A). Mineral compositional zoning along with experimental constraints show that a cold magma body (850-950 °C), likely a remnant of previous eruptions at La Palma, was progressively rejuvenated by the injection of deep hotter magmas that increased the temperature of the bottom portion of the reservoir up to 1135 °C. Such a reactivation started 10-15 years prior to eruption date, as indicated by olivine and clinopyroxene diffusion profiles (Fig. 1 B-C) and corroborated by geophysical signals and changes of surficial fluid geochemistry monitored during that period. At least four different injections were necessary to achieve such high

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temperatures, the last mafic recharge prior to eruption onset occurring in mid-October 2018. This was followed by a post-injection cooling phase which continued up to the date of the eruption, during which the top portion of the rejuvenated body re-entered the stability field of amphibole. This cooling phase which preceded the eruption could potentially explain the absence of seismic signals at ~10 km, as revealed by the revision of the precursory seismic catalogue since 2017. The fact that the rocks emitted during the first half of the eruption do not bear textural or compositional evidence for a mafic recharge occurring a short time prior the eruption suggest that the eruption triggering is linked to the internal evolution of the reservoir (volatile build up) or to external factors.

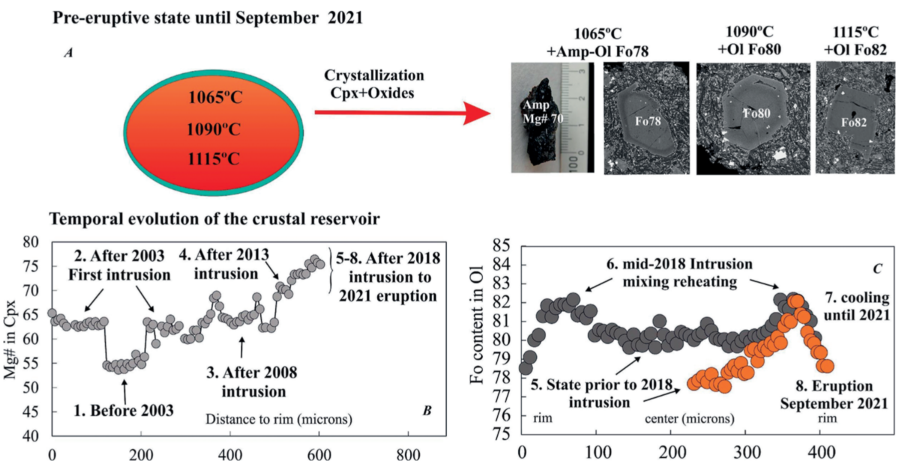

Fig. 1. A) Schematic view of the thermal inner structure of the shallow reservoir that fed the initial phase of La Palma 2021 eruption and the related mineralogy deduced for each magma. Compositional profiles of coexisting Clinopyroxene (B) and Olivine (C) allowing the identification of the different replenishment episodes experienced by this reservoir and the deduced time scales (modified from Andújar *et al*., 2025)

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MEGAPILLOW BODIES WITHIN THE LAVA DELTA OF THE 2021 TAJOGAITE VOLCANO AT LA PALMA (CANARY ISLANDS)

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Abstract

In 2021, the eruption of the Tajogaite volcano (La Palma Island) generated two subaerial lava deltas, occupying areas of 5.4 and 53 ha, as well as a submarine area of approximately 30 ha and 3 Mm^3. By detailed submarine topography observations made with multibeam echo sounder (MB710) and images taken from the Liropus 2000 ROV (Remotely Operated Vehicle) manned from the oceanographic vessel Ángeles Alvariño (IEO-CSIC), we managed to map and identify megapillow lavas corresponding to the Tajogaite volcano's submarine delta. Some of the megapillows reach up to 4.5 m in diameter and nearly 15 m in length (megapillow lava tubes with a flat base). They are stacked on several levels, originating from an autoclastic breccia at the base and upper insular slope close to 35°. These megapillow lavas are also accompanied by pillow lavas (with hawksbill shell jointing on the external surface), autoclastic breccias, collapse breccias, hyaloclastites and resedimented-brec-

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cias. The emission of sheet lava flows, with low and moderate flow rates, has generated in La Palma lava delta, the largest known world basanitic megapillow lavas. We also investigate how variations in flow rate and slope angle may influence the formation and distribution of these structures. Analyzing the evolution and geomorphology of these volcanic structures on submarine lava deltas, particularly in the insular slope, can represent a fundamental information for understanding the processes related to potential landslides and tsunami generation.

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REMOBILIZATION OF CRYSTAL MUSHES DAYS TO MONTHS BEFORE HISTORICAL CUMBRE VIEJA ERUPTIONS

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ABSTRACT

Only two of the 14 historical eruptions in the Canary Islands —the 2011–2012 Tagoro (El Hierro) and the 2021 Tajogaite (La Palma) events— have been studied using modern volcano monitoring techniques. For older eruptions, historical accounts describe felt seismicity but provide ambiguous records of pre-eruptive unrest. To better constrain the dynamics and timescales of magmatic processes leading to past eruptions —a key step for improving future eruption forecasting— we must turn to the rock record. Here we synthesize textural and chemical data from crystals erupted during the seven historical events (1585, 1646, 1677-1678, 1712, 1949, 1971, 2021) at Cumbre Vieja volcano. Our focus is on zoning patterns in olivine and clinopyroxene macrocrysts. Most of these crystals show reverse zoning, with low-Mg# cores overgrown by high-Mg# rims, indicating late-stage recharge by more primitive magma. Clinopyroxenes often have complex cores, featuring patchy zoning, resorption surfaces, prismatic apatite inclusions, and melt channels linked to vesicles. These cores display Mg# as low as ~55 and enriched incompatible trace element contents, implying crystallization from evolved tephritic–phonolitic melts. Olivines have simpler Fe-Mg zoning, but phosphorous maps reveal a similarly complex growth history. We interpret this recurring macrocryst record as evidence of a consistent pre-eruptive process at Cumbre Vieja: rejuvenation and remobilization of pre-existing mushy magma bodies by ascending basanitic melts. Crystal rims then crystallize from this recharge melt

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shortly before eruption. Diffusion chronometry of reversely zoned olivines yields short timescales between mush rejuvenation and eruption onset —ranging from days to a few months across all seven eruptions studied. For the Tajogaite eruption, these crystal-derived timescales are consistent with the period of accelerating seismicity starting eight days before eruption onset. However, the crystals do not appear to record deeper unrest processes that may have begun as early as 2017. Overall, our results suggest that at Cumbre Vieja, «immediate» eruption run-up is typically short, highlighting the need for continuous monitoring to detect rapid transitions from unrest to eruption.

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CRYSTAL CARGO PERSPECTIVES ON MAGMA ASSEMBLY AND DYNAMICS DURING THE 2021 TAJOGAITE ERUPTION, LA PALMA, CANARY ISLANDS

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Abstract

The 2021 eruption of Tajogaite was the longest duration eruption, most voluminous, and had the largest human impact in recorded history on La Palma, Canary Islands. Extensive geophysical and geochemical data were collected during both the preceding unrest and eruptive event. Petrological monitoring was largely restricted to rapid stereo microscope observation and a few supporting in-depth studies using analytical instruments off-island. Here, we utilise time-series samples of lava and tephra from the Tajogaite eruption collected with near-daily frequency to understand the magmatic processes responsible for changes in petrological, geochemical, and geophysical observations. We combine published whole-rock major and trace element data with new QEMSCAN textural and mineral abundance data, major element analyses of the major macrocryst phases, and trace element data from clinopyroxene

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to illustrate magma plumbing system processes, supported by pressure and temperature modelling of mineral growth. Finally, we calculate olivine Fe-Mg diffusion timescales from early erupted tephra, and compare them with timescales of the climactic unrest period.

Our data indicate that more-evolved and mineralogically-diverse magmas were tapped during the first week of the eruption, with little evidence for magma mixing. Magma mixing only becomes apparent when more primitive magmas erupted after the first ~10 days, exemplified by reverse-zoned olivines. Nonetheless, clinopyroxene barometry suggests that much of the erupted material is fed from the upper mantle at all stages of the eruption. Timescales of this process overlap with, and extend, the record of climactic geophysical unrest, suggesting that destabilisation of the magma system started before geophysical methods alone could detect and resolve variations from background. The chemical compositions of the crystal cargo are surprisingly uniform from Stage 2 (~5 - 10 days of activity) to eruption cessation (after 85 days of activity), and changes in whole-rock and tephra glass compositions observed by previous studies are not obviously mirrored in the mineral record. We highlight the importance of combining both whole-rock and mineral scale observations to understand how eruptions progress, and ultimately end.

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RAPID RESPONSE PETROLOGY: DURING AN ACTIVE VOLCANIC ERUPTION: TECHNIQUES, TIMING, COSTS AND APPLICATIONS

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Abstract

When monitoring volcanic activity, understanding how an eruption will evolve and end is as important as predicting when and where it will begin. During an active eruption, volcanic rocks (magma), glasses (melt), and crystal cargoes (minerals) become available for study, whilst geophysical signals often become noisier. Compositions of the petrological signals directly record magma system dynamics that prime, drive, modulate, and halt eruptions. Petrology is unique in that it can access the present and the past, offering clear potential not only for understanding syn-eruptive processes, but also for immediate application in risk assessment, hazard management, and civil protection. Near real-time petrological monitoring is already growing in use (Re *et al*., 2021; Kent *et al*., 2023), we advocate its broader adoption by providing a resource-efficient scientific template. For effective monitoring, a rapid-response strategy is essential to optimise resources. The aim is to acquire meaningful data about the evolving active magmatic system. We assess the use of various traditional and advanced methods, considering key aspects such as sample preparation, analysis time, cost and informative value for effective monitoring. Our group learned from the Tajogaite eruption that preparation prior to the eruptive crisis would have improved our response. In brief, petrological monitoring data and applications include: optical microscopy, SEM and QEMSCAN, which analyse mineral compositions and textures to track magma cooling, crystallisation, ascent and eruptive style; XRD, which identifies minerals and glass proportions and compositions indicative of magma

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composition, cooling, and eruption; XRF, which measures whole-rock elemental changes recording magma source and temperature; microthermometry, which uses fluid inclusion-determined temperatures and pressures to reconstruct magma storage depths and ascent dynamic; and, micro-CT, which offers rapid, non-destructive 3D imaging of porosity, vesicularity, and mineral distribution, key to understanding magma ascent, fragmentation, and degassing.

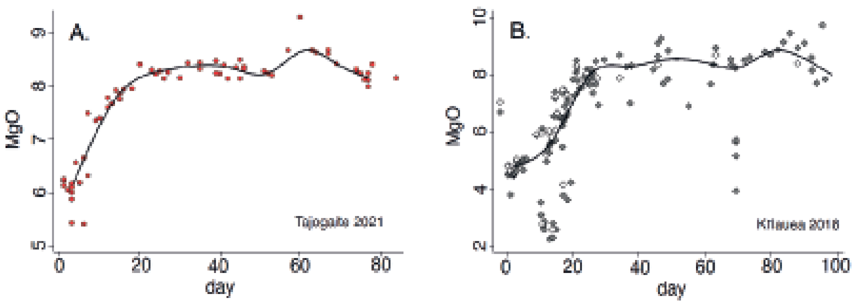

Fig. 1. Across-eruption time series variation in MgO for two recent mafic eruptions. [A] Tajogaite 2021, red circles - whole-rock lavas and tephras (Scarrow *et al*., 2024), lines of best fit through the data in all graphs are spline functions with nine cross- median knots calculated using Stata statistical software; [B] Kīlauea 2018, whole-rock lavas white diamonds – 'conventional' X-ray fluorescence spectroscopy data, dark grey diamonds – 'rapid' energy dispersive X-ray spectroscopy data, note the clear and consistent overlap between the two datasets (Gansecki *et al*., 2019). All data are recalculated to 100 wt. % dry with Fe recalculated as FeOT, expressed as wt. %. Note the systematic ~0.5 wt .% reduction in MgO 15-20 days before the end of each eruptive period. From (Scarrow *et al*., 2024).

Thus, integrating petrological information, particularly from daily time series samples (see Fig. 1), with real-time data such as geophysical, gas geochemistry, and phenomenological monitoring can provide critical insights into connections between: earthquake depths and magmatic storage, intrusion and rejuvenation (Kahl *et al*., 2022); eruption dynamics, for example lava effusion and flow rates (Gansecki *et al*., 2019); and, mush mobilisation and filter pressing (Scarrow *et al*., 2024).

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DECODING LINKS BETWEEN MAGMATIC PROCESSES AND ERUPTION DYNAMICS: WHOLE-ROCK TIME SERIES PETROLOGY OF THE 2021 TAJOGAITE ERUPTION, LA PALMA

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ABSTRACT

We present an integrated petrological study of the 2021 Tajogaite eruption, examining magmatic processes that initiated, sustained, and terminated surface volcanic activity. High temporal resolution sampling of near-continuously erupted alkali-basalt lava and tephra over the 85-day event reveals magma plumbing system dynamics from compositional trends. Initial deposits were mineralogically varied, reflecting mobilisation of shallow, evolved mush perturbed by fresh deep, primitive magma influx (Stage 1 - initiation). Transition to more primitive, uniform compositions recorded progressively deeper tapping of pre-existing magmatic zonation (Stage 2 - evacuation). The final stage (Stage 3 - waning) was characterised by more evolved magma compositions, with tephra glass compositions suggesting a proportionately larger role

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of mush interstitial melts. We suggest this reflects shutdown of mantle-derived magma supply, a key process in eruption termination, and compression-driven melt extraction of less mobile melts. Correlation with geophysical monitoring data demonstrates how near-real-time petrological monitoring can improve understanding of when an eruption may end.

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TIME-RESOLVED OXYGEN ISOTOPE VARIATIONS IN 2021 LA PALMA LAVAS; IMPLICATIONS FOR MAGMA STORAGE AND UPPER MANTLE ENDMEMBER VALUES

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Abstract

Time-resolved sampling of recent eruptions offers insight into temporal changes during single eruptive events (Day *et al.*, 2022). Here we report oxygen isotope ratios ($\delta^{18}O$ values) from time-resolved lava samples of the 2021 La Palma eruption (September-December 2021). Early tephrite lavas (up to day 20) show significant $\delta^{18}O$ variability (+4.9 to 5.8 ‰), whereas subsequent basanite lavas show a more restricted range (+5.3 to 5.7 ‰). The larger $\delta^{18}O$ variability in early tephrites is associated with more radiogenic Sr and Os isotope ratios and coincides with the presence of partially reacted amphibole and gabbro micro-xenoliths. This suggests pre-eruptive interaction of the early erupted tephrite magmas with sub-island Jurassic oceanic crust that contains low-$\delta^{18}O$ gabbros and relatively high Re/Os and Sr isotope ratios. Seismic evidence further implies that initial tephrite lavas were supplied from a Moho-

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level reservoir at 8-14 km depth, which places their original storage reservoir into the Jurassic ocean crust. Subsequent basanite lavas were in turn supplied from a deeper magma reservoir located in the upper mantle (>20 km), coinciding with a very narrow range of primitive mantle $\delta^{18}O$ values. These later values are likely the best representation of regional mantle values and fall slightly below average Atlantic MORB, implying the presence of a plume component in the mantle under La Palma.

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PRELIMINARY RESULTS ON THE SPATIAL VARIABILITY OF CRUSTAL AND MANTLE XENOLITHS IN LA PALMA (CANARY ISLANDS, SPAIN): INSIGHTS INTO THE LITHOSPHERIC STRUCTURE AND CRUST-MANTLE INTERACTION

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ABSTRACT

We present preliminary petrographic and geochemical observations on a new suite of crustal and mantle xenoliths from historical and prehistoric eruptions of La Palma, including the 2021 Tajogaite eruption. The studied samples comprise upper mantle peridotites and pyroxenites, lower crustal gabbros, and a diverse range of ultramafic cumulate rocks (Fig. 1). This work aims to constrain the provenance, pressure-temperature conditions and spatial distribution of these xenoliths to better understand the lithospheric structure beneath the island. Peridotites are dominated by coarse-grained, refractory lithologies (harzburgites, dunites and wehrlitic dunites), with anhedral textures and, in some cases, intracrystalline deformation features (e.g., subgrain formation, undulose extinction), particularly in olivine from harzburgites. Clinopyroxenes are mostly interstitial or vein-associated. Amphibole, when present, is confined to xenolith-host interfaces or late-stage interstitial melt pockets. All peridotites contain abundant secondary fluid and multiphase solid inclusions, while primary inclusions are observed only in Cr-diopsides of a clinopyroxenite sample. Amphibole-rich cumulate rocks are widespread, comprising brown amphibole and pale brown clinopyroxene, often in poikilitic or intergrown textures. Olivine is subordinate, anhedral and enclosed in amphibole. Zoning in clinopyroxene and the presence of interstitial opaque phases and rare plagioclase suggest polybaric crystallization and open-system evolution. One dunite sample, with elongate, tabular, undeformed olivines, hosting primary fluid and multiphase solid inclusions, is tentatively interpreted as of shallow cumulate origin. Gabbros, often olivine-bearing, show large, zoned, light-brown clinopyroxenes partially replaced by amphibole, and contain interstitial plagioclase.

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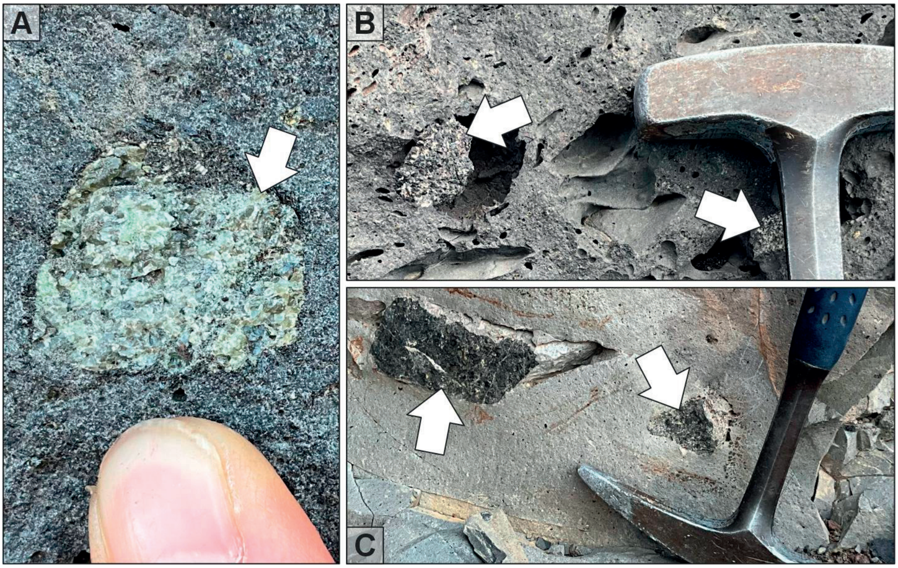

Fig. 1 Representative xenoliths from different eruption sites across La Palma. (A) Upper mantle harzburgite from the 2021 Tajogaite eruption. (B) Lower crustal gabbro from the 1677-1678 eruption. (C) Cumulate rocks from prehistoric eruptions of the Taburiente volcanic edifice in the northern part of the island.

Spatially, mantle xenoliths are most abundant in the southern part of the island (e.g., 1677-1678 and 1971 eruptions), while crustal xenoliths dominate further north (e.g., 1585 and prehistoric eruptions). Preliminary barometric estimations, based on whole-rock geochemistry, suggest that the melting depth of the host basaltic magma was around 86-91 km for both the 1971 Teneguía and the 2021 Tajogaite eruptions, while the xenoliths represent distinct shallow upper mantle and lower crustal provenance levels from 40 to approximately 10 km. This observation is consistent with literature, and in case of the 2021 eruption, available geophysical data. Thus, in the 2021 eruption, xenoliths allow for potential integration with high-resolution geophysical monitoring data to evaluate source dynamics during active eruptions.

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VOLATILE-RICH BASANITIC MAGMATISM IN THE CANARY ISLANDS: A COMPARATIVE STUDY OF THE 2021 TAJOGAITE ERUPTION AND MONOGENETIC ERUPTIONS FROM TENERIFE

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Ramón Casillas[2], Bruno Scaillet[3]

Abstract

The 2021 Tajogaite eruption on La Palma offered an exceptional opportunity to investigate the architecture of ocean island magmatic systems through the real-time integration of geophysical, gas, and petrological monitoring, providing not only valuable insights into the volcanic process but also crucial information for understanding this type of eruption. However, despite the wealth of data produced from this event, comparative studies with analogous mafic systems elsewhere in the archipelago remain limited. Consequently, this study addresses that gap by comparing the volatile budget and magma storage architecture of the Tajogaite eruption with three monogenetic basanitic eruptions from Tenerife (Fasnia, Arafo and Arenas Negras) (Fig. 1), based on detailed petrological data, melt inclusion (MI) analysis and H_2O-CO_2 solubility modeling specifically calibrated for the Canary Islands' mafic-intermediate alkaline compositions (Jiménez-Mejías *et al*., 2021). Olivine-hosted MIs from the 2021 Tajogaite eruption contain 1.3-2.21 wt. % H_2O and 2200-5000 ppm CO_2, though the presence of pure CO_2 fluid inclusions in different crystals (Dayton *et al*., 2023) indicates that these CO_2 contents could underestimate the parental melt CO_2 (Burton *et al*., 2023). In comparison, Tenerife MIs are also volatile-rich, with H_2O ranging from 0 to 2.30 wt. % and dissolved CO_2

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concentrations reaching ~1 wt. % in the melt. Restored CO_2 contents (glass + bubble) exceed 1.7 wt. % yet remains below primitive melt estimates since the observed MI CO_2/Nb (0-298) and CO_2/Ba (0.1-52) ratios fall below the canonical values for undegassed mantle melts (~500 and ~133, respectively), implying early CO_2 degassing at >1.5 GPa and/or mantle heterogeneities and melt mixing. The Tajogaite plumbing system was dominated by two reservoirs at ~10-14 km and 33-39 km, separated by an aseismic zone.

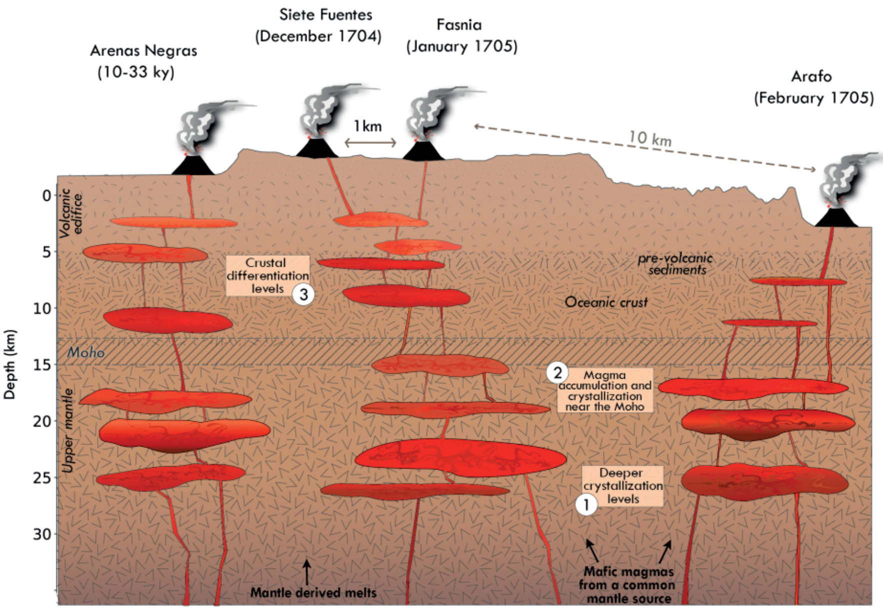

Fig. 1. Crystallization depths and model for the magma plumbing system beneath Arenas Negras, Fasnia and Arafo from melt inclusions and Clinopyroxene-melt thermobarometry. Cross-section with lithological boundaries following the assumed structure. Magma storage and crystallization in the upper mantle are envisioned as a complex system with interconnected reservoirs, replenished by mafic magma batches that may interact and mix, as indicated by mineral zoning patterns. Major magma storage levels are indicated: (1) deep storage and crystal fractionation; (2) temporary stalling in a storage zone near the Moho; (3) magma crystallization and differentiation at crustal levels.

In Tenerife, MIs and barometric constraints indicate a similar but more extensive distributed system with storage at multiple levels: deep upper mantle (~42-51 km), transitional reservoirs (~14-30 km), and shallow crustal zones (3-12 km). Therefore, although both islands function as independent systems, they are sustained by deeply sourced, CO_2-rich basanitic magmas, emphasizing the important role of deep carbon in the dynamics of intraplate volcanism across the Canary Islands.

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MAGMATIC VOLATILES IN THE FOURTH DIMENSION (MV4D): INNOVATIVE TECHNIQUES FOR QUANTIFYING MANTLE SOURCE VOLATILE SIGNATURES

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Abstract

Magmatic volatiles influence eruption explosivity and gas emissions posing hazards to communities. Magma volatile contents are controlled by mantle source compositions which have been modified over time by convective and tectonic processes, creating mantle heterogeneities. Basaltic eruptions at oceanic islands can sample these heterogeneities and capture their diverse geochemical signatures in olivine-hosted melt inclusions (MIs). However, the extent to which melting and mobilisation of mantle heterogeneities influences magma volatile budgets during a single eruption remains poorly understood. The MV4D project aims to address this challenge by studying time-stamped MIs from the 2021 Tajogaite eruption. We combine state-of-the-art 3D imaging and

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Raman analyses with a novel technique for measuring heavy halogens (Cl, Br, I) in MIs. The first objective of MV4D is to reconstruct the total volatile content of the MIs by identifying and correcting for post-entrapment processes like bubble formation and precipitation of nanoscale crystals on the bubble walls (Fig. 1A). These nanoscale precipitates can contain up to 85 % of a MI's carbon budget, and ignoring them in analyses can lead to significant underestimation of magmatic volatile concentrations. We have interrogated bubble-MI-host relationships in 3D via X-ray computed tomography to assess post-entrapment processes (Fig. 1B). We will capture the full volatile content of the MIs by analysing bubble wall precipitates via 3D Raman (Fig. 1A).

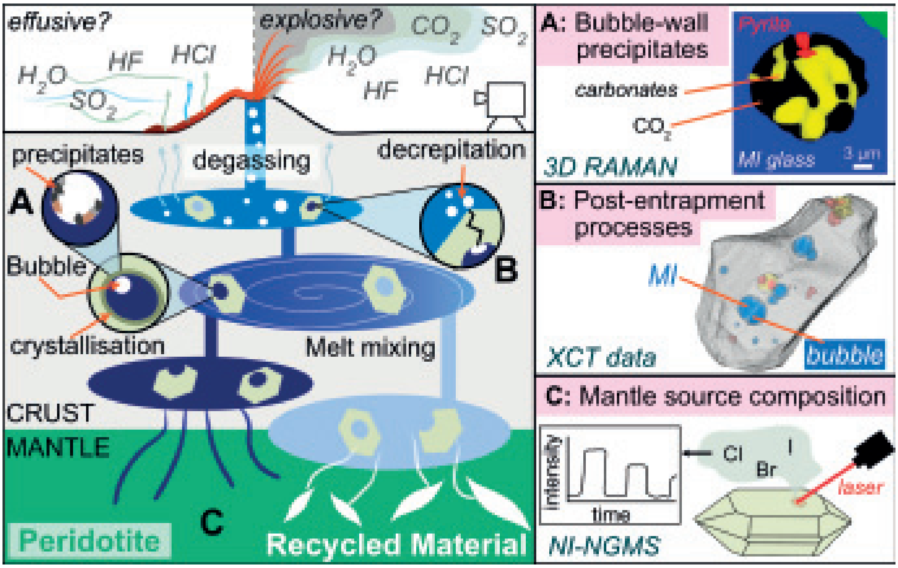

Fig. 1. Left - Schematic showing magma plumbing system feeding basaltic eruptions with multiple magma reservoirs (blue) with olivine crystals (pale green) trapping melt inclusions. A – melt inclusion (MI) hosted bubble walls may contain precipitates. B: fracturing can lead to volatile loss from MI records. C: different mantle sources may be captured in trapped MIs. Right: techniques to be applied – titles A, B, C link to diagram on the left. Upper panel shows an example of 3D RAMAN data of a MI-hosted bubble with precipitates. B: 3D rendering from x-ray computed tomography scan of an olivine (grey) with MIs (blue), bubbles (white), oxides (pink) and embayments (yellow). C: schematic showing the process for neutron-irradiated noble gas mass spectrometry (NI-NGMS).

Our second objective is to trace the melting of mantle heterogeneities during the 2021 Tajogaite eruption by analysing Cl, Br and I in MIs (Fig. 1C). Halogens are sensitive tracers of recycled material, making them ideal for tracking time-dependent sampling of different mantle reservoirs. We will use neutron-irradiated noble gas mass spectrometry (NI-NGMS) to measure halogens in individual MIs. We will then construct a high-resolution time series of volatile contents in melts and their mantle sources. By linking temporal variations in magma CO_2, H_2O, SO_2 and halogen contents with in situ gas flux measurements and observed changes in eruptive style, we aim to evaluate whether time-dependent differential sampling of heterogeneous mantle reservoirs influenced eruption dynamics during the 2021 Tajogaite eruption.

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LOOKING INSIDE THE MAGMATIC SYSTEM OF THE ERUPTING TAJOGAITE VOLCANO THROUGH A JOINT ANALYSIS OF FLUID INCLUSIONS AND SEISMICITY

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ABSTRACT

The 2021 Tajogaite eruption, despite its devastating effects on the communities of the island of La Palma, presented a unique opportunity for testing new monitoring devices thanks to technological and instrumental improvements of the last years and testing new methods or improving well established methods. Our study focuses on speed up the tracking of magma movement in volcanic system during an ongoing eruption to try to forecast the volcano behavior. We introduced a novel method for near real-time monitoring of magma ascent by integrating fluid inclusion barometry with ongoing seismicity data (Zanon *et al*., 2024). We performed microthermometric analysis of fluid inclusions in fresh crystals (olivine, clinopyroxene, amphibole) from daily-collected lavas and tephra. Fluid inclusions —tiny bubbles of gas trapped in minerals— provide insights into the depth and pressure of magma storage. By analysing CO_2-rich fluid inclusions in olivine crystals from basaltic volcanoes, we identified multiple magma batches present ascending through the magma system and estimated their ascent rates and storage depths. In particular, we identified a source zone located between 27 and 31 km in depth, and two depth ranges of magma stagnation: the first, between 22 and 27 km, and the second, between 4 and 16 km. These results are in agreement with the temporal evolution of the seismicity during the eruption (D'Auria *et al*., 2022) and with the structure of the crust and the upper mantle inferred from seismic tomography studies (Ortega-Ramos *et al*., 2024). Furthermore, our findings enabled

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us to estimate magma ascent velocities (including ponding times) varying from 0.01 to 0.1 m/s along the eruption.

In conclusion, this methodology, used for the 2021 Tajogaite eruption, provides a faster and cost-effective complement to classical petrology by enabling near-real-time comparison with geophysical techniques, allowing for the tracking of magma movement during eruptions. Integration of petrological barometry and seismic monitoring could substantially enhance volcanic hazard forecasting during eruptive crises.

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Topic 4

Volcanic hazards

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HURST EXPONENT TIME VARIATION OF VT EARTHQUAKES AND GEODYNAMICS OF THE TAJOGAITE ERUPTION

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Abstract

The Hurst exponent (H) quantifies the persistence or memory of natural dynamical processes and is typically associated with fractional Gaussian noise (fGn), as opposed to fractional Brownian motion (fBm). It is calculated using rescaled range (R/S) analysis (Mandelbrot & Wallis, 1969; Pérez-López *et al*., 2006). These natural processes described as self-organized-criticality (SOC, Bak & Tang, 1989) include earthquakes and volcanic eruptions. Volcano-tectonic (VT) earthquakes are a consequence of magma dynamics, and the study of earthquake clustering preceding an eruption can provide insights into the system's potential behavior. This approach assumes the application of Shannon entropy theory, which quantifies the uncertainty and randomness inherent in complex systems. Active volcanoes are typically monitored through a combination of VT earthquake records, diffuse gas emissions, and surface deformation measurements using GNSS networks in conjunction with InSAR remote sensing. We have applied the R/S analysis to the time distribution of VT earthquakes (IGN, 2022) with the aim to analyze the H exponent variation in time, during the days previous to the Tajogaite volcanic eruption (Fig. 1). For this purpose, we constructed the GEOS diagram (Mandelbrot & Wallis, 1969; Pérez-López *et al*., 2006) using the MARTE R-code developed by Benito-Parejo (2015). Additionally, we compared the temporal evolution of the H-exponent with the b-value and other parameters, such as the SSAM signal provided by IGN. Our results suggest that it is possible to identify a point of no return in the GEOS diagram, which could serve as a warning indicator for an imminent eruption when used in conjunction with other volcanic precursors.

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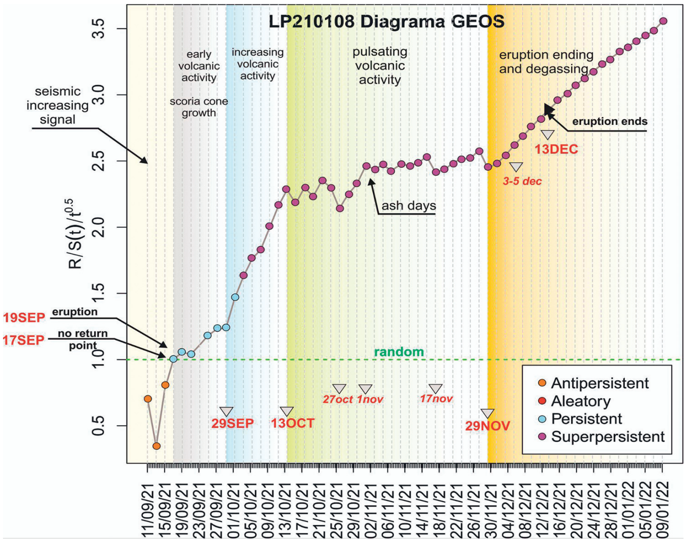

Fig. 1. Hurst exponent of the VT earthquakes by depth foci

This potential early-warning signal offers a lead time ranging from 48 hours to several days, and in some cases, up to a couple of weeks. It is important to note that this proxy has been applied in the context of a basaltic/mafic effusive eruption associated with dike intrusion and the formation of a monogenetic cinder cone. Therefore, its effectiveness may depend on the type of volcanic eruption, and further analyses are needed to assess its broader applicability.

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OPERATIONAL FORECASTS DURING UNREST AND ERUPTION OF LA PALMA 2021 ERUPTION_LESSONS LEARNED

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Abstract

The 2021 eruption in La Palma has been the longest and biggest eruption on the island in the last 500 years. Fifty years after the precedent eruption at La Palma, and only ten years after the submarine eruption at El Hierro, a rapid volcanic unrest started on 11 September 2021 and culminated in an eruption only 8 days later, 19 September. The eruptive process lasted 85 days, being the longest and largest eruption in volume of magma occurred on the island in historical times. Throughout the 8 days of pre-eruptive unrest, several geophysical and geodetic parameters accelerated notably, pointing to an increase in the probability of an eruption. Hazard assessments, together with real-time monitoring data, were key tools in the decision-making of the emergency managers. Shortly after the eruption started, lava flow hazard maps were computed, based on probabilistic maximum slope models and pre-defined input parameters characteristic of the island of La Palma. These maps allowed the emergency managers to identify the most probable paths for the lava flows and thus anticipate which populations might need to be evacuated. On the other hand, ash and gas dispersal forecasts were also delivered from the first days of the eruption. Communication with the emergency managers was constant, with daily meetings of the scientific committee since 13 September 2021. In this presentation we will discuss some aspects that could improve the communication between scientists and emergency managers during unrests and eruptions, yielding to a most efficient and rapid decision making.

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PREDICTIVE 3D MODELING OF THE TAJOGAITE ERUPTION: ASSESSING LAVA PATHS AND BARRIER EFFECTS

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Abstract

The 2021 Tajogaite eruption (Cumbre Vieja, La Palma) produced extensive lava flows that devastated over 12 km² of land and destroyed thousands of buildings (Civico *et al*., 2022). This disaster underscores the need for improved hazard assessment and predictive tools to manage future volcanic crises. Numerical lava flow models have become essential for hazard and risk assessment, real-time flow forecasting, and evaluating mitigation measures (Dietterich *et al*., 2017). Advances in computational power and modeling techniques now allow high-resolution simulations to be run rapidly, enabling near-real-time predictions of lava flow paths and at-risk areas. Accurate and fast models are crucial for constructing hazard maps and guiding interventions such as diversion barriers, which aim to redirect lava flows away from critical infrastructure. In this work, we present a three-dimensional Navier–Stokes lava flow model that incorporates an energy equation to capture temperature-dependent viscosity. The software is based on the work of Biagioli *et al*. (2025). The model is first validated against controlled laboratory experiments of lava flowing downslope (Dietterich *et al*., 2017; see Fig. 1a). The simulated flow-front advance and spreading show good agreement with experimental observations, demonstrating the model's accuracy. We then apply the model to the 2021 Tajogaite eruption, making this the first fully 3D simulation of the Tajogaite lava flows. We model lava flow on real topography and explore scenarios involving artificial diverging barriers or deflectors placed to steer the flow.

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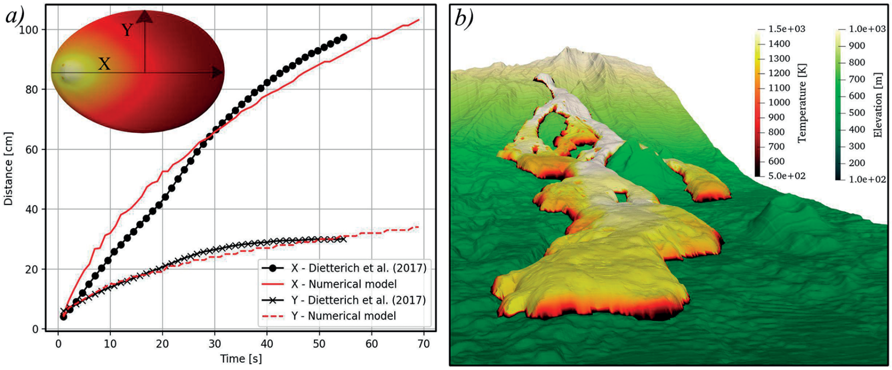

Fig. 1. *a*) Experimental (Dietterich *et al.*, 2017) and numerical flow-front distance (X) and width (Y) over time. *b*) Snapshot of the modeled lava flowing downslope and cooling over the topography of La Palma

Fig. 1b illustrates the modeled lava field for Tajogaite allowing us not only to identify the preferential flow paths but also to evaluate the temporal evolution of the temperature field. Our high-resolution 3D simulations provide insight into lava flow dynamics and deliver early predictions of affected regions, supporting emergency decisions such as evacuations and infrastructure protection during volcanic eruptions.

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PARTIAL CONE COLLAPSES AS A RECURRENT VOLCANIC HAZARD IN STROMBOLIAN ERUPTIONS: OBSERVATIONS FROM TAJOGAITE (2021) AND IMPLICATIONS FROM TIMANFAYA (1730-1736)

Inés Galindo[1], David Sanz-Mangas[1], María del Carmen Romero[2], Nieves Sánchez[1], Juana Vegas[1], Juan Carlos García López-Davalillo[1], Esther Martín[3]

Abstract

Volcanic cone collapses represent a critical, although frequently underestimated, hazard during effusive eruptions. While large-scale edifice failures are extensively documented, the incidence and impact of partial cone collapses occurring during ongoing Strombolian activity deserve to be considered a frequent volcanic threat. These events have the capacity to induce abrupt alterations in lava flow dynamics, generate secondary hazards, and significantly complicate hazard management strategies. The 2021 Tajogaite eruption in La Palma provided an unprecedented opportunity for the real-time observation and documentation of a series of partial cone collapses (Fig. 1). At least three major collapses have been identified, one of them described by Romero *et al.* (2022). All observed collapses generated dramatic changes in the cone morphology and produced debris avalanches that directly influenced the change in direction of subsequent lava flows, thereby highlighting their fundamental role in eruptive evolution and derived hazards. Previously, comprehensive field investigations of the historical Timanfaya eruption (1730-1736) in Lanzarote (Romero *et al.*, 2020), Canary Islands, provided geological evidence indicative of analogous partial cone collapse mechanisms. These earlier studies of the geomorphology and stratigraphy of ancient deposits, demonstrated the need of re-evaluating other volcanic deposits —specifically certain blocky lava flows— that might be genetically linked to these collapse processes. Such blocky lava flows, conventionally interpreted as effusive products, could represent syn-

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eruptive debris avalanches resulting from these partial collapses, thus potentially serving as proxies for past instability events. This contribution emphasizes the need to recognize and integrate partial cone collapses into the volcanic hazard assessments associated to Strombolian eruptions.

Fig. 1. Debris avalanche deposit (on the left) formed during the eruption of Tajogaite volcano

The observations from Tajogaite eruption, together with re-interpretations of historical geological records from Timanfaya, demonstrate that these phenomena are not isolated occurrences but rather recurrent processes that critically influence eruptive patterns and present an often-overlooked hazard to exposed communities and critical infrastructure. Further systematic research aimed at identifying these specific deposits within ancient volcanic fields is crucial for a comprehensive understanding of their spatial and temporal frequency and overall impact.

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RADIOISOTOPIC CHARACTERIZATION AND RADIOLOGICAL ASSESSMENT OF THE TAJOGAITE ERUPTION (2021, LA PALMA)

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Abstract

Volcanic eruptions represent a significant source of natural radionuclide emissions into the environment. Although these emissions are natural, they can alter the radioisotopic composition of surface soils and, as a result, increase the average annual radiation dose received by nearby populations. Despite this, radiological studies of volcanic eruptions remain limited. The 2021 Tajogaite eruption on La Palma Island (Canary Islands, Spain) offers a unique opportunity to assess these effects. The eruption, located on the western flank of the Cumbre Vieja rift zone, lasted 85 days and released vast amounts of lava, pyroclasts, lapilli, and ash (Carracedo *et al*., 2022). Over 1200 hectares were covered by lava flows, causing severe damage to homes, infrastructure, and agricultural land. Lava flows eventually reached the sea, forming lava deltas, while western winds transported ash across the island. Radon emissions, although less studied, were also recorded due to their potential radiological relevance. This study presents a radioisotopic characterization of the volcano's eruptive products and a preliminary assessment of the associated radiological impact. Activity concentrations of the main natural radionuclides from ^{238}U, ^{235}U, ^{232}Th decay chains, along with ^{40}K, were measured in 40 samples of lava, ash and xenopumice using alpha and gamma spectrometry. These results were compared with data from the 2011 Tagoro submarine eruption of El Hierro Island. To evaluate the terrestrial impact, a campaign was conducted across the island in July 2023, including over 150 in situ gamma dose rate measurements and the collection of 80 soil samples. Interpolation maps (Fig. 1) created using ArcGIS revealed maximum absorbed dose rates and ^{226}Ra activity concentrations near the eruption area – values significantly higher than the

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world average (UNSCEAR, 2000) and those reported in 2013 (López-Pérez *et al.*, 2021). Additionally, submarine sediment samples collected near the lava deltas during two oceanographic campaigns (January 2022: 72 samples; June 2023: 29 samples), are currently undergoing the radioisotopic analysis. This will help assess the potential radiological impact on the marine environment.

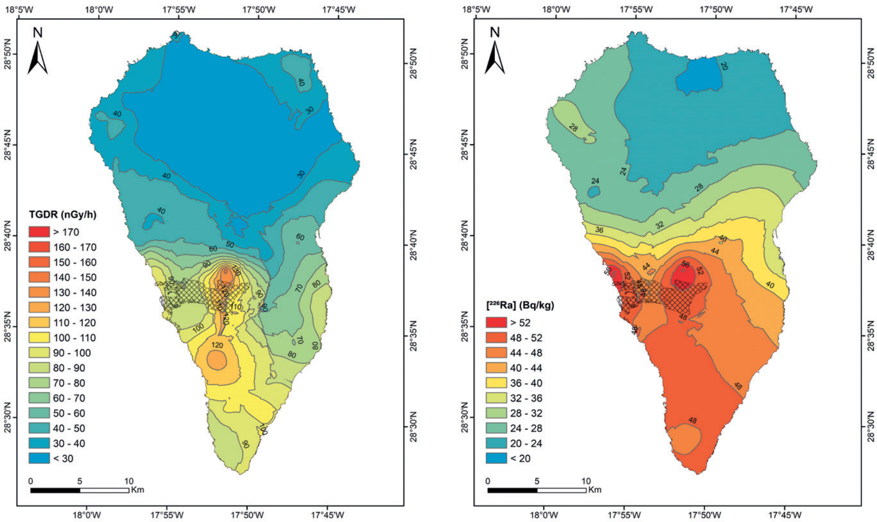

Fig. 1. Terrestrial Gamma Dose Rate (TGDR) distribution map (a) and activity concentration distribution of ^{226}Ra (b) of La Palma Island (July 2023). The dotted area delimits the extent of the lava flows

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MESSENGERS FROM BELOW AN OCEAN ISLAND: XENO-PUMICE IN HISTORICAL ERUPTIONS ON LA PALMA

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Abstract

Frothy inclusions of exotic origin (xeno-pumice) have been increasingly identified in volcanic rocks in the Canary Islands over the last decade (e.g. Jägerup *et al*., 2023). La Palma is historically the most volcanically active island in the archipelago and xeno-pumice occurs in the 3 kyr Las Indias eruption, the 1585, 1949, 1971, and 2021 AD deposits. Xeno-pumice have high glass contents, low density, and significant vesiculation, which indicates partial melting, inflation, and degassing of the protolith. We find that the major and trace element characteristics and oxygen isotope ratios of the La Palma xeno-pumice allows to divide them into two broad groups: 1) former oceanic sediments with continental and mixed continental and island-derived detritus, and 2) recycled igneous rocks of plutonic and volcanic derivation (dominan-

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tly trachytes and phonolites). Specifically, xeno-pumice derived from quartz-rich sedimentary rocks exhibit high silica contents (> 70 wt. % SiO_2) and elevated oxygen isotope ratios (> 12 ‰), while igneous derived xeno-pumice are feldspar-rich and exhibit intermediate SiO_2 wt. % and $\delta^{18}O$ values that range from magmatic to hydrothermally altered ones (c. 5.5 to 12 ‰). The occurrence of xeno-pumice may increase the overall gas budget of an eruption.

Notably, the Las Indias and the 1949 eruption deposits contain a significant amount of sedimentary xeno-pumice and both events are associated with explosive, phreatomagmatic eruption styles. For the 2021 eruption, in turn, the overall volume of xeno-pumice relative to the total volume of erupted juvenile materials is likely too small to show a discernible effect on eruptive style. We conclude that sufficient amounts of xeno-pumice, e.g. early in a new eruption episode, could increase the potential for explosive hydromagmatic eruptive styles, even in seemingly water-poor areas.

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CONTINUOUS MONITORING OF INDOOR CO_2 AND RADON IN TWO WATER WELLS AT ARIDANE VALLEY, LA PALMA

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Abstract

Indoor air quality in volcanic regions has received little research attention despite the potential health risks posed by the accumulation of volcanic gases in enclosed spaces. Since April 2023, 15 months after the Tajogaite eruption ended (Dec.'21), CO_2 concentrations >10 % vol. have been measured in several water wells of Aridane Valley, at 5 km away from Tajogaite edifice, which had never had problems due to the presence of CO_2 before. These CO_2 anomalies began when the wells resumed pumping activities after being mostly inactive for 18 months. A sharp increase in dissolved CO_2 of endogenous origin was also observed in the extracted water. In May 2023, CO_2 and radon (Rn) sensors were installed in the powerhouses of two water wells with anomalous CO_2 concentrations. Gas concentrations were measured every hour, as well as air moisture (Hr), air temperature (T) and barometric pressure (P). In water well #1 (May'23-Nov.'23) and #2 (Dec.'23-May'25), indoor CO_2 concentration ranges from 0.01 to 10 % (maximum detection limit), with average values of 1 and 2%, respectively. Regarding indoor Rn concentrations, in water wells #1 (May'23-Nov.'24) and #2 (July'24-Jan.'25), peak values of up to 6,000 and 10,000 Bq/m^3 and average values of 284 and 1,700 Bq/m^3, respectively, were recorded, well above the reference level of 300 Bq/m^3 set out in the Spanish law (RD 1029/2022). Both Rn and CO_2 concentrations in

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#1 and #2 water wells show significant variations with large daily oscillations. Joint analysis of the time series of CO_2 and Rn with the water flow rate (volume pumped), piezometric level and local precipitation, does not indicate significant correlation.

In contrast, Rn and P show an inverse correlation, as do CO, and P, though to a lesser extent, reflecting the influence of the barometric tide on CO_2 and Rn emissions, with both gases reaching their maximum daily concentrations during the low barometric tide, at around 4:00 and 16:00 local time. These results highlight the need for continuous monitoring of indoor air quality, even long after eruptive activity has ceased, as volcanic gas emissions can persist and pose significant risks in enclosed environments.

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THERMAL MODELING OF LAVA FLOW COOLING DYNAMICS FROM THE TAJOGAITE ERUPTION

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ABSTRACT

Following the 2021 eruption on La Palma (Canary Islands), the reconstruction of critical infrastructure and the recovery of agricultural land have been severely hampered by the slow cooling rates of the extensive lava flows. To address this challenge, two cooling models were developed to provide more accurate estimations of cooling times: the Homogeneous and the Heterogeneous models (González-de-Vallejo *et al.*, 2024). This latter model considers the lava flow as an anisotropic and heterogeneous medium, accounting for the specific geological and thermal properties at different locations. It incorporates the vertical stacking of distinct lithological layers, mainly compact basalt and scoriaceous breccias, and acknowledges their different thicknesses and thermal conductivities. Furthermore, the model integrates the presence of cavities and lava tubes, which significantly influence thermal behavior. Three key dimensionless parameters were defined to build the model: the Thermal

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Conductivity Reduction Coefficient (CRC), which accounts for the material composition and its thermal conductivity; the Thickness Ratio (TR), relating the measurement depth to the total flow thickness; and the Cooling Factor (CF), which combines the CRC and TR to quantify their joint effect on the cooling rate. Based on *in-situ* data from geotechnical boreholes (Rodríguez-Santana, 2022), the model calculates site-specific cooling coefficients derived from Newton's Law of Cooling (Maruyama & Moriya, 2021).

This allows for the simulation of cooling curves to predict the time required for the lava to reach temperatures suitable for reconstruction activities. While this Heterogeneous model offers a more realistic representation of the actual cooling process compared to the Homogeneous one, its application requires detailed lithological and thermal data obtained from direct site investigations. This methodology provides a crucial tool for engineers and planners to develop safer and more efficient strategies for reconstruction in volcanically active regions.

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THERMAL AND GEOTECHNICAL ASSESSMENT TO SUPPORT URBAN REDEVELOPMENT IN ZONES AFFECTED BY THE TAJOGAITE LAVA FLOWS (LA PALMA, CANARY ISLANDS)

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ABSTRACT

On September 19, 2021, a volcanic eruption began in the Montaña Rajada area on the island of La Palma. Once its impact on the territory had stabilized, social and economic recovery measures began to be implemented under the legal framework for territorial and urban planning (Copernicus, 2021). The work was carried out by the Canary Islands Volcanological Institute (INVOLCAN) for the Canary Islands Government's public company «Territorial and Environmental Management and Planning (GESPLAN)». The aim was to assess the thermal and geotechnical conditions of the lava flows generated by the eruption of the Cumbre Vieja volcano in 2021 (González de Vallejo *et al.*, 2024), with the objective of supporting urban planning and reconstruction on the island. The study focused on the Aridane Valley and included in situ and drone-based temperature measurement campaigns, surveys up to 10 meters deep, and geomechanical characterization of geotechnical units, following the GETCAN-011 Guide (Gobierno de Canarias, 2011) and the Technical Building Code, CTE (Gobierno de España, 2006).The results show a heterogeneous thermal distribution, with temperatures of up to 200°C at depths of 8 meters in some boreholes (S4), while others (S9) show values close to ambient tem-

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perature, suggesting progressive cooling or the existence of cavities. Two types of lava flows were identified: «aa» (low in scoria and geotechnically favorable) and «pahoehoe» (with internal cavities, less favorable), with thicknesses varying between d»5 m and e»20 m. Areas with high fracturing and cavities that condition geotechnical zoning were also detected.

For urban planning purposes, three categories of terrain were defined: favorable, conditioned (with greater uncertainty), and unfavorable. 22.7 % of the evaluated area (64.5 ha out of a total of 283 ha) is considered suitable for urban development. It is recommended to use shallow foundations, avoiding deep drilling that could release residual heat, as well as conducting geotechnical reconnaissance campaigns with boreholes and geophysical surveys to identify volcanic tubes. The main geotechnical risks are differential settlement in «aa» type flows and collapse due to cavities in «pahoehoe» flows. The zoning is valid until 2028 but requires continuous thermal monitoring to update urban viability.

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CHARACTERIZATION OF LOCAL SEISMIC RESPONSE IN THE ARIDANE VALLEY (LA PALMA) THROUGH HVSR ANALYSIS

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Abstract

Over the last 500 years, La Palma (Canary Islands) has experienced several volcanic eruptions, accompanied by intense volcanic seismicity. These volcanic events are capable of generating moderate-magnitude earthquakes ($M \geq 4.0$) with very shallow hypocenters, as observed during the 2021 Tajogaite volcanic eruption. During this event, the most affected area was the Aridane Valley, a major geological feature of the island, formed by a giant gravitational landslide of the Cumbre Nueva volcanic edifice. The geological complexity of the area could lead to local seismic amplification effects during volcanic earthquakes. For these reasons, local seismic microzoning surveys are crucial for analysing seismic hazards. In 2022, the Instituto Volcanológico de Canarias (INVOLCAN) performed a seismic microzonation survey with 200 ambient noise measurements in the Aridane Valley. Ambient noise measurements were conducted across both urban and rural areas, including natural environments. We applied the Horizontal-to-Vertical Spectral Ratio (HVSR) method (Nakamura, 1989) to the dataset recorded to identify the predominant frequencies of each point. The information obtained was compared with the existing geological and geotechnical data. Moreover, seismic data from permanent seismic stations in the area were also examined to assess temporal changes in the HVSR curves (Seivane *et al.*, 2024), allowing for the possible observation of variations during the pre-eruptive phase of the Tajogaite eruption. The

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preliminary results obtained revealed medium-to-low resonance frequency values, possibly related to gravitational landslide deposits, and high frequencies associated with thin layers covering ancient lavas.

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APPLICATION OF GEOSPATIAL TECHNIQUES FOR THE STUDY OF THE LAHAR HAZARD OF THE TAJOGAITE VOLCANO (LA PALMA, CANARY ISLANDS)

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Abstract

The PRISMAC project (1/MAC/2/2.4/0112), co-financed by the INTERREG VI D Madeira-Azores-Canary Islands MAC 2021-2027 Territorial Cooperation Program, aims primarily to analyze, mitigate, and manage natural hazards, with a particular focus on landslide movements, which are increased by the effects of climate change. To achieve this, harmonized methodologies for susceptibility and risk analysis are being developed, enabling the identification of high-risk areas within the participating Macaronesian regions. This will facilitate the creation of monitoring systems, early warning, and alarm mechanisms, which are essential for reducing the impact of these phenomena on populations and infrastructure. On September 19, 2021, a Strombolian volcanic eruption initiated on La Palma Island in the Canary Islands. This eruption led to the destruction of approximately 73 Km of road infrastructures, numerous residential structures, and agricultural lands. The event produced lava flows covering an area of approximately 12 Km^2, characterized by both aa and pahoehoe textures. In the context of climate change, one of the study sites is the west flank of the Tajogaite volcano, where a potential geohazard of lahar flows associated with intense precipitation of ash deposits has been identified, along with the instability of the slopes of the new volcanic cone following the eruption in the study by González de Vallejo *et al*. (2024). Prior to installing meteorological stations, precipitation data —such as those reported in the

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study by Santamarta *et al*. (2025), which analyzes local climate change scenarios in the Canary Islands using its SICMA climate prediction platform—were employed (Fig. 1). Additionally, geospatial analyses and computer techniques based on the work of Schilling (2014), who developed GIS tools for automated mapping of lahar inundation zones, are being used to optimize the possible location of the meteorological station on the Tajogaite flank.

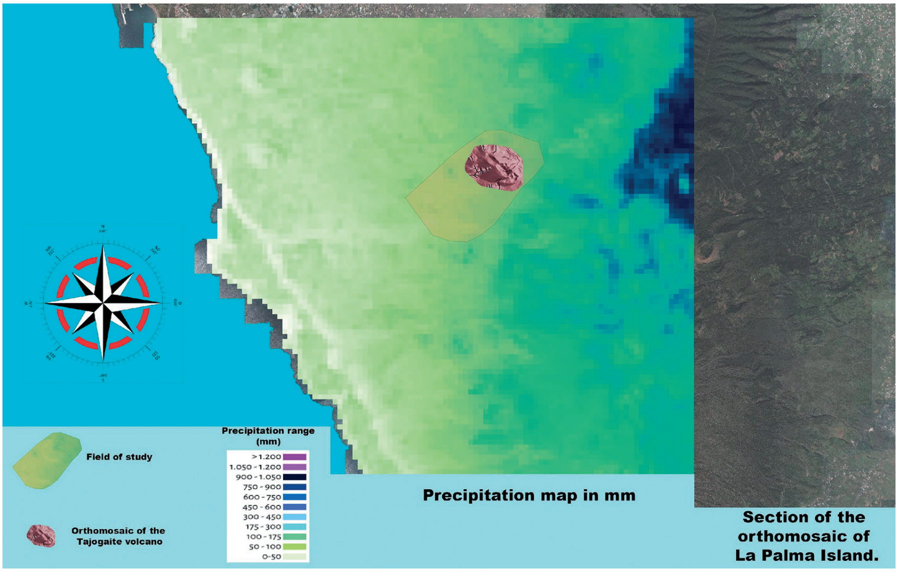

Fig. 1. Overlay of precipitation map (Font: SICMA) on West orthomosaic section of La Palma Island. The area of field study is showed

Combined with drone technology, these methods will study the volume of material susceptible to landslides using Digital Terrain Models (DTMs) and monitoring technologies to improve risk management in this vulnerable environment and contribute to the recovery of La Palma, as outlined in Law 2/2024, of May 29, on territorial and urban planning measures for the economic and social recovery of La Palma following the Cumbre Vieja volcanic eruption (Gobierno de Canarias, 2024).

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TAJOGAITE'S LAVA FLOW FIELD IMPACT: A WARNING FOR AUCKLAND'S VOLCANIC RESILIENCY

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ABSTRACT

Recent eruptions on La Palma are useful analogues for the Auckland Volcanic Field (AVF), due to common hazards and exposure. Both regions have monogenetic basaltic eruptions with scoria cones, lava flows, and significant tephra fall; on top of this, the areas are densely populated. This equates to heightened vulnerability of residents and infrastructure. The AVF is a distributed system of 53 known volcanic centres, scattered across New Zealand's largest city of 1.6 million people (GNS Science, 2020). While the AVF is considered active, it has not experienced unrest since 1446. Through support from National Geographic and the Natural Hazards Commission Toka Tū Ake, we have studied the chronology of evolving infrastructure impact in Tajogaite's lava flow field, improving our understanding of the likely damage of future eruptions. For the impacted buildings in the 2021 lava flow field, a Damage State was assigned using a data compilation of drone-based aerial footage, satellite data, and detailed, in-person investigations. These Damage States were then assessed alongside the lava flow characteristics at each location to understand any relationships between them. Subsequently, this data can inform modelling of similar eruptions in the AVF and resulting building damage. Through a time-series analysis of the eruption, along with damage evaluation, we have been able to explore the evolving impact on infrastruc-

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ture and compare Damage States acquired through the different methods. This has shown that residential building damage is complex and non-binary, and that the satellite data overestimates the damage incurred to an individual building, especially around flow margins.

This work forms the basis for scenario modelling in the event of an eruption in the densely populated Auckland area. With a specific focus on the Mt Eden lava flow, we will soon use lava flow modelling approaches to explore the variability in damage output and aim to provide an assessment of impact using current land use and property data. This study has accumulated a significant and uniquely detailed dataset, providing key inputs to applying damage state scenarios to other urban volcanoes, ultimately enabling the assessment of potential impacts for other eruptions.

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THERMAL AND GEOMECHANICAL ANALYSIS OF LAVA FLOWS FROM TAJOGAITE ERUPTION FOR THE RECOVERY OF AGRICULTURAL ACTIVITY (LA PALMA, CANARY ISLANDS)

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ABSTRACT

On September 19, 2021, a Strombolian eruption began on the island of La Palma (Canary Islands), marking one of the most impactful volcanic events in the island's recent history. The eruption lasted for 85 days and caused severe damage, particularly to infrastructure and agricultural land. Lava flows buried over 370 hectares of farmland —mainly banana plantations— with maximum thicknesses reaching up to 70 meters. More than 7,000 people were directly affected, and the total economic impact exceeded 840 million euros, with approximately 200 million corresponding to agricultural losses. After the eruption ended in December 2021, one of the most urgent challenges was the safe and efficient recovery of productive land. To address this, the Canary Islands Volcanological Institute (INVOLCAN), with funding from the Government of the Canary Islands, carried out the LPAgricultura project between 2023 and 2024. This project not only assessed the feasibility of resuming agricultural activity on lava-covered terrain and proposed practical rehabilitation solutions but also served as a technical foundation for the development of the regional legal framework, specifically the Decreto-ley 3/2024, of March

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11, on agrarian measures for the economic and social recovery of the island of La Palma following the Cumbre Vieja volcanic eruption. The project combined remote sensing techniques —such as drone-based thermographic surveys— with on-site fieldwork, including measurements of surface and subsurface temperatures (Fig. 1; González-de-Vallejo *et al.*, 2024).

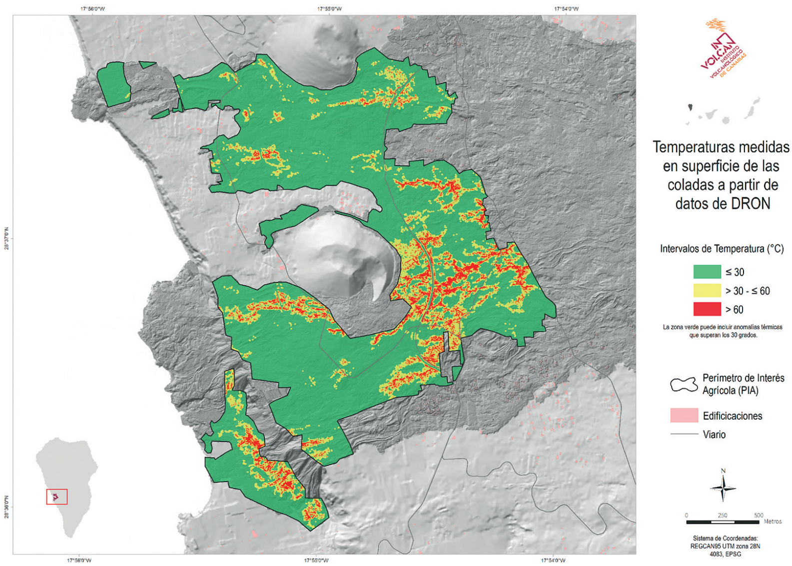

Fig. 1. Surface temperatures of lava flows measured from DRONE flights

In addition, key geomechanical aspects were evaluated, such as the presence of cavities, terrain stability, and load-bearing capacity, in order to ensure the safety of future agricultural operations. Based on the results, a simple yet effective land recovery strategy was proposed: minor surface leveling followed by the application of a topsoil layer. This method provides thermal insulation while creating a suitable base for replanting. The approach offers a replicable, cost-effective, and scalable solution for restoring agricultural productivity in volcanic environments under similar conditions.

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GEOTECHNICAL MAPPING FOR TERRITORIAL PLANNING IN THE ARIDANE VALLEY FOLLOWING THE TAJOGAITE ERUPTION (LA PALMA, CANARY ISLANDS)

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Abstract

On September 19, 2021, the island of La Palma experienced one of the most destructive volcanic eruptions in its recent history. The Strombolian event affected over 7,200 people, destroyed 73 km of roads, housing, and infrastructure, and covered 12 km² with lava flows reaching thicknesses of up to 70 meters (Carracedo *et al*., 2022). Economic losses exceeded 1.2 billion euros. Even more than two years after the eruption, residual temperatures above 500 °C persist in some sectors, severely constraining access and reconstruction activities (INVOLCAN, 2022). To support informed territorial planning, a comprehensive geotechnical mapping effort was undertaken by the Instituto Volcanológico de Canarias (INVOLCAN). The study involved surface and subsurface temperature monitoring (down to 10.3 meters), geomechanical assessments on accessible slopes, diffuse CO_2 gas emission surveys, and ambient seismic noise measurements using the H/V spectral ratio method (Nakamura,

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1989). Additionally, probabilistic volcanic hazard modelling was used to simulate potential lava flow trajectories from plausible future eruptive centers (Charco *et al*., 2020). The combined dataset enabled a multi-parameter evaluation of ground behavior under post-eruptive conditions. The analysis led to the classification of terrain into three main categories of geotechnical suitability: low, moderate, and high. It also identified zones with active degassing, elevated thermal gradients, and variable mechanical properties that pose constraints to urban development. These findings were used to develop an integrated quality index for each reconstruction area («bolsas de reconstrucción»), offering a robust, evidence-based tool to guide land-use decisions, infrastructure design, and risk-informed investment strategies (Fig. 1).

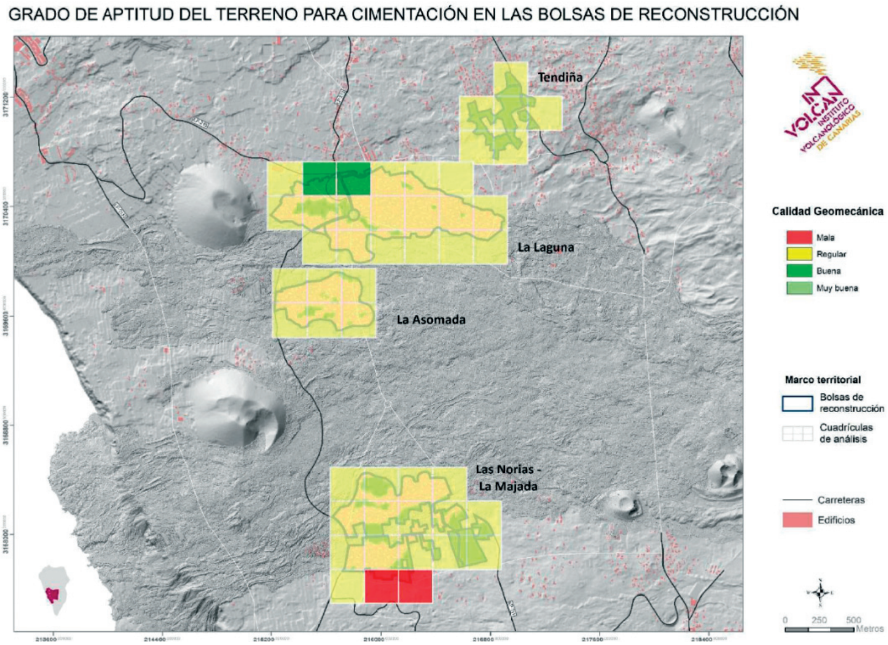

Fig. 1. Map of the four reconstruction zones (blue outline) showing soil suitability for foundations by grid cells (grey squares). Colors indicate geomechanical quality: red (poor), yellow (fair), green (good), and light green (very good). Territorial boundaries, roads (black lines), and buildings (pink) are also shown.

This geotechnical cartography is a key reference for achieving safe, adaptive, and resilient reconstruction planning in volcanic terrains.

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BOUNCING SPALLATION BOMBS DURING THE 2021 LA PALMA ERUPTION, CANARY ISLANDS, SPAIN

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ABSTRACT

Incandescent pyroclasts of more than 64 mm in diameter erupted from active volcanoes are known as bombs and pose a significant hazard to life and infrastructure. Volcanic ballistic projectile hazard assessment normally considers fall as the main transport process, estimating its intensity from bomb location and impact cratering. We describe ballistically ejected bombs observed during the late October 2021 episode of eruption at La Palma (Canary Islands) that additionally travelled downhill by rolling and bouncing on the steep tephra-dominated cone. These bouncing bombs travelled for distances >1 km beyond their initial impact sites, increasing total travel distance by as much as 100%. They left multiple impact craters on their travel path and frequently spalled incandescent fragments on impact with substrate, leading to significant fire hazard for partially buried trees and structures far beyond the range of ballistic transport. We term these phenomena as bouncing spallation bombs. The official exclusion zone encompassed this hazard at La Palma, but elsewhere bouncing spallation bombs ought to be accounted for in risk assessment, necessitating awareness of an increased hazard footprint on steep-sided volcanoes with ballistic activity.

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CASCADING IMPACTS OF THE 2021 TAJOGAITE ERUPTION: AN INTEGRATIVE FORENSIC AND ROAD NETWORK ANALYSIS APPROACH

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Abstract

The 2021 Tajogaite eruption on La Palma caused extensive cascading impacts to critical infrastructure (CI), particularly to the road network, disrupting decision-making, response, and recovery. An integrative Post-Event Impact Assessment (PEIA) was applied to understand the causal order of impacts from compounded volcanic hazards (lava flows and tephra fallout), utilising a graph-theory road network analysis. Traditional PEIAs aim to identify complex relationships within systems affected by volcanic eruptions. The integrative causal-order approach —adapted from Domínguez *et al*. (2021)— discretizes impacts into three orders, physical (direct damage), functional (loss of service), and systemic (effects in dependent sectors). Applied to Tajogaite, the vent location near populated areas, long duration (85 days), and magnitude (>12 km² lava, >190 km² tephra, 187 m cone) devastated the western road network, fragmenting connectivity. Lava runout reconstruction was possible via PEVOLCA and Copernicus Emergency Management Service (© 2021 European Union, EMSR546). Tephra impacts were analyzed using deposit reconstruction (Bonadonna *et al*., 2022, 2023) and Intensity Scales (Blake *et al*., 2017), revealing patterns based on wind shifts and accumulation. Whilst lava is highly destructive, tephra is disruptive, affecting skid resistance, visibility, and traffic flow. Five road functionality scenarios (FL-0 to FL-V) tracked spatial and temporal impacts. Agriculture was strongly affected by direct impact, lack of irrigation water, but also due to the dependence on the road network. Whilst

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PEIA identifies causal paths, it cannot quantify connectivity loss over space and time. Graph theory, using high-resolution hazard reconstructions, quantifies connectivity by modeling roads as nodes and edges, providing objective measures of connectivity and travel-time. Three performance phases —disturbance, degraded, and restorative were identified from Edge Closeness Centrality (ECC) (Fig. 1).

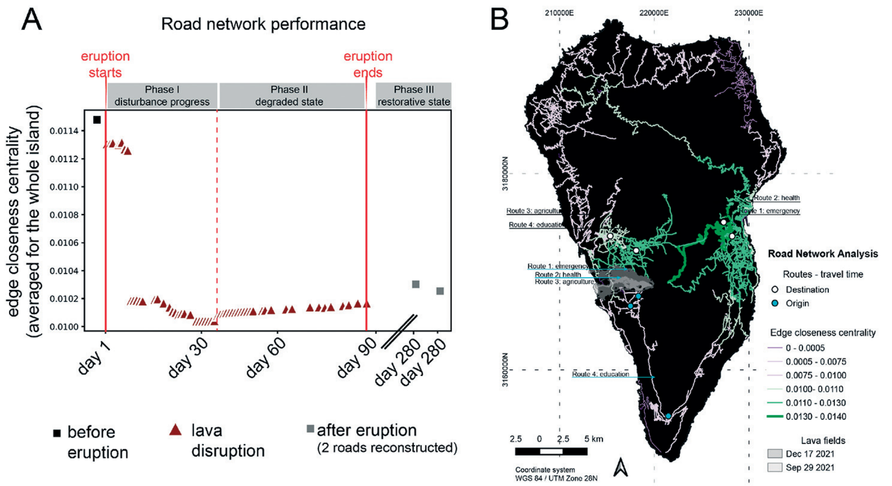

Fig. 1. A) Temporal evolution of Edge Closeness Centrality (ECC) showing three phases of road network performance. Restorative phase indicates ECC with two roads reconstructed after the eruption. B) ECC 6 months after the eruption. The Origin-Destination of four routes are also indicated. ECC indicates the closeness in distance from one edge to all the others (modified from Domínguez *et al.*, 2025).

Combining forensic PEIA with graph network analysis offers a powerful framework for quantifying and understanding cascading impacts of volcanic eruptions on CI. This methodology is adaptable to other CI networks beyond roads and should be expanded with physically meaningful, hazard-specific indicators. Network analysis for vulnerability and resilience assessments using historical and potential eruption scenarios can guide infrastructure planning and emergency preparedness, particularly in small islands with scarce land-use flexibility.

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Topic 5

Geophysical and geodesy monitoring

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A DIGITAL TWIN PROTOTYPE OF THE 2021 LA PALMA ERUPTION BASED ON DATA-DRIVEN MODELING OF MAGMA CHAMBER PRESSURE EVOLUTION

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Abstract

The 2021 eruption of Cumbre Vieja on La Palma provides a unique opportunity to explore the use of data-driven methods in real-time understanding and forecasting of volcanic activity. Here, we present a digital twin prototype of this eruption. The model is designed to assimilate observational data simulating and forecasting the evolution of pressure change within the magma reservoir throughout the eruption. A central insight of this work is the strong empirical relationship between GNSS-derived ground displacements and the cumulative volume of erupted magma. Despite both variables exhibiting exponential trends, their correlation appears approximately linear during the course of the eruption (Charco *et al.*, 2024). This observation motivates a minimal conceptual model in which pressure loss in a magma reservoir drives both surface deformation and eruptive flux. The model's simplicity allows for efficient data assimilation and opens the possibility of real-time forecasting of eruption duration. The digital twin prototype operates within the framework of data-driven modeling, continuously integrating time series of GNSS displacement data and estimates of erupted magma volume. Data assimilation is performed using an Ensemble Kalman Filter (EnKF) algorithm (Evensen, 2003), which updates internal model states and parameters in response to new observations, enabling improved tracking of the eruption's internal dynamics (Fig. 1). Notably, the framework is able to estimate, from early eruption data, the likely total erupted volume and approximate duration of the event.

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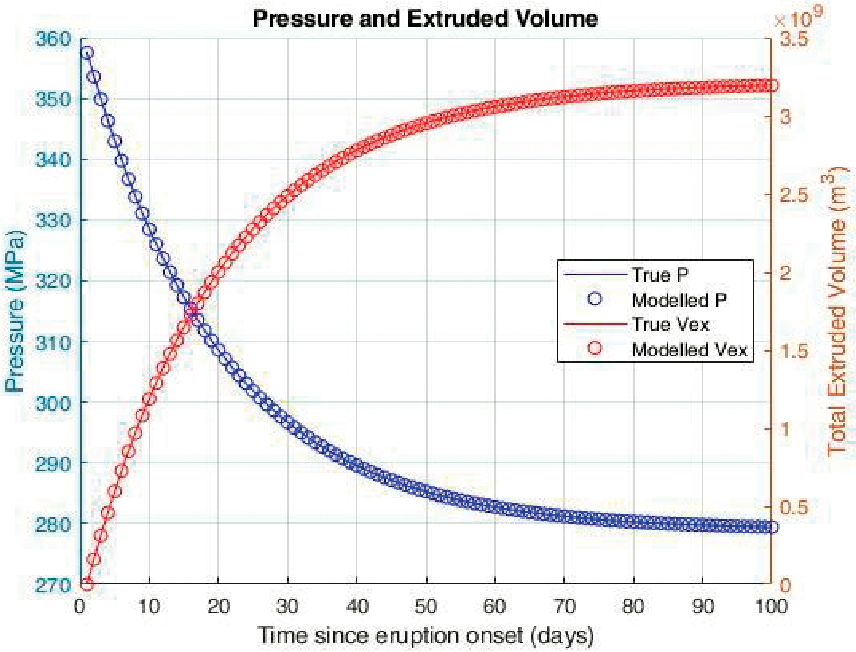

Fig. 1. Blue Circles: Modelled Chamber Pressure using an EnKF algorithm with synthetic GNSS and Extruded Volume Time Series. Blue Line: Synthetic True Chamber Pressure. Red Circles: Modelled Extruded Volume obtained from the Blue Circles. Red Line: Synthetic True Extruded Volume

The aim of the research is to demonstrate the feasibility of building lightweight, predictive digital twins of volcanic eruptions by combining physical insight with modern data assimilation techniques. While still in prototype form, the system offers a promising step toward tools that could support volcanic crisis management by providing short- to medium-term eruption forecasts based on accessible geodetic and eruptive data.

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ENTROPY-BASED SEISMIC MONITORING OF THE TAJOGAITE VOLCANO, LA PALMA

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Abstract

Seismological techniques are widely used to detect volcanic unrest and forecast eruptions. Among recent advances, Shannon Entropy (SE) analysis has proven effective in volcano monitoring. This method is based on the premise that, as an eruption approaches, coherent seismic sources begin to dominate the wavefield, reducing the signal's entropy. In contrast, during dormant periods, ambient noise prevails, resulting in higher entropy values. SE is typically applied to a single component per station and has shown promising results in diverse volcanic settings, such as Colima (Mexico) and Cumbre Vieja (Canary Islands) (Rey-Devesa *et al*., 2023a, b, c). In this study, we propose an extension of this approach using cross-entropy (CE) between station pairs (Shannon, 1948; Shannon & Weaver, 1949). CE not only detects coherent signals but also enables source localization through simple Gaussian interpolation of CE values. We applied this method to seismic data from the permanent network, Red Sísmica Canaria, of the Instituto Volcanológico de Canarias (INVOLCAN) on La Palma, prior to the 2021 Tajogaite eruption. A marked decrease in both SE and CE values was observed weeks before the

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eruption. The CE-based source location remained temporally and spatially stable, aligning with the area where the eruption eventually began. Moreover, stronger anomalies were detected in the hours leading up to the eruption. These early signals could have significantly supported evacuation decisions. Therefore, we suggest that combining SE and CE analyses offers a valuable tool for the automatic seismic monitoring of active volcanoes.

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VOLCANIC MONITORING USING LONG-PERIOD MAGNETOTELLURIC DATA: CANARY ISLANDS

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ABSTRACT

Geophysical methods are essential tools for volcanic monitoring, which is usually carried out using seismic and ground deformation methods. Electromagnetic (EM) methods are not commonly used despite their potential as volcanic monitoring tools, as they are sensitive to temperature and the presence of fluids (TED2021-131882B-C41,42 & 44). Among the EM methods, the magnetotelluric (MT) method is particularly valuable as it provides information on the electrical resistivity of the subsurface across a wide range of depths (tens of meters to hundreds of kilometers). Thus, during a volcanic eruption, MT could provide spatial and temporal information about the presence and variations in fluid characteristics as magma rises. MT has proven effective in characterizing magmatic systems in volcanic environments (e.g., Bedrosian *et al*., 2018; Hill *et al*., 2020), as well as in detecting changes in the distribution of electrical resistivity over time (e.g., Aizawa *et al*., 2011, 2013; Piña-Varas *et al*., 2023). An innovative MT volcanic monitoring experiment was conducted during the syn- and post-eruptive stages of the Tajogaite volcano eruption in 2021 (Piña-Varas *et al*., 2023). The main difference with previous studies is that in this case long-period MT was used, giving remarkable results showing resistivity changes in the vicinity of the volcanic cone of orders of magnitude in a matter of days. These results highlight the strong potential of MT as a volcanic monitoring tool and provide new insights about the evolution of the fluid pathways during the post-eruptive stage (Piña-Varas *et al*., 2023).

Given the favorable results of this initial experiment, a volcanic monitoring network using MT has begun to be set up in different islands of the

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Canary archipelago. At present, there is one site measuring continuously in La Palma (the same that was installed during the eruption of 2021) and two new sites (April 2023) installed in the island of Tenerife (Fig. 1). Since the deployment of the first MT site in 2021, important improvements have been made in the installation of the sensors, remote access to data, processing, etc. It is expected that further improvements will be implemented and the network will be further expanded in the near future.

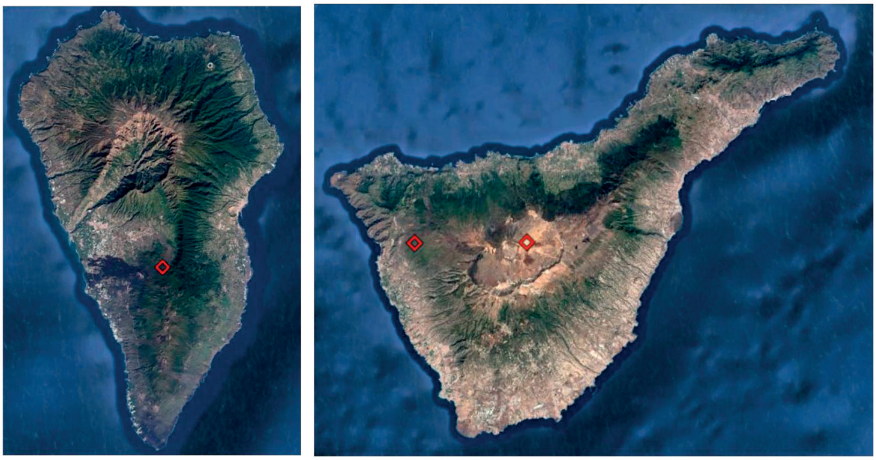

Fig. 1. Emerging MT volcanic monitoring network in the Canary Islands. Red symbols: Long-period MT sites currently installed where continuous information is available. Left: La Palma Island; right: Tenerife Island

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UNVEILING THE MAGMATIC PLUMBING SYSTEM OF THE TAJOGAITE VOLCANO USING DRONE MAGNETOMETRY

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ABSTRACT

La Palma Island (Canary Islands) has been the focus of numerous geophysical studies due to its recent volcanic activity. This work presents the results derived from two complementary aeromagnetic studies developed in the frame of the GEOTHERPAL project (TED2021-131882B-C41,42,44), highlighting the importance of magnetic methods for imaging volcanic crustal structures. Three-dimensional inversions of magnetic anomalies were applied both at a regional scale (Romero-Toribio *et al.*, in press), using data acquired by the Instituto Geográfico Nacional (Socías & Mézcua, 1996), and in detail over the Tajogaite volcano, using a new drone-based dataset collected two years after the 2021 eruption. The regional magnetic model revealed three main high magnetic susceptibility bodies, corresponding to dyke complexes at Cumbre Vieja, as well as lateral low susceptibility areas along the flanks, consistent with hydrothermal alteration processes (Romero-Toribio *et al.*, in press). Two older high susceptibility bodies located on either side of Northern Cumbre Vieja were found to have played a key role in the emplacement of the fault systems that controlled the 2021 Tajogaite eruption. The high-resolution magnetic survey over Tajogaite produced the first detailed anomaly map of this volcanic edifice (Fig. 1), leading to a magnetic susceptibility model that identified structures down to approximately 300 m depth. Low susceptibility was detected beneath the main edifice, interpreted as the feeding conduit remaining likely above its Curie temperature two years after the eruption. Anomalies along the Tazacorte and Mazo faults (Rodríguez-Pascua *et al.*, 2024) were

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also identified, along with a low-susceptibility signature elongated in a SW-NE direction, suggesting a still-hot magmatic pathway that was active prior to the onset, coinciding with the location of the most recent seismic swarm (Suárez *et al.*, 2023).

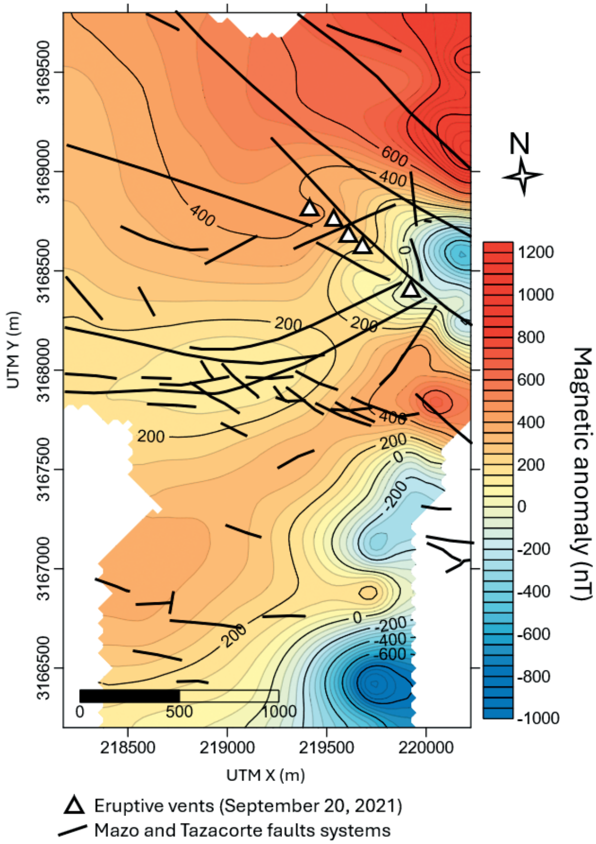

Fig. 1. Magnetic anomaly map of the Tajogaite volcano, acquired by drone at an altitude of 1142 m above sea level, two years after the eruption

Both studies have been integrated with geophysical datasets, including seismicity (Suarez *et al.*, 2023) or post-eruption magnetotellurics (Piña-Varas *et al.*, 2023). This enabled the conceptualization of an updated geodynamic model for the eruption, improving our understanding of its last-stage magmatic feeding system. We confirm the value of high-resolution drone-based aeromagnetic surveys in providing critical information on active volcanic environments.

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A SEISMIC ARRAY APPROACH TO UNDERSTANDING VOLCANIC TREMOR DURING THE 2021 TAJOGAITE ERUPTION

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Abstract

During the first stages of the 2021 Tajogaite eruption in La Palma, Canary Islands, the University of Granada deployed two seismic arrays for research and monitoring purposes. They had apertures of about 400 m and were located at distances of 4 km SE and 2 km NE from the eruption site. We use data from October 2021 to estimate the apparent slowness vectors of the seismic wavefield in different frequency bands between 0.8 and 3.6 Hz. The tremor wavefronts are characterized by apparent slownesses compatible with the propagation of surface waves impinging on the arrays from directions of ~300 and 260ºN, respectively. Strikingly, these directions are slightly deviated from the active vents. Moreover, temporal changes in the propagation azimuths suggest an apparent westward migration of the source. In order to estimate the location of the volcanic tremor source considering the effects of volcano topography and 3D velocity heterogeneities, we perform computer simulations based on a finite-difference method to define a synthetic slowness vector model (Almendros *et al*., 2001). We use a 1.5 Hz source time function and time series of point sources mimicking the long-lasting character of volcanic tremor. The velocity model is obtained from the travel-time tomography of D'Auria *et al*. (2022). The results during the selected period point to a source region extending WSW from the crater area. These observations are consistent with other structural and geophysical evidence and lead us to conclude that volcanic tremor in the 1-3 Hz band originated in deeper sections of the plumbing system, away from the processes occurring in the external vents.

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TSX-TDX-PAZ INSAR TIME SERIES OF LA PAMA ERUPTION 2021: A RADAR HIGH-RESOLUTION INTERPRETATION OF GROUND DEFORMATION

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ABSTRACT

Ground deformation, a common precursor of volcanic activity, can be measured with Synthetic Aperture Radar Interferometry (InSAR) using radar images acquired by satellites. This technique is widely used both in volcanic monitoring activities and in the study of volcanic systems and their behaviour. Typically, C-band sensors have been the most widely used in volcanic areas for several reasons. Their greater and easier availability of data and better performance in the presence of vegetation, located in many volcanic areas, are perhaps the two main reasons. However, compared to sensors operating in C-band, the use of high-resolution radar for volcanic monitoring has some important advantages such as lower acquisition frequencies and the possibility of detecting smaller deformations, which could even be missed by longer wavelength sensors. The high-resolution X-band constellation, formed by the Terra SAR-X (TSX), TanDEM-X (TDX) and PAZ satellites has been operational since 2019 as a whole, and since 2007, 2010 and 2019 the TSX, TDX and PAZ satellites have been in service respectively. The latter is the first Spanish Earth Observation radar satellite, operated by the company HISDESAT and with a mixed civil-military character. By properly combining acquisitions from the constellation formed by these three satellites, updated results can be obtained with a frequency of 4 days, instead of for example the 6-12 days currently provided by the Sentinel 1 constellation (C-band). It must be considered that a high frequency of data acquisition is essential in volcanic monitoring tasks, since it allows to update observations of a phenomenon that can evolve fast in very short periods of time. In this communication we show the InSAR time series from the TSX-TDX-PAZ constellation, processed with Gamma software, before, during and after the La Palma eruption of 2021. The results obtained will be compared with those from Sentinel 1 with a double

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purpose. On one hand results derived conclusions about the evolution of the volcanic system in La Palma which led to eruption in 2021. On the other hand, they help to redesign the InSAR service of the IGN volcanic monitoring system by routinely using X-band and C-band images over not only La Palma, but for the Canary Islands.

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SPATIOTEMPORAL SEISMIC ANALYSIS OF THE 2021 LA PALMA ERUPTION USING KERNEL DENSITY ESTIMATION

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ABSTRACT

On September 11, 2021, a significant increase in seismic activity and ground deformation was recorded on La Palma island, followed, days later and after the preventive evacuation of the population, by a volcanic eruption that began on September 19. The rapid interpretation of geophysical data and continuous monitoring of the phenomenon's evolution made it possible to avoid fatalities during the event. This study analyzes the spatiotemporal distribution of over 8,500 earthquakes recorded between 2017 and the present, distinguishing three main periods: the phase prior to the onset of seismicity associated with the 2021 eruption (before September 11), the active period up to September 27, and a third stage following a marked decrease in seismic and volcanic activity identified on that date (c. f. Ubide *et al*., 2023). To this end, the kernel method (Amador Luna *et al*., 2024) was applied to the seismic catalogs provided by the IGN, using both filtered and relocated datasets as well as unfiltered data. The objective was to identify areas of higher seismic concentration and to recognize the main structural orientations associated with the different deep magmatic reservoirs. The results allow the identification of four mechanically distinct levels (Fig. 1), each characterized by specific seismic alignments. From shallowest to deepest: (I) a shallow level (0-6 km), with a N-S orientation vertically aligned with cluster II; (II-III) a composite intermediate level (6-17 km), showing two distinct high-density seismic clusters in

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the southern part of the island —a smaller one to the northwest (II), and a deeper one to the southeast (see II and III); and (IV) a mantle-level zone (deeper than 6 km), with a NE-SW orientation. The temporal evolution of these orientations reflects the ascent of the magma through different reservoirs (like those identified in D'Auria *et al.*, 2022) until its emergence at the surface.

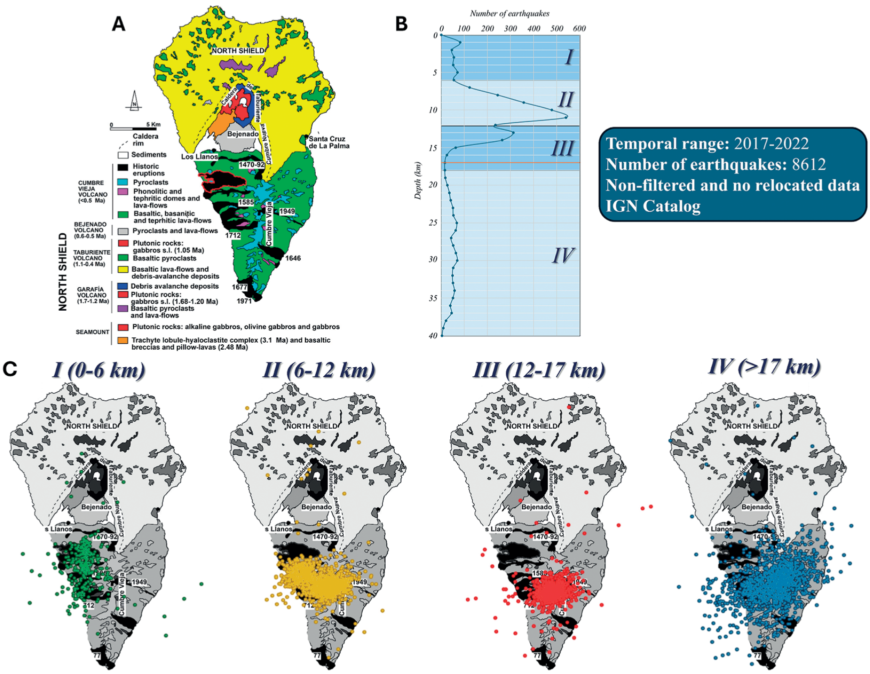

Fig. 1. A. Geological map of La Palma Island (from Casillas *et al.*, 2025). B. Depth distribution of seismicity associated with the 2021 La Palma eruptive event (including pre-eruptive seismicity since 2017 and post-eruptive seismicity through 2022). The different seismogenic levels are delimited based on seismic frequency mínima: I: 0-6 km; II: 6-12 km; III: 12-17 km; and IV: >17 km. Red line represents theoretical depth of the Moho from bibliography. C. Scatter plots for each of the identified seismogenic levels

This approach provides a better understanding of the internal structure of the La Palma volcano using a simple, rapidly applicable technique that is highly useful for near real-time monitoring of seismic and volcanic activity, ultimately contributing to more efficient risk management and the planning of evacuation strategies when necessary.

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UAS-BASED MULTITEMPORAL REMOTE SENSING OF THE TAJOGAITE CONE, 2021 CUMBRE VIEJA ERUPTION (LA PALMA, CANARY ISLANDS, SPAIN)

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ABSTRACT

The 2021 Tajogaite eruption (Cumbre Vieja volcanic ridge) is the largest historical eruption on La Palma Island. Over the course of almost 3 months, the volcano produced profound morphological changes in the landscape, affecting both the natural and the anthropic environment over an area of tens of km^2. Here we present the results of six UAS (Unoccupied Aircraft System) surveys (March 2022 to July 2024) coupled with Structure-from-Motion (SfM) photogrammetry that allowed us to produce high-resolution (up to 0.2 m/pixel) DSMs (Digital Surface Models) and orthophotomosaics (up to 0.1 m/pixel) (Fig. 1). We quantitatively documented the morphology of the newly formed volcanic cone and characterized its morphological evolution through time. Topographic change detection was performed by differencing our surveys and a pre-eruption surface to detect elevation, volumetric, and areal variations. We documented and quantified a variety of geomorphological processes and their interaction, such as the dismantling of the volcanic edifice, including episodes of gravitational collapse, the growth and propagation of faults and fractures dissecting the new cone, as well as the evolution of collapse structures within the lava field. The identification and characterization of the abovementioned features are relevant for understanding volcanic edifice evolution and its stability, for the assessment of the hazards related to tourist frequentation, and for the safety of the personnel involved in the monitoring activities.

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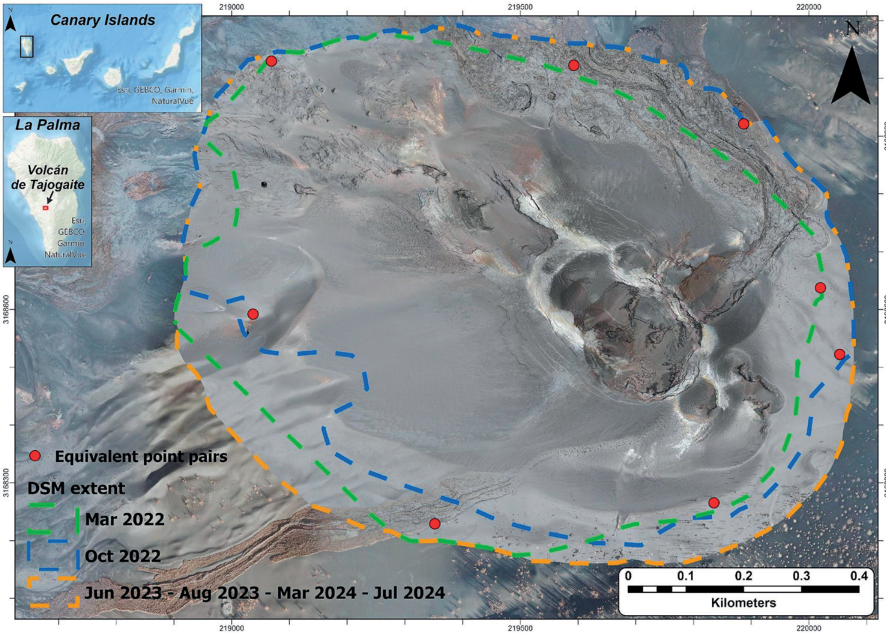

Fig. 1. Extension of UAS surveys at the Tajogaite cone between March 2022 and July 2024

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GNSS MONITORING DURING THE 2021 LA PALMA ERUPTION

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Abstract

Ground deformation monitoring is one of the primary tasks carried out by the Spanish Instituto Geográfico Nacional (IGN) as part of its volcanic monitoring service. During the 2021 La Palma eruption, GNSS was one of the key techniques used to assess ground deformation throughout the eruptive process. The data obtained from the continuous GNSS stations provided valuable insights into the evolution of magmatic activity. Prior to the onset of the eruption, just two days after seismicity began, surface deformation was detected mainly at GNSS stations located near the area where the eruption vent later formed. The measured deformation was consistent with a magma intrusion inferred from the seismic data. In the last two days before the eruption, GNSS station LP03, the closest to the vent, recorded a significant change: a sudden increase in displacement magnitude accompanied by a shift in displacement direction toward the southwest. At the same time, seismicity migrated northward and became shallower. During the eruption, the more distant GNSS stations around the island recorded a regional deflation centered in the eruptive zone. In contrast, the closest stations, particularly LP03, captured variations associated with shallow volcanic activity. Preliminary results were shared in near real time during PEVOLCA meetings and more refined subsequent analysis has enabled a detailed correlation with other geophysical observables. These findings confirm the critical role of GNSS in both real-time volcanic monitoring and the retrospective analysis of eruptive processes.

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TOWARDS REAL-TIME MONITORING OF PRE-ERUPTIVE SEISMIC ACTIVITY USING DEEP LEARNING: LESSONS FROM THE 2021 TAJOGAITE ERUPTION

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ABSTRACT

The 2021 eruption of Tajogaite (Cumbre Vieja, La Palma) was preceded by a complex seismic sequence that marked the onset of magma migration from depth to the surface. Understanding and monitoring these pre-eruptive signals in real time is essential for early warning and risk mitigation in volcanic environments. In this work, we present a fully automated system for real-time detection and analysis of volcano-tectonic earthquakes, developed using deep learning techniques and applied to the pre-eruptive phase of the Tajogaite eruption. The system continuously processes seismic waveforms from local networks and automatically detects, classifies, and locates earthquakes with minimal delay. It leverages a neural network trained on regional data to identify events and extract key parameters such as magnitude and hypocentral location, providing near-instantaneous results suitable for operational monitoring. When applied to the days leading up to the 2021 eruption, the system identified a much denser and more detailed picture of the seismic swarm than was available in standard manual catalogs. This included the early onset of deep seismicity, the progressive migration of hypocenters towards the surface, and the clustering of events in the days before the eruption — all of which

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are critical for interpreting volcanic unrest. This approach demonstrates the potential of machine learning to support real-time volcano monitoring, not as a replacement for expert analysis, but as a powerful complementary tool. Our findings highlight how automation can improve the speed and resolution of seismic surveillance during critical pre-eruptive periods, and how such systems can be integrated into operational workflows for future crises.

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FINITE SOURCE MODELLING OF VOLCANIC EARTHQUAKES BEFORE AND DURING THE 2021 TAJOGAITE ERUPTION: INSIGHT INTO THE ERUPTIVE DYNAMICS

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ABSTRACT

The September 19, 2021, eruption of the Tajogaite volcano (La Palma, Canary Islands) was preceded by a week of intense seismic activity. Hypocenters migrated westward and upward, following the path of bent and twisted dike. During the precursory phase, earthquakes reached a magnitude of up to 3.4; however, on the morning of Sunday, 19th September 2021, just a few hours before the eruption onset, a magnitude 4.1 earthquake shook the island, marking the opening of eruptive vents (Copernicus, 2021). During the eruption, several earthquakes with a magnitude of $M \geq 4$ were recorded, with hypocenters located at depths between X and Y (D'Auria *et al.*, 2022). In this work, we analyse the mechanism of these earthquakes using a finite fault model with rectangular or elliptical geometry. We model the full wavefield using a discrete wavenumber approach (Cotton & Coutant, 1997), parametrising individual seismic sources using a grid of point sources. We apply this methodology to a selected subset of earthquakes with magnitudes greater than 4.0, demonstrating how the fault geometry and mechanics are related to the local crustal structure and the dynamics of dike propagation. In particular, we focus our analysis on the vent opening phase, showing the relationship between local volcano-tectonic dynamics and the earthquake mechanism.

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MAGMA ASCENT DURING THE 2021 TAJOGAITE ERUPTION THROUGH GEODETIC IMAGING

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ABSTRACT

The eruption of Tajogaite in 2021 was preceded by notably brief seismic precursors of just eight days. Seismicity began on September/ 11 with a westward and upward migration of hypocenters. Ground deformation was registered starting one day after the seismic activity began, localised on the western side of the island. The maximum GNSS-recorded uplift just before eruption onset was on the order of 15/ cm. After the onset of the eruption on September 19, deformation continued to increase until reaching its maximum on September 22. After this peak, the ground deformation shifted and showed a nearly steady deflation trend in the following months. A detailed study of the eruption's dynamics was conducted by combining GNSS and Sentinel-1 time series from both ascending and descending orbits. Combining the non-linear inverse modelling with the precise distribution of seismicity revealed the geometry and location of the source responsible for the observed deformation. This joint modelling resulted in a twisted dike bending eastward. Using this geometry, we conducted a spatio-temporal inverse modelling to understand the evolution of the dike in the days preceding the eruption. To achieve this, we utilised a 3D finite element computational environment, taking into account the island's topography. Our 4D modelling of the dike ascent revealed the correspondence between magmatic intrusion and pre-eruptive seismicity. The magma ascended through two branches, and crustal rheology affected the

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magma propagation process (Fig. 1). The early shallow deformation was related to the ascent of hydrothermal fluids beneath the Cumbre Vieja volcano. Our study reveals the need for advanced modelling to understand pre-eruptive processes in basaltic volcanoes (Przeor *et al.*, 2024).

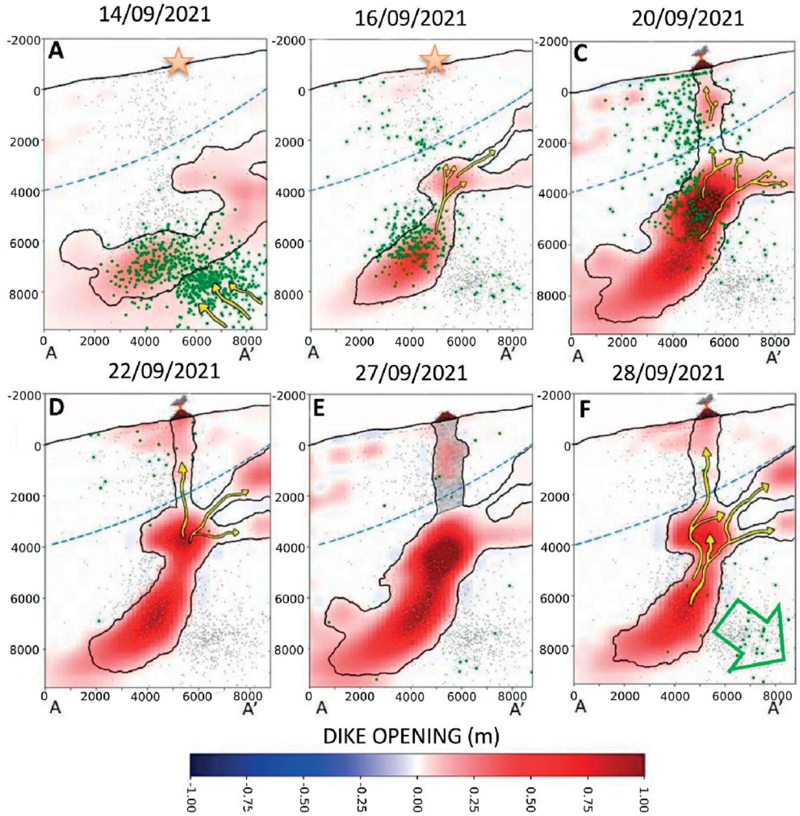

Fig. 1. Schematic model of the plumbing system dynamics for key dates. Orange stars represent the location of the site of the volcanic vent in the days preceding the eruption. The symbols of the volcano represent the location of the actual volcanic vent. Yellow arrows represent the magma ascent directions, while the green arrow indicates the incipient collapse of the magma reservoir. The blue dashed lines represent the limit of the rheological boundary.

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SPATIO-TEMPORAL VELOCITY VARIATIONS OBSERVED DURING THE PRE-ERUPTIVE EPISODE OF TAJOGAITE ERUPTION INFERRED FROM AMBIENT NOISE INTERFEROMETRY

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ABSTRACT

This study, published by Cabrera-Pérez *et al*. (2023), investigates the pre-eruptive phase of the 2021 Tajogaite eruption (Canary Islands, Spain) using ambient noise interferometry. On Sept. 19th, 2021, a volcanic eruption began on the island of La Palma (Canary Islands, Spain). The pre-eruptive episode was characterised by seismicity and ground deformation that started approximately 8.5 days before the eruption. In this study, we applied ambient noise interferometry to the data recorded by six broadband seismic stations operated by Instituto Volcanológico de Canarias, allowing us to estimate velocity variations during the weeks preceding the eruption. About 9.5 days before the eruption, we observed a reduction in seismic velocities registered next to the

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eruptive centres that opened later. Furthermore, this zone overlaps with the epicentres of a cluster of volcano-tectonic earthquakes located at shallow depths (<4 km) and detached from the main cluster of deeper seismicity (Fig. 1).

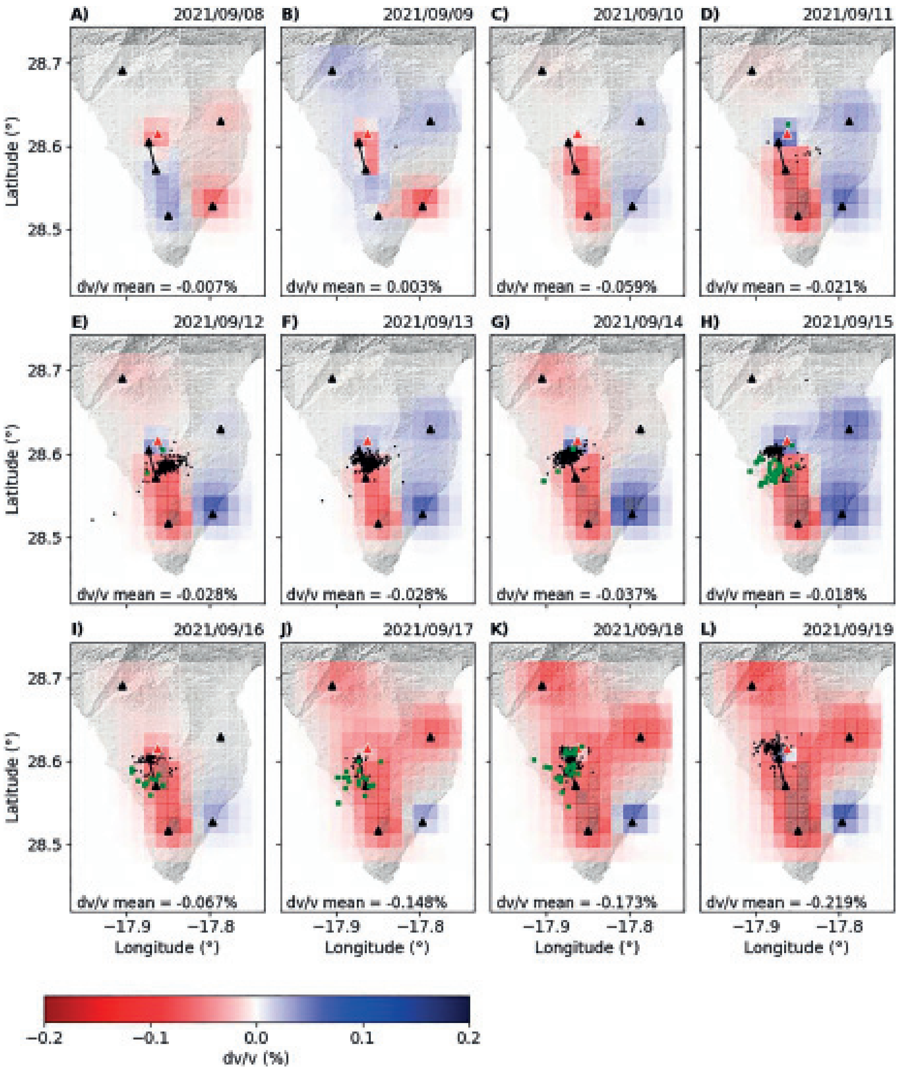

Fig. 1. Spatial distribution of *dv/v* for different dates in September 2021. The green and black dots represent the seismicity related to the fluid injection and magmatic intrusion, respectively. Seismic stations appear like black triangles, and a red triangle shows the 2021 eruptive vent. The black line represents the approximate raypath of the station pair PLPI-PPMA, which is the closest to the eruption site

The timing and location of these velocity drops suggest they are linked to hydrothermal fluid release and magmatic ascent, resulting in structural damage and elastic strain accumulation within the crust —a process supported by prior documented velocity decreases related to magmatic and hydrothermal activity (e.g., Ueno *et al*., 2012; Yukutake *et al*., 2016).

We conclude that the decrease in seismic velocities and the occurrence of such a shallow earthquake cluster are the result of hydrothermal fluid released by the ascending magma batch and reaching the surface faster than the magma itself. This study highlights the sensitivity of ambient noise interferometry for detecting early signals of magmatic and hydrothermal activity, although it is less effective once intense volcanic tremor begins. The findings demonstrate the value of integrating seismic velocity monitoring with other geophysical and geological data to improve eruption forecasting. Early identification of velocity anomalies provides critical insight into subsurface processes, offering a powerful tool for volcanic hazard assessment.

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EDGE-DETECTION TECHNIQUES APPLIED TO A DAS DATASET RECORDED DURING THE 2021 TAJOGAITE ERUPTION (LA PALMA, CANARY ISLANDS)

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Abstract

Distributed Acoustic Sensing (DAS) has emerged as a transformative technology in seismology, enabling the conversion of existing fiber-optic cables into dense linear arrays of virtual sensors. This approach is particularly valuable in volcanic environments, where dense coverage is difficult to achieve with conventional instrumentation. By providing high-resolution records of ground motion, DAS holds strong potential for detecting and characterizing seismic phases associated with volcanic processes. Yet, the massive data volumes produced—often several terabytes per experiment—demand the development of efficient analysis strategies capable of extracting meaningful information in real time. In this study, we present a novel methodology that leverages edge-detection techniques to enhance the identification of seismic phases in DAS recordings. Specifically, we employ the Discrete Cosine Transform (DCT) to treat DAS data as images, applying edge-enhancement filters to highlight the onsets of P- and S-wave arrivals. This image-processing perspective provides an effective alternative to classical phase-picking methods, which are often challenged by DAS data heterogeneity. Once the phases are characterized, we implement relative location strategies to estimate hypocentral positions without requiring precise knowledge of the fiber's geometry—an inherent limitation of submarine and buried cables. We test this methodology on DAS datasets acquired from submarine cables in the Canary Islands, with particular focus on signals recorded during the 2021 Tajogaite eruption on La Palma. The results demonstrate that DCT-based detection, combined with relative reloca-

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tion, enhances the spatiotemporal resolution of seismic event analysis. This is especially relevant for volcanic islands and offshore regions, where conventional networks are sparse and costly to maintain. Our findings highlight the potential of integrating image-processing concepts into seismic DAS workflows, providing new tools for the rapid detection and relative location of volcanic seismicity. This work underscores the importance of innovative data processing in advancing DAS applications, paving the way toward real-time monitoring systems that improve our understanding of eruptive dynamics and contribute to more effective hazard assessment.

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STUDY OF THE MAGMATIC SOURCE AND CRUSTAL STRUCTURE OF CUMBRE VIEJA BY RECEIVER FUNCTIONS

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ABSTRACT

The receiver function analysis (RF) is a commonly used and well-established method to investigate subsurface crustal and upper mantle structures, removing the source, ray-path and instrument signature. RF gives the uniqueness of sharp seismic discontinuities and information about P-wave (P) and shear-wave (S) velocity below the seismic station. This work aims to study the crust and the upper mantle of La Palma up to 50 km depth by using RF analysis. Because of the geological context as an active island, it is expected that Mohorovičić's discontinuity has a complex geometry under Cumbre Vieja and possibly a high anisotropy can be present. This makes the application of conventional RF function analysis difficult. That is why in this study, we applied the frequency-domain RF inversion using multi-taper deconvolution. After that, we have applied the transdimensional approach to determine 1D profiles of P and S wave velocities in terms of probability distributions, as well as the probability of a discontinuity to be located at a given depth. This approach does not require establishing «a priori» the number of layers to be used for the inversion. Our results allowed us to correlate the different discontinuities besides the stations we got deployed around Cumbre Vieja. We have seen five different layers with a significant change in their Vp/Vs ratios. These results are compared with the seismicity observed during the 2021 Cumbre Vieja eruption, mainly located at the base of the crust (10-15 km) and in the upper mantle (20-30 km), indicating the presence of two magmatic reservoirs at these depths.

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Topic 6

Geochemical monitoring

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THE NOBLE GAS AND CARBON ISOTOPIC SIGNATURE OF THE 2021 TAJOGAITE ERUPTION (LA PALMA, CANARY ISLANDS)

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Abstract

The 2021 Tajogaite eruption on La Palma provided a unique opportunity to investigate the temporal evolution of magmatic volatiles and mantle source characteristics beneath the Canary Islands. We analyzed the elemental (He-Ar-CO_2-N_2) and isotopic (He-Ar-Ne) compositions of fluid inclusions (FI) in olivine and clinopyroxene phenocrysts from Tajogaite lavas, tracking significant temporal changes during the eruption (Fig. 1). From mid-October, we observed increasing He-CO_2-N_2 concentrations in FI, paralleled by elevated $^{40}Ar/^{36}Ar$ ratios (>500) and a shift in lava composition toward more primitive signatures, including higher Mg# (up to 59), elevated CaO/Al_2O_3, and increased Ni and Cr contents. These geochemical changes indicate a growing contribution of deeper, less-degassed magma sourced from the mantle (15-30 km), corroborated by mineral thermobarometry and FI barometry. Despite these compositional shifts, $^3He/^4He$ ratios (Rc/Ra) remained constant throughout the eruption at MORB-like values (7.38 ± 0.22 Ra), suggesting an isotopically homogeneous magma source. The He isotopic signature aligns with those from the 1677 San Antonio eruption (7.37 ± 0.17 Ra) but is more radiogenic than the >9 Rc/Ra values recorded in the Caldera de Taburiente. Modeling indicates that the He isotope composition reflects three-component mixing among MORB-like mantle, a radiogenic source, and a minor high-$^3He/^4He$ (>9 Ra) endmember. The simultaneous presence of both MORB-like and high-$^3He/^4He$ signatures across La Palma points to small-scale mantle heterogeneities. To further characterize carbon behavior, we analyzed $\delta^{13}C$ values and $CO_2/^3He$ ratios in FI from Tajogaite and San Antonio lavas, and ultramafic xenoliths. $\delta^{13}C$ values ranged from -4.94 ‰ to -2.71 ‰ with $CO_2/^3He$ ratios of $3.37\text{-}6.14 \times 10^9$. Comparable isotopic signatures in xe-

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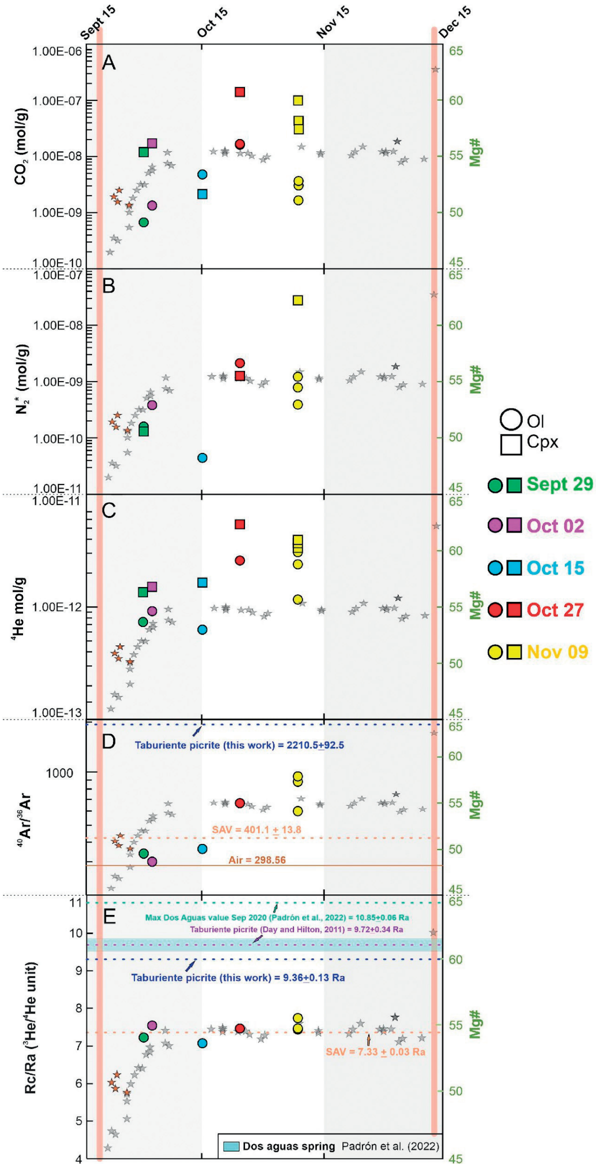

Fig. 1. Temporal variation of He, CO_2 and N_2 concentrations and $^{40}Ar/^{36}Ar$ and Rc/Ra ($^3He/^4He$ ratio corrected for atmospheric contamination) ratios between September 29th and November 9th. Gray and brown stars in figures A-E represents the variability of bulk Mg# after Day *et al*. (2022) and Pankhurst *et al*. (2022), respectively. Orange and dark blue dotted lines represent the averages for the San Antonio lava (SAV) and the picrite here studied, respectively. The light blue represents the variability of $^3He/^4He$ in the Dos Aguas spring during the eruption. Red lines indicate the beginning and the end of the eruption

noliths and previous data from the Taburiente Caldera suggest island-wide carbon isotope homogeneity.

This signature likely reflects either variable degassing of a common mantle source ($\delta^{13}C \sim -1.7$ ‰) or mixing between depleted mantle carbon and recycled crustal carbon ($\delta^{13}C = 0$ ‰). The presence of crustal carbon components in La Palma, El Hierro, and Lanzarote indicates regional-scale metasomatic enrichment of the Canary Islands mantle.

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DEVELOPMENT OF PORTABLE XRF AS A TOOL FOR RAPID MAGMA CHARACTERISATION: INITIAL APPLICATION TO 2021 TAJOGAITE ERUPTION

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Abstract

Understanding when and how volcanic eruptions will end is a key question for managing volcanic hazard. Detailed, near-daily sampling of recent mafic eruptions has shown that in some cases, erupted magma compositions begin to change in the days- weeks prior to eruption cessation (e.g. Scarrow *et al.*, 2024). To date, near-live petrological data has been limited to well-resourced, global north countries, producing a gap in how petrological data could be used in responding to eruptive activity depending on resource availability. The advent of portable X-ray fluorescence (pXRF) has the potential to bridge this gap. Use of pXRF in mining industries and archaeology for rapid identification of key elemental concentrations in bulk samples has been widely adopted. However, application of pXRF methodologies on volcanic samples is limited and to date has required close collaboration with developers (Steiner *et al.*, 2017). In this contribution we make use of existing detailed characterisation of the eruptive products from the 2021 Tajogaite eruption from La Palma, Canary Islands (e.g. Scarrow *et al.*, 2024), where glass and whole rock compositions are shown to change approximately 2 weeks before eruption cessation, with no corresponding change in the crystal cargo (Scarrow *et al.*, 2024, Chamberlain *et al.*, 2025; Longpré *et al.*, 2025,). We use the same powders, hand samples and tephras analysed by Scarrow *et al.* (2024) to co-

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llect pXRF data on magmatic compositions. We investigate the different calibration methods, analytical procedures, and the effects of different types of samples (lava, tephra, powder) to assess the reliability of pXRF methods. We consider the barriers to, and potential application of pXRF spectroscopy in monitoring future eruptive episodes.

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DISSOLVED HYDROGEN AND SEISMICITY IN VOLCANIC OCEANIC ISLANDS: THE CANARY ISLANDS CASE

NATIVIDAD LUENGO-OROZ[1], PEDRO TORRES-GONZÁLEZ[1], WALTER D'ALESSANDRO[2]

ABSTRACT

Volcanic eruptions are phenomena difficult to predict, especially on oceanic volcanic islands with few historical records available. Dissolved gas sampling has proved to be a relevant tool for volcano monitoring in this specific volcanic context (Torres-González *et al.*, 2020; Amonte *et al.*, 2022). Different magmatic gaseous species have historically been studied, identifying some of them as powerful tools to detect volcanic unrests like carbon dioxide and helium (Capasso *et al.*, 2005). In La Palma, El Hierro and Tenerife islands (Canary Islands), dissolved gas samples were taken every two-three months in groundwater galleries and wells following headspace analysis method (Caspasso & Inguaggiato, 1998). Dissolved hydrogen concentration in those samples was determined at INGV laboratories in Palermo (Italy). Variations in dissolved hydrogen concentrations related to seismic swarms both in La Palma (prior to Tajogaite eruption in 2021) and Tenerife islands have been detected, pointing to a relationship between seismicity and hydrogen generation due to stress occurrence during seismic and/or magmatic unrest (Zgonnik, 2020; Torres-González *et al.*, 2020). Regarding El Hierro island, there is no clear evidence of this relationship after the Tagoro submarine eruption in 2011-2012. Since before the eruption no data was collected, we cannot conclude if the same behavior was followed. In Tenerife three groundwater sampling points were studied, two of them located at the north of Las Cañadas caldera and the other one on the southern zone of the island. Dissolved H_2 in the first ones responded to seismic swarms located close to Teide volcano. The southern point seemed to react to seismic swarms located nearby. Besides, both

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northern and southern points showed H_2 dissolved peaks likely related to deep seismicity located offshore near the NO Rift. In La Palma, a tide pool located on the west coast was sampled. Every seismic swarm detected on the island since October 2017 until the Tajogaite eruption in 2021 has been associated with a change in dissolved hydrogen at the mentioned sampling point. Two wells have been sampled in El Hierro since the end of 2012, after the Tagoro volcano 2011-2012 submarine eruption. In both locations, in the north part of the island —El Golfo—, dissolved H_2 peaks have been detected but no temporal relationship with seismicity on the island has been observed.

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MANTLE HETEROGENEITY BENEATH LA PALMA ISLAND REVEALED BY HELIUM ISOTOPES MEASURED IN GAS AND WATER SAMPLES

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Abstract

The isotope composition of helium, an inert noble gas, carries precious information about the source of sampled fluids and the activity status of volcanic systems (Torres *et al.*, 2020). It has been frequently measured in fluid samples collected since 2013 in many sites of La Palma including the craters newly formed during the 2021 Tajogaite eruption. Sampling sites were all from the Cumbre Vieja volcanic edifice except Dos Aguas, which is in the Taburiente caldera. Collected samples were analysed for the chemical composition of the gases and the isotopic composition of C and He. Samples can be subdivided in two main groups which seem fed by two different mantle sources. The first group comprises samples from Cumbre Vieja edifice showing R/Ra values spanning from 1.27 to 7.70 and plotted against 4He/20Ne ratios (Fig. 1) evidence a mixing trend between atmospheric air and a MORB-type mantle end-member (R/Ra 8±1). Samples taken at Dos Aguas, forming the second group, show R/Ra values from 8.15 to 9.92 defining a mixing trend between atmospheric air and a mantle end-member (R/Ra ~9.8) significantly enriched in a deep mantle component (Fig. 1). Based on helium isotope composition measurements of fluid inclusions in olivine and clinopyroxenes, previous studies hypothesised a heterogeneous mantle beneath the Canary archipelago (Day & Hilton, 2011, 2021). Until recent times, data were not enough to show heterogeneities in the mantle sources of fluids rising up in the island of La Palma. The recent eruption of Tajogaite volcano in 2021, sharply increased the interest of researchers for this island. The huge amount of data gathered since then allowed researchers (Sandoval-Velásquez *et al.*, 2023, 2024) to

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recognize small scale heterogeneities in the mantle source beneath La Palma. The data on water and gas samples gathered in the present study are in line with those obtained from fluid inclusions and allow to differentiate a MORB-type source that fed the Tajogaite eruption and all fluid manifestations of the Cumbre Vieja volcanic edifice and another source more enriched in a deep-mantle component which is only found at Dos Aguas gas manifestation and in the picrites of the Taburiente Caldera.

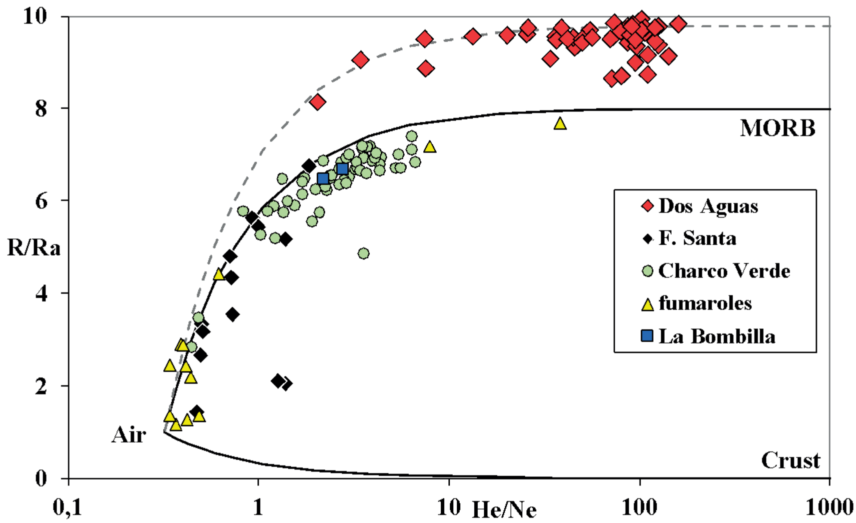

Fig. 1. R/Ra vs. He/Ne binary graph measured in fluids collected on the island of La Palma

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PRECURSORY GEOCHEMICAL SIGNALS OF THE 2021 TAJOGAITE ERUPTION THROUGH AUTOMATIC GEOCHEMICAL STATIONS

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Abstract

On 7-9 and 13-14 of October 2017 two intense seismic swarms occurred beneath Cumbre Vieja (La Palma, Canary Islands), which meant the first seismic evidence of the magmatic rise that would produce the 2021 Tajogaite eruption. As part of the geochemical monitoring of Cumbre Vieja volcano, diffuse CO_2 emission and soil gas 222Rn activity were continuously measured before, during and after the 2021 Tajogaite eruption at Cumbre Vieja volcano, at two different geochemical stations: LPA04 and LPA01, respectively. LPA04, located at the southernmost part of Cumbre Vieja, depicted seasonal variations in the diffuse CO_2 emission, with values in the range 50-100 g m-2 d-1 in the summer (dry) season and lower values in winter. The seasonal variations were broken after October 2017 seismic swarms: it measured relatively constant values around 250 g m-2 d-1 in the first half of 2018 and a sustained increase in the emission values, reaching the maximum of the series, up to 900 g m-2 d-1 at the beginning of 2021. The 222Rn activity in the soil gas measured at LPA01, located in the north-east part of Cumbre Vieja, showed also a sustained increase in 2021 from negligible values up to 10 kBq m-3. Similar behavior was observed in two geochemical stations before the 2011-2012 submarine eruption of El Hierro, Canary Islands (Padilla *et al*., 2013). The dilatant expansion in the crust caused by the strain-stress changes during the magmatic rise takes the form of new cracks which open up between and through the grains. Thus, the 222Rn activity in the soil gases can respond to strain-stress changes and show precursory increases before the eruption. The results of the geochemical monitoring through automatic

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stations before the 2021 Tajogaite eruption confirm the utility of these volcanic activity monitoring techniques and provide useful information on the origin of geophysical signals and for eruption forecasting.

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TRACKING MAGMA DEGASSING DYNAMICS DURING THE 2021 TAJOGAITE ERUPTION USING DAILY OP-FTIR MEASUREMENTS

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Abstract

Between September and December 2021, the Cumbre Vieja volcano on La Palma (Canary Islands) produced an 85 day explosive effusive eruption of basanitic magma after over fifty years of quiescence. Explosive activity was concentrated at the vents of the newly formed Tajogaite cone, where rapid shifts occurred between vigorous lava fountains, Strombolian bursts, and ash rich explosive jets. Simultaneously, lava spattering and effusive flows emerged from lower flank vents. From October 3, 2021, until the end of the eruption, daily measurements of volcanic gas composition were carried out using open path Fourier transform infrared (OP FTIR) spectroscopy, enabling real time tracking of degassing associated with both explosive and effusive activity (Asensio-Ramos *et al.*, 2025). Results revealed a clear compositional dichotomy between the two degassing regimes. Explosive emissions displayed extremely high CO_2/SO_2 and CO_2/HCl molar ratios, which correlated closely

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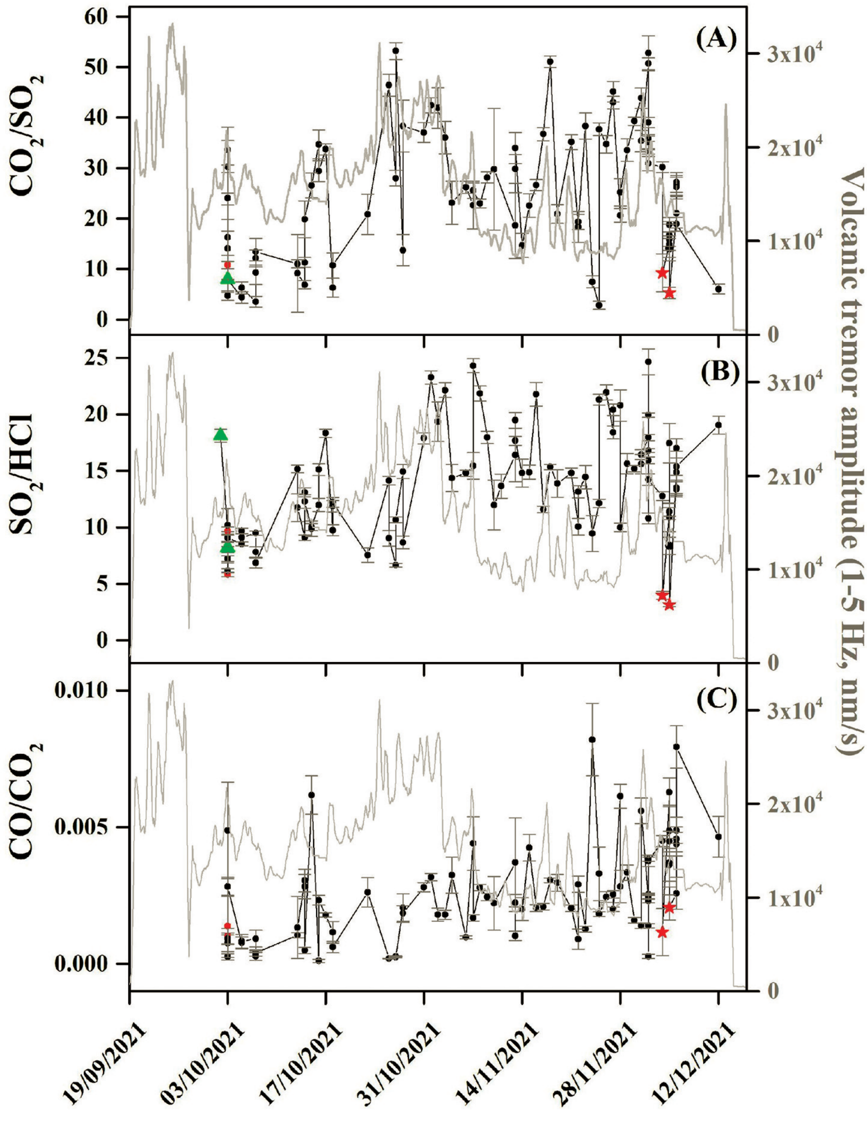

Fig. 1. Temporal variation of the (A) CO_2/SO_2, (B) SO_2/HCl and (C) CO/SO_2 daily mean molar ratios in eruptive gases from Tajogaite summit vents, from October 3 to December 12, 2021. The grey line indicates the volcanic tremor amplitude (1-5 Hz) registered in PLPI station during the eruption. Red solid circles correspond to measurements of effusive degassing on October 3, 2021, the green triangle to the measurements done from more than 8 km away from the vents, and red stars to the measurements targeting a vent on lava flow on December 4 and 5, 2021

with seismic tremor intensity. In contrast, effusive outgassing exhibited much lower CO_2/SO_2 ratios and relatively higher fractions of H_2O, sulfur, and chlorine. Ratios of $CO/COS/CO_2$ were consistent with petrological evidence for an oxidized magmatic system, favoring sulfur solubility and late stage SO_2 release. Integrating these findings with eruption rates and petrological data indicated gas fractionation at a very shallow conduit branching beneath the Tajogaite cone. Through this system, pre exsolved CO_2 rich gases were discharged via the summit vent, while CO_2 depleted gases and most of the magma exited through lateral effusive branches.

An apparent increase in CO_2/SO_2 and SO_2/HCl ratios in explosive emissions during the eruption's first half coincided with the injection of progressively more mafic basanitic magma. Nevertheless, possible measurement artifacts, given the difficulty of isolating pure explosive gases in that period, cannot be ruled out. This study provides the first detailed dataset on volcanic gas geochemistry during a subaerial eruption in an Ocean Island Basalt (OIB) setting. It demonstrates the effectiveness of OP FTIR spectroscopy for real time monitoring of eruptions, offering crucial insights into magma transport and the interplay between explosive and effusive degassing.

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DIFFUSE HE/CO_2 AND H_2/CO_2 DEGASSING RATIOS AT CUMBRE VIEJA VOLCANO: A GEOCHEMICAL TELEGRAM OF THE TAJOGAITE ERUPTION (LA PALMA, CANARY ISLANDS)

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Abstract

Located in the northwestern sector of the Canary Islands, La Palma (708 km^2) is among the youngest (~2 Ma) and most historically active volcanic islands in the archipelago. On September 19, 2021, a volcanic eruption initiated on the southwestern slope of the Cumbre Vieja rift zone, the most active basaltic volcanic system in the region. The eruption, predominantly fissural in nature, was characterized by Strombolian dynamics with intermittent phreatomagmatic episodes, and persisted until December 13, 2021.This work presents a geochemical assessment of diffuse soil emissions of helium (He), hydrogen (H_2), and carbon dioxide (CO_2) across the Cumbre Vieja system, with a focus on the diagnostic significance of the He/CO_2 and H_2/CO_2 molar ratios. Helium, due to its noble gas properties —chemical inertness, radiological stability, and low solubility— serves as a reliable indicator of deep magmatic contributions. Hydrogen, frequently observed in volcanic and geothermal systems, is involved in redox reactions and exhibits high mobility through porous media. Since 2002, systematic gas surveys have been performed at 600 fixed sampling locations, collecting soil gases at ~40 cm depth using a stainless-steel probe. Helium concentrations were measured using a quadrupole mass spectrometer, while H_2 and CO_2 were analyzed via micro gas chromatography. Spatial interpolation using sequential Gaussian simulation (sGs) enabled the construction of distribution maps for gas ratios. The results indicate notable increases in both He/CO_2 and H_2/CO_2 ratios preceding and during

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seismic unrest episodes between 2017 and 2021. During the eruptive period of the 2021 eruption, the elevated ratios coincided with a significant increase in deep seismicity, which was interpreted as a supply of magma from deep sources, and occurred prior to the maximum in diffuse CO_2 emissions. In volcanic environments where visible degassing manifestations (e.g., fumaroles) are absent, monitoring diffuse soil gas emissions becomes essential. The combined analysis of He and H_2 fluxes provides valuable insights into subsurface magmatic processes and strengthens early warning capabilities during phases of volcanic unrest.

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TRACKING HYDROGEOCHEMICAL CHANGES ASSOCIATED WITH VOLCANIC ACTIVITY ON LA PALMA (CANARY ISLANDS)

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ABSTRACT

La Palma Island (708 km²), located at the northwestern of the Canary Archipelago, is one of the youngest and most volcanically active islands in the region. Over the last 123,000 years, volcanic activity has been confined to the Cumbre Vieja volcanic system, situated in the island's southern sector. The most recent eruption (Tajogaite eruption), occurred from 19 September to 13 December 2021 on the western flank of Cumbre Vieja. This fissural and highly Strombolian event, with a Volcanic Explosivity Index (VEI) of 3 (Bonadonna *et al*., 2022), represents the longest historical eruption recorded on La Palma. In the absence visual degassing features a the surface (fumaroles, bubbling gases,...), the study of groundwater geochemistry has become a powerful tool for volcano monitoring, as aquifers act as natural traps that hinder the gases and volatiles exsolved from the silicate melts beneath the volcano. Since 2017, following recurrent seismic swarms, a hydrogeochemical monitoring program was established at three sites: Las Salinas (well), and Peña Horeb and Trasvase Oeste (horizontal galleries). In addition to these main sites, a CO_2-rich cold mineral spring known as Dos Aguas, located at the bottom of Taburiente Caldera (out of Cumbre Vieja), has been monitored. *In situ* measurements of temperature, pH, and electrical conductivity (EC), were done regularly with lab analyses of major ions, and isotopic composition of water and dissolved CO_2. Significant temporal variations were detected in several parameters, including pH, alkalinity, ion concentrations, and $\delta^{13}C$-CO_2, which were temporally correlated with seismic activity and the eruption onset.

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These variations are interpreted as responses to magmatic gas input (e.g., CO_2, H_2S, H_2) into the aquifer system. Las Salinas presented the highest electrical conductivity values, while Peña Horeb showed the highest bicarbonate content. Isotopic data pointed to meteoric recharge, modulated by varying degrees of magmatic gas interaction.

The observed results underscore the value of integrating hydrogeochemical observations into volcanic monitoring strategies, particularly in settings lacking evident surface degassing features. Groundwater chemistry and isotopic signatures offer valuable insights into subsurface volcanic processes and contribute to improved eruption forecasting.

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EARLY PRECURSORY CHANGES IN THE ^{3}HE/^{4}HE RATIO PRIOR TO THE 2021 TAJOGAITE ERUPTION AT CUMBRE VIEJA VOLCANO (LA PALMA, CANARY ISLANDS)

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Abstract

The ascent of magmas from the mantle toward subcrustal or crustal levels outgas volatiles with $^{3}He/^{4}He$ ratios higher than those of fluids from more evolved melts previously located in the crust. $^{3}He/^{4}He$ ratio has been monitored at Dos Aguas cold mineral spring (DA), located at the bottom of Taburiente caldera in La Palma Island, since 1991 to date, as an important volcano monitoring tool able to provide early warning signals of future volcanic unrest episodes. DA, in terms of noble gases, is the only location in the Canarian archipelago where it is possible to identify a primordial component of the Canary mantle source. A significant increase was observed from 2011 to 2012, when the $^{3}He/^{4}He$ ratio reached the highest value of the period 1991-2019: 10.24 R_A (being R_A the ratio in atmospheric helium) in September 2012. At that time, this was the highest $^{3}He/^{4}He$ ratio reported from the Canarian archipelago measured either in the lavas or terrestrial fluids (Padrón *et al.*, 2015). We suggest the occurrence of aseismic magma rising episodes beneath La Palma within the upper mantle towards an ephemeral magma reservoir in the period 2011-2012. Later, in the period 2017-2020, magma rising continued and produced seismic swarms that were accompanied also by the highest $^{3}He/^{4}He$ ratio measured at Dos Aguas (10.85 R_A in September, 2020). In 2021, $^{3}He/^{4}He$ ratio decreased from values ~10.15 R_A at the beginning of the

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year to ~9.83 in the second half of the year, including the eruptive period. $^3He/^4He$ ratio values suggest that upward magma migration that caused the 2021 Cumbre Vieja eruption likely started in or before 2012 (Padrón *et al*., 2022). DA has demonstrated to be an excellent place to monitor the deep magmatic plumbing system of La Palma Island, able to provide the earliest precursory signal of the upcoming eruptive phase of Cumbre Vieja.

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ASSESSMENT AND MONITORING OF CARBON DIOXIDE HAZARDS IN RESIDENTIAL ZONES OF PUERTO NAOS AND LA BOMBILLA, LA PALMA (CANARY ISLANDS)

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ABSTRACT

The 2021 eruption of the Tajogaite volcano on La Palma represented Europe's most significant volcanic impact on an urbanized area in over 75 years (Rodríguez *et al*., 2024). In its aftermath, a persistent and anomalous emission of carbon dioxide (CO_2) has emerged as the primary volcanic hazard, acutely affecting the coastal communities of Puerto Naos and La Bombilla, situated approximately 6 km from the eruptive vents. This diffuse degassing poses a silent but lethal threat, as CO_2 is a colorless, odourless gas denser than air, allowing it to accumulate to dangerous concentrations in low-lying and enclosed spaces. To characterize and manage this ongoing threat, since December 2021, 94 periodic surveys of diffuse CO_2 emission have been undertaken in La Bombilla (see Fig. 1), coupled with regular monitoring of ambient air quality at various heights (15 cm and 150 cm) in both communities. The results reveal a highly dynamic system. Diffuse CO_2 emission rates in La Bombilla have shown significant temporal variation, ranging from 2.4 to 170 t d^{-1}, with a mean of 15.7 t d^{-1}. The peak emission rate was recorded during the initial post-eruptive phase. Isotopic analysis of the soil gas yields $\delta^{13}C\text{-}CO_2$ values between -8.63 ‰ and -4.22 ‰ vs. VPDB (average = -5.55 ‰), confirming a deep-seated magmatic origin for the emissions. Eight outdoor CO_2 concentration surveys were conducted along the streets of Puerto Naos between July 2022 and March 2023, whereas 17 surveys were performed at La

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Bombilla between July 2022 and December 2023, periods when vehicle traffic was absent. The surveys revealed hazardous outdoor ambient CO_2 levels, with peak concentrations at 15 cm above ground reaching 86 % in Puerto Naos and 87 % in La Bombilla. These findings underscore a critical and persistent public health risk. The continuous, long-term monitoring of these residential zones is therefore indispensable for safeguarding public health, while innovative mitigation strategies are actively being investigated to address the extraordinary risk posed by these gas emissions.

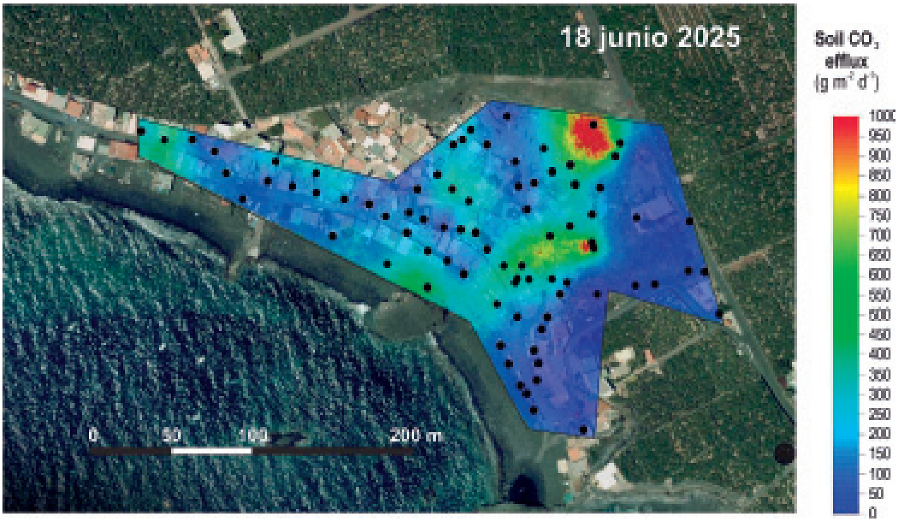

Fig. 1. Spatial distribution map of soil CO_2 efflux measured at La Bombilla, La Palma, June 2025

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THE IMPACT OF DIFFUSE CO_2 EMISSIONS IN INHABITED AREAS OF THE ARIDANE VALLEY COAST: INFLUENCE ON SEWER NETWORKS AND CESSPOOL

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Abstract

Following the eruption of the Tajogaite volcano (Cumbre Vieja, La Palma, 2021), there have been persistent diffuse emissions of CO_2 (Padrón *et al*., 2015) in the coastal towns of Puerto Naos and La Bombilla, keeping these areas under restricted access due to risks to public health. Monitoring by the IGN and INVOLCAN confirms the magmatic-hydrothermal origin of the gas (Padrón *et al*., 2015; Chicco *et al*., 2020). Research has identified patterns of high concentrations, especially in sewer systems, garages and cesspools in both locations (Moyer *et al*., 2009). This type of geogenic hazard due to CO_2 in volcanic areas has been widely documented in Lazio (Italy) (Beaubien *et al*., 2003). Using Senko SGT-N and Blackline G7 portable detectors, the most affected areas have been mapped, with concentrations in confined spaces exceeding 50,000 ppm and up to 200,000 ppm in extreme cases, highlighting the need for priority action in underground infrastructure. The work presented also includes specific measurement campaigns in sewerage networks, documenting the role of ventilation (Moyer *et al*., 2009) and the effect of implementing siphon systems and experimental hydraulic plugs in sewers. The tests show that installing siphon elbows and hydraulic plugs drastically reduces CO_2 concentrations from values above 50,000 ppm to just 500 ppm, validating the approach as an immediate mitigation measure. On the other hand, outdoor and indoor CO_2 levels were analysed using LORA beacons installed by the IGN, identifying that open spaces such as beaches can be considered safe areas ('green zones'), except for the restricted area of Playa Chica (IGN, 2023). In homes, most nodes have values below the danger thresholds, although the need for individualised diagnoses at anomalous points is noted. The resulting proposals include: the widespread installation of siphons in sewerage networks, selective ventilation in manholes, identification and sealing of inactive cesspools, as well as underground sampling to map deep flows and improve territorial planning.

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Fig. 1. Instantánea tomando mediciones en una alcantarilla

The spatial distribution suggests structural control and preferred migration routes in the urban subsoil (Beaubien *et al*., 2003). All of this recognises the unique nature of the phenomenon and the opportunity to develop pioneering protocols for managing the risk of diffuse volcanic degassing in urban centres.

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ANALYSIS AND STABILITY OF POST-ERUPTION CO_2 CONCENTRATIONS IN PUERTO NAOS AND LA BOMBILLA: RESULTS FROM THE LORA-IGN, ALERTACO_2, AND DEMASE NETWORKS

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ABSTRACT

Following the eruption of La Palma in 2021, abnormal CO_2 emissions in Puerto Naos and La Bombilla have led to the implementation of a pioneering environmental monitoring system to assess habitability and protect public health, following established approaches in active volcanic areas where CO_2 flow/concentration networks and campaigns allow for the characterisation of sources, temporal variability and associated risk (Chiodini *et al*., 2000; Cardellini *et al*., 2016). This paper presents the results obtained from three monitoring systems: the LoRa beacon network installed by the National Geographic Institute (IGN) (Fig. 1A), the deployment of indoor sensors from the AlertaCO_2 project, and preliminary data collected by the DEMASE outdoor network (Fig. 1B), in line with previous experiences that highlight the value of continuous, multiscale CO_2 monitoring for risk management in volcanic and peri-volcanic contexts (Cardellini *et al*., 2016; Tarchini *et al*., 2022; Gurrieri *et al*., 2023). The temporal analysis of data from LoRa beacons over more than a year of operation reveals a fundamental finding: the stability of CO_2 concentrations at most of the monitored points. Trends remain generally constant and within ranges considered safe (usually below 1,000 ppm), with no sustained decreases or increases over time. Although some nodes may occasionally reflect increases associated with specific events, these are isolated and do not alter the overall pattern of stability. This behaviour is consistent with observations in other volcanic settings where, despite local episodes, the background regime can remain stable in inter-eruptive periods if there is no significant reorganisation of the deep feed or hydrothermal system (Cardellini *et al*., 2016; Tarchini *et al*., 2022). Similarly, data obtained through the DEMASE network outdoors —with stable average values around 894 ppm between April and June

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2024— corroborate the absence of significant fluctuations or critical episodes of CO_2 accumulation in the outdoor urban environment, a result that is consistent with risk assessments in populated environments with diffuse emissions where atmospheric ventilation and local morphology modulate surface accumulation (Tarchini *et al*., 2022; Gurrieri *et al*., 2023).

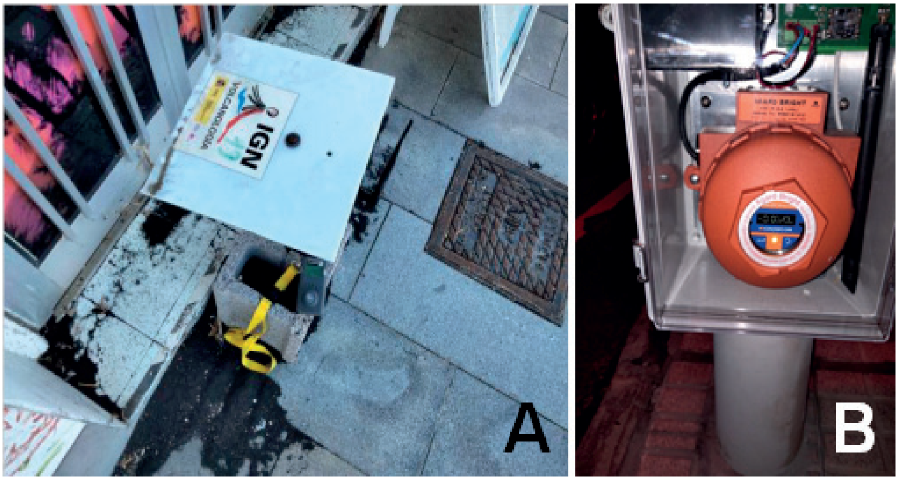

Fig. 1. A. Beacon LoRa IGN; B: Sensor DEMASE.

Indoors, the AlertaCO$_2$ project, with more than 1,290 sensors installed, shows equally stable and downward trends in most living spaces, contributing to the safe recovery of homes and common areas with between 85 and 97 % of measurements below the 1,000 ppm threshold. These results emphasise the usefulness of dense and continuous networks for health and civil protection decision-making, as well as the importance of combining indoor concentration measurements with environmental observations and, where appropriate, with external geochemical indicators of the volcanic system (Chiodini *et al*., 2000; Gurrieri *et al*., 2023). This study highlights stability as a dominant feature in the evolution of CO_2 concentrations, consolidating the importance of continuous monitoring and multiscale analysis for health and geological management in post-eruptive volcanic contexts, in line with the evidence accumulated in Italian volcanic fields and other similar areas (Cardellini *et al*., 2016; Tarchini *et al*., 2022; Gurrieri *et al*., 2023).

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CITIZEN SCIENCE AND COLLABORATIVE MONITORING: KEY TOOLS FOR MANAGING THE RISK OF DIFFUSE CO_2 EMISSIONS IN PUERTO NAOS AND LA BOMBILLA

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Abstract

Following the volcanic eruption on La Palma (2021), the coastal towns of Puerto Naos and La Bombilla face a prolonged challenge from diffuse CO_2 emissions, with clear implications for habitability and public health. This work integrates the contributions of citizen measurement campaigns (neighbourhood participation, accompaniments organised by firefighters and the environment department of the Cabildo de La Palma) and detailed analyses in a large sample of homes and premises, in line with citizen science approaches applied to environmental and risk monitoring that have proven useful for characterising exposures and raising public awareness (Joseph *et al*., 2019; Hecker *et al*., 2018). Discretionary measurements taken during monitoring, using approved detectors (Fig. 1a and Fig. 1b), carried out between November 2023 and March 2024, show that between 85% and 90% of the homes monitored in Puerto Naos have indoor concentrations compatible with international health limits (ALTER and international criteria). Episodes of extreme accumulation (>40,000 ppm) are concentrated in enclosed spaces, basements, garages and the sewage system, where urban morphology and the existence of cesspools are determining factors; this pattern is consistent with the literature that highlights the importance of ventilation, substrate permeability and building configurations in gas accumulation in volcanic and peri-volcanic environments (Viveiros & Silva, 2024). The «structure-by-structure» diagnosis, supported by citizen surveillance and mitigation tests (ventilation, sealing of wells, installation of siphons), has demonstrated that most risks are localisable and manageable, reinforcing the value of participatory frameworks to guide interventions and operational decision-making (Hecker *et al*., 2018; Joseph *et al*., 2019). In La Bombilla, there are still more cases with elevated parameters, linked to self-construction on porous volcanic substrates and inadequate sanitation systems,

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which coincides with reviews that identify areas of diffuse degassing as a ‘silent risk’ requiring specific assessment and design/resilience measures at the building and planning level (Viveiros & Silva, 2024).

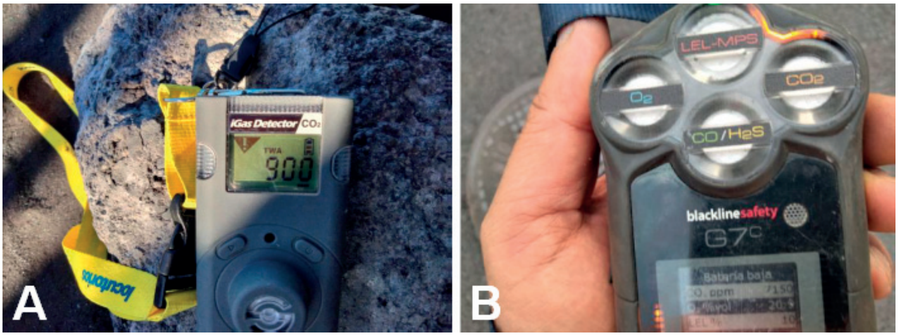

Fig. 1. A: Seiko iGas CO_2 detector; B: G7 Multigas Blackline detector.

The study highlights the importance of sharing information on trends and historical data with the population, and the need for sensible and transparent emergency protocols, in line with the principles of citizen science to strengthen risk communication, participation and institutional responsiveness (Hecker *et al*., 2018). In conclusion, the combination of citizen science, monitoring protocols and collaborative technical work in the field has been essential for the contextualised interpretation of data and for the design of tailored solutions that can be exported to other geological and volcanic risk scenarios. Responsible access to information, continuous monitoring and mitigation systems tailored to the realities of each environment and dwelling are advocated, in line with recent recommendations on areas of diffuse CO_2 degassing and its health and urban management (Viveiros & Silva, 2024), and with experiences that show that participatory schemes can provide useful data, awareness and support for environmental health decisions (Hecker *et al*., 2018; Joseph *et al*., 2019).

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Topic 7

Other methods of monitoring

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A NEW APPROACH TO 1993 MAGNETIC ANOMALY DATA IN LA PALMA ISLAND

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ABSTRACT

The Geomagnetism Area of the Instituto Geográfico Nacional (IGN) of Spain has recently completed a program of recovery and compilation of digital data from the majority of the aeromagnetic surveys conducted by several institutions in the Iberian Peninsula and its surrounding maritime areas between 1974 and 2005 (Instituto Geográfico Nacional, 2007). In addition, the original data of the survey conducted by IGN for its 1993 *Mapa de Anomalías Magnéticas de Canarias* (Map of Magnetic Anomalies of the Canary Islands) (Socías & Mezcua, 1996) have been recovered. In this article, this Total Field (F) anomaly data measured in 1993 and subsequently continued to the altitude of 3200 m is presented in an improved way. By using modern GIS techniques, new maps have been created: one for the whole of the Canary Islands at a scale of 1:2,250,000 and another one for each island at the scale of 1:200,000 (Fig. 1, Núñez *et al*., 2024). In the present paper, the focus is set on La Palma Island, for which additional resources that link geomagnetic anomaly with other natural features, such as historical volcanic activity or topography, are presented. The work carried out here is also the starting point to further magnetic researches in the Canary Islands and could also serve as the basis for future educational work aimed at bringing geophysical research closer to non-specialists.

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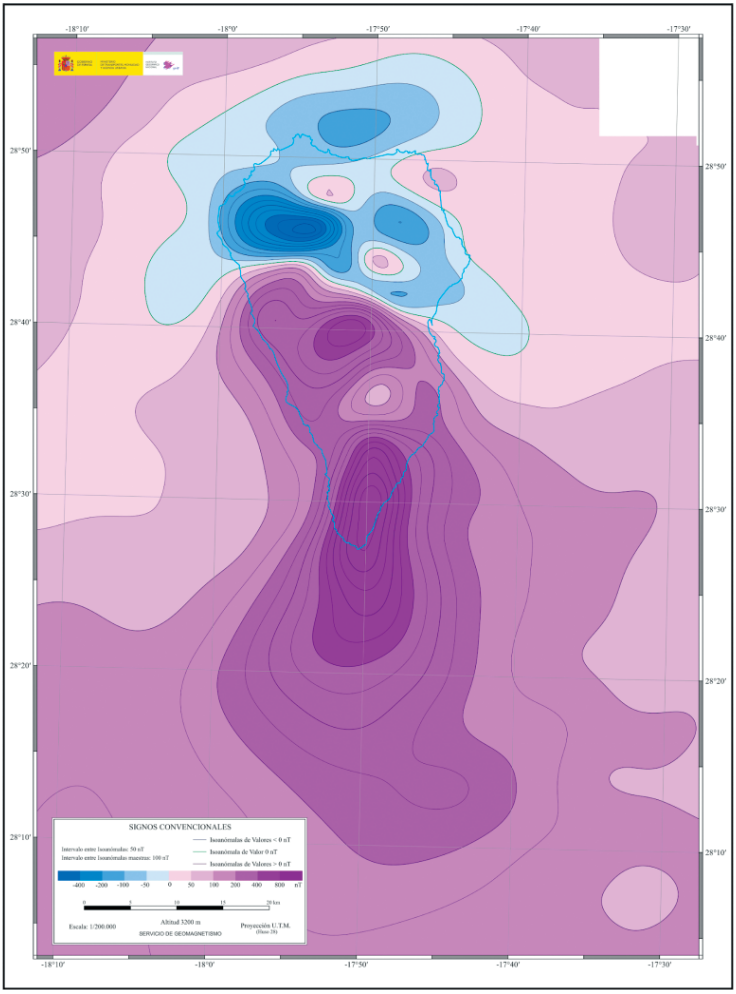

Fig. 1. Map of magnetic anomalies on La Palma (Núñez *et al*., 2024)

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GEOTHERMAL ANOMALIES PRECEDING THE 2021 TAJOGAITE ERUPTION

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Abstract

Identifying the physicochemical signals that accompany volcanic unrest and precede eruptions remains one of the most complex challenges in natural hazard monitoring and risk mitigation. While traditional surveillance focuses on seismicity, deformation, and gas emissions, recent findings suggest that thermal variations at the surface may also provide valuable precursory information (e.g., Reath *et al*., 2019). For instance, Girona *et al*. (2021) showed that some volcanoes exhibit slight but persistent radiant heat emissions —termed low-temperature (low-T) geothermal anomalies— for years prior to eruption. This was revealed through ~16 years of long-wavelength (~11 μm) thermal infrared data from NASA's MODIS sensors aboard the Terra and Aqua platforms. However, key questions remain: What are the spatiotemporal patterns of these low-T anomalies? How are they linked to subsurface processes? We tackle these questions by addressing the following challenges: First, we developed SSTAR (*Subtle Surface Thermal Anomalies Recognizer*), an open-access, standalone, user-friendly application designed to identify subtle (~1-5 K) thermal anomalies over large areas (~1-10s km^2) using MODIS data. Building on the approach developed by Girona *et al*. (2021), SSTAR performs pixel-level analysis, tracks the spatiotemporal evolution of anomalies, quantifies uncertainties, and features an interactive user interface. Second, we

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applied SSTAR to analyze La Palma Island (Canary Islands) from 2002 to 2022, revealing low-T anomalies that emerged more than a decade before the 2021 Tajogaite eruption —located not at the eruptive vent, but ~10-12 km to the north in Taburiente Caldera and near the site of the 1971 Teneguía eruption. Third, we examined digital aerial orthophotographs from PNOA (*Spanish National Orthophoto Program*) and Sentinel-2 imagery, confirming that the low-T anomalies in La Palma were not caused by anthropogenic factors, thereby supporting a volcanic origin.

Fourth, we designed finite element simulations (COMSOL Multiphysics) to interpret our remote sensing results by modeling coupled heat and volatile transport. Numerical results suggest these anomalies may be driven by latent heat release from the condensation of rising hydrothermal H_2O in the shallow crust. Altogether, our work highlights low-T anomalies as a promising observable for tracking volcanic unrest in regions like the Canary Islands, offering valuable insights to improve eruption forecasting from space.

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GEOLOGICAL MONITORING WITH DRONES DURING THE TAJOGAITE ERUPTION (2021)

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Abstract

This abstract describes the application of drones for daily geological monitoring during the Tajogaite eruption in La Palma (2021). Daily flights were carried out in collaboration with the Air Works Service (STA) of the IGME-CSIC and the Drone Service of the Canary Islands Government's Emergency and Rescue Group (GES), who had previously collaborated during the Argaga landslide emergency in La Gomera in 2020. The drone teams were also on standby, providing support to the emergency by responding to alerts about the opening of new emission vents, landslides, and other critical events. The information gathered was crucial for emergency management. The methodology involved the interpretation of videos and images from the flights, with cartography generated in a GIS (IGME-CSIC, 2021). This mapping was more detailed than that provided by Copernicus Services and wasn't affected by meteorological factors, except on the few days of strong wind when drones couldn't fly. Summary videos with scientific criteria were produced and screened at daily meetings for the intervention group, the scientific committee of the Special Civil Protection and Emergency Response Plan for Volcanic Risk in the Canary Islands (PEVOLCA), and the steering committee. This significantly improved understanding of the eruptive process and facilitated decision-making (Camuñas *et al*., 2024). Additionally, drone data enabled the daily mapping of lava flow advancements and their monitoring. Aerial images were fundamental for identifying and mapping fractures, faults, and small rockfalls and landslides associated with the seismovolcanic process. Finally, ortho-

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mosaics and digital elevation models were generated to study morphological changes in the volcanic cone and lava deltas throughout the eruption.

This experience highlights the invaluable contribution of drone technology in responding to volcanic emergencies, mainly when the pilots are, or are guided by, geological experts. In addition to geophysical and geochemical monitoring, geological monitoring is of paramount importance during volcanic eruptions, and the use of drones have proved to be the best tool for this in emergency environments where the access to the study area can be hazardous.

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EVALUATION OF SCANNING ELECTRON MICROSCOPY AS A PETROLOGICAL MONITORING TOOL: APPLICATION TO VOLCANIC GLASS FROM THE CUMBRE VIEJA 2021 ERUPTION (LA PALMA, CANARY ISLANDS)

KATHERIN VEGA VASQUEZ, DIEGO GONZÁLEZ-GARCÍA, ÁLVARO MÁRQUEZ*

ABSTRACT

The compositional variability of magmas in the Canary Islands, ranging from basanites to phonolites, reflects a complexity that is not always evident in surface geophysical or geochemical signals. Therefore, accurate petrological characterization of volcanic products is essential to reconstruct the internal processes of the magmatic system during an eruption. In this context, having accessible, rapid, and reliable analytical methodologies is crucial to integrate petrological monitoring into response capabilities during future volcanic eruptions. This study evaluates the applicability of scanning electron microscopy (SEM) as an alternative to electron probe microanalysis (EPMA) for the compositional characterization of volcanic glass, based on the analysis of pyroclasts emitted during the 2021 Tajogaite eruption. Reference materials and five samples collected during the eruption were used, and various SEM measurement conditions were assessed to establish an analytical protocol capable of obtaining accurate compositions. Furthermore, the results were compared with previous EPMA data, the compositional evolution of the glass was analyzed, and a practical protocol was designed for the rapid and effective application of this technique during future eruptive events in the Canary Islands. Results indicate that among the evaluated analytical conditions, a thorough adjustment of the automatic acquisition time parameter yielded the best performance, enabling the detection and quantification of Mn, P, and Cl at low concentrations, which were not detected under fast or precise configurations. This mode requires an acquisition time of 10 to 11 minutes per analysis, achieving a

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balance between precision and speed for effective volcanic eruption response. Regarding correction models, P/B-ZAF was more suitable for quantifying MgO (Fig. 1), while Phi (Rho, Z) provided better results for SiO_2, TiO_2, FeO, CaO, and K_2O. For Al_2O_3 and Na_2O, both methods performed similarly. Commonly used ratios (CaO/Al_2O_3 and K_2O/TiO_2) were also accurately traced.

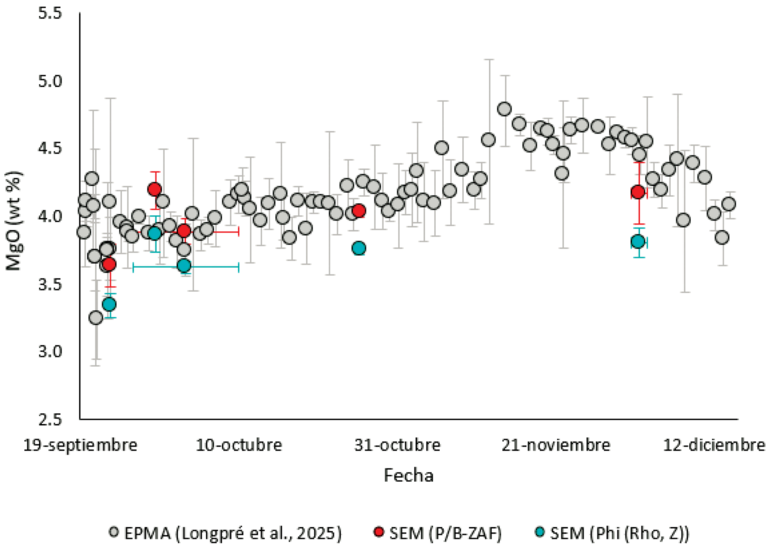

Fig. 1. Temporal evolution of MgO in volcanic glass from the Cumbre Vieja 2021 eruption: comparison between SEM (P/B-ZAF and Phi(ñ,Z) corrections) and EPMA (Longpré *et al.*, 2025)

Overall, SEM time series adequately reproduced compositional variations recorded by EPMA (Fig. 1). For SiO_2, Na_2O, and P_2O_5, compositional trends throughout the eruptive event were maintained, though minor deviations from reference data were observed. These results indicate that petrological monitoring by SEM can be effectively integrated into quick response efforts to volcanic eruptions in the Canary Islands.

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CONTRIBUTIONS OF THE LA PALMA SMART ISLAND PROJECT TO VOLCANIC RISK MANAGEMENT: BEFORE, DURING, AND AFTER THE TAJOGAITE ERUPTION

JUAN ANTONIO BERMEJO DOMÍNGUEZ*

ABSTRACT

The 2021 Tajogaite volcano eruption posed a major challenge for La Palma island, requiring a fast, integrated, and coordinated technological response. The La Palma Smart Island project, launched prior to the event, provided a strategic infrastructure based on sensors, information systems, and intelligent governance. It played a key role throughout all phases of the volcanic emergency: before, during, and after the eruption. In the pre-eruption phase, air quality and meteorological sensors, as well as camera systems, were deployed and integrated into a unified island data hub. This system, built on open standards, enabled the rapid development and reuse of tools and applications. The HUB served as the core integrator for all agencies involved in the emergency —including the Island Council (Cabildo), local municipalities, the Government of the Canary Islands, the Spanish State, scientific institutions, and civil protection teams— facilitating interoperability, operational coordination, and more efficient, joint decision-making. All information is centralized at www.volcan.lapalma.es. During the eruption, the project provided continuous technological support: real-time alert systems, connected loudspeakers, mobile applications, QR-based access control, push-notification platforms, dozens of web apps, and geospatial monitoring. Existing sensor networks were integrated with coordinated drone flights, enabling the production of up to two high-resolution lava flow perimeters per day. This information, openly published through the HUB, proved essential for insurance claims, damage assessment, and aid allocation. In the post-eruption phase, the system continues to support territorial analysis, GIS-based planning, the development of a digital twin, and persistent gas monitoring. The AlertaCO_2 project stands out, with over 200 outdoor CO_2 sensors and a platform for public data access and analy-

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sis: www.alertaco2.lapalma.es. Citizen participation was a key element, with initiatives such as «Revivir el Valle» for reconstruction and the collective naming of the new volcanic cone as «Tajogaite». This is not a scientific study, but rather a practical, institutional approach based on the real-life experience of a local public administration managing a complex volcanic emergency. It aims to share lessons learned from a perspective of territorial governance, public service, digital transformation, and risk management.

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GEOCHEMICAL CHARACTERIZATION OF VOLCANIC MATERIALS USING A PORTABLE XRF EQUIPMENT: EVALUATION OF ITS APLICABILITY FOR SYN-ERUPTIVE PETROLOGICAL MONITORING (LA PALMA 2021, CANARY ISLANDS)

Juan S. Gómez-Hurtado[1], José F. Mediato[2], Álvaro Márquez[1]

Abstract

The goal of this study is the evaluation of the potential applicability of a portable X-ray fluorescence (pXRF) equipment for syn-eruptive monitoring of geochemical changes of erupted magmas during a volcanic emergency. The case study is the 2021 eruption of Tajogaite volcano, at Cumbre Vieja rift (La Palma, Canary Islands). This monogenetic hybrid eruption emitted, during 85 days (Sept. 19–Dec. 13), more than 150 x 106 m^3 of lava flows and 56 x 106 m^3 of pyroclastic materials, with a mafic composition evolving from tephrites to basanites (e.g., Day *et al*., 2022; Ubide *et al*., 2023; Longpré *et al*., 2025). In this work, the semi-quantitative geochemical composition of the pyroclastic fall material was evaluated as a proxy of possible changes in magma composition. Analyses with the pXRF at different pyroclastic levels were made of selected geochemical elements useful for the evaluation of the eruption evolution and the magmatic processes involved. Two columns of pyroclastic materials representing the entire eruptive event (Mediato *et al*., 2023) were analyzed. First, a granulometric analysis was made to evaluate the most appropriate grain size for the analysis with the pXRF. Data obtained from pXRF were then compared with published geochemical results characterizing the geochemical evolution of the Tajogaite eruption, obtained in the laboratory (e.g, whole-rock XRF (Day *et al*., 2022) and matrix LA-ICP (Ubide *et al*., 2023)). In this way, an evaluation of both the values and the trends of selected geochemical elements were made. Results show that the values obtained for elements such as Ni, Cr, Sr or Zr were very close to those obtained for the same dates with laboratory-based techniques in contemporaneous

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samples, showing specially very good results for detecting the evolution of temporal trends and changes in magma composition (Fig. 1). Our results show the great potential applicability of pXRF equipment for petrological syn-eruptive monitoring, even with the restricted range of magma compositions emitted in a monogenetic mafic eruption, provided an appropriate sample selection and preparation.

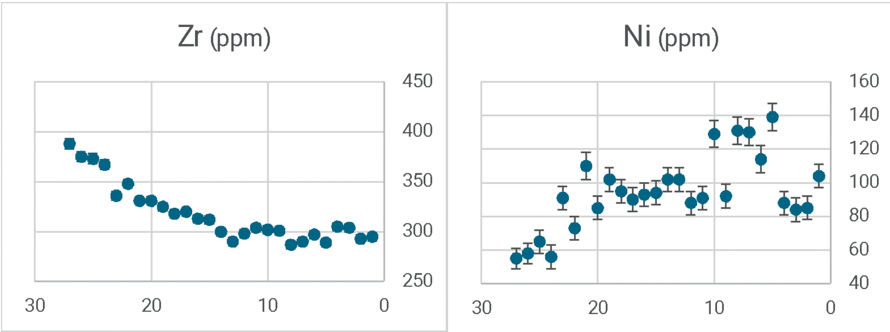

Fig. 1. Variation of Zr and Ni contents at the different levels in one of the pyroclastic sequences analyzed (time evolution from left to right: level 1 is the shallowest, representing the end of the eruption).

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CANIBET: A BAYESIAN DECISION-SUPPORT TOOL FOR NEAR REAL-TIME PROBABILISTIC ERUPTION FORECASTING IN THE CANARY ISLANDS

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ABSTRACT

Currently, our understanding of volcanic systems often does not allow us to predict the exact timing of an eruption precisely. However, from a probabilistic standpoint, it is feasible to estimate the degree of confidence associated with the likelihood of an eruption quantitatively. In this context, the analysis of volcanic phenomena using Bayesian inference tools has been successfully applied in various regions worldwide, employing different methodologies. One of the most effective is the use of Bayesian Event Trees (BET, Newhall & Hoblitt, 2002), which, when combined with fuzzy membership functions —defined through expert elicitation (Jacobs, 1995)— allow the assignment of probabilities to different precursor events of an eruption (Marzocchi *et al.*, 2008). These methodologies help identify anomalous levels in the volcanic activity using (near)real-time volcano monitoring data, from which a global anomaly score can be derived and used to infer about the probability of an eruption. In this work, we present CANIBET (CANary Islands Bayesian Event Tree), a tool based on a three-node BET (Selva *et al.*, 2012; Ferrara *et al.*, 2025) that estimates the probabilities associated with three key processes involved in eruptive dynamics: the presence of unrest, the magmatic origin of that unrest, and the eventual occurrence of an eruption. This tool has been specifically adapted to the volcanic context of three islands in the Canary Archipelago —Tenerife, La Palma, and El Hierro— within the framework of the DIGIVOLCAN project. To assess the predictive capability of the model,

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we performed a retrospective analysis of the Tajogaite eruption that occurred on La Palma in September 2021. The results demonstrate that this type of tool can be highly effective when the expert elicitation process is well adapted to the specific characteristics of the volcanic system under study. In such cases, CANIBET allows for a dynamic and near real-time estimation of eruptive probability, providing valuable support for decision-making in volcanic risk management.

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GROUND PRESSURE GRADIENT ANALYSIS AS A TOOL FOR MONITORING DIFFUSE GAS DEGASSING AT PUERTO NAOS AND LA BOMBILLA (LA PALMA, CANARY ISLANDS)

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ABSTRACT

The 2021 Tajogaite eruption on La Palma (Rodríguez *et al*., 2024) has created a persistent geohazard from the diffuse emission of volcanic CO_2 in the inhabited areas of Puerto Naos and La Bombilla. To improve hazard assessment, this study evaluates the subsurface fluid pressure gradient as a novel physical parameter for delineating pathways of hazardous gas migration. To enhance the understanding and mitigation of this ongoing threat, a pressure gradient study in Puerto Naos and La Bombilla is being carried out. The primary objective is to map pressure gradients identifying zones of significant advective flow. To do so, field campaigns were conducted between November 2024 and June 2025 across 274 sites in paved and unpaved areas of Puerto Naos, and one additional in La Bombilla. A custom-designed instrument was used to measure the differential pressure between the shallow subsurface and the atmosphere, from which the pressure gradient (Pa·m-1) was calculated (Natale *et al*., 2000). The results for November 12, 2024 survey in the unpaved area (70 points), showed a maximum of 582 Pa·m-1 with an average of 37.6 Pa·m-1. February 19, 2025, survey in the same area showed a maximum of 10.5 Pa·m-1 and average of -0.26 Pa·m-1. Highest diffuse CO_2 efflux values (max. 45 g·m-2·d-1) measured at the same time showed a certain correlation with highest pressure gradients. The March 2025 survey, with 204 points in the paved area, showed a maximum

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of 724.6 Pa·m-1 and an average of 58.2 Pa·m-1, being identified two anomalous areas. The June survey was performed in paved and unpaved areas with 261 sites, showing maximum values of 5.54 Pa·m-1 and an average of -0.36 Pa·m-1. February 2025 survey at La Bombilla (32 sites) showed a maximum value of 4.5 Pa·m-1 and an average of 0.8 Pa·m-1, with a fairly strong correlation with high CO_2 efflux (Fig. 1).

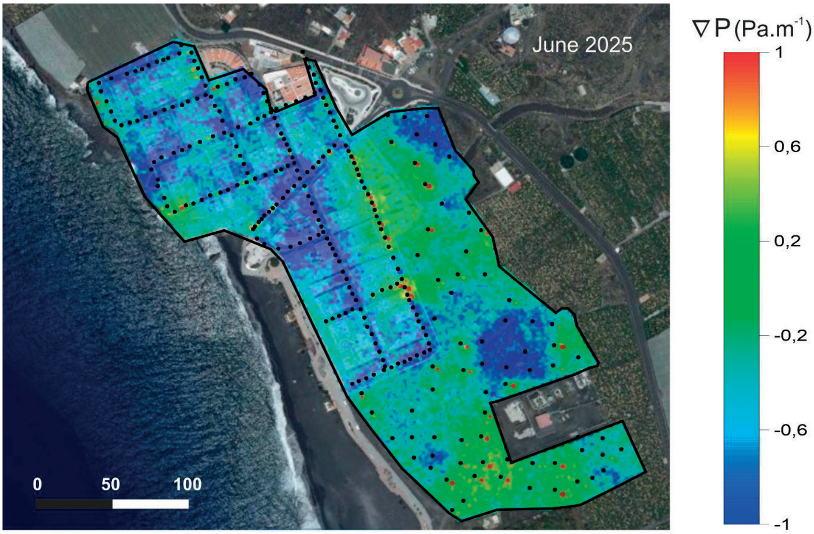

Fig. 1. Spatial distribution map of pressure gradient for the survey carried out in June 2025 at Puerto Naos

Measuring subsurface fluid pressure gradients is a key method for identifying the physical drivers and pathways of volcanic gas emissions. Integrating this data with existing geochemical monitoring can significantly improve hazard maps and long-term risk management strategies for populated volcanic regions.

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UNVEILING HEAT PATTERNS: INTEGRATING DRONE THERMOGRAPHY AND GEOSPATIAL ANALYSIS OF LAVA FLOWS FROM THE TAJOGAITE VOLCANO

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Abstract

On September 19, 2021, a volcanic eruption on the island of La Palma (Canary Islands, Spain) caused significant damage, destroying 1,676 buildings, affecting 73.8 km of roads, and burying 370 hectares of agricultural land under lava flows up to 70 meters thick. In total, the eruption impacted more than 7,000 people and resulted in economic losses exceeding 840 million euros, including approximately 200 million euros in agricultural damages. Following the eruption, the need for reconstruction efforts in both urban and agricultural areas became urgent. The LPAgricultura and LPUrban projects were developed to address these challenges. The work was carried out by the Instituto Volcanológico de Canarias (INVOLCAN) for the Canary Islands Government's public company «Territorial and Environmental Management and Planning» (GESPLAN). A central task involved high-resolution drone thermography to map residual heat anomalies across the lava fields. Thermal mosaics were processed and integrated with pre-existing digital elevation models (DEMs), enabling advanced spatial analysis to correlate heat persistence with lava thickness and morphological features. This workflow allowed the identification of

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critical hot zones that could affect reconstruction efforts (González-de-Vallejo *et al.*, 2024). By combining drone-based thermal imaging with geospatial analysis techniques, this methodology provided a rapid and high-precision tool for post-eruption management. The results have been instrumental in prioritizing reconstruction and supporting the safe recovery of affected areas.

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Topic 8

Emissions to the atmosphere

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VOLCANIC MONITORING FROM SOLAR ABSORPTION FOURIER TRANSFORM INFRARED SPECTROMETRY

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ABSTRACT

Using ground-based remote sensing methods, the 2021 eruption of the Tajogaite volcano on La Palma (Canary Islands, Spain) provided a unique opportunity to monitor volcanic gas emissions. In this study, we demonstrate how Fourier Transform Infrared (FTIR) spectroscopy was used to analyze the composition and temporal evolution of the volcanic gas plume during the eruption. High-resolution solar absorption FTIR spectra were acquired at the Izaña Atmospheric Observatory (IZO, Tenerife, Spain) under the framework of the Network for the Detection of Atmospheric Composition Change (NDACC). These measurements enabled the quantification of key trace gases, including SO_2, CO_2, HCl, HF, CO, and NH_3. The results highlight the effectiveness of FTIR spectroscopy as a robust tool for real-time volcanic gas monitoring, understanding of plume transport, and contribute to ongoing efforts in hazard assessment and early warning systems.

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TRACKING SULPHATE TRANSPORT DURING TAJOGAITE ERUPTION (LA PALMA) WITH COMPACT DUAL-WAVELENGTH LIDARS AND PHOTOMETER OBSERVATIONS AT IZO AND ATOLL

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Abstract

The Cumbre Vieja eruption on La Palma (Canary Islands) from 19 September to 13 December 2021 emitted large amounts of sulfur dioxide (SO_2), fine aerosols (mainly sulfates), and ash. Advanced ground-based remote sensing instruments, including CE376 lidar and CE318 sun-photometer, were deployed at Izaña Observatory (IZO, Tenerife) and ATOLL (Lille, France) to monitor the plume evolution. At IZO, ~140 km from the volcano, thin aerosol layers reached the free troposphere on 23-24 September, with injection heights around 4.5 km. Lidar-derived depolarization ratios (PLDR < 0.06), Ångström exponents (EAE > 1.6), and volume size distributions indicated fine, spherical, non-ash aerosols. Vertical profiles revealed multiple elevated sulfate-rich layers, with minimal ash likely removed near the source (González *et al*., 2025). At ATOLL (~3000 km downwind), a volcanic SO_2 plume arrived on 19-20 October. Lidar observations showed two main layers up to 4-5 km. Lower layers had higher PLDR (up to 0.22), suggesting coarse, nonspherical ash, while upper layers exhibited reduced PLDR and elevated EAE (~1.8), consistent with fine sulfates. Size distributions confirmed a mixed

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aerosol population. Back-trajectory analysis, supported by satellite SO_2 and Aerosol Chemical Speciation Monitor (ACSM) sulfate data, excluded Saharan dust influence and confirmed volcanic origin (Sánchez-Barrero, 2024). To enhance aerosol characterization, an inversion strategy using the GRASP algorithm (Dubovik *et al*., 2021) was applied, integrating sun-photometer and CE376 lidar observations. This integrated approach enables the retrieval of both column-integrated and vertically resolved aerosol properties, demonstrating its robustness and applicability to volcanic events.

The contrasting observations at IZO and ATOLL reveal the spatio-temporal variability of volcanic aerosol composition and highlight the importance of coordinated multi-site lidar-photometer networks for improving the assessment of aerosol transport, composition, and atmospheric impacts during volcanic eruptions.

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TAJOGAITE VOLATILE BUDGETS USING GROUND-BASED DIRECT-SUN SPECTROSCOPIC MEASUREMENTS

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ABSTRACT

The 2021 eruption of Cumbre Vieja (La Palma, Canary Islands) offered a unique opportunity to characterize the Cumbre Vieja degassing using existing atmospheric observation networks. In this study, we combined satellite and

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ground-based remote sensing measurements to monitor volcanic gas emissions throughout the eruption. Measurements were conducted using two types of FTIR spectrometers, the mobile EM27/SUN and the high-resolution IFS-125HR, deployed up to 140 km from the volcano and contributing to major global monitoring networks. In La Palma, the EM27/SUN was combined with a DOAS instrument in direct-sun configuration to increase the number of measured volcanic gas species. Using SO_2 fluxes retrieved from Sentinel-5P (TROPOMI) observations and species-to-SO_2 ratios derived from FTIR and DOAS measurements, multi-species emission fluxes were estimated over the entire eruptive period. These results were cross-validated with independent petrological approach, showing strong consistency and highlighting the critical role of atmospheric networks in volcanological research.

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ANALYSIS OF AEROSOL PROPERTIES FROM THE CUMBRE VIEJA VOLCANIC ERUPTION USING MULTI-INSTRUMENTAL OBSERVATIONS

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Abstract

Between September and December 2021, the Cumbre Vieja eruption on La Palma (Spain) provided a unique opportunity to study volcanic aerosol emissions. Continuous atmospheric measurements were carried out in Fuencaliente, less than 9 km from the vent, using a sun photometer, a ceilometer, and an all-sky camera. Although the intensity of the eruption caused cloud-screening algorithms to misclassify some major emission events, the nighttime imagery from the all-sky camera enabled reliable identification of the volcanic plume (Fig. 1, left), and nighttime continuous aerosol optical depth (AOD) measurements that complete the gaps in the photometer data (Román *et al.*, 2025). AOD, sky radiance, and ceilometer backscatter profiles were processed using the Generalised Retrieval of Atmosphere and Surface Properties (GRASP) algorithm (Dubovik et al., 2021), allowing retrieval of vertically resolved aerosol properties. These include volume concentration (Fig. 2, right), extinction, scattering, backscattering, and absorption coefficients, as well as size distribution, single scattering albedo, and refractive index. Thanks to the vertical resolution of the dataset, it is also possible to estimate the radiative heating rate induced by the volcanic aerosols (García *et al.*, 2022). Overall, this study delivers a comprehensive near-source characterization of the optical and microphysical properties of the aerosols emitted during the eruption, along with their radiative implications.

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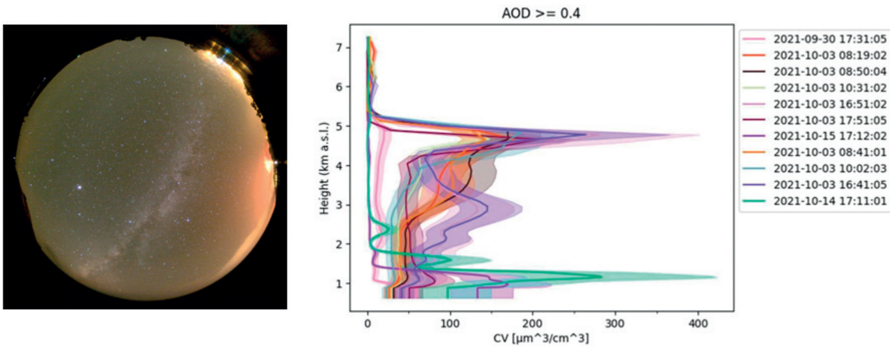

Fig. 1. Left side: All-sky camera image from the eruption on October 6th, 2021. The bright red light on the right is the volcanic eruption. Right side: Vertical profiles of volume concentration, for the days with AOD < 0.4. Shadow band represent the standard deviation

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VOLCANIC-DRIVEN PARTICLE NUCLEATION AND GROWTH AT IZAÑA OBSERVATORY DURING THE 2021 TAJOGAITE ERUPTION

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Abstract

Atmospheric aerosols influence climate, ecosystems, air quality, and human health. Modeling studies suggest that volcanic eruptions are significant natural sources of aerosol precursors, but direct observations of particle nucleation and growth during such events remain scarce. We investigated the impact of the 2021 Tajogaite eruption (La Palma, Spain) on new particle formation (NPF) at Izaña Atmospheric Observatory (IZO, Tenerife, 2440 m a.s.l.). The dataset includes aerosol number size distributions (10-500 nm), sulfur dioxide SO_2 concentrations, and HYSPLIT back-trajectories. Results show recurrent and sustained NPF during the eruption, including exceptional nighttime growth episodes —phenomena rarely observed at IZO under typical free-troposphere conditions. According to our previous studies, NPF at IZO typically occurs during daytime upslope winds, with peak frequencies between May and August and growth rates of 0.4-0.6 $nm \cdot h^{-1}$ (García *et al*., 2014). However, during the eruption, we observed intense daytime NPF events and several nighttime episodes of particle growth from September to December, especially during periods of volcanic SO_2 advection, as confirmed by Fourier Transform Infrared (FTIR) measurements (Taquet *et al*., 2025) and back-trajectories. One of these volcanic events occurred on the night of 24 November, when an anomalous particle growth from 70-80 nm to > 100 nm (Fig. 1a) was observed under high SO_2 levels (~2000 ppb; Fig. 1b). This suggests the arrival of already formed particles that continued growing (by gas-to-particle conversion) for several hours in the free troposphere. Subsequently, around

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noon, a pronounced daytime NPF event occurred, with particle diameters increasing from ~10 nm to over 100 nm (Fig. 1a). This growth persisted well into the night, which indicates a continuous supply of volcanic precursors. These volcanic-driven events deviate from the regular NPF pattern at IZO, associated with transport of anthropogenic SO_2 and biogenic emissions from the boundary layer (Rodríguez *et al*., 2009).

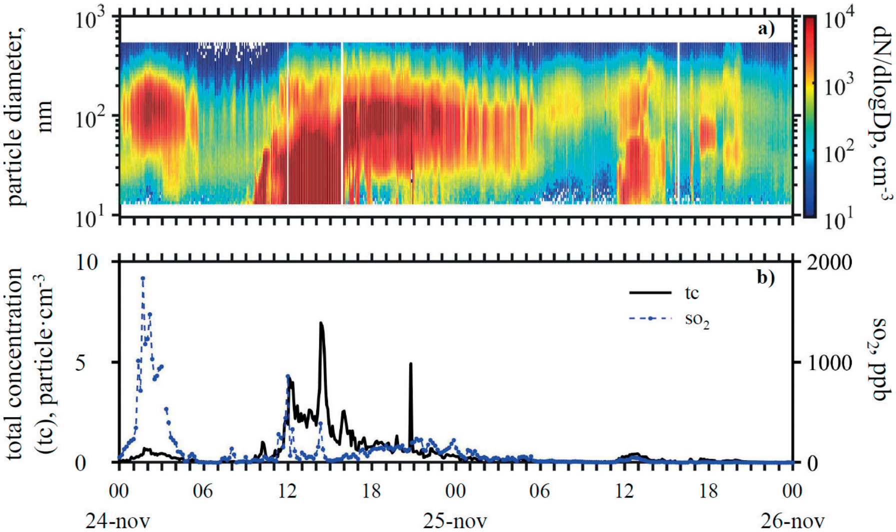

Fig. 1. (a) Aerosol particle number size distribution (10-500 nm) measured by the SMPS at IZO from 24 to 26 November 2021. The color scale represents the particle number concentration per logarithmic size bin (dN/dlogDp). (b) Total particle number concentration (tc, black line, left axis) and in-situ SO_2 (blue dashed line, right axis)

The long-range influence of volcanogenic gases over 140/ km highlights their potential for regional atmospheric impacts, with implications for cloud condensation nuclei formation and radiative forcing. This study provides the first evidence of both daytime volcanic-induced NPF and nighttime particle growth in the subtropical North Atlantic, enhancing our understanding of aerosol formation in pristine, high-altitude environments during volcanic events.

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NONLINEAR AND MULTIFRACTAL ANALYSIS OF RADON TIME SERIES AT DIFFERENT LOCATIONS IN PUERTO NAOS AND LA BOMBILLA (LA PALMA, CANARY ISLANDS)

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Abstract

Since the Tajogaite eruption in 2021, wide areas on the western flank of Cumbre Vieja volcano have been affected by post-eruptive degassing processes, including the coastal area of Puerto Naos and La Bombilla. As part of the monitoring of this phenomenon and to assess the possible risk to people's health, a radon emission monitoring network has been installed since July 2024 using continuous recording techniques. In this study, hourly time series of Rn concentration at nine locations in Puerto Naos and La Bombilla were analyzed during approximately one year between 2024 and 2025. Spectral, nonlinear and multifractal analysis tools were applied to characterize the dynamic patterns of Rn in indoor environments. Most stations showed a dominant 24 h cycle, attributable to daily processes such as natural ventilation or ambient temperature. At several sites, secondary (12h and 6h) cycles were also identified, possibly linked to semi-daily modulations or intermittent ventilation. At certain locations, a cycle of approximately 0.7 years was detected, suggesting weak seasonality. However, as an annual observation cycle has not yet been completed, a clear annual cyclicity cannot be confirmed. It is likely, however, that slow phenomena such as rainfall or infiltration, together with fast processes such as tides, are interacting to varying degrees depending on location and altitude. Non-linear behavior and non-Gaussian distributions were

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evident in all stations, implying the presence of complex dynamics that cannot be explained by simple linear models. These complexities may be caused by multiple environmental factors such as atmospheric pressure, ventilation or wind regime.

The fractal dimension obtained was close to 1.8 in most cases, indicating a high degree of complexity with possible chaotic or multifractal components. In addition, the Hurst exponent showed an average value close to 0.8, suggesting an autocorrelated and persistent behavior in time. To further characterize these dynamics, the Multifractal Detrended Fluctuation Analysis method was used, which confirmed the presence of multifractality in the series. In conclusion, Rn series show complex, nonlinear and multiscale structures that vary at each location. These characteristics are key to improving the prediction and mitigation of radiological risk in confined spaces using advanced models.

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TAJOGAITE 2021 VOLCANIC ERUPTION (LA PALMA, SPAIN): A RAPID DEPLOYMENT FOR ATMOSPHERIC MONITORING

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ABSTRACT

The Tajogaite (La Palma) 2021 volcanic eruption was the first subaerial eruption in a 50-year period in the Canary Islands (Spain), from 19 September 2021 to 13 December 2021, with a duration of 85 days. To complement the observation and monitoring of the evolution of the volcanic ash cloud, the State Meteorological Agency of Spain (AEMET), through the Izaña Atmospheric Research Center and the Territorial Delegation of AEMET in the Canary Islands and in collaboration with numerous national, international institutions and research networks, conducted a rapid deployment of scientific atmospheric instrumentation at seven measurement stations in La Palma.

Measurements encompassed various objectives such as to characterize the vertical structure of the eruptive plume, to contribute to the implementation of an emergency air quality network and to monitor the emissions of gases and particles resulting from the volcanic eruption. In addition, atmospheric composition measurements from the Izaña Atmospheric Observatory (AEMET), located on Tenerife at 2373 m a.s.l. and ~140 km from the eruptive centre, recorded various impacts of the volcanic dispersion cloud throughout the eruptive process. The results highlight the rapid response of scientific collaboration in the atmospheric monitoring of the Tajogaite eruption as a key example of the contribution of science for society.

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CARBON ISOTOPIC CHARACTERIZATION OF CO_2 EMISSIONS FROM THE TAJOGAITE ERUPTION, CUMBRE VIEJA VOLCANO, LA PALMA (CANARY ISLANDS)

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Abstract

The 2021 Tajogaite eruption at La Palma, sustained by a magmatic CO_2 content of 4.5 ± 1.5 wt %, produced 28 ± 14 Mt CO_2 during the 86-day duration (Burton *et al.*, 2023). The eruption represented an excellent opportunity to investigate the characteristics of the mantle source feeding the current volcanism in the Canary Islands and the origin of such a huge amount of CO_2 released by an intra-plate oceanic island eruption. In situ gas sampling, both from ground-based positions and by unpiloted aerial system (UAS) during the 2021 Tajogaite eruption was performed for carbon isotope measurements. The results of the carbon isotope values lie between -1.5 ‰ and +1.5 ‰ (Fig. 1, Ericksen *et al.*, 2024), being significantly heavier than those measured in cold CO_2-rich gas discharges from springs on La Palma (Padrón *et al.*, 2015) and in olivine and clinopyroxene-hosted fluid inclusions (Sandoval-Velasquez *et al.*, 2024). The carbon isotope values prove the presence of a deep crustal carbon reservoir in the local mantle under La Palma with a δ13C ~0 ‰ that was included or remobilized by the magmatic system that drove the 2021 Tajogaite eruption.

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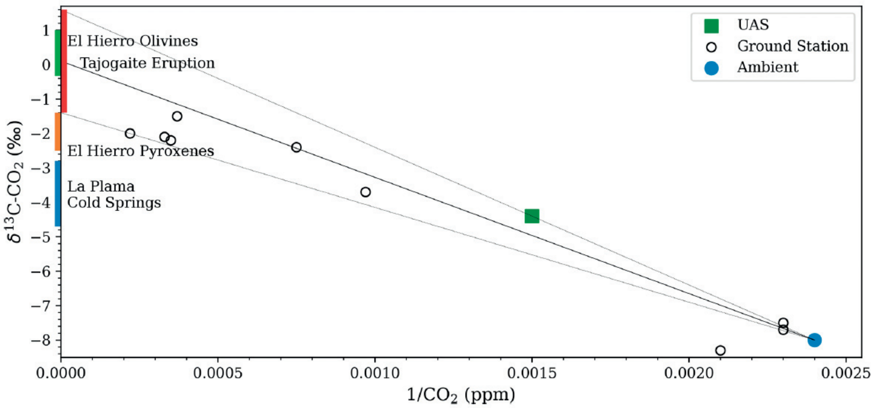

Fig. 1. Keeling plot showing standard air and samples collected on the ground and with the UAS (Ericksen *et al*., 2024)

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QUANTIFYING VERY HIGH H_2O MASS FLUX FROM THE 2021 TAJOGAITE ERUPTION (LA PALMA, SPAIN) USING GROUND-BASED THERMAL IMAGERY

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Abstract

Water vapor, the most abundant gas in volcanic emissions, remains significantly under-measured compared to SO_2. The 2021 Tajogaite eruption offered a key opportunity to quantify H_2O mass flux from a major effusive basaltic eruption. In this study, we used a portable thermal infrared camera (FLIR-T660) to acquire high-frame-rate thermal imagery of the volcanic plume. The H_2O flux was derived by extracting the plume's temperature and width and calculating its transit velocity by tracking gas features across consecutive frames. These plume-derived parameters were combined with on-site atmospheric measurements and integrated into mass and energy conservation equations to obtain H_2O flux (Witter *et al*., 2012). Time series revealed highly variable emission rates. Birnbaum *et al*. (2023) identified variability in the flux at the vent, explained by fluctuations in explosive volume flux that correlated with long-period (1-5Hz) tremor and sustained increases in explosive flux. The total H_2O released during the 85-day eruption is estimated at 597.9 ± 24 Mt, with the most intense degassing period occurring between September 22-26, peaking at an exceptional 1.6×10^5 kt/d. The H_2O emission rate showed a general log-linear decrease, closely paralleling the SO_2 flux during the eruption's initial phase (Esse *et al*., 2025) but exhibiting different behavior at final stages. Considering the average H_2O/SO_2 ratio 13.9 from Asensio-Ramos *et al*. (2025), and the 28 ± 14Mt CO_2 estimated by Burton *et al*. (2023), an emission rate of 953.6Mt H_2O is calcula-

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ted; a value almost twice of that the 597.9Mt H_2O calculated in this study. Assuming 597.9Mt H_2O and 28Mt CO_2 from Burton *et al*. (2023), a 21.3 mass ratio is obtained, which is in the same range as that estimated by other authors (see Asensio-Ramos *et al*., 2025).

The large, simultaneous H_2O and SO_2 emissions in September 2021 point to an efficient, shallow degassing system, likely fed by both pre-existing gas and new magma from a deeper reservoir (Esse *et al*., 2025) as identified from seismic data. This research validates a powerful new method for measuring volcanic water vapor, providing crucial data that helps improve degassing models and fills a major knowledge gap in volcanology.

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MONITORING POST-ERUPTIVE SO_2 EMISSIONS FROM TAJOGAITE VOLCANO (LA PALMA, CANARY ISLANDS)

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ABSTRACT

The 2021 Tajogaite eruption on La Palma was not only notable for its physical impacts on the landscape and communities but also for the substantial volume of volcanic gases it released into the atmosphere. Over the course of the eruption, a significant amount of CO_2 and SO_2 was emitted (Burton *et al.*, 2023; Asensio-Ramos *et al.*, 2025; Esse *et al.* 2025). These emissions had significant implications for local air quality (Milford *et al.*, 2023). Following the end of the eruption, SO_2 emission monitoring from Tajogaite volcano was continued (Rodríguez *et al.*, 2023), as the relatively low ambient background concentrations make SO_2 an ideal target gas for detecting residual volcanic degassing during the post-eruptive phase. Measurements were conducted using both car- and UAV-mounted ground-based miniDOAS systems (Fig. 1), enabling high-resolution tracking of SO_2 fluxes from different vantage points. This surveillance provided valuable insights into the evolution of the volcanic system and supports early detection of any reactivation signs. Approximately 90 measurements of SO_2 emission rates were conducted between December 14, 2021, and August 8, 2023. The standard deviation of daily estimates was around 20%. Emission values ranged from 669 to 0.7 tons per day, showing a clear declining trend throughout the post-eruptive phase. Between December 14 and 31, 2021 (18 measurements), SO_2 emission rates reached a maximum of 699 tons/day, with an average of 262 tons/day and a minimum of 29

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tons/day. In 2022, 64 measurements were carried out, with maximum, average, and minimum values of 464, 88, and 29 tons/day, respectively. In 2023, 9 measurements indicated a further decline, with values ranging from a maximum of 11.6 tons/day to an average of 4.1 tons/day and a minimum of 0.7 tons/day. The low post-eruptive SO_2 flux observed in 2023 (<10 tons/day) generally suggests limited residual magma degassing and a low probability of short-term eruptive activity. However, persistent SO_2 emissions, even at low levels, may reflect ongoing deep magmatic processes.

Fig. 1. SO_2 flux measurements conducted with UAV-mounted miniDOAS instrumentation

The progressive decline in SO_2 flux is likely linked to the gradual cooling and depressurization of the shallow magma reservoir beneath Tajogaite, as well as evolving permeability within the volcanic conduit system that influences gas escape efficiency.

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SYN- AND POST-ERUPTIVE TRACE ELEMENT EMISSIONS FROM TAJOGAITE VOLCANO (LA PALMA, CANARY ISLANDS)

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Abstract

Volcanic eruptions emit not only major gases such as carbon dioxide (CO_2) and sulfur dioxide (SO_2) but also trace amounts of metals and metalloids bound to volcanic ash, aerosols, and gases. These elements —including arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), selenium (Se), thallium (Tl), tungsten (W), antimony (Sb), beryllium (Be), and copper (Cu)— can be transported over long distances by atmospheric currents. Of particular concern are toxic elements such as As, Cd, Pb, and Cr, which pose serious health and environmental risks due to their persistence, bioaccumulation, and potential for long-term ecological damage. The 2021 eruption of Tajogaite (Cumbre Vieja, La Palma, Canary Islands) released substantial amounts of CO_2 and SO_2 into the atmosphere (Burton *et al.*, 2023; Asensio-Ramos *et al.*, 2025; Esse *et al.*, 2025). SO_2 fluxes were monitored using a combination of ground-based techniques (e.g., miniDOAS in traverse mode) and satellite observations (Hayer

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et al., 2022). Data from the TROPOMI instrument on Sentinel-5P were integrated with the PlumeTraj back-trajectory model to produce sub-daily SO_2 flux estimates (Esse *et al*., 2025; Hayer *et al*., 2022). OP-FTIR measurements conducted throughout the eruption revealed consistently high CO_2/SO_2 ratios in the plume, allowing for a total CO_2 output estimate of approximately 28 Mt (Burton *et al*., 2023Asensio-Ramos *et al*., 2025). Following the eruption, SO_2 degassing from the Tajogaite vent continued during the post-eruptive phase and was monitored using both car-mounted and UAV-mounted miniDOAS instruments (Rodríguez *et al*., 2023). Concurrently, air particulate matter (PM_{10}) was sampled using low-volume collectors in accordance with EN 12341:2014 (Fig. 1).

Fig. 1. PM_{10} samples were collected using a low-volume sampler operating sequential 24-hour sampling on 47 mm quartz filters

Filters were analyzed for trace metals (Pb, Cd, As, Ni) using the EN 14902:2005 standard method. Immission levels of SO_2 and toxic metals at air quality stations significantly exceeded background values during both eruptive phases. By combining trace metal/SO_2 ratios in PM_{10} with measured SO_2 fluxes, we estimated average emission rates of 1314 kg·d^{-1} for Pb, 264 kg·d^{-1} for Cd, and 115 kg·d^{-1} for As. These findings highlight the considerable burden of toxic elements released into the atmosphere during volcanic eruptions.

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QUANTITATIVE STOICHIOMETRIC APPORTIONMENT OF AEROSOL SALTS OF THE TAJOGAITE VOLCANIC ERUPTION

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ABSTRACT

Atmospheric aerosols influence air quality, ecosystems and climate. Such influence on climate is modulated by the interaction of aerosols with solar radiation and the ability of aerosols to act as cloud condensation nuclei to form clouds. Volcanic eruptions may release high amounts of SO_2, HCl and HF which result in the formation of sulfate, chloride and fluoride aerosols. During the eruption and post-eruption of Tajogaite (September 2021 to April 2022), we performed remote FTIR measurements of HCl and HF, in-situ measurements of SO_2 and collected daily bulk and size segregated PM_{10} aerosol samples for performing a speciation of the major volcanic salts (López-Darias *et al*., 2025). The aerosol composition was determined by analyzing the samples by ion chromatography and ICP-OES and ICP-MS for elemental composition. We applied an original stoichiometric apportionment methodology to investigate the atmospheric chemistry involved in the formation of secondary aerosols. We found that sulphate was mainly present as Na_2SO_4 (accounting for 33 % of total SO_4^{2-}), NH_4HSO_4 (16 %), K_2SO_4 (11 %), $MgSO_4$ (6 %), $(NH_4)_2SO_4$ (2.2 %), and 30 % as excess $SO_4^{=}$ relative to measured cations. Na_2S_4 and $MgSO_4$ were formed via quick interactions between SO_2 and vol-

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canic-glass within the eruption plume, so the concentrations of these salts decreased quickly at the end of the eruption; in contrast, concentrations of NH_4HSO_4 and excess sulphate persisted during post-eruption degassing. Cl^- was mainly present as NaCl (98 % of total Cl^-), whereas F^- was present as CaF_2 (94 % 98 % of total F-). Lava flows enhanced ammonia emissions from agricultural-soils; as a result, 87 % of nitrate was present as NH_4NO_3; this ammonium nitrate salt is rarely observed in the Canary Islands, however, the high humidity linked to volcanic water emissions favored the stabilization of the NH_4^+-NO_3^- chemical bond.

The chemical speciation we present here is not generally included in climate models, which usually represent the volcanic aerosol simply as «sulphate». This representation may contribute to improving the assessment of the influence of aerosols on climate.

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THE CONTRIBUTIONS OF PRIMARY EMISSIONS AND CONDENSATION TO TRACE ELEMENTS IN THE AEROSOLS OF THE TAJOGAITE ERUPTION

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Abstract

The trace elements contained in atmospheric aerosols influence air quality, ecosystems and climate. During the eruption and post-eruption of Tajogaite we performed a daily sampling of tephra fall (September to December 2021) and bulk and size segregated PM_{10} aerosol samples (September 2021 to April 2022) with the objective of better constraining the trace elements in the volcanic aerosols. The PM_{10} samples were collected with a high-volume sampler and Dekati™ cascade impactor. Aerosol and tephra samples were analyzed using ion chromatography, ICP-OES and ICP-MS. During tephra-fallouts, giant particles (mm-to-cm size) settled rapidly, while gas-phase species condensed onto smaller particles. This resulted in the condensation of trace metals and other elements in the fine (0.1-1 mm) and ultrafine (< 0.1 mm) size ranges of the aerosol particles. We found that aerosols are enriched, with respect to tephra, in Bi, Tl, Mo and other volatile and/or chalcophile trace elements, characteristic of volcanic emissions, in contrast to refractory elements such as Sr, Co or V, among others. We applied a modified version of the minimum slope technique (Rodríguez & Cuevas, 2007; Rodríguez *et al.*, 2021) to apportion each trace element between the primary aerosols and secondary aerosols, i.e. segregate what portion of each trace element is associated with the primary emission of quenched lava fragments (volcanic-glass and rock-forming minerals) and with condensation processes. This determination was done for

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60 analyzed elements. We found that the contribution of condensation experienced a high variability, being as low as < 10 % for V, Mn or Co, among others, and higher than 80 % for Tl, Pb, or Bi, among others. These results have implications on how the trace elements should be included in models to assess their influence on biogeochemical cycles and climate.

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SEA WATER SOLUBILITY OF TRACE METALS IN THE VOLCANIC AEROSOLS OF TAJOGAITE

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ABSTRACT

Volcanic eruptions release high amounts of trace elements relevant to the ecosystems and climate into the atmosphere. Those contained in the large tephra particles deposit relatively near the emissions area, whereas those related to tiny-micrometer aerosol particles blow in the atmosphere for weeks, reaching remote regions after long-range atmospheric transport (100s-to-1000s of kilometers). The deposition of these trace elements in the open ocean influences the seawater composition, with potential implications on the composition and growth of phytoplankton and consequently on the atmosphere-ocean CO_2 exchange and climate (Moore *et al*., 2013). These inputs may provide limiting/co-limiting micronutrients as iron (Fe), cobalt (Co) or copper (Cu); some of which may also be toxic in high concentrations, as is the case of Cu. Thus, the atmospheric transport and deposition of trace elements have implications on the biogeochemical cycles, ecosystems and climate. The objective of the study is to investigate the solubility in seawater of Fe, Cu, Co and aluminium (Al) in the volcanic aerosols collected during the eruption of Tajogaite. This contributes to identifying the physico-chemical mechanisms governing metal dissolution. From September 2021 to the end of January 2022, we collected daily samples of particulate matter (aerosol particles) smaller than 10 microns (PM 10) in the area affected by the eruption, at El Paso (860 m. a.s.l.) and Los Llanos de Aridane (364 m. a.s.l.). The samples were collected using a high-volume air sampler (30 m^3 h^{-1}) on quartz microfibre filters (150 mm diameter). The gravimetric determinations of PM 10 concentrations were performed following the reference method (EN 12341:2015). The PM 10 samples were subject to a quantitative chemical characterization, including

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water-soluble ions by ion chromatography, major and trace elements by ICP-AES and ICP-MS and organic carbon and elemental carbon by TOT/TOR. A total of 60 elements and chemical species were determined, including total Fe, Cu, Co and Al (López-Darias *et al*., 2025). The soluble fraction of Fe, Cu, Co and Al was determined by Solid Phase Extraction technique using real seawater (Rodríguez *et al*., 2021).

We found that the solubility of the study trace elements experiences a high variability, within the range of 0.01-3.3 % for iron, 0.01-3.1 % for aluminium, 0.15-71 % for cobalt and 0.05-8.3 % copper. During the eruption, sulphate was mainly present as Na_2SO_4 (accounting for 33% of total SO_4^{2-}), NH_4HSO_4 (16 %), K_2SO_4 (11 %), $MgSO_4$ (6 %), (NH_4), SO_4 (2.2 %), and 30 % as excess $SO_4^=$ relative to measured cations. Periods of high solubility of the study trace elements are observed during periods characterized by high concentrations of excess $SO_4^=$, suggesting a direct link between the intensity of acidic volcanic activity, the mobilization of metals in dissolved form and the formation of sulphate-trace metals.

Acknowledgements

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Topic 9

Air quality and health

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ASSESSING PLUME HEIGHT DURING THE 2021 TAJOGAITE ERUPTION (LA PALMA) USING DUAL MONITORING TECHNIQUES: IMPLICATIONS FOR SATELLITE-DERIVED SO_2 MASS ESTIMATES

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ABSTRACT

The 2021 eruption of Tajogaite volcano in La Palma (Canary Islands, Spain) caused major disruptions to public health and aviation. To monitor the event, the Instituto Geográfico Nacional (IGN) deployed a surveillance network to estimate the eruptive column height, while the Spanish Meteorological Agency (AEMET), in coordination with ACTRIS-Spain and other institutions, conducted a comprehensive atmospheric monitoring campaign. This included four ground-based aerosol profiling instruments —one MPL-4B lidar and three ceilometers— along with an existing Raman lidar on the island. This study focuses on characterizing the eruption through two key parameters: the height of the dispersive plume (h_d) and the eruptive column height (h_{ec}).

Data from both IGN and AEMET were analyzed, revealing good agreement between the two independent datasets, with an average difference of 258.6 meters in h_d measurements. Three main eruptive phases were identified, spanning from explosive Strombolian to effusive activity, influenced by seismicity and meteorological conditions. A comparison between AEMET ground-based measurements and the CALIOP satellite-derived aerosol layer height product (ALH_CALIOP) showed that the satellite consistently underestimated the plume height, with a mean difference of 615.0 meters (or 392.2 meters excluding 6 October data). The study also evaluated the effect of plume height assumptions on volcanic SO_2 emission estimates derived from the NASA MSVOLSO2L4 satellite product. When a fixed plume height of 8 km was used instead of the observed h_{ec} values, SO_2 mass estimates were significantly underestimated —by 56.2 % on average and up to 84.7 % in some cases. These results highlight the critical role of accurate, ground-based plume height measurements for improving satellite-derived volcanic gas emission estimates, especially during dynamic and complex eruptive events.

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CHARACTERIZATION OF THE SPECTRAL RADIATIVE FORCING AND EFFICIENCY OF THE TAJOGAITE VOLCANIC PLUME OVER THE IZAÑA OBSERVATORY

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ABSTRACT

On September 19, 2021, a volcanic eruption began on La Palma Island (Canary Islands, Spain), offering a unique opportunity for a multidisciplinary assessment of the volcanic plume's impact. This study presents estimates of the spectral direct radiative forcing (ΔF) and radiative forcing efficiency (ΔF^{eff}) based on solar radiation measurements taken at the Izaña Observatory (IZO; https://izana.aemet.es), located on Tenerife Island, approximately 140 km from the Tajogaite volcano. During the eruption, IZO was affected by volcanic aerosols, Saharan dust, and their mixtures. Three representative cases were identified using ground-based lidar, satellite data (Sentinel-5P TROPOMI), reanalysis products (MERRA-2), and backward trajectory analysis (FLEXTRA), and further characterized through sun photometry in terms of their optical and microphysical properties. Although volcanic aerosols exhibited higher ΔF values than dust events due to greater aerosol loads, their ΔF^{eff} was lower. The spectral ΔF^{eff} at 440 nm ranged from -1.9 to -2.6 $W \cdot m^{-2} \cdot nm^{-1} \cdot AOD^{-1}$ for dust and mixed aerosols, and from -1.6 to -3.3 $W \cdot m^{-2} \cdot nm^{-1} \cdot AOD^{-1}$ for volcanic aerosols, considering solar zenith angles between 30° and 70° (more information in García *et al.*, 2023).

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THE IMPACT OF VOLCANIC ASH FROM THE TAJOGAITE ERUPTION ON THE RESPIRATORY SYSTEM

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Abstract

Particles released by volcanic emissions can affect the health of populations as far as thousands of kilometers away from the source (Stewart *et al*., 2022). In the context of explosive volcanic eruptions, respirable size (i.e. <10 µm) volcanic particles are dominated by ash, which is composed of mineral and amorphous fragments of quenched magma (Eychenne *et al*., 2022). Previous studies showed that different minerals (e.g., crystalline silica, olivine, feldspars) may induce different levels of cytotoxicity, inflammation and oxidative stress (Damby *et al*., 2015; Grytting *et al*., 2022). However, what processes are affected by the volcanic particles and how they may affect human health remain to be determined. The 2021 basaltic Tajogaite eruption generated Particulate Matter pollution peaks on the island of La Palma (LP), causing concerns on the potential health impact for the exposed population. In this study, we compare respirable ash samples from the Tajogaite, the dacitic Plinian Mount Saint Helens (MSH, May 1980), and the andesitic Tungurahua (TUN, August 2006) eruptions. We assessed *in vitro* the effects of these respirable volcanic ash samples and a respirable positive control (Min-U-Sil Quartz) on

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lung tissue cells using the human A549 alveolar epithelial cell line, after 24h and 48h exposure. We determined by RNA-seq and RT-qPCR the gene expression patterns, cell structure by electron microscopy, and the effects on cell death and cell cycle with biochemical assays. RNA-seq analysis highlighted significant differential gene expression in cells treated with volcanic ash from LP, MSH and TUN. Gene ontology and pathway enrichment analyses revealed that volcanic ash from LP and MSH regulated common pathways, including apoptosis and cell cycle (Fig. 1).

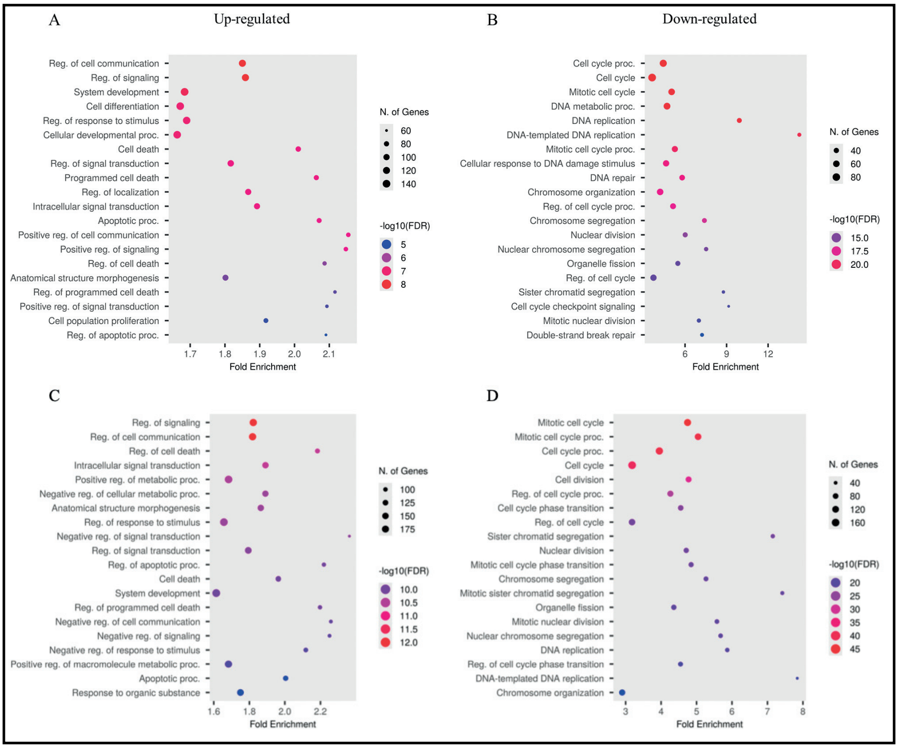

Fig. 1. Gene Ontology Analysis on Respirable Volcanic Ash from Tajogaite (A-B) and Mount Saint Helens (C-D) eruptions in A549 Cell line after 24 h exposure. Top 20 of GO biological process annotations for (A-C) up-regulated genes and (B-D) down-regulated genes. The Y-axis lists the annotations in descending order of –log10 (FDR) while the X-axis shows the fold enrichment and the number of up- or down-regulated genes associated with each pathway

Additionally, specific pathways, like inflammation and oxidative stress, were induced in MSH-treated cells but not in LP-treated cells. Electron microscopy evidenced morphological changes of the cells, as well as, the particles internalization processes induced by the different ash treatments. The biochemical assays led us to confirm the differential effects of the ash treatments on cell death and cell cycle, thus highlighting the toxic potential of Tajogaite respirable ash compared to the MSH and TUN counterparts. Understanding the toxicity profiles of volcanic ash can guide preventive measures and reduce the risk of long-term respiratory effects following eruptions.

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HEALTH IMPACT OF LONG-TERM EXPOSURE TO VOLCANIC PARTICLE DEPOSITS

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ABSTRACT

The 2021 Tajogaite eruption of Cumbre Vieja (La Palma) was associated with widespread and impactful tephra deposits, with a whole tephra blanket of ~ 2×10^7 m^3 (Bonadonna *et al*., 2022). The tephra sequence is dominated by an alternation of lapilli-bearing and ash-dominated fallout layers (Bonadonna *et al*., 2023) that might affect the health of humans and animals for many years after the eruption. Since the eruption of Mount St. Helens in the 1980s, many studies investigated the acute respiratory health hazard of fine inhalable volcanic ash (e.g., Horwell & Baxter, 2006), but knowledge gaps remain regarding whether long-term exposure can trigger the development of respiratory as well as more systemic diseases. In recent studies (Sauzéat *et al*., 2022, 2025), we demonstrated that mice chronically exposed to artificial laboratory-crushed and metal-rich volcanic ash deposits from La Soufrière de Guadeloupe volcano (proof-of-concept study) by multiple exposure pathways presented an organ-specific and isotopically-typified metallomic deregulations associated with pathophysiological changes, preferentially impacting the reproductive system. Mice are also characterized by (i) altered oxidative stress status correlating with isotopic variations of redox-sensitive elements and (ii) hepatic alterations, which might exacerbate testicular defects and impact on fertility. Based on a comparative *in-vivo* approach, this study aims to investigate the long-term reprotoxic effect of the Tajogaite ash. For that, the elemental concentrations and Cu-Zn-Fe isotope measurements coupled to histochemical, proteomic and transcriptomic analyses were measured in blood, liver and two organs of the male reproductive system (testis, seminal vesicle). The samples were collected on wild-type and mice exposed over two months to volcanic ash samples from the Tajogaite and Ubinas volcanoes, two ash samples with distinct health-relevant physico-chemical properties.

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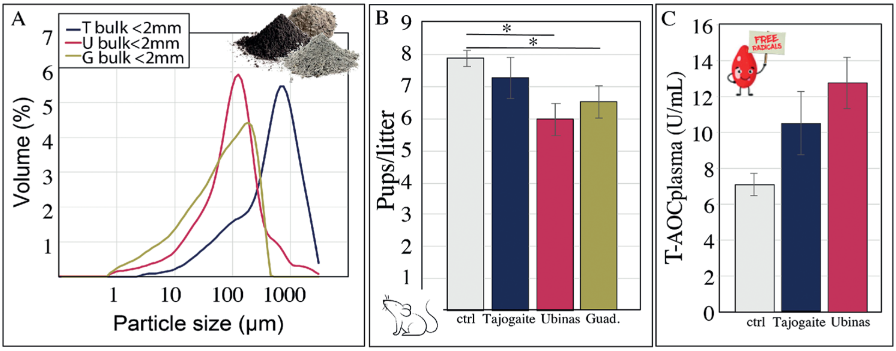

Fig. 1. Sample-dependent volcanic ash reprotoxicity. (A) Grainsize distribution for total volcanic ash deposits, (B) Reproduction tests and (C) Blood plasma total antioxidant capacity (T-AOC). «T» stands for Tajogaite ash samples in comparison to ash from Ubinas (U) and la Soufrière de Guadeloupe (G) volcanoes.

Our results confirm that prolonged exposure to metal-rich volcanic ash might contribute to testicular toxicity, likely mediated by oxidative stress and/or hepatic dysfunctions (Fig. 1). The ash reprotoxicity is sample-dependent, with greater effects observed in cristobalite-rich and fine-grained samples that release higher content of potentially toxic and reactive oxygen species (ROS)-inducer elements (e.g., Fe and Cu). Our results also open perspectives for using redox-sensitive isotope tools as early signs of oxidative stress.

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PHYSICOCHEMICAL PROPERTIES OF THE PM_{10} PRODUCED BY THE 2021 TAJOGAITE ERUPTION ON THE ISLAND OF LA PALMA, CANARY ISLANDS

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Abstract

Explosive volcanic eruptions can inject vast amounts of particles and gases into the atmosphere, potentially impacting air quality by increasing PM_{10} (particulate matter finer than 10 µm in size) in the ambient air (Thorsteinsson *et al.*, 2012). What are the sub-10 µm particles produced by volcanic eruptions, particularly in the case of basaltic activity known to have low fragmentation efficiency? The September to December 2021 basaltic eruption of Tajogaite on the island of La Palma, Canary Islands, was characterized by hybrid activity, i.e., synchronous emplacement of lava flows and production of tephra in fountaining and strombolian activity (Bonadonna *et al.*, 2022). The eruption produced a sustained volcanic gas plume, and a sporadic haze plume formed due to the lava flow entering the sea and vaporizing seawater (Esse *et al.*, 2025). We sampled PM_{10} in the ambient air below the path of the volcanic ash plume on October 1, 2021, as well as the tephra depositing on the ground,

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and characterized the particle size distribution of both. The airborne samples' mineralogical content, near-surface chemistry, and surface texture were determined by Raman spectroscopy, scanning electron microscopy, and EDS analyses. We also leached the samples and quantified the composition of the leachate solution in major ions and trace elements by ion chromatography and ICPMS analyses. We demonstrate the ubiquitous presence of sub-10 µm volcanic ash (glass shards and fragments, euhedral crystals, and crystal fragments) in the ambient air (Fig. 1).

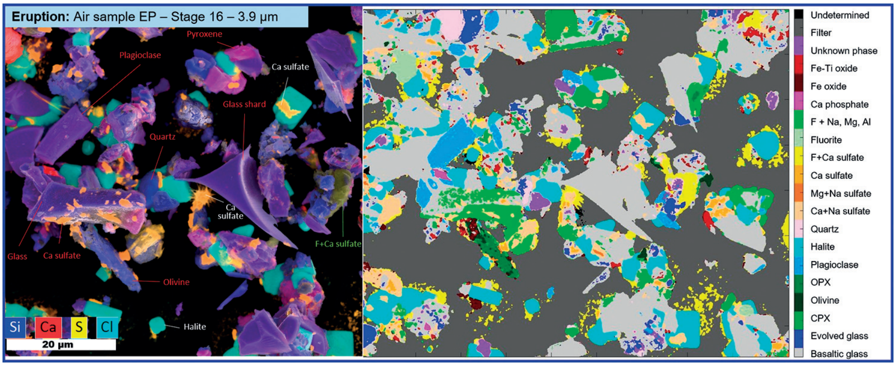

Fig. 1. Example of airborne samples collected on October 1st, 2021 in El Paso, La Palma, on a 16-3.9 µm cascade impactor stage. (Left) SEM-EDX map of particles collected on the impactor stage showing the composition in silicon, calcium, sulfur and chlorine. The phases indicated in red were identified based on their EDX spectra. (Right) Phase map reconstructed using an image analyses routine developed for the purpose of this study.

Particles from sea aerosol as well as from aerosol originating from the condensation/transformation of volcanic gas are also identified. Evidence for interaction of the sub-10 µm volcanic ash surfaces with volcanic gas/aerosol as well as the background atmosphere loaded in sea aerosol are also observed. We analyse the dispersion pattern of these sub-10 µm volcanic particles comparing evidence from the ground tephra samples and satellite and air quality monitoring data, and determine the amplitude of their impact on air quality. Finally, we discuss the possible health implications in case of human exposure.

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LONGER EXPOSURE TIME IS ASSOCIATED WITH HIGHER ACUTE OCULAR AND RESPIRATORY SYMPTOMS AMONG INTERVENING PERSONNEL DURING TAJOGAITE VOLCANO ERUPTION

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Abstract

Exposure to various gases emitted during volcanic activity can produce acute health effects in the general population (Hansell *et al*., 2006), particularly among professionals working in the exclusion zone (Carlsen *et al*., 2019; Candal-Pedreira *et al*., 2024). The aim of this study was to evaluate the relationship between exposure time in the exclusion zone and acute symptomatology among participants in the ISVOLCAN study. The ISVOLCAN study (Rodríguez-Pérez *et al*., 2024) is a prospective observational cohort involving a randomly selected general population from La Palma and a voluntarily enrolled high-exposure group comprising professionals and volunteers who accessed the volcano's exclusion zone during eruption-related tasks. During the recruitment phase (2022-2023), an epidemiological questionnaire was administered, which included variables related to acute symptomatology and exposure time in the exclusion zone (number of hours per day and number of

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days) during the eruption. The primary outcome variables were acute ocular symptoms and respiratory tract (RT) symptomatology, classified into lower respiratory tract (LRT: cough, dyspnea, or wheezing), upper respiratory tract (URT: nasal/ear and pharyngeal), and global RT symptoms. The analysis included 220 intervening personnel. The type of professional and volunteer groups was as follows: 56.4 % emergency services, 9.4 % state security forces, 22.8 % cleaning workers, 5.4 % scientists and 5.9 % other occupational groups. The mean age was 45.7 (± 11.6) years, with 77.2 % male. The median number of hours per day and the median number of days worked by interveners in the exclusion zone were 8.5 (IQR:8-12) and 60 (IQR:20-80), respectively. Symptoms were reported in 35.6 % of cases for the LRT, 34.2 % for the URT, and 50.5 % for the RT, while ocular symptoms were present in 43.6 % of individuals.

In the multivariate logistic regression analysis (Table 1) an association was detected between the daily number of hours (> 8 hours) and the number of days (> = 60 days) for both LRT symptomatology (OR:2.41; 95 % CI:1.04-5.58 and OR:2.38; 95 % CI:1.04-5.47, respectively) and RT symptomatology (OR:2.30; 95 % CI:1.08-4.93, OR:2.41; 95 % CI:1.12-5.21, respectively). For ocular symptomatology only differences were found for the daily number of hours (> 8 hours); OR:2.58; 95 % CI:1.23-5.41). Longer exposure time in the exclusion zone was associated with increased respiratory and ocular symptomatology, despite occupational protective measures.

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AIR QUALITY BEYOND GASEOUS EMISSIONS: MICROPLASTIC INPUTS IN VOLCANIC ENVIRONMENTS —A COMPARATIVE STUDY OF TAJOGAITE AND TEIDE

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ABSTRACT

Volcanic eruptions release gases and particulate matter that can deteriorate air quality and cause severe damage to the human respiratory system. These effects can occur not only during eruptions but also long after they cease. Accordingly, the monitoring of volcanic particulate output is essential for evaluating air quality (Sicard *et al*., 2022). Beyond this, the pristine nature of newly formed volcanic landscapes offers a unique opportunity to study air quality regarding the input of another class of particulate matter of growing concern: microplastics (MPs). MPs, along with other anthropogenic particles such as textile-derived cellulosic fibres, have been identified across a wide range of environmental compartments worldwide. Their small size facilitates long-range atmospheric transport, allowing them to travel hundreds of kilometres from their points of origin and settle in remote soils (Cao *et al*., 2024). Once deposited, they may accumulate, disrupt soil structure, impact local flora and fauna, and ultimately enter trophic networks. This study is founded on the premise that the exclusion zone of Tajogaite offers a strategic site for inves-

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tigating the initial stages of MP colonisation in a virgin environment, largely isolated from anthropogenic influences such as tourism. To this end, two preliminary sampling campaigns were carried out in December 2024, during which air samples (n = 8) were obtained via dry deposition using a passive sampling method, and soil samples (n = 7) were collected from the uppermost 5 cm of soil using corers (Fig. 1). The selected protocols enabled direct comparison with parallel studies conducted in Teide National Park, an older volcanic environment in the Canary Islands subjected to intense touristic pressure. In this latter site, 72 air samples and 78 soil samples were obtained.

Fig. 1. Sampling point for airborne microparticles collected via dry deposition

Air samples from Tajogaite and Teide National Park respectively showed a mean concentration of 3,539.1 ± 1,457.5 and 4,520.4 ± 561.4 items·m^{-2}·day^{-1}. The physicochemical nature of the particles was similar at both sites, being the archetypal particle a colourless cellulosic microfibre under 1 mm in length. Soil samples are currently under analysis and will contribute to estimating the extent of anthropogenic contamination in volcanic environments, informing future monitoring efforts and guiding conservation and policy strategies.

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NUMERICAL MODELLING OF SUBAERIAL CO_2 DISPERSION FOR HAZARD ASSESSMENT IN PUERTO NAOS (LA PALMA, CANARY ISLANDS)

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Abstract

The 2021 Tajogaite eruption in the Cumbre Vieja volcano (La Palma, Canary Islands), which began on September 19, 2021, and lasted 85 days, caused extensive damage due to the lava flows and ash fall. However, since the middle of November 2021, some areas, located approximately 5 km southwest of the eruptive centre, have been affected by intense diffuse CO_2 emissions. Among them are the urban centres of La Bombilla and Puerto Naos. These emissions prevented the populations of these two centres from returning to their homes due to high concentrations of CO_2 in both indoor and outdoor environments. In this work, we model the CO_2 dispersion process in Puerto Naos to obtain hazard maps with the maximum CO_2 concentrations that can be reached in the town's outdoor environment. To achieve these results, we combined field observations with numerical modelling. Field surveys were conducted in low-wind conditions, measuring CO_2 concentration with portable sensors at 15 and 150 cm above the ground at measurement points spaced approximately 10 m apart along the streets of Puerto Naos. We performed numerical modelling using the software TWODEE-2, a code for modelling the dispersion of heavy gases based on the solution of shallow water equations (Folch *et al.*, 2009). For this purpose, we utilised a detailed digital topographic model that included the edifices of Puerto Naos. We determined the gas emission rates from discrete source points under no-wind conditions using a trial-and-error approach. Subsequently, we repeated the numerical modelling, keeping the same sources and simulating all the realistic wind conditions in

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terms of direction and intensity. For each simulation, we determined the maximum CO_2 concentration at various elevations above ground level. This enabled the creation of a hazard map showing the maximum CO_2 outdoor concentrations for each part of the town.

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INDOOR CO_2 HAZARD MONITORING AT LA BOMBILLA AND PUERTO NAOS (LA PALMA, CANARY ISLANDS) BY MEANS OF ALKALINE TRAPS

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Abstract

Although typically harmless when dispersed in the atmosphere, volcanic carbon dioxide (CO_2) is a significant hazard because it is denser than air. This allows it to accumulate in low-lying areas and poorly ventilated spaces, where it can reach dangerous concentrations. Levels above 3 % can cause serious health problems, while concentrations over 15 % can be quickly fatal. The danger is often invisible and can be sharply stratified, meaning a small difference in elevation can be the difference between safety and death. In the aftermath of the 2021 Tajogaite eruption on La Palma, Canary Islands, this phenomenon presented a significant public safety challenge. Anomalously high indoor CO_2 concentrations, reaching up to 20 % in some cases, were detected within buildings in the coastal towns of La Bombilla and Puerto Naos. In Puerto Naos, these hazardous accumulations were predominantly measured on ground floors and in basements, and their distribution was not uniform, exhibiting significant spatial heterogeneity across the area. Because atmospheric CO_2 is typically ultradilute, chemical sorbents with strong CO_2-binding capacity are widely used for reliable detection and capture. For this study, a monitoring network of 45 alkaline trap stations was installed inside ground floor rooms (street level) of buildings in Puerto Naos. The traps consisted of 1.2 M KOH solutions, which were replaced weekly. Weekly surveys were con-

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ducted from May to October 2022 with the aim of identifying locations where traps consistently retained higher CO_2 loads, indicating areas with the greatest hazard (Fig. 1). Statistical analysis of the data revealed that approximately 75 % of the variance in weekly CO_2 retention by the alkaline traps was associated with an endogenous volcanic CO_2 source, while the remaining 25 % appeared linked to external variables, such as ventilation conditions or building characteristics.

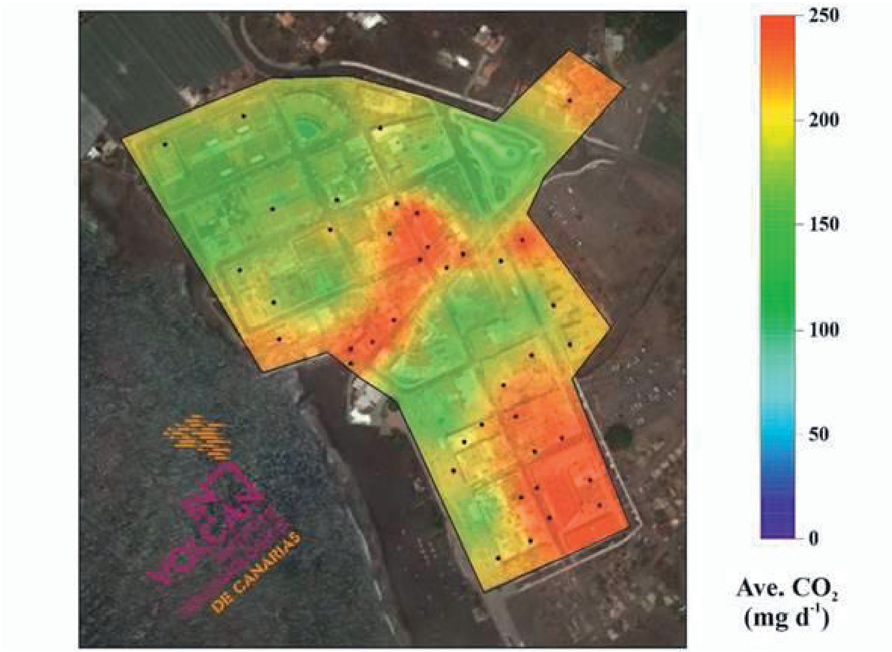

Fig. 1. Spatial distribution of average CO_2 captured by alkaline traps (mg d-1) installed on the ground floor of buildings in Puerto Naos in one of the May 2022 campaigns. The map highlights zones with elevated CO_2 retention, indicating areas of greater volcanic degassing impact and potential indoor hazard

The study validates the use of alkaline trap surveys as an effective methodology for delineating areas of varying hazard levels. By precisely mapping these zones, this approach provides essential data for enhancing quantitative risk assessment and developing robust strategies to protect residents and infrastructure from the ongoing dangers of volcanic degassing.

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ALERTA CO_2 PROJECT: DEPLOYMENT OF A HIGH-RESOLUTION INDOOR CO_2 MONITORING NETWORK IN PUERTO NAOS AND LA BOMBILLA (LA PALMA, CANARY ISLANDS)

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Abstract

During the last days of the 2021 Tajogaite eruption, anomalous CO_2 degassing was detected, significantly impacting the neighbourhoods of La Bombilla and Puerto Naos, both located approximately 6 km southwest of the volcanic vent. CO_2 enters homes and premises through hydraulic and electrical conduits and the vertical structure of the buildings themselves, causing an accumulation of indoor CO_2 that reaches high or very high concentrations. These urban areas, although not directly damaged by lava flows, were included in the exclusion zone due to high volcanic-hydrothermal CO_2 concentrations (>5-20 %), as it implies a corresponding reduction in the oxygen (O_2) content. CO_2 is an invisible, toxic, and asphyxiating gas that can be lethal at concentrations exceeding 14% by volume. Immediate ventilation is required if the CO_2 concentration exceeds 2,000 ppm, while immediate evacuation of indoor spaces is recommended if the CO_2 concentration exceeds 1.5 % (15,000 ppm). In the post-eruptive period, various institutions deployed their own gas monitoring networks to delineate CO_2 anomalies, but their number (fewer than 100) proved insufficient. The findings from these studies, coupled with the ob-

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servation of dead fauna (insects, birds, lizards, and small mammals) attributed to high CO_2 concentrations and low O_2 levels in the air, highlighted the critical need for more real-time CO_2 monitoring stations. The objective was to precisely identify the CO_2 anomalies where air concentrations exceeded hazardous thresholds, thereby assisting authorities in decision-making regarding the safe return of residents to their homes and businesses.

Indoor air quality based on CO_2 concentration

ALERT	Classification	CO_2 (ppm)	Observations	Precautionary actions
BLACK		> 15.000	EXTREMA	ACCESS SHOULD BE PROHIBITED
PURPLE	EXTREMELY UNFAVORABLE	> 5.000	DANGEROUS	EVACUATION IS RECOMMENDED
GARNET	VERY UNFAVORABLE	2.001 - 5.000	HIGH	IMMEDIATE VENTILATION IS REQUIRED
RED	UNFAVORABLE	1.600 - 2.000	Relatively HIGH	VENTILATION IS REQUIRED
YELLOW	REGULAR	1.001 - 1.599	TOLERABLE	VENTILATION IS RECOMMENDED
GREEN	REASONABLY GOOD	771 - 1.000	ACCEPTABLE	NONE
BLUE	GOOD	≤ 770	OPTIMUM	NONE
GREY		NO DATA		On-site verification

Table 1. Indoor Air Quality as a function of CO_2 concentration.

The ALERTA CO2 project, a collaborative effort between the IGN and INVOLCAN institutes, received € 3 million in funding from the Spanish Government. Its goal is to install approximately 1,800 real-time sensors, developed by Sieltec Canarias (www.sieltec.es) that transmit data to a 24-hour monitoring room. In July 2025, 1,486 sensors (measurement concentration up to 4 %, 25 % and 100 %) had been installed (1,481 indoor and 5 outdoor). 162 sensors were deployed in La Bombilla and 1,303 in Puerto Naos, plus 13 mobile stations and 8 located outside these areas. Thanks to ALERTA CO2, more than 780 properties (houses or stores) were allowed to be occupied (with an occupancy licence provided by the Cabildo de La Palma) under safe conditions (see Table 1).

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DETECTION OF THE VOLCANIC CARBON DIOXIDE IN THE AIR OF PUERTO NAOS AND LA BOMBILLA (LA PALMA, CANARY ISLANDS) BY STABLE ISOTOPE SURVEYS

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Abstract

In November 2021, anomalous carbon dioxide (CO_2) emissions were first identified in the coastal neighbourhoods of La Bombilla and Puerto Naos, located on the western flank of La Palma, approximately 5 km southwest of the Tajogaite vents that erupted earlier that year. To better understand the dynamics of volcanic CO_2 degassing in these populated areas, extensive field surveys were conducted over the following two years. Between October 19, 2022, and February 22, 2024, a total of 27 measurement campaigns were carried out in Puerto Naos, yielding roughly 2,200 individual data points. In La Bombilla, 17 surveys were performed from March 2, 2023, to February 22, 2024, providing approximately 700 measurements. All campaigns employed a Delta Ray analyzer installed on an electric vehicle, enabling mobile surveys at 140 cm above ground level. The Delta Ray is a state of the art mid infrared isotope ratio infrared spectrometer (IRIS) capable of simultaneously measuring $\delta^{13}C$ and $\delta^{18}O$ in CO_2 with a precision of 0.05 ‰, allowing for highly accurate isotopic characterization of gas sources. The results revealed a wide variability in CO_2 concentrations and isotopic compositions. In Puerto Naos, measu-

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red CO_2 levels ranged from background values of about 420 ppm to peaks of 4,500 ppm, with $\delta^{13}C$-CO_2 signatures ranging from 9.0 to 2.7 ‰ vs. VPDB. In La Bombilla, concentrations were generally higher, ranging from 420 to 8,000 ppm, while $\delta^{13}C$-CO_2 values varied between 8.1 and 0.7 ‰ (Fig. 1).

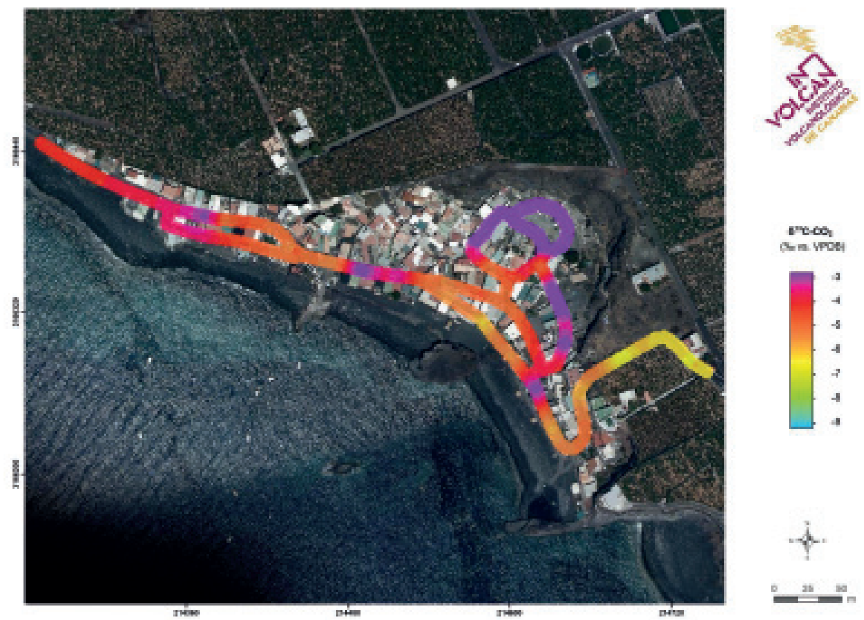

Fig. 1. Spatial distribution of δ13C-CO_2 values (‰ vs. VPDB) measured with a Delta Ray IRIS spectrometer in the village of La Bombilla (La Palma) during one of the 2023-2024 survey campaigns. Mobile transects at 140 cm above ground level reveal isotopic variations linked to volcanic CO_2, with less 13C-depleted signatures corresponding to areas of higher concentrations

Spatial analysis showed that the highest CO_2 concentrations in both areas were systematically associated with $\delta^{13}C$-CO_2 values less depleted in ^{13}C, strongly pointing to a volcanic origin for the excess CO_2. These findings demonstrate the effectiveness of combining high resolution stable isotope measurements with mobile survey techniques to track volcanic gas emissions in inhabited zones. The results not only improve our understanding of the processes governing CO_2 release following the 2021 Tajogaite eruption but also highlight the potential risks associated with persistent volcanic degassing in residential areas. In particular, the approach provides a valuable tool for identifying hazardous sectors where elevated volcanic CO_2 concentrations may impact air quality and human safety.

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INDOOR RADON MONITORING AND DATA ANALYSIS IN PUERTO NAOS AND LA BOMBILLA (LA PALMA, CANARY ISLANDS)

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ABSTRACT

Radon, ^{222}Rn, is a radioactive gas naturally present in the near-surface layers of the atmosphere. Its temporal and spatial flux variations across the soil-air interface represent a promising tool for monitoring and understanding geodynamical processes. However, a significant portion of these variations is influenced by external environmental factors such as temperature, atmospheric pressure, precipitation, or the specific characteristics and location of the measurement setup, including structural properties of nearby buildings. Since late November 2021, anomalous CO_2 degassing has been observed in the neighbourhoods of La Bombilla and Puerto Naos, located on the western flank of La Palma, approximately 5 km southwest of the 2021 Tajogaite eruption vents. To complement these observations, a network of radon monitoring stations has been deployed in the affected area (see descriptive Table). In order to filter out non-endogenous modulations in the radon signal, we have implemented time-series analysis techniques based on multivariate and frequency-domain methods. Additionally, we have developed and applied a set of simplified numerical simulations using a diffusive-advective radon transport model from the subsurface into indoor environments. These simulations incorporate the effects of varying atmospheric pressure and potential ventilation within rooms. By modifying boundary conditions and key parameters governing fluid and

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radon transport, we can construct a range of theoretical radon concentration models. This modeling approach enables the identification of signal components that might not directly be attributable to atmospheric modulations or structural factors, thereby helping to isolate signals potentially linked to deep-seated geodynamic processes. Defining a robust background level of radon emissions under controlled conditions enhances the reliability of correlations drawn between radon concentration anomalies, CO_2 degassing, and subsurface dynamics.

Station	Number of measurements (Bq m^{-3})	Range (Bq m^{-3})	Mean (Bq m^{-3})	Standard Deviation (Bq m^{-3})
15_"Playa Chica" garage (0 floor)	7911	0.0 - 4207,0	2674,3	904,4
17_"Paseo Marítimo" garage (-1 floor)	5418	0.0 - 701719,0	4034,7	20306,0
19_Apartment (1st floor)	408	0.0 - 330,0	31,2	36,0
21_Store (0 floor)	5301	0.0 - 629032,0	280,5	8639,0
22_"La Roca" Hall Building (0 floor)	6564	0.0 - 11496,0	1611,5	1030,3
23_"Playa Chica" Apartment (0 floor)	13733	0.0 -58532,0	1121,1	1492,3
18_SPAR garage (-1 floor; 0 meter)	6855	0.0 -1084,0	66,5	171,5
18_SPAR garage (-1 floor; 1 meter)	7301	0.0 -4894,0	328,9	195,7
18_Pharamacy (0 floor; 0 meter)	14930	0.0 -16209,0	780,1	805,2
18_Pharmacy (0 floor; 1 meter)	6675	0.0 -142687,0	580,4	3431,6
20_Garage C/Mauricio D. (-1 floor)	7911	0.0 - 4207,0	2674,3	904,4

1 Table. Descriptive statistic of the recorded variables by radon sensors

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THE OXIDATIVE POTENTIAL OF PM_{10} RESPIRABLE PARTICLES DURING THE ERUPTION OF TAJOGAITE

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Abstract

Epidemiological studies have found associations between exposure to atmospheric aerosols, or particulate matter (PM), in the ambient air and morbidity and mortality. More recently, it has been found that inhaled aerosols have the potential to generate reactive oxygen species (ROS), inducing oxidative stress at the cellular level. The objective of this study is to determine the oxidative potential (OP) of the respirable PM_{10} particles (< 10 µm) samples collected during the eruption and post-eruption of Tajogaite (La Palma, Canary Islands). As far as we know, this is the first study of OP of volcanic PM_{10} aerosols. From September 2021 to the end of January 2022, we collected PM_{10} samples in two sites affected by the volcanic smog: El Paso (860 m a.s.l.) and Los Llanos de Aridane (364 m a.s.l.). The samples were collected using a high-volume air sampler (30 m^3 h^{-1}) on quartz microfibre filters (150 mm diameter). The gravimetric determinations of PM_{10} concentrations were performed following the reference method (EN 12341:2015). The PM_{10} samples were subjected to a quantitative chemical characterization, including water-soluble ions by ion chromatography, major and trace elements by ICP-OES and ICP-MS and organic carbon and elemental carbon by TOT/TOR. A total of 60 elements and chemical species were determined (López-Darias *et al*., 2025). The OP of PM_{10} samples was determined using two widely applied acellular assays: ascorbic acid (OP^{AA}) and dithiothreitol (OP^{DTT}) (Bates *et al*., 2019; Calas *et al*., 2018; López-Caravaca *et al*., 2024). The OP^{DTT} is generally more sensitive to active redox organics, whereas OP^{AA} is more sensitive to transition metals such as cupper, iron and others. We found average values of OP of 30.2 nmol min^{-1} m^{-3} (OP^{AA}) and 4.9 nmol min^{-1} m^{-3} (OP^{DTT}) (Fig. 1). The-

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se values are much higher than those typically observed in urban air. We found higher OP at El Paso than at Los Llanos de Aridane site (Fig. 1). At both sites the time series of OP^{AA} showed a much higher correlation with copper (Cu) and lead (Pb) concentrations than with any other chemical or bulk PM_{10} concentrations. At El Paso, the correlations with Cu and Pb were even higher than at Los Llanos de Aridane; moreover, high correlations with thallium (Tl) and rubidium (Rb) were also observed at this site, but not at Los Llanos de Aridane.

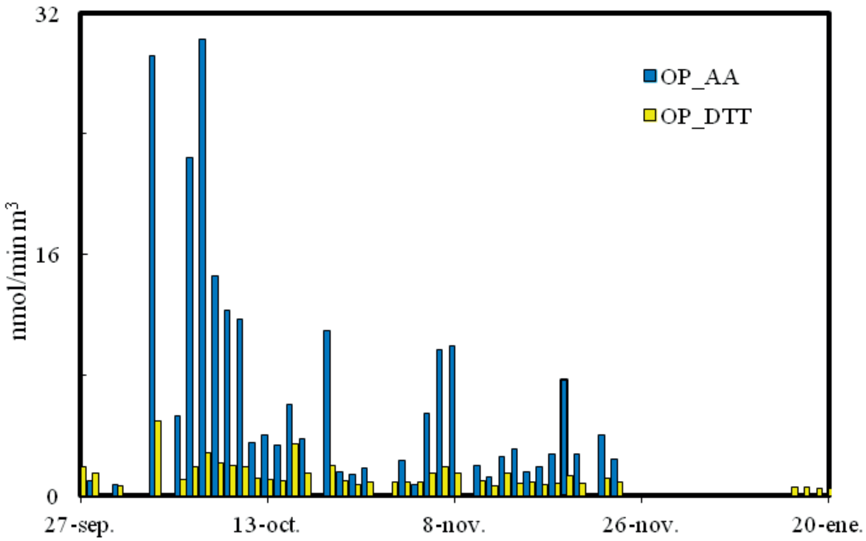

Fig. 1. Diagram of OP measurements in PM_{10} samples collected during the 2021 eruption of Tajogaite

The overall results suggest that high OP values are linked to soluble trace metals. The high OP^{AA} values at El Paso seems to be associated with fresh volcanic aerosols, potentially exhibiting greater reactivity and acidity, which would enhance metal solubility and therefore increase their oxidative potential. These findings underscore the importance of taking the chemical composition of aerosols into account when evaluating air quality and public health risk in eruption-affected areas. Reliance on PM_{10} mass concentration alone may significantly underestimate the toxicological relevance of inhalable volcanic particles.

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ULTRAFINE PARTICLES IN THE AMBIENT AIR OF LA PALMA DURING THE ERUPTION OF TAJOGAITE

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ABSTRACT

Volcanoes emit large quantities of aerosols and gaseous aerosol precursors increasing the particle number concentration in the ambient air, with implications on air quality and climate. These emissions result in the formation of ultrafine particles (UFP) (< 100 nanometers -nm- diameter), which reach the alveoli and bloodstream. These emissions also increase the number of cloud condensation nuclei, resulting in decreases of the mean droplet size (Breen *et al*., 2021; Haghighatnasab *et al*., 2022) and contributing to the observed decreases in global mean precipitation in the years after major eruptions (McGraw & Polvani, 2024). We investigated the formation of UFP during the Tajogaite eruption. During the eruption and post-eruption we conducted continuous monitoring of particle size distribution (10-400 nm), from 28-September-2021 to 11-April-2022. We used a TSI™ nano - Scanning Mobility Particle Sizer (SMPS) - NanoScan 3910 at two sites: Los Llanos (until 19 January 2022) and El Paso (from 19 January 2022 onward). At Los Llanos, we also measured black carbon (AE33 aethalometer), SO_2, NO_x, PM_{10} and $PM_{2.5}$. During the eruption UFPs showed high variability, with low background levels (< 103 cm-3) alternated with extremely high concentrations, with values within the range (1h averages) 50-100 ·103 particles·cm-3. Within the first five weeks of eruption, the lava flows caused fires over towns and banana crops, resulting in high concentrations of black carbon and Aitken mode particles (50-100 nm size) (up to 60 $\cdot 10^3$ cm^{-3}). The concentration of nucleation particles (< 20 nm) remained low during the first 6 weeks of eruption, then they experienced an important increase (with values of up to 30-100 $\cdot 10^3$ cm^{-3}) associated with high SO_2 concentrations near the ground due to the decrease of the altitude of the SO_2 plumes (Milford *et al*., 2023). These particles associated with SO_2 and nucleation (mode at 10-20 nm) have a markedly different size distribution with respect to those observed during fires (mode at 100 nm) (Fig. 1). After the end of the eruption, UFPs concentrations decrease rapidly, becoming

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primarily associated with vehicle emissions. These results show that the eruption of Tajogaite was associated with extremely high concentrations of UFP in the ambient air.

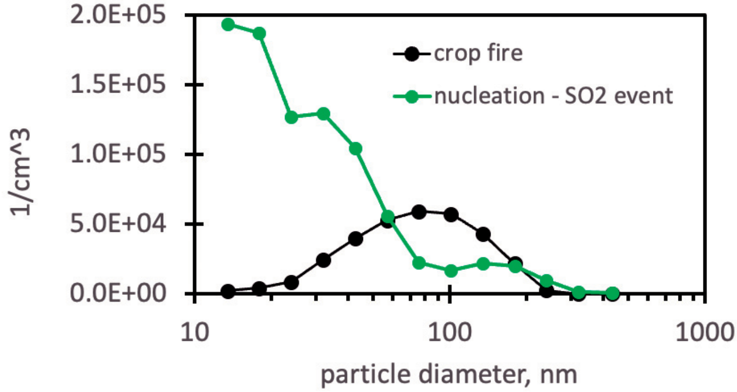

Fig. 1. Number size distribution of aerosol particles at Los Llanos de Aridane during a nucleation & SO_2 event and during a fire event linked to the advance of the coladas over the crops

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Topic 10

Geological Heritage

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CHANGES IN THE NATURAL LANDSCAPE IN THE ERUPTION OF TAJOGAITE 2021 (LA PALMA, CANARY ISLANDS, SPAIN)

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ABSTRACT

Volcanic activity has marked the evolution of La Palma, located in the northwest of the Canary Islands, which is an important laboratory for geomorphological and biogeographical processes. Cumbre Vieja is the study area, a stratovolcano with more than 80 monogenetic basaltic volcanoes and lava and pyroclasts fields, where the historical volcanic activity has been concentrated (Romero Ruiz, 1991). A descriptive analysis method has been followed, from the perspective of Physical Geography, of the changes in the natural landscape (landforms, vegetation and land use). The study area was visited between September 2021 and October 2022 in several fieldworks, to carry out a morphological characterization of the eruption, also following previous studies by geographers. The changes in vegetation and land use have been approached through photographies taken with a *Dji Mavic 2 Pro* drone, orthophotographs (2020-2022 from the GRAFCAN Spatial Data Infrastructure) and studies on the vegetation of the Canary Islands to assess the impact of the eruption. The Tajogaite eruption starts on 19 September 2021 at an altitude between 804 and 1100 m a.s.l. and ends on 13 December 2021, 85 days (the longest eruption in La Palma and the fourth in the Canary Islands). The morphological changes observed have been described as a main scoria cone of 200 m in height and 800 m in diameter with several craters, spatter cones, hornitos, eruptive fissures, and abundant lava flows covering an area of 12.25 km^2, including two lava deltas (Punta del Perdido, 0.05 km^2, and Las Hoyas, 0.75 km^2), that have expanded the surface of the island (Romero Ruiz *et al.*, 2023, 2024; Ferrer *et al.*, 2023; Dóniz-Páez *et al.*, 2024). A total area of 1,193 ha of natural vege-

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Fig. 1. Changes in the natural landscape in the Tajogaite eruption 2021: a) scoria cone formation (Strombolian and Hawaiian eruption); b) *aa* and *pahoehoe* lava flows; c) main scoria cone and craters; d,e) lava fields affecting a neighbourhood and the Canary pine forest; f) lava delta and new beaches; g) roads recovery works; h) areas not affected by lavas (kipukas)

tation has been estimated to be affected by the eruption: anthropized areas of thermo-sclerophyllous scrubland (broom shrubland, 'tabaibales' and *Rumex lunaria* scrub) (859 ha), and *Euphorbia* scrub and shrublands ('Tabaibal-Cardonal') (194 ha); canary pine forest (118 ha); and coastal salt marshes (22 ha).

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TAJOGAITE 2021: GEOHERITAGE OR HATED GEOHERITAGE?

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Abstract

The Tajogaite eruption marked a turning point in the eruptions of La Palma and the Canary Islands. «It generated profound negative impacts on the community, but also an important geovolcanic heritage for geotourism» (Dóniz *et al*., 2023). The last eruptive events still fresh in the population's memory, in Tenerife (1909), El Hierro (2012), and La Palma (1949-1971), caused minor damage to the environment and even provided an incentive to the economy, motivated by the tourist flow generated, especially evident in the eruption of Teneguía. In the eruptive fissure that gave rise to the Tajogaite volcanic edifice, the explosive eruption did emit a significant amount of pyroclasts —bombs, lapilli and ash— that seriously damaged the tree vegetation on the western slope of part of Cumbre Vieja and buried a large urban area, resulting in the collapse of homes and industrial and service buildings of all kinds; as well as a high emission of lava flows that advanced unstoppably towards the ocean, destroying residential, industrial and service urban spaces. Populated areas such as El Corazoncillo, El Paraíso, Alcalá, Tajuya, Las Norias, Las Salgadas, La Condesa, Todoque, etc. have been severely damaged or completely destroyed by lava flow, which in some places have reached 60 meters high. 3,026 buildings were damaged, and 370 hectares of farmlands (banana plantation were devastated. 7,000 people were evacuated, and a random accident while removing ash from a roof caused one death. However, the destruction of Las Manchas cemetery was the shock that unleashed the deepest hatred toward the volcano. In 2025, 200 residents of La Palma are still living in prefabricated homes. The emission of volcanic gases, mainly CO_2,

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has led to additional evacuations in the Puerto Naos area for three years. Greenhouse owners, by Decree Law 33/2924 of March 11, are authorized to rebuild their properties in the same location as before the eruption.

Fig. 1. People living with their backs to the volcano. La Palma (Canary Islands)

As a result, restoration licenses are granted for 45 hectares, with the expectation of restoring 150 hectares. The restoration and road construction are erasing a unique geomorphological heritage created by Tajogaite, a hint of valuing the volcano.

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AN APPROACH TO THE ANTHROPOCENIC TECHNOFOSSILS OF THE 2021 TAJOGAITE ERUPTION (LA PALMA, SPAIN) AND THEIR GEOTOURISM INTEREST

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Abstract

The anthropocenic technofossil refers to evidence of human technological activity preserved in Earth's strata that will persist for millions of years (hominids's mineralized traces) and have every chance of being numerous, widespread and enduring (Haff, 2013; Zalasiewicz *et al*., 2014; Dibley, 2018). This paper makes a first approach to the inventory and classification of anthropocenic technofossils from the Tajogaite eruption based on fieldwork carried out during and after the eruption. The place where the eruptive fissure opened and the area affected by the volcanic materials varied from natural to rural and urban areas (Dóniz-Páez *et al*., 2024a). In this sense, the pyroclasts (ash, lapilli, bombs and scoria) and lava flows from Tajogaite volcano affected crop fields, houses, infrastructures and others. As a result of the interaction of volcanic materials and uses, we can find different human elements that have been buried by the ash and lapilli or incorporated into the lava flows. These evidences correspond to the definition of anthropocenic technofossils and are of great interest for geotourism due to their innovative character. The main technofossils are associated with lava flows in urban environments, but there are also good examples of ashes that have buried houses, cars or irrigation ponds. However, the imprinted tyre tracks; garage doors or fence gratings embedded in lava flows; the moulds of garden walls and gates in lava flows; pieces of houses, roof tiles, molten glass and metal elements (fences, cars, containers, power lines, etc.) embedded in lava flows; houses and crop walls interstratified in lava flows, among others (Fig. 1). It is clear that this work

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is only a first attempt to identify and classify the anthropocenic technofossils in order to enhance their value and propose future geotourism strategies for local territorial development around the great geotourism interest aroused by the geographic heritage of the Tajogaite volcano (Dóniz-Páez *et al.*, 2024b).

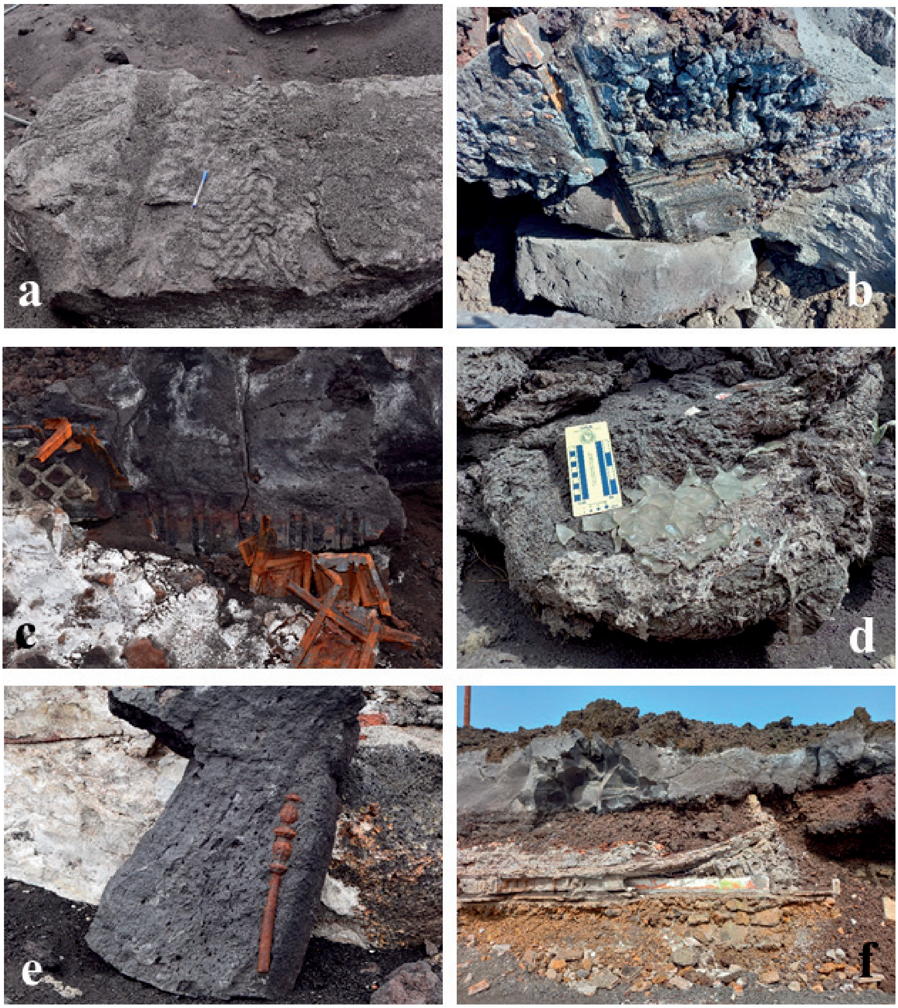

Fig. 1. Example of different anthropocenic technofossils associated with the Tajogaite eruption. a-tyre impressions in the lava; b and c-iron door moulds in the lava flows; d- molten glass between the lavas; e-iron grating embedded in a lava blocks and f-house buried and stratified under the lavas. Source: authors

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GEOMORPHOLOGY AND GEOHERITAGE OF 2021 TAJOGAITE VOLCANIC ERUPTION, SPAIN

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Abstract

Tajogaite volcano eruption (TV) caused a deep change in the natural and anthropic landscape of the Aridane Valley with negative effects for the population and its activities, but it created a new landscape unit with natural features unique in the Canary Islands and described in very few other volcanoes in the world (Romero *et al*., 2024). In this sense, the aim of this work is to characterise the geomorphology of TV and to highlight its high geodiversity and geoheritage in relation to other historical volcanoes in the Canary Islands. TV is a monogenetic basaltic eruption located on the West flank of Cumbre Vieja volcanic rift on La Palma and it's the last eruption occurred between 19 September and 13 December 2021 (Fig. 1). The methodology used is mainly based on photo-interpretation and fieldwork during and post eruption. TV is a fissural eruption (NNW-SSW) with several aligning vents. The dynamics comprised Strombolian style explosions to Hawaiian phases with lava fountains. The erupted products consisted mainly tephra (ash, lapilli, scoria and bombs) and lava flows. The volcanic geoforms are associated with the formation of volcanic edifices, lava and lapilli fields. The former includes one fissural scoria cone (200 m high and 800 m diameter) with nine main craters with explosive and effusive vents; multiple hornitos have also been built at the northern base of the main cinder cone, and various effusion lava vents (Fig. 1). The lava surfaces covered an area of more than 12 km^2 and are characterized by their superficial morphological diversity: Aa, pahoehoe, blocks and balls lava flows, lava deltas, lava lake, lava tubes, jameos, (collapsed lava tunnel), channels, shatter rings, lava breakout, etc. can be recognized. The main non-volcanic geoforms are debris avalanche in the SW of scoria cone, cliffs and beaches in lava delta (Ferrer *et al*., 2023), impact bombs or debris

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flows, ripples and nebka dunes in lapilli field. First results show that TV has a high diversity of volcanic and non-volcanic geoforms associated with the eruption (Dóniz-Páez *et al*., 2022) and has a very high geodiversity and geoheritage compared to other historical eruptions in the Canary Islands.

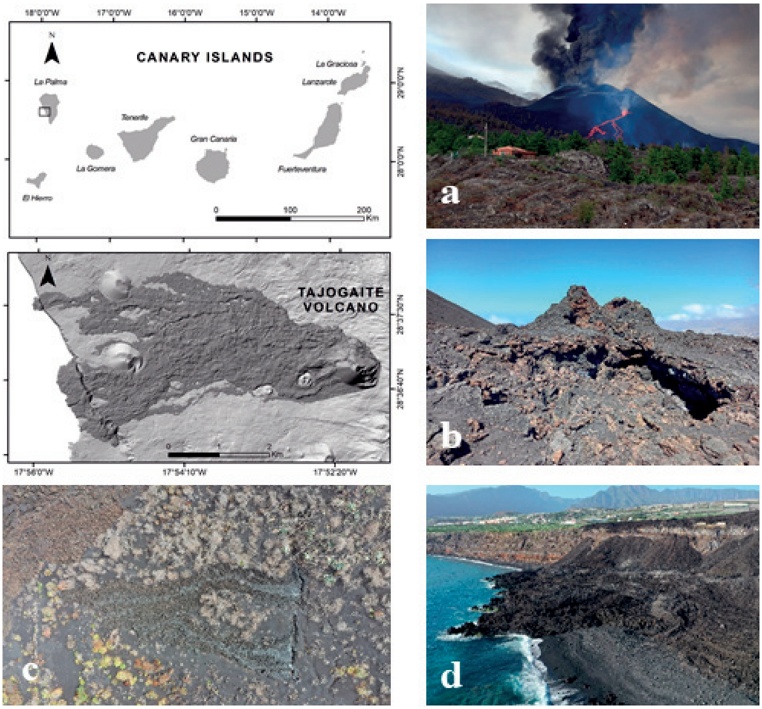

Fig. 1. Location Tajogaite eruption and main geoforms: a-scoria cone with lava flows and eruptive column; b-hornitos-spatter; c-fissure effusive (photo R. Ubaldo); and d-lava delta with new beaches (photo R. Ubaldo). Source: authors.

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LAVA BREAKOUT FROM 2021 TAJOGAITE VOLCANIC ERUPTION, LA PALMA, SPAIN

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ABSTRACT

Canary Islands are a volcanically active region that has experienced multiple historical eruptions over time, being the most recent the eruption of the Tajogaite volcano (TV) (2021) on the island of La Palma. TV is a monogenetic basaltic eruption located on the West flank of Cumbre Vieja volcanic rift on La Palma and it's the last eruption occurred between 19 September and 13 December. One of the characteristics that make to this volcano singular is the important presence of pahoehoe lava flows, many of the which are associated with secondary lava flows (lava breakouts) (Romero *et al*., 2024). In the case of Tajogaite and in the context of the lava fields generated by historical volcanism in the Canary Islands, the importance of the secondary lava flows in relation to the total lava emitted is only comparable to those generated during the Timanfaya eruption (Lanzarote, 1730-1736). In general, lava breakouts have previously been described in areas relatively close to emission centres. However, at Tajogaite, they can be found distributed across almost the entire surface of the lava field, with clear tendency to concentrate in specific altitudinal zones, coinciding in this way with areas of higher human activity previous to the eruption (Fig. 1). This study aims to analyze the secondary lava flows in the Tajogaite lava field, incorporating territorial variables that allow a quantitative analysis using primarily basic Qgis tools. This analysis focuses on identifying correlations between the location characteristics of secondary lava flows at Tajogaite and the essential geographic factors that influence their formation, morphological features, and emplacement. The results show a clear connection between the topographic features previous to the eruption, many of which are of anthropogenic origin, and the distribution of lava morphologies, including lava breakouts or secondary lava flows.

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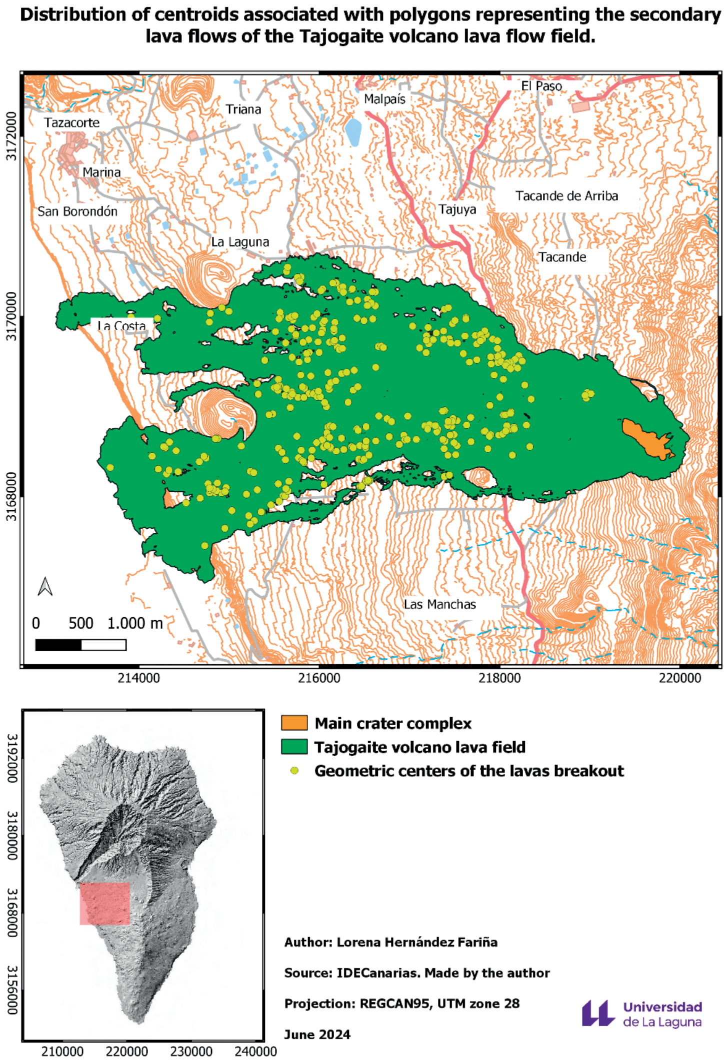

Fig. 1. Distribution of centroids associated with polygons representing the secondary lava flows of the Tajogaite volcano lava flow field. Source: IDE-Canarias

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GEOHERITAGE AND GEOCONSERVATION RESEARCH TO PROTECT THE 2021 TAJOGAITE VOLCANO (LA PALMA ISLAND, SPAIN)

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Abstract

The eruption of the Tajogaite Volcano in 2021 has led to a scientific breakthrough across various disciplines. Undoubtedly, this eruption has also demonstrated how Science can contribute to prevention and recovery after a geological disaster of this magnitude. Among all these disciplines, geological heritage has been applied for the first time since the volcanic emergency phase (Ferrer *et al*., 2023). This latest eruption on La Palma Island has highlighted the scientific challenge of determining the most valuable volcanic features for protection. A new methodology was specially designed in 2022 to identify the EVIs (Spanish acronym for Volcanic Elements of Interest) and assess their scientific and touristic value (Vegas *et al*., 2022). The results have allowed to select EVIs that should be legally protected to ensure a sustainable socioeconomic development that does not endanger the conservation of the most valuable features of this volcano. The identification and mappings of EVIs have been used this methodology have been used by the Canary Islands Government (Decree Law 9/2023, of December 18), on the adoption of «territorial and urban planning measures for the economic and social recovery of the island of La Palma after the volcanic eruption of Cumbre Vieja», where they are protected under the category of 'land for precautionary protection' as an initial procedure for their inclusion in the Natural Protected Areas of Canary Islands. Unfortunately, to date, the declaration of a protected area has not been approved by the Canary Islands Regional Government. During the nearly four years since the end of the eruption, strong damages and impacts have caused irreversible loss of the most valuable volcanic elements. This fact shows the importance of quick scientific assessment of geoheritage in order to include

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the most valuable areas in the new territorial and urban plans to be carried out immediately after the eruption has ended.

This approach offers the most robust guarantee for the geoconservation of volcanically active regions. Nevertheless, the current situation underscores the protracted timeframe required to achieve legal protection for the geological heritage associated with this eruption. As a result, many EVIs have already been seriously affected or have completely disappeared. Losing this geoheritage means losing the legacy of the eruption forever.

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SUSTAINABLE GEOTOURISM DEVELOPMENT AND TRAINING INITIATIVES FOR THE LLANO DEL JABLE-CABEZA DE VACA-TAJOGAITE VOLCANO TRAIL, LA PALMA ISLAND

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ABSTRACT

Volcanic eruptions, while destructive, can also present unique opportunities for geotourism development and economic recovery in affected regions. This abstract details the collaborative efforts undertaken in La Palma, Canary Islands, to leverage the post-eruptive landscape of the 2021 Tajogaite Volcano for sustainable geotourism, focusing on the newly established Llano del Jable-Tajogaite Volcano Trail. This initiative showcases a successful public-private participatory model that involves scientific institutions, local governments, and the tourism sector. Following the Tajogaite eruption, the Instituto Geológico y Minero de España (IGME-CSIC), in conjunction with the Cabildo de La Palma and the El Paso City Council, designed a dedicated geo-trail (Vegas *et al*., 2024). This pathway has since been actively utilized by tourism companies, with local guides receiving specialized training. To formalize and enhance this capacity building, in May and June of 2025, IGME-CSIC and the El Paso City Council offered a «Microcredential in Geological Heritage and Geotourism: The Llano del Jable-Tajogaite Volcano Trail.» This short course aimed to equip nature tourism professionals with robust scientific knowledge and interpretative tools to communicate the geological processes of the 2021 eruption effectively. Twenty-five people, between the ages of 25 and 63, took part in this course and were trained in the geological interpretation of the trail and its relationship with previous land uses and the current volcanic landscape.

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Fig. 1. Training course on geological interpretation of the Llano del Jable-Cabeza de Vaca-Tajogaite Volcano Trail. Microcredencial CSIC 2025

The training focuses on nature tourism guides in the volcano's access quadrant and personnel from the El Paso City Council. Remaining spots are allocated to unemployed individuals, especially those qualified as mountain guides. This strategic approach ensures high-quality geological interpretation and visitor experience, while contributing to local employment. This approach features a secure access quadrant for guides, allowing compatibility between scientific research and touristic activities. It is a model for transforming a natural calamity into a sustainable resource for the economy, employment, and promotion, making the Tajogaite geotrail a key reference in national and international geotourism.

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TERCEIRA (AZORES, PORTUGAL) AND LA PALMA (CANARIAS, SPAIN) AS NATURAL LABORATORIES FOR ADVANCING GEOTECHNOLOGIES: FROM LAVA TUBE CONSERVATION TO SPACE RESEARCH

Ana Pires[1*], André Dias[1], Paulo Rodrigues[1], Rui Moura[2,3], Ana Z. Miller[4,5], Juana Vegas[6], Octavio Fernández-Lorenzo[7], Paulo Barcelos[8], João Carlos Nunes[9] and Helder I. Chaminé[10,3]

Abstract

This ongoing research explores the use of geotechnologies in subterranean environments, with a specific focus on lava tubes, through two distinct case studies (see Fig. 1). The first study examines the methodologies applied at Natal Cave, located on Terceira Island in the Azores archipelago, Portugal. This research was part of the CAMões mission (Caving Analog Mission: Ocean, Earth, and Space Exploration), the first space analog mission conducted in Portugal (Pires *et al.*, 2023). The second case study focuses on the current mapping efforts for newly formed lava tubes on La Palma, which resulted from the 2021 Tajogaite volcanic eruption (Miller *et al.*, 2020). The findings from the experimental field in La Palma provide groundbreaking three-dimensional models of these lava tubes, created using advanced photogrammetric techniques and optimized algorithmic approaches for mapping and geo-visualization. This research represents a pioneering effort to document and preserve the lava tube systems formed by the 2021 eruption. A key innovation in both case studies is the integration of high-resolution FARO laser scans

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[6] IGME-CSIC, Spain.
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[8] Speleology Association «Os Montanheiros», Terceira Island, Portugal.
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for 3D documentation and spatial analysis within lava tubes. This terrestrial laser scanning technology generates accurate point clouds, enabling precise geometric reconstruction of underground environments. In La Palma, these scans were enhanced by advanced photogrammetric techniques and algorithmic methods, resulting in highly detailed three-dimensional models that significantly improve our understanding of the morphology and structure of the tubes. The use of FARO technology has proven essential in capturing complex underground topographies where traditional mapping techniques may fall short.

Fig. 1. A) FARO Laser Scans measurements at Natal Cave in Terceira Island (Azores Archipelago, Portugal); B) and C) La Palma 3D scans acquisition on the surface and underground (Canarias, Spain) (Image credits: A) Mara Leite; B) and C) Nicasio Jimenez-Morillo)

Additionally, the research highlights the use of an unmanned ground vehicle (UGV) named LINCE, which is equipped with cutting-edge mapping sensors. LINCE demonstrated operational success in extreme underground conditions, further validating the feasibility of remote exploration in hazardous and inaccessible environments. By combining photogrammetry, terrestrial laser scanning, and autonomous robotics, this research establishes a novel framework for non-invasive exploration, documentation, and preservation of volcanic subterranean systems. Integrated technologies have significant implications for geological studies on Earth and future exploration missions beyond our planet (Léveillé & Datta, 2010; Titus *et al.*, 2021; Carrer *et al.*, 2024).

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5 GEOROUTES: FIRST PHASE FOR THE CREATION OF A GEOLOGICAL PARK IN LA PALMA

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ABSTRACT

In November 2022, the Department of Environment of La Palma Island Council, awarded Telesforo Bravo Foundation, a contract for development services for «first phase of the creation of a Geological Park in La Palma». The project consisted of bibliographical selection, fieldwork, routes design, and a workshop on the Geological Park initiative. The island of La Palma boasts a rich geological heritage of special significance throughout its natural areas. It combines the ancient, with a «Paleo-Palma» that broadly occupies the northern part of the island, which has suffered mega landslides (Ancochea *et al.*, 1994), and a «Neo-Palma» with the Cumbre Vieja ridge, which is extraordinarily active and has seen three eruptions in just over 70 years, resulting in ’A’ā and «Pahoe-hoe» lava flows, volcanic tubes and lava channels of spectacular beauty (de la Nuez Pestana *et al.*, 2018). It is also the only island along with Fuerteventura and La Gomera where the Basal Complex, emerges, as well as spectacular pillow lavas formed below sea level and which are now found from 400 meters above sea level. It is also possible to find fossils and molds of plants and a unique aquifer, the «COEBRA», which feeds the springs of «Marcos y Cordero» (Bravo & Coello, 1979). We cannot fail to mention the Caldera de Taburiente, which gives its name to all the volcanic calderas in the world. It’s very difficult to find such a varied and exceptional geological heritage in such a small area. This is the right time for this initiative, as the Tajogaite eruption has brought the island international recognition, and it’s already receiving many visitors interested in its geology and volcanism. The goal is to showcase this heritage and turn it into a resource that generates additional incomes for the island and its inhabitants (Carcavilla *et al.*, 2008). We wanted this history, which dates back just under two million years, to be embraced and valued by the people of La Palma. We wanted them to share it with their neighbours and visitors, thus making it possible to distinguish local agriculture, restaurants and hospitality businesses, active tourism, and commer-

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ce Carcavilla *et al*., 2011). In order to achieve these targets we designed five routes: one for each natural area of the Island.

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PROPOSALS FOR RECOGNITION AND RECOVERY OF THE MEMORY OF THE POPULATION AFFECTED BY THE TAJOGAITE VOLCANO

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Abstract

The eruption of the Tajogaite volcano not only caused massive destruction to homes, infraestructures, and facilities. It also devastated the memories, dreams, and everyday spaces of many residents of Aridane Valley. For the full recovery of the affected population, it is not enough to rebuild material possessions; the trauma suffered must be addressed (Glockner, 2000), and areas must be established that allow us to remember what was lost and reveal aspects that are impossible to quantify and that do normally not appear in scientific studies (de León Hernández, 2024) There are many volcanically active territories around the world, that periodically suffer the effects of eruptions (Oppenheimer, 2023). Their inhabitants cope with the effects in various ways. Some communities do not forget to create spaces to remember not only the characteristics of the volcanic phenomenon they experienced. Also the memories of their lost existence: images of their homes, of their families living there, of the activities they carried out, of their traditions and common places (Coello Bravo, 2024). After the 2021 eruption, we've seen major roads built in record time. The work of the builders, has been recognized at the roundabouts installing steamrollers and shovels. The only attempt to commemorate the suffering of the population has been the placement of the so-called «Door of the Future». In our opinion, this is an insufficient and isolated initiative that does not do justice to those affected. There are examples that could be adapted on La Palma, such as the «Eldheimar Museum» in Iceland, dedicated to the Surtsey Island eruption and billed as «a collection of memorabilia from the volcanic eruptions on the Westmannaeyjar Islands». Another example is the «Gunung Merapi Museum», dedicated to the Merapi volcano in Indonesia, which has a section called Volcanoes, Humans and Merapi. There are also local initiatives to preserve the memory of the victims of Tajogaite. Filmmaker

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José Victor Fuentes, directed «Un volcán habitado» with David Pantaleón, a film released in 2023. It contains dozens of audio files of conversations about the volcano, as well as impressive images of the eruption Fuentes is willing to provide the film material for continuous playback in a designated space in El Paso.

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DO CHILDREN UNDERSTAND THAT THEY LIVE ON A VOLCANO?

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Abstract

This work presents preliminary results from the development of an educational resource for primary school students, designed to enhance their conceptual understanding of volcanism (Perales-Palacios *et al*., 2021). The didactic approach is rooted in meaningful learning, combining visual aids with hands-on materials, particularly through the use of an interactive book. While the resource is contextualized for the island of Tenerife, both its design and pedagogical principles are adaptable to similar volcanic environments, such as the island of La Palma. The implementation of this resource took place within the framework of the Ciencia a lo Grande project, funded by the Tenerife Island Council and coordinated by the Scientific Culture and Innovation Unit of the University of La Laguna (Cienci@ULL). The broader goal of this initiative is to support the professional development of active Primary Education teachers by reinforcing foundational physical and chemical concepts —such as heat transfer and matter composition— through the lens of volcanic phenomena. To evaluate the effectiveness of the resource, a pilot study was conducted focusing on upper primary students (ages 10-12). The study assessed their understanding of the volcanic environment in which they live, using children's drawings as the primary data source. These drawings, produced after participation in a hands-on activity, served to assess both the knowledge gained and persistent misconceptions. Each drawing was analyzed using descriptive statistics and coded across several parameters. Statistical tools were then applied to interpret the influence of each factor. Beyond the scientific content, this resource aims to improve natural hazard preparedness and resilience. It promotes values such as environmental awareness, scientific curiosity, and respect for the local ecosystem. Ultimately, this educational approach seeks

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not only to deepen students' comprehension of geological processes but also to foster a stronger territorial identity and a meaningful connection to the natural and cultural heritage of the Canary Islands.

Fig. 1. Primary school students are using the interactive book on volcanism and engaging in a game to reconstruct the geological history of Tenerife

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Topic 11

Marine and coastal environment

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CORALLINE ALGAE (RHODOPHYTA, CORALLINALES) EARLY COLONIZERS OF THE LITTORAL LAVA FLOWS OF THE RECENT VOLCANIC ERUPTION OF LA PALMA (CANARY ISLANDS)

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ABSTRACT

The eruption of the Tajogaite volcano (La Palma, Canary Islands) occurred between September 19 and December 13, 2021. The lava flowed into the sea on the western shore of La Palma and a new rocky shore was formed. Once the eruption ended and the safety protocols allowed it (February 2022), several bimonthly samplings were carried out in the intertidal and shallow subtidal in order to evaluate the contribution of coralline algae in the early stages of colonization of these new substrates. The identification was carried out by morpho-anatomical and molecular studies. Just two months after the end of the eruption, coralline algae had already settled on the surface of volcanic rocks initially colonized by bacteria and diatoms. The first multicellular colonizers were annual ephemeral minute and thin species of the genus *Hydrolithon*. *Hydrolithon* crusts bearing a large number of minute triangular vegetative propagules were very common, suggesting that vegetative reproduction by specialized propagules may play a relevant role in these early stages. These *Hydrolithon* were later covered and replaced by other slightly thicker non-fertile crusts. Both small confluent crusts of *Porolithon* and crusts that ended up forming *Corallina*-type erect geniculate branches became the coralline algae dominant (Fig. 1). Trichocytes, isolated or in dense groups, were very obvious in all coralline algae that took part in these early stages of colonization of the new volcanic substrates.

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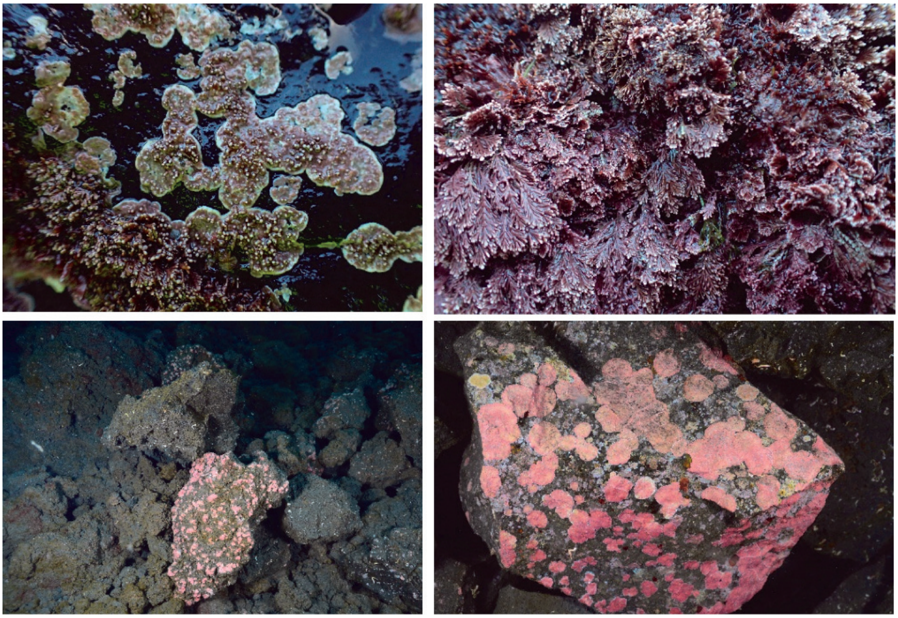

Fig. 1. Colonization of new volcanic substrates by *Corallina* and *Porolithon*

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RECOVERY FROM SCRATCH: RAPID RESPONSE OF FISHES TO A NATURAL DISASTER

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Abstract

Natural disasters affect the dynamics of marine ecosystems, among the most frequent are volcanic eruptions. This new sterile material can wipe out all preexisting life forms. In September 2021, the Tajogaite volcano erupted, forming extensive underwater flows. The objective of this work has been to describe the colonization process of fish in these habitats. Data collection campaigns have been carried out every 2-3 months using the fixed-point methodology up to 20 meters deep. From the first 7 months, the density of fish per transect was already the same as in the control area. The number of individuals was initially low, but by month 7 there was a large incorporation of juveniles and recruits. There is still a difference in terms of the diversity found in the new flows and the control areas, but the colonization process has been without species replacement. Meaning that the species that initially colonized continue to dominate the seascape. This study shows how resilient our ecosystem is against a natural disaster such as a volcanic eruption, providing very valuable information for the correct management of resources.

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IMPACTS OF THE TAJOGAITE LAVA DELTA FORMATION ON THE MARINE ENVIRONMENT: LAVA-INDUCED UPWELLING AND ABRUPT CHLOROPHYLL DEPLETION

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Abstract

The 2021 Tajogaite eruption in La Palma (Canary Islands, Spain) emitted vast volumes of lava during 85 days, which reached the ocean on several occasions at the western flank of the island. Most of these flows merged to create a primary lava delta, covering an area of 48 Ha, with an additional 30 Ha underwater. Here we characterize the effects of the lava-seawater interaction on the surrounding marine environment. The area was sampled during two multidisciplinary oceanographic cruises: the first one comprised the days before the lava reached the ocean and after the first contact; and the second took place a month later, when the lava delta was already formed but still receiving lava inputs. Physical-chemical anomalies were found in the whole water column at different depths up to 300 m in all measured parameters, such as turbidity (+9 NTU), dissolved oxygen concentration (-17.17 µmol kg^{-1}), pH$_{T25}$ (-0.1), and chlorophyll-*a* concentration (-0.33 mg m^{-3}). Surface temperature increased up

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to +2.3 ºC (28.5 ºC) and surface salinity showed increases and decreases of -1.01 and +0.70, respectively, in a radius of 4 km around the lava delta. In the water column, the heated waters experimented a lava-induced upwelling, bringing deeper, nutrient-rich waters to shallower depths; however, this feature did not trigger any phytoplankton bloom. In fact, integrated chlorophyll-*a* showed an abrupt decrease of -41% in just two days and -69% a month later, compared to prior conditions. The chlorophyll-*a* depletion reached a distance larger than 2.5 km (not delimited).

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MONITORING BENTHIC COMMUNITIES IN THE SUBMARINE LAVA FLOW OF TAJOGAITE VOLCANO UNDER THE FRAMEWORK OF THE MARINE STRATEGY DIRECTIVE

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Abstract

The 2021 eruption of the Tajogaite volcano on La Palma (Canary Islands) resulted in a new submarine lava flow, providing a rare and valuable opportunity to study early stages of ecological succession and habitat colonization in a recently formed marine environment. Volcanic events of this magnitude occurring in easily accessible locations are infrequent, making this case a valuable opportunity to study their effects on benthic ecosystems (González-Vega *et al.*, 2024). Monitoring these areas offers critical insights into the natural recovery capacity and resilience of marine communities following extreme disturbances (Sangil *et al.*, 2024). Since 2022, scientific diving surveys have been conducted annually on the submerged lava flow to track the development of biological communities over time. These surveys focus on infralittoral rocky reef assemblages, including fish, cephalopods, and benthic invertebrates, and are complemented with measurements of environmental parameters such as substrate roughness, slope, sedimentation, and bottom type. Sampling is performed at depths between 10 and 16 meters along standardized transects (Fig. 1). Although the surveys were not specifically designed to investigate volcanic impacts, they form part of the

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long-term, standardized monitoring framework established under the Marine Strategy Framework Directive (European Parliament, 2008), which seeks to achieve or maintain Good Environmental Status (GES) in European marine waters. The inclusion of lava-affected sites within this program demonstrates the potential of systematic monitoring to detect and analyze ecosystem changes in response to unforeseen natural events. Two monitoring stations were established directly on the Tajogaite lava field and have been surveyed in 2022, 2023, and 2024. Each station includes four 50-meter transects for invertebrates and six for fish.

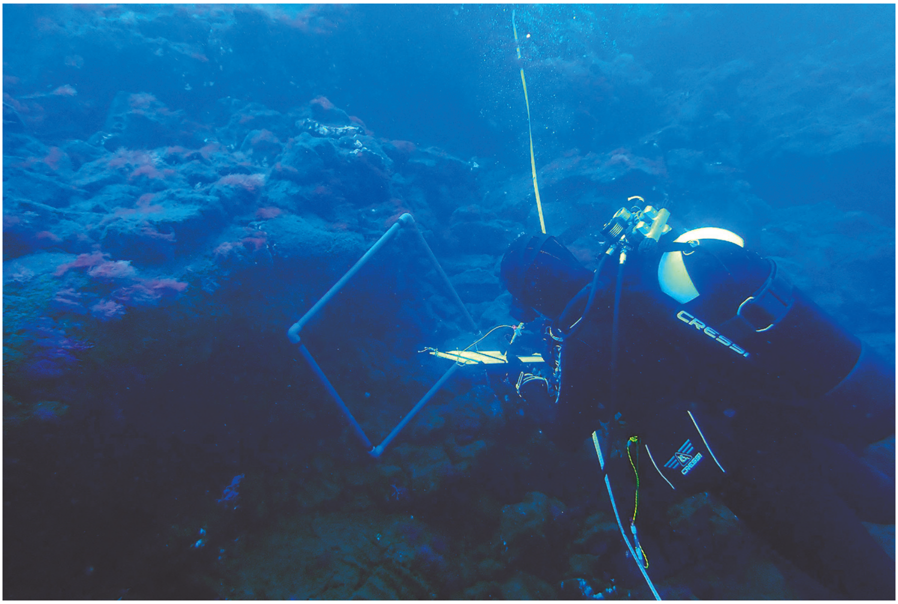

Fig. 1. Diver sampling invertebrates on the new submarine lava flow formed by Tajogaite

Preliminary analyses reveal clear differences in species richness, composition, and abundance, both between the lava-affected sites and nearby reference areas, and across years at the same sites, reflecting temporal changes in community structure. These patterns reflect different stages of succession and habitat colonization, with some pioneering species beginning to establish stable populations. While targeted ecological studies are essential for fully understanding post-eruption dynamics, long-term monitoring efforts like this provide a robust framework for observing ecological processes and contribute essential data for marine conservation and policy-making under the MSFD.

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BENTHIC COMMUNITIES ACROSS RECENT AND HISTORICAL VOLCANIC LAVA FLOWS OF AN OCEANIC ISLAND

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ABSTRACT

Volcanic eruptions create new seafloor habitats that serve as natural laboratories to study primary succession in marine benthic ecosystems (Jewett *et al.*, 2010). On La Palma (Canary Islands), lava flows of different ages from the recent 2021 Tajogaite eruption to older flows from 1949 (San Juan) and 1585 (Jedey) form a substrate age gradient ideal for investigating community assembly over ecological time. We assessed macroalgal communities, larval settlement, and microinvertebrate assemblages across three lava flows of increasing age (<1, 73, 473 years). Standardized photoquadrats, rock sampling, and larval settlement collectors were used at all sites. PERMANOVA analyses revealed significant differences in community composition across lava flows for all biological components: macroalgae (Pseudo-F = 7.17, P = 0.0047), larvae (Pseudo-F = 5.15, P = 0.0002), and microinvertebrates (Pseudo-F = 3.79, P = 0.0009). Macroalgal cover was significantly lower on the youngest flow, with distinct species assemblages compared to older substrates (Fig. 1A). Larval traps showed higher diversity and abundance on intermediate and older flows, with clear differentiation among all three sites (Fig. 1B). Microinvertebrate communities also varied strongly with substrate age (Fig. 1C). The 73-year-old lava supported the richest and most diverse invertebrate assemblage, dominated by polychaetes (*Trypanosyllis zebra*), gastropods (*Bittium incile*), and ophiuroids (*Ophioderma longicaudum*). In contrast, the youngest and oldest flows were comparatively depauperate, being dominated by early colonizers in the youngest and by late-stage specialists in the oldest (Connell & Slatyer, 1977). These patterns reveal a consistent trajectory of ecological

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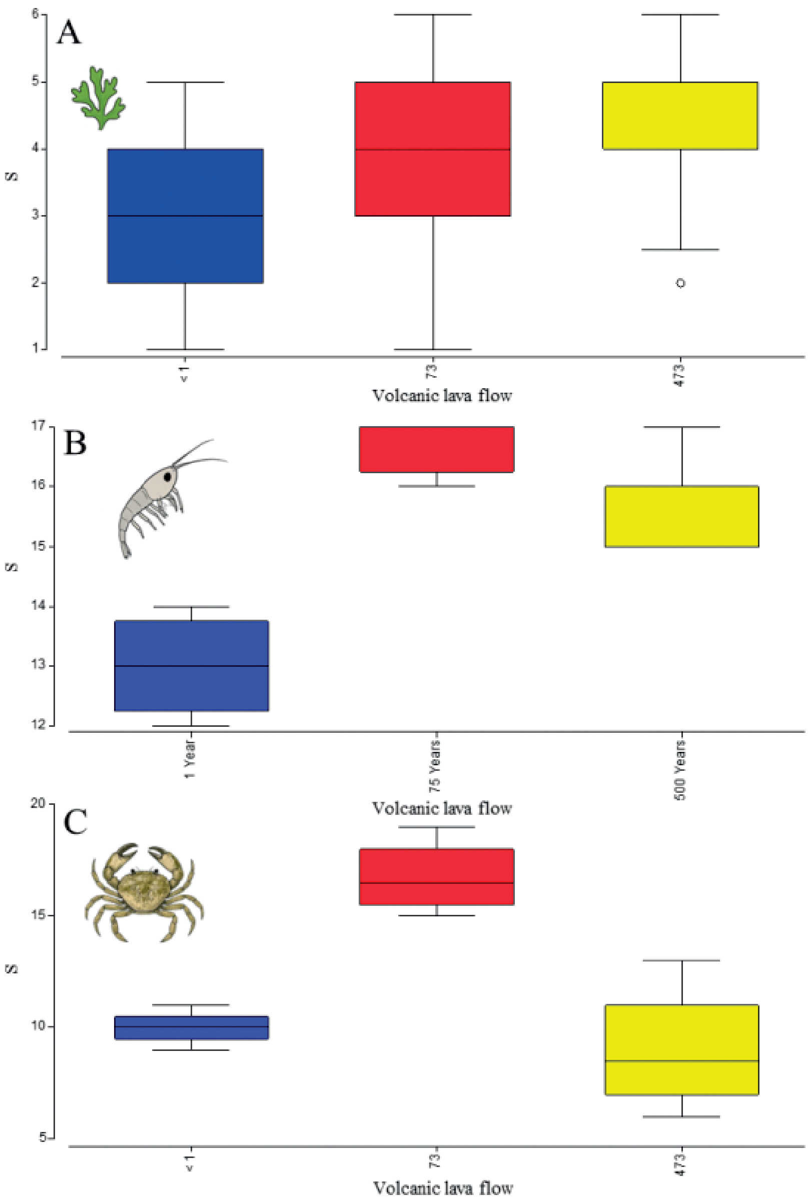

Fig. 1. Boxplots showing species richness across three volcanic substrates of different ages (<1 year, 73 years, 473 years) on La Palma Island for three benthic communities: (A) macroalgae, (B) larval settlers, and (C) sessile and low-motility invertebrates. Richness is represented by the number of taxa per sampling unit. Colors indicate substrate age (blue: <1 year; red: 73 years; yellow: 473 years).

succession, with peak diversity and structural complexity occurring at intermediate substrate ages. The observed shifts reflect successional stages where early colonizers are replaced by more specialized taxa as habitats mature (Margalef, 2012). Notably, benthic invertebrates and macroalgae are foundational components of coastal food webs, supporting ecosystem functioning through primary production and trophic transfer (Dalsgaard, 2003).

This chronosequence-based study underscores how geological age structures benthic community development and highlights the value of volcanic islands for exploring long-term recovery and resilience dynamics in marine ecosystems.

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ADAPTIVE RESPONSES OF THE SEA URCHIN *ARBACIA LIXULA* TO NATURAL ACIDIFICATION DRIVEN BY VOLCANIC CO_2 VENTS

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Abstract

Volcanic CO_2 vents offer exceptional natural laboratories to investigate species adaptation to ocean acidification (OA) under long-term, ecologically relevant conditions (Hernández *et al.*, 2024). On the southern coast of La Palma Island (Fuencaliente, Canary Islands), submarine CO_2 emissions generate a persistent pH gradient (8.1 to 7.4) (González-Delgado *et al.*, 2021) analogue to future ocean chemical conditions. Despite being a calcifying species typically sensitive to acidification, the black sea urchin *Arbacia lixula* lives across this gradient, suggesting potential adaptive responses (Fig. 1). Over the past seven years, we have conducted an integrative series of studies on population genomics, skeletal morphology, and trophic ecology. Genomic analyses identified 14,883 SNPs, with 432 loci significantly correlated with pH variation (González-Delgado *et al.*, 2024). Despite the small geographic scale, population genomic structure reflected clear divergence along the gradient. Candidate genes were associated with development, membrane function, and biomineralization. Morphometric analyses revealed consistent changes under low-pH conditions, including smaller body size, thinner spines, and increased skeletal robustness despite reduced carbonate saturation in seawater, suggesting morphological plasticity and structural optimization. In parallel, stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) indicated a dietary shift from an omnivorous strategy with carnivorous tendencies toward a predominantly herbivorous diet in acidified zones, with increased reliance on turf algae and non-calcified organic matter. Together, these findings provide strong evidence for the mul-

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tifaceted adaptation of *A. lixula* to natural OA. This work underscores the importance of La Palma's volcanic system not only as a unique model for studying eco-evolutionary responses to global change, but also as a refuge for remarkable species.

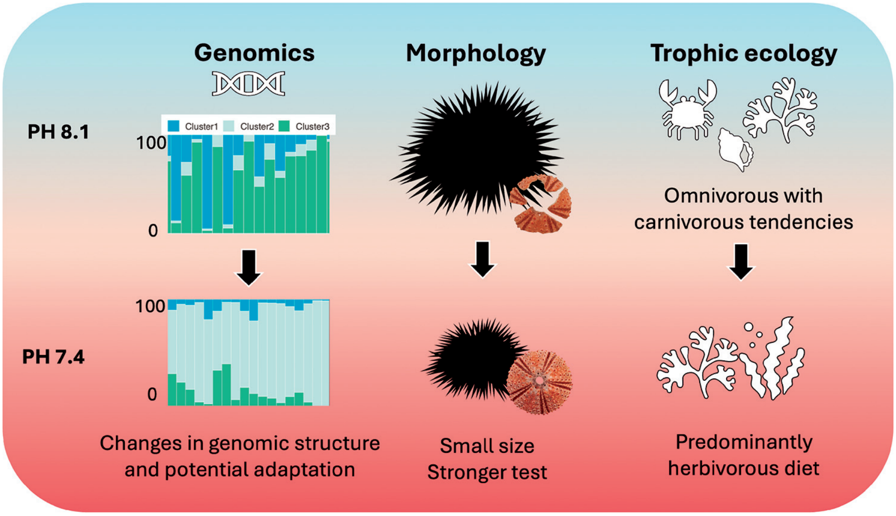

Fig. 1. Summary of the multi-level adaptive responses of *Arbacia lixula* under natural acidification at the CO_2 vent system in La Palma (Canary Islands)

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SHALLOW-WATER HYDROACOUSTIC DETECTIONS OF VOLCANOTECTONIC SEISMICITY DURING THE TAJOGAITE VOLCANIC ERUPTION (LA PALMA, SPAIN)

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Abstract

Volcanic processes generate a variety of seismic events that can be detected by both on-land and underwater sensors (Chouet, 1996; Okal, 2008). During the 2021 subaerial eruption of the Tajogaite volcano on La Palma Island (Canary Islands, NW Africa), an underwater acoustic sensor was strategically deployed to monitor seismic activity (Alcázar-Treviño *et al*., 2025). This study presents marine passive acoustic monitoring data from a moored hydrophone deployed offshore at approximately 77 m depth in a total water column of 80 m, near the coast of La Palma, 2.38 km southeast of Tazacorte harbor and 7 km from the newly formed Tajogaite volcano. The hydrophone was deployed at the same location and depth both during and after the eruption. We compare hydrophone recordings with island's seismic network and earthquake database from the Instituto Geográfico Nacional (IGN, 1999). By calculating acoustic metrics and analyzing low-frequency bands (< 100 Hz), we identified 712 impulsive acoustic signals consistent with seismic events recorded in the

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seismic catalogue. These acoustic signals were double-pulsed, low-frequency (≤ 50 Hz with peak frequencies ≤ 15 Hz) and exhibited sound levels that well correlated with earthquake magnitudes. Our findings demonstrate that shallow-water hydro-acoustics can detect and estimate the magnitude of volcano-tectonic earthquakes in the studied scenario. These results encourage for the integration of hydro-acoustic monitoring in conjunction with on-land seismic stations to enhance the overall monitoring of the investigated volcanic area seismic activity.

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KINETICS OF FE(II) OXIDATION IN A VOLCANIC COASTAL ENVIRONMENT: TWO YEARS OF MONITORING AFTER THE TAJOGAITE ERUPTION

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Abstract

The 2021 volcanic eruption on La Palma (Canary Islands, Spain) formed the Tajogaite volcano and lasted 85 days, being the longest eruptive event in the island. This volcanic episode resulted in substantial environmental alterations, including the formation of two lava deltas on the island's western coast (Tazacorte). A significant release of iron occurred, resulting in substantial alterations to the biogeochemistry of the local marine environment. These changes have the potential to impact bioavailability and ecosystem structure over extended periods. As demonstrated in González-Santana *et al*. (2024), previous studies have examined iron fractionation during the eruption, suggesting a persistent fertilization effect. The present study constitutes a progression of the preceding research by focusing on the post-eruptive Fe(II) oxidation kinetics. This enables the evaluation of the transformation and regeneration processes in the impacted coastal system. A total of seven research cruises were conducted in the area surrounding the lava deltas between January 2023 and December 2024. A total of 10 surface stations were selected, with seawater samples analyzed at each location. The analytical procedure employed was Flow Injection Analysis with Chemiluminescence detection (FIA-CL) (Santana-González *et al*., 2018). All kinetic measurements were performed under controlled laboratory conditions (T = 15 °C, pH = 8.0, and 100 % oxygen saturation) to isolate the effects of iron speciation. Further experimentation was conducted to assess the impact of temperature (5, 10, 15, and 20 °C), pH (7.5, 7.8, and 8.0), and particle size (using filters of 0.2 and 0.02 μm). Oxidation rate constants (k') ranged from 0.021 to 0.300 min^{-1},

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corresponding to half-life values ($t_{1/2}$) between 2.3 and 33.4 minutes, with notable spatial variability. Colloidal sized particles were associated with reduced oxidation rates. Activation energies derived from temperature-dependent kinetics averaged ~120 kJ·mol^{-1}, consistent with organic complexation control.

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SYMBIOTIC MICROBIOME FROM THE OFFSPRING OF TWO SPECIES OF SEA URCHIN LIVING AT A VOLCANIC CO_2 VENT

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Abstract

Bacterial symbioses are fundamental to diverse aspects of animal biology, including in acclimatation and adaptation to environmental conditions (e.g., Efremova *et al*., 2024). This generality applies to sea urchins, which associate with different bacterial communities based on developmental stage, feeding conditions, and life-history strategy (Carrier *et al*., 2024). Here, we test whether the microbiome helps the host adapt to future ocean conditions driven by climate change. We use coastal volcanic vents in La Palma (Canary Islands, Spain) as a natural laboratory, where a persistent pH gradient simulates future ocean acidification scenarios (González-Delgado *et al*., 2021). We reared and studied the offspring of the sea urchins *Arbacia lixula* and *Paracentrotus lividus* living in the acidified volcanic vent system (pH = 7.4) and compared their bacterial communities to a genetically-distinct population living in ambient conditions (González-Delgado *et al*., 2024) (pH = 8.1) (Fig. 1). Furthermore, we tested for plasticity in the host-associated bacterial community by culturing offspring from the populations just outside the volcanic vent in both ambient and low-pH conditions.

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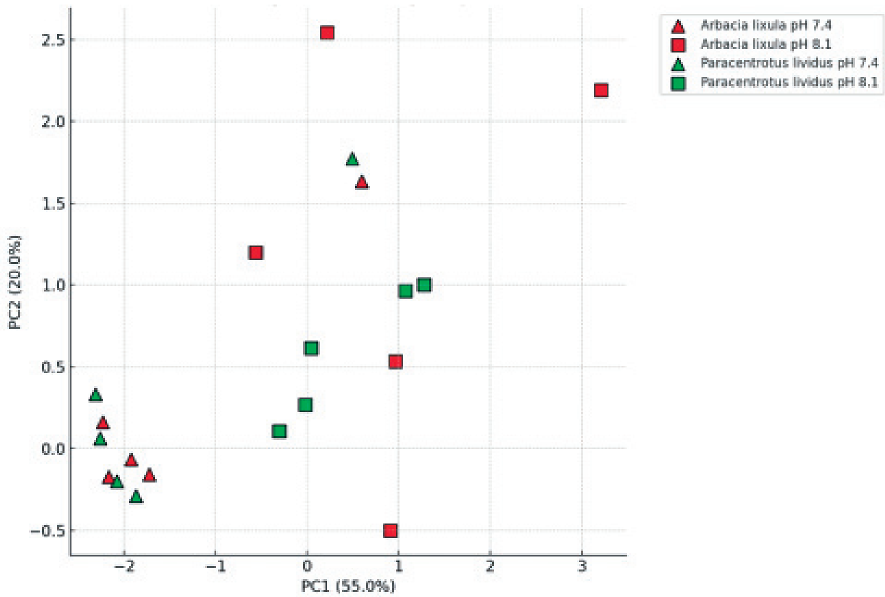

Fig. 1. Principal Components Analysis comparing the microbiomes of the larvae from populations of the two species of sea urchin, *Arbacia lixula* and *Paracentrotus lividus* inhabiting the vent system (pH 7.4) and ambient location (pH 8.1)

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EPISODIC IRON FERTILIZATION OF COASTAL WATERS BY THE 2021 TAJOGAITE VOLCANO ERUPTION: SIZE FRACTIONATED DYNAMICS AND BIOGEOCHEMICAL IMPLICATIONS

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Abstract

Natural sources of iron (Fe) to the surface ocean, such as dust deposition, riverine discharge and glacial melt, are supplemented intermittently by volcanic inputs. However, the magnitude and speciation of the latter remain poorly understood. In this study, we present a comprehensive investigation of iron (Fe) dynamics during the 85-day 2021 Tajogaite eruption on La Palma (19 September-13 December), during which sustained ash fallout and multiple lava flows interacted extensively with coastal waters. Sampling seawater across a high-resolution temporal and spatial grid revealed peak total Fe concentrations exceeding 1900 nmol L^{-1}. Size-fractionation analyses demonstrated that particulate Fe (>0.2 μm) dominated the input (99 %; 1920 ± 50 nmol L^{-1}), while colloidal Fe (0.02–0.2 μm) accounted for 0.7 % (14.5 ± 0.5 nmol L^{-1}), with truly soluble Fe (<0.02 μm) accounting for 0.03 % (maxima up to 0.66 ± 0.05 nmol L^{-1}) —an elevation of around an order of magnitude over typical open Atlantic values. Following new lava entries, hydrothermal-style plumes formed at the lava-seawater interface. These were characterised by elevated temperatures (+2 °C), decreased pH (down to 7.8) and pronounced turbidity (NTU > 30). These conditions facilitated the rapid aggregation of fine ash into larger particles. Over the following weeks, we observed a systematic shift towards smaller size classes: the ash particulates underwent mechanical disaggregation and chemical dissolution, thereby increasing the colloidal and soluble iron (Fe) pools via reverse scavenging and desorption processes.

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Our findings highlight volcanic eruptions as potent and episodic sources of iron fertilisation in iron-limited coastal regions. The initial, particulate-dominated pulse can fuel short-term phytoplankton blooms, while the later release of colloidal and soluble iron can prolong the supply of nutrients and influence carbon drawdown. Current biogeochemical models, which largely omit transient volcanic iron sources, may therefore underestimate regional productivity and CO_2 sequestration. We therefore advocate integrating volcanic ash deposition and lava-seawater interactions into coastal nutrient budgets and Earth system models. Further multidisciplinary studies are essential to quantify volcanic contributions across diverse tectonic settings and refine projections of their role in marine nutrient cycling and climate regulation.

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ACIDIFICATION AND CARBONATE DISRUPTION AT THE LAVA-SEAWATER INTERFACE DURING THE 2021 TAJOGAITE ERUPTION

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Abstract

The interaction between molten lava and seawater during the 2021 Tajogaite eruption in La Palma created a natural laboratory to investigate extreme biogeochemical perturbations in coastal waters. Here we present high-resolution temporal and spatial data on the carbonate system and physicochemical properties of seawater during 13 field campaigns from September 2021 to January 2022, covering three distinct lava entry events. Seawater exposed to the lava-seawater interface showed rapid and severe acidification, with pH values decreasing by up to one unit and carbonate saturation states of calcite and aragonite dropping by more than 90 %. These changes were driven by the addition of acidic magmatic volatiles, the titration of carbonate alkalinity, and thermal enhancement of CO_2 outgassing, with surface waters reaching 50 °C and fugacity values exceeding 4,500 μatm. Our proton mass balance suggests that at least 860 mmol of Hz were added across the affected area, resulting in an average proton concentration of 0.31 μmol kg^{-1} in ~2.7 million m^3 of seawater. Despite the magnitude of these perturbations, physicochemical recovery occurred within weeks, aided by dilution, the buffering capacity of seawater, and favourable geochemical conditions including mineral-rich delta formation and natural submarine CO_2 venting. These results provide a robust framework to understand the short-term resilience of coastal carbonate systems following high-temperature volcanic perturbations and offer analogues for future ocean acidification scenarios.

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IMPACT OF THE TAJOGAITE VOLCANO ERUPTION ON IRON-BINDING LIGANDS IN THE COASTAL WATERS (LA PALMA, CANARY ISLANDS)

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Abstract

The 2021 eruption of Tajogaite volcano (La Palma) significantly altered the nearby coastal environment and chemistry through the formation of lava delta. Iron (Fe) is essential for marine life, with over 99 % of its speciation controlled by organic ligands. These compounds are key in Fe solubility and bioavailability in marine systems. However, knowledge of Fe-organic speciation and the role of the lava deltas on its biogeochemical cycle remains limited. This study investigates the impact of the Tajogaite eruption on the Fe-organic speciation by measuring the labile Fe-binding ligands (L_{Fe}) and their conditional stability constants ($\log K^{cond}_{Fe'L}$) by competitive ligand exchange-adsorptive cathodic stripping voltammetry (CLE-ACSV) method, using TAC as a competitive ligand. Different detection windows were applied (2, 5 and 10 µM TAC) to determine the optimal experimental conditions for comparing the different environments along the sampling years. Accordingly, the L_{Fe} concentrations ranged between 2.32 and 12.38 nM, with a maximum measured in February 2023 near the southern lava delta (28.616ºN), and April to September 2024 at northern stations of the lava delta (28.624ºN) with 11.20 nM. The minimum of L_{Fe} concentration was observed at offshore station 10 (17.932ºW, 28.599ºN) that is considered the control station. These Fe-binding ligands can be ranked as weak ligands (L_2-type) according to the measured $\log K^{cond}_{Fe'L}$ that were between 9.33 and 10.73 under the studied conditions. This study reveals clear spatial and temporal variability, suggesting local Fe-ligand production related to biological development in the delta lava. Then, the new deltas are acting as a substrate on which benthic organisms develop and act as a local source of ligands several years after the eruption and keeping Fe in solution that may help the recovery of the ecosystem.

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VETERINARY PATHOLOGY CONTRIBUTIONS TO VOLCANIC ERUPTIONS IN THE CANARY ISLANDS

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AYOZE CASTRO-ALONSO[1]

ABSTRACT

In volcanic eruptions, terrestrial and marine biodiversity can be affected with direct associated mortalities in the early stages or over a long period of time. In these situations, it is crucial the intervention of professionals that can provide the necessary knowledge, experience and capacities to understand the impact of the natural environmental alterations in the animal health. This work reports the contributions of the Veterinary Pathology team of the Institute of Animal health and Food Security (University of Las Palmas de Gran Canaria, IUSA_ULPGC) to examine the fishes found dead during two recent volcanic eruptions in the Canary Islands (El Hierro and La Palma). The El Hierro eruption (Tagoro volcano, 2011), resulted in high and early mortality of the fish population during the first stage of the underwater eruption (Caballero *et al*., 2023). The corresponding lesions were physical injury such as exophthalmia, gastric eversion, ocular hemorrhages, over-inflation and congestion of swim bladder (Fig. 1A and 1B) and the presence of gas bubbles in eyes and skin. These findings are related to the dramatic changes in the reported physical-chemical water conditions (severe anoxia, increased temperature, decreased pH) and to the potential development of decompression and/or gas oversaturation syndromes. In La Palma volcanic eruption (Tajogaite volcano, 2021), the lava flow aroused gradually and slowly to the coastal water, creating the lava delta. Besides, this eruption produced a huge amount of ashes and volcanic particles. These conditions had a lower and gradual impact on fish populations in terms of mortality. The corresponding lesions were the result of the entry of this volcanic material and particles into the fishes, affecting the respiratory (Fig. 1C) and digestive systems (Fig. 1D). The results of the present study described two different injury patterns on fish mortality directly related to different types of volcanic eruptions occurring in the Canary Islands.

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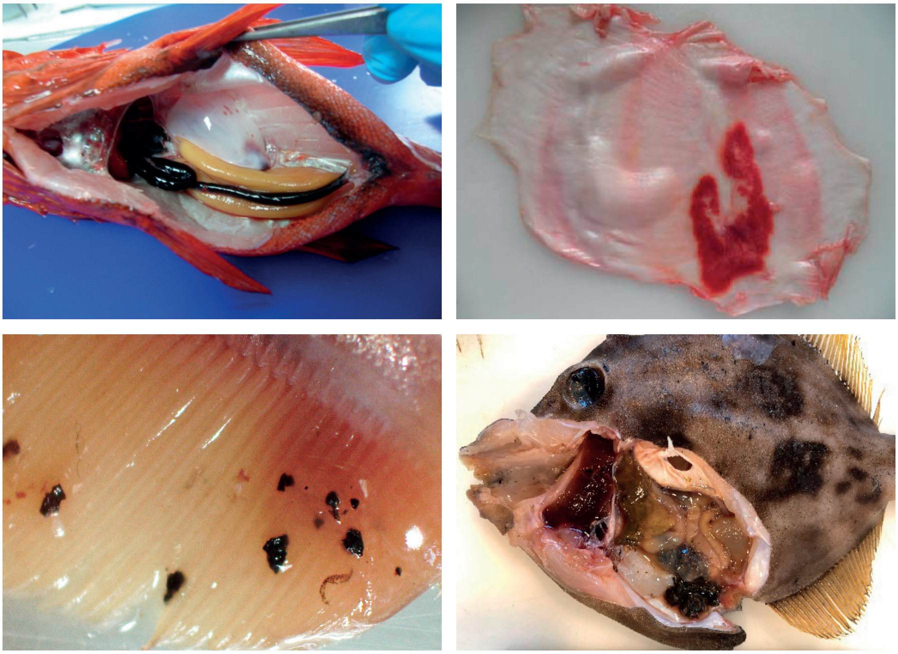

Fig. 1. Over-inflation (A) and congestion (B) of swim bladder in a fish dead during the El Hierro eruption (Tagoro volcano). Presence of volcanic particles in the gill (C) of fish dead during La Palma eruption (Tajogaite volcano). Impaction of material volcanic in the intestine (D) of fish dead during Tajogaite eruption

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EFFECTS OF THE TAJOGAITE VOLCANIC ERUPTION ON ZOOPLANKTON ABUNDANCE AND BIOMASS AROUND LA PALMA ISLAND

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Abstract

Zooplankton communities have been extensively studied around the Canary Islands, including during the 2011-2012 submarine eruption off El Hierro Island, where notable community shifts were observed due to strong physical and chemical disturbances in the water column. Recently, the Cumbre Vieja ridge, the most volcanic active region in the archipelago, erupted on 19th September 2021, forming the Tajogaite volcano on La Palma Island. This event led to substantial ash deposition both on land and into the surrounding ocean, potentially altering physical and biological conditions in the marine environment. This study examines the zooplankton community composition before, during, and after the Tajogaite eruption, using samples collected aboard the R/Vs *Ramón Margalef* and *Ángeles Alvariño* during three oceanographic surveys conducted on September 26th 2021 (VULCANA-III-0921) before the lava reached the ocean, October 26th 2021 (VULCANA-III-1021) coinciding with the contact of the lava with the shore, and on February 2th 2022 after the end of the eruption (VULCANA-III-0222). Our results show a shallower euphotic zone during the eruption, coinciding with increased turbidity and significant changes in environmental parameters such as sea surface temperature, dissolved oxygen, and mixed layer depth. A total of 16 zooplankton groups

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were identified, with Copepoda, Chaetognatha, and Ostracoda dominating across all periods. Zooplankton abundance and biomass peaked during September 2021 (before the lava reached the shore) and in February 2022 during the post-eruption period, while the lowest values were recorded during October 2021, when volcanic ash was most prominent in the water column. Acoustic data did not reveal a loss in acoustic densities at 38 and 120 kHz frequencies between September 26th and 30th, 2021. Significant correlations were found between the zooplankton community structure and environmental variables. Notably, large copepods decreased, while Chaetognatha increased in relative abundance during October. By contrast to some previous volcanic events, chlorophyll concentrations appeared unaffected by ash deposition.

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ASSESSMENT OF THE IMPACT OF THE TAJOGAITE VOLCANIC ACTIVITY ON ARTISANAL FISHERIES AROUND LA PALMA ISLAND

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ABSTRACT

The eruption of the Tajogaite volcano, which occurred between September and December 2021, impacted the coast of Tazacorte as well as the activity of the artisanal fishing fleet. Due to the lack of prior information regarding the spatial distribution and abundance of fish species, an analysis was conducted on available capture time series for the island, spanning from 2007 to 2023. This analysis aimed to determine the potential effects of seismicity related to the volcanic eruption, identify structural change points within the series, and evaluate the repercussions for stock status. Upon comparing landings by the Tazacorte's fleet to those from Santa Cruz de La Palma, a decline was observed in landings of many benthodemersal species targeted by the fleet in the months preceding the eruption, suggesting a possible relationship between seismicity and fishery dynamics. Additionally, the decrease observed in Santa Cruz's landings —mostly displaying a temporal lag compared to those in Tazacorte— indicates that both the pre-eruptive and eruptive processes have had repercussions on stocks throughout the insular context. Wavelet coherence analysis reveals the existence of correlations between catch time series and seismicity associated with the eruption (Fig. 1), as well as prior to it, in addition to correlations with meso-scale climatic conditions (i.e., North Atlantic Oscillation - NAO index) throughout the entire study period (2007-2023). Therefore, to understand these relationships, a more in-depth analysis of fish species response mechanisms to these phenomena is necessary.

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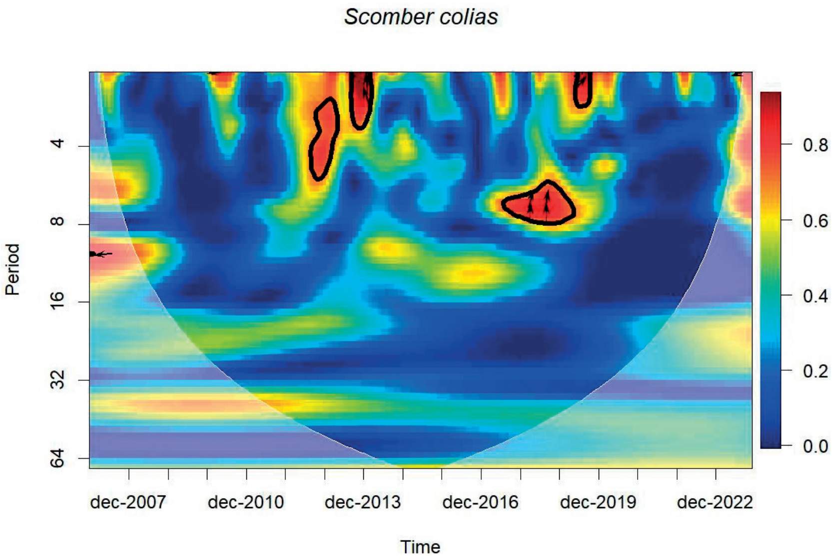

Fig. 1. Wavelet Coherence plot between the seismicity time series on La Palma Island and the catch time series of atlantic chub mackerel (*Scomber colias*)

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MICROALGAL DIVERSITY ON NEW VOLCANIC SUBSTRATES (LAVA DELTAS) OF LA PALMA

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Abstract

The 2021 eruption of Cumbre Vieja (La Palma, Canary Islands) offered a unique opportunity to study primary microbial succession and benthic community assembly on newly formed volcanic substrates. As part of the NATURGRAD project («Environmental Gradients as Natural Laboratories to Understand the Future and Evolution of Benthic Communities»), we characterized microalgal and cyanobacterial diversity along environmental gradients shaped by volcanic activity. Samples were collected across zones of varying impact and analyzed through a polyphasic approach integrating light microscopy and cultivation in selective media (L1, Seawater + vitamins, BG110H). Preliminary data reveal diverse microbial assemblages dominated by cosmopolitan taxa, including diatoms (Navicula, Amphora, Striatella), cyanobacteria (Phormidium, Leptolyngbya, Nostoc, Chroococcus), dinoflagellates (Amphidinium, Prorocentrum), and green (Ulva, Enteromorpha) and red algae (Bangia). Patterns of diversity are consistent with findings from other volcanic systems such as Kamchatka (Allaguvatova *et al*., 2022), Surtsey (Magnússon *et al*., 2014), and Vulcano Island (Johnson *et al*., 2013). These environments act as «natural laboratories» for ecological research, demonstrating that early colonization is often driven by phototrophic microorganisms with high physiological plasticity, fast reproduction, and the ability to fix nitrogen and sequester carbon (Allaguvatova *et al*., 2022). Notably, the response of benthic microalgae to CO_2 gradients, as observed in Vulcano Island, supports the hypothesis that community structure is sensitive to environmental chemistry and disturbance history (Johnson *et al.,* 2013). Our study contributes to a growing body of work linking microalgae diversity in extreme environments, offering insights

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into resilience and functional roles of pioneer taxa in these types of habitats, primary productivity, and early ecosystem development. These findings are especially relevant in the context of global change, where volcanic and other high-disturbance environments serve as analogues for future ecological scenarios.

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MACROALGAL COLONIZATION ON THE TAJOGAITE LAVA DELTAS: 3 YEARS OF CHANGE

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Abstract

Due to its connectivity and continuity, landslides and volcanic eruptions are amongst the few natural events that are capable of producing drastic changes in the marine ecosystems (Cooke *et al*., 2023). These events are the only ones capable of completely altering the seabed, triggering processes of primary ecological succession where a virgin substrate has to be colonized from scratch by all organisms. Despite being events that occur recurrently throughout the world, the primary succession of marine environments has been scarcely studied (Godwin & Kosaki, 1989; Pinault *et al*., 2013), and in particular the role of marine macroalgae play in this process, not only as primary producers but also as providers of refugee and structure to the ecosystem on shallow coastal environments. During the Tajogaite volcanic eruption, four lava flows reached the coast of La Palma, forming two independent lava deltas with a total sub-aerial surface of ca. 45 ha, extending locally to depths of more than 250 m below sea level (Lozano Rodríguez *et al*., 2023), creating a highly heterogeneous rocky environment in an area previously dominated by sandy bottoms (Martín-García *et al*., 2013). These lava deltas provide a unique opportunity to study the processes of colonization and primary succession, providing information on how marine communities recover in the Canary Islands. This study describes the process of primary succession on the submarine lava deltas by macroalgae from two months after the end of the eruption up to 36 months, and compares the evolution of the macroalgal community with a control area. Results show a rapid occupation of all available substrate by opportunistic species (mainly colonial microalgae and ectocarpaleans), a slow but steady incorporation of species as time passes, and demographic explosions

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of some species rarely found in unaffected areas. Winter storms especially affect the substrate, and produce cyclic returns to prior states each year as new substrate is exposed and must be colonized again. The presence of perennial species is still scarce, which shows that the colonization is still ongoing, and the macroalgal community is still far from a complete recovery after three years of study.

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INTEGRATED PROGRAMME FOR MONITORING THE MARINE ECOSYSTEM AT THE LAVA DELTAS OF LA PALMA: THE DELTA PROJECT APPROACH

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Abstract

The recovery of marine ecosystems after volcanic eruptions remains poorly understood, requiring integrated observational strategies that encompass both physicochemical and biological processes at high spatio-temporal resolution. These strategies must ensure long-term continuity and adapt to dynamic environments. This need is particularly relevant on the western coast of La Palma (Canary Islands), where the 2021 Tajogaite volcanic eruption reshaped the shoreline and perturbed the local biogeochemical equilibrium. The resulting lava deltas have created new benthic habitats whose evolution remains largely uncharacterised, offering a unique natural laboratory to investigate colonisation and succession processes in a post-eruption setting. The DELTA project implements a comprehensive marine observation programme to study post-eruption environmental changes and biological recolonisation in the marine area affected by the Tajogaite eruption. The strategy combines multidisciplinary oceanographic surveys, autonomous underwater vehicles, remote operated vehicles (ROVs), a moored oceanographic buoy, and passive acoustic monitoring (Fig. 1), enabling a high-resolution characterisation of Essential Ocean Variables (EOVs) —such as temperature, salinity, and dissolved oxygen— and Essential Biodiversity Variables (EBVs), including taxonomic richness and community composition. The cross-scale and multi-platform approach establishes a robust framework to assess ecosystem dynamics and underscores the importance of integrated monitoring strategies in contexts of natural disturbance. Since November 2023, the DELTA project has conducted three multidisciplinary oceanographic cruises focused on characterising the physicochemical properties of seawater and identifying organisms through environmental DNA (eDNA) metagenomics. In parallel, three glider missions

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monitored water column properties at depth, providing high-resolution vertical profiles of key oceanographic variables. Passive acoustic monitoring via three hydrophone deployments has enabled the detection of cetaceans and offered insights into the region's acoustic biodiversity.

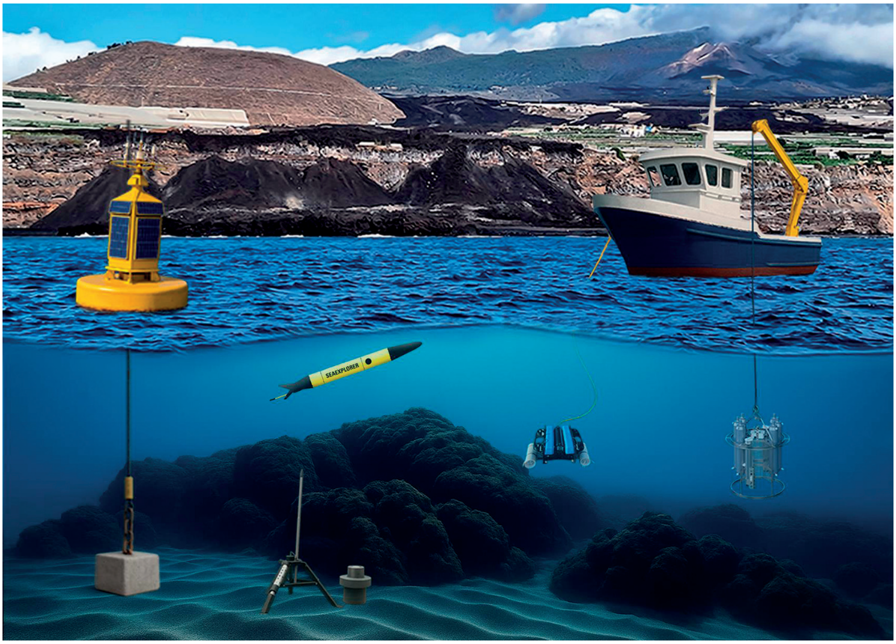

Fig. 1. Representation of the integrated methodologies for monitoring the marine ecosystem (DELTA project)

Additionally, a ROV survey recorded approximately 240 minutes of underwater video, providing detailed visual observations on benthic habitats and colonisation patterns, significantly enhancing the knowledge of the area. The DELTA project provides an operational framework for long-term monitoring of emergent volcanic coastal habitats, delivering critical data to support post-eruptive ecological modelling. This approach not only advances our understanding of the recovery of volcanic marine ecosystems but also provides a replicable model for future monitoring efforts in other Atlantic islands.

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A FRAMEWORK FOR MONITORING MARINE COLONISATION OF THE TAJOGAITE LAVA DELTAS

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ABSTRACT

The 2021 Tajogaite eruption on La Palma resulted in the formation of extensive new lava deltas, drastically transforming adjacent shallow-water environments. These newly formed basaltic substrates provide a rare opportunity to study primary ecological succession and the reorganisation of marine trophic networks following extreme disturbance. Within the DELTA project, three non-invasive methodologies are being used to monitor this recolonisation process, providing insights into the resilience of volcanic island coastal ecosystems. Environmental DNA (eDNA) metabarcoding was performed on water-column samples collected with Niskin bottles and plankton nets, using COI, 12S, 16S and 18S markers to survey a broad taxonomic spectrum. Niskin samples returned 43 species-level taxa spanning Bacteria, Chromista, Plantae and Animalia. While plankton net samples revealed 90 species-level taxa from the same kingdoms (excluding Bacteria due to mesh size). Unexpected detections of non-regional barcodes (e.g., *Sparisoma viride* instead of the local *S. cretense*) highlights the need of *in situ* validations and the development of a Macaronesian genetic reference library. Fish assemblages were characterised using stereo-video ROV line-transects across six shallow sites (two controls and four over the new lava deltas) recording species abundance (MaxN), 3D body length and behaviour. Assemblages included reef-associated labrids, sparids and pomacentrids such as *Thalassoma pavo* and *Chromis limbata*. Notable records included schools of *Seriola rivoliana* (n = 32), *Acanthocybium solandri* (n = 4) and multiple sightings of *Aulostomus strigosus*. Cetacean presence was assessed through opportunistic sightings recorded by whale-watching vessels, revealing monthly occurrence patterns pre- and post-eruption. To study finer-scale temporal variations, bottom-moored hydrophones were deployed, detecting echolocation clicks produced by dolphins, mostly occu-

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rring nocturnally. The combined use of eDNA, ROV surveys and cetacean monitoring reveals rapid species return across trophic levels (from microbes to top predators) on the new lava deltas. While the early presence of mid and higher trophic species likely reflects reoccupation by mobile fauna rather than true recolonisation, these observations provide critical indicators of initial ecosystem recovery and the progressive re-establishment of benthic trophic structures. These findings offer valuable baseline metrics for long-term monitoring of ecosystem resilience in volcanic islands.

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THE EFFECTS OF THE TAJOGAITE VOLCANO OVER THE CIRCALITTORAL AND BATHYAL BENTHIC COMMUNITIES THROUGH ECOLOGICAL AND FAUNISTIC ANALYSES

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ABSTRACT

Volcanoes are capable of altering and modifying their surrounding environment, generating a series of changes that, for the most part, can be partially studied once volcanic eruption is over (Martín-García *et al*., 2015; Sotomayor-García *et al*., 2019; Beinart *et al*., 2024). However, using remotely operated vehicles (Liropus 2000 ROV), we analysed, during the eruptive process, the bathyal and circalittoral seabed of areas affected by submarine lava flows (Fig. 1), as well as oceanographic parameters of the seafloor (González-Vega *et al*., 2024). Video surveys were revised using VIER software (De La Torre *et al*., 2024) to elaborate a dataset of total living and dead organisms observed at the vicinity of the Tajogaite volcano area, including a control area located in front of La Bombilla village. Through PERMANOVA, SIMPER, and PCO analyses, along with various diversity metrics, the adverse effects of the volcano on benthic communities were studied from 400 to 50 meters below sea level (mbsl). Particularly, structure and composition of the community was assessed per bathymetric level (Upper Bathyal, Lower Circalittoral, and Upper Circalittoral) analysing differences by functional groups. On the other hand, the same analyses were conducted for dead specimens observed during surveys at the impact and control area. Results suggest a marked negative effect at all bathymetric levels, especially in the upper circalittoral, along with significant mortalities of Stichopathes gracilis and remains of various orga-

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nisms in the affected area. Furthermore, the probable role of turbidity as a primary factor responsible of mortality rates of corals and other organisms was confirmed. Nevertheless, continued and expanded monitoring of the areas impacted by the Tajogaite volcano is recommended in order to improve understanding of the eruption's effects.

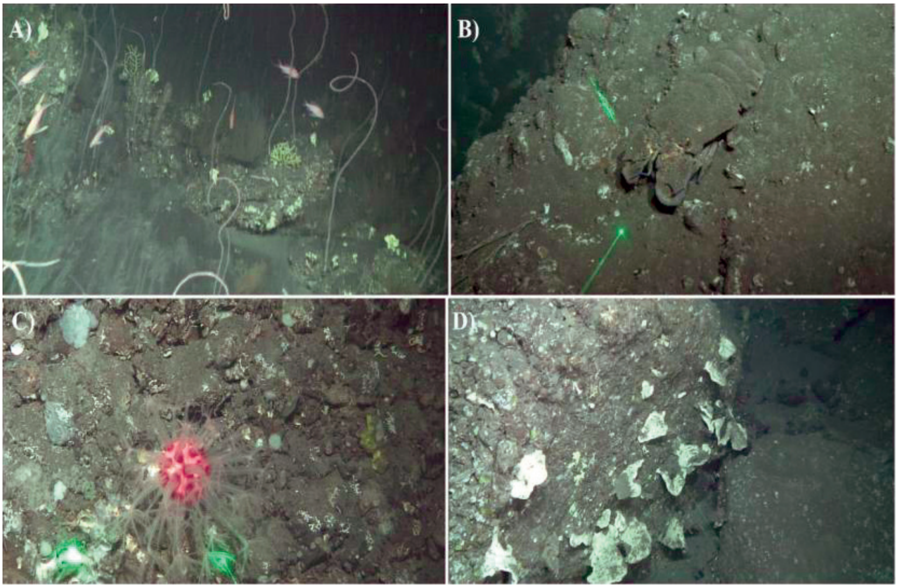

Fig. 1. Imagery of benthic life obtained from ROV immersions at the impact area of the Tajogaite volcano. Lasers beams were separated by 10 cm wide. A) Lower circalittoral community with *S. gracilis*, *Paramuricea* sp. or Anthias anthias, among others. B) *Scyllarides latus* lobster totally covered by volcanic ash at upper bathyal (UB) bathymetric range. C) *Anthomastus canariensis* octocoral observed over rocky substrate at UB. D) Lithistida indet. white-massive sponges partially covered by ash deposition

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FISHERIES DISRUPTED: ASSESSING THE SPATIAL AND SOCIOECONOMIC IMPACTS OF THE 2021 TAJOGAITE ERUPTION ON ARTISANAL FISHERIES IN LA PALMA (CANARY ISLANDS)

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Abstract

The 2021 eruption of the Tajogaite volcano on La Palma (Canary Islands, Spain) triggered major transformations in the coastal marine environment, with significant repercussions for traditional artisanal fisheries. Beyond the physical destruction of benthic habitats by lava flows, fishers have faced regulatory restrictions that further limit access to key fishing grounds. These measures include an initial blanket fishing ban across the affected area, followed by the establishment of progressively smaller exclusion zones around the newly formed lava deltas, effectively reducing the operational marine area for the local artisanal fleet. This study quantifies the spatial and socioeconomic consequences of these combined impacts. Drawing on benthic community maps (Martín-García *et al*., 2013) and spatial data on fishing effort —collected through interviews with the island's two fishing cooperatives and supplemented with GPS records— we estimate the total loss of accessible fishing area, which varies depending on gear type. Where possible, these losses are broken down by benthic habitat or community. In addition, official catch statistics and average market prices are used to analyze changes in landings before and after the eruption, providing a measure of the economic impact on the local fisheries sector. Our findings highlight the urgency of adaptive fisheries management and the need for targeted socio-economic support measures to ensure the long-term resilience of affected coastal communities.

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FIGHTING FOR SPACE: FROM DISORDER AND OPPORTUNISM TO COMPETITION AND ZONATION

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Belen Roger-Baynat[1], Marta Sansón[1].

Abstract

This study examines the temporal changes in intertidal communities following the 2021 eruption of Tajogaite volcano. Primary succession was characterized by initial colonization by opportunistic algae, which rapidly covered the substrate in the absence of macroherbivores. This algal proliferation triggered herbivore blooms during early succession stages, occurring without significant predation pressure. As succession advanced, mollusc grazing became a key regulator of algal biomass, leading to shifts toward dominance by less palatable algal species. Herbivory was the dominant interaction in early stages, with low competition and limited trophic complexity. Increasing species richness and trophic interactions marked later succession phases, including mollusc predation that controlled herbivore populations and facilitated the arrival of hermit crabs through shell availability. In mature communities, interaction networks became more complex and stable, exhibiting clear vertical zonation influenced by desiccation gradients and biotic interactions. Strong interspecific competition emerged, with dominant species excluding weaker competitors, while higher trophic levels —such as predatory crabs, mollusc, sea stars, and sea urchins— contributed to community regulation. These observations from a natural laboratory of primary succession highlight how biotic interactions transition from facilitation to competition and play a critical role in shaping the ecological development of dynamic volcanic intertidal ecosystems.

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RISE AND DECLINE OF GROUPERS AT TAJOGAITE LAVA DELTAS: LESSONS FROM A SHORT-TERM MARINE PROTECTED AREA

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Abstract

Fishing pressure is the primary anthropogenic impact affecting benthic communities in rocky habitats across the Canary Islands. Only fully protected marine reserves are free of its effects. During the eruptive phase of the Tajogaite volcano, and for a period of just over three years afterward, the newly formed lava deltas acted as a no-take marine reserve. Navigation and all maritime activities, including fishing, were prohibited due to safety regulations. Consequently, recolonization processes (primary colonization and ecological succession) occurred in the absence of this major anthropogenic disturbance. To assess community recovery, we monitored grouper species (*Epinephelus marginatus*, *E. costae*, *Mycteroperca fusca*, and *Serranus cabrilla*) as bioindicators. These species are territorial, slow-growing, and occupy top trophic levels, making them especially vulnerable to fishing pressure. Over the first three years, we observed a progressive increase in grouper populations. All individuals that colonized the new habitats originated from larval settlement, as no juveniles or adults were observed after the eruption. This confirms the low dispersal capacity of these species. As the settlers grew over time, population size structure shifted progressively toward larger size classes. After three years, grouper densities in the lava deltas were five times higher than in control zone. This recovery trend reversed sharply following the removal of fishing and navigation restrictions. Within less than one month, grouper populations started to decline drastically, reaching levels typical of overfished areas in the region in a few months. This study demonstrates the significant regenerative potential of reef fish communities in the absence of fishing pressure, emphasizing the ecological value of strict protection. However, the rapid population collapse following the reintroduction of fishing highlights the vulnerability of these ecosystems and underscores the urgent need for effective and sustained marine conservation measures.

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Topic 12

Terrestrial biodiversity

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THE FATE OF TERRESTRIAL BIODIVERSITY DURING AN OCEANIC ISLAND VOLCANIC ERUPTION

Manuel Nogales[1], María Guerrero-Campos[1,2,3], Thomas Boulesteix[1], Noémie Taquet[1], Carl Beierkuhnlein[4,5,6], Robin Campion[7], Silvia Fajardo[8], Nieves Zurita[8], Manuel Arechavaleta[8], Rafael García Becerra[9], Frank Weiser[5], Félix M. Medina[10]

Abstract

Volcanic activity presents a valuable opportunity to examine how organisms respond ecologically to catastrophic environmental destruction, a key factor in biodiversity change on islands (Weiser *et al.*, 2022). However, despite this great scientific interest, no study of biodiversity at an erupting volcano has yet been undertaken. On La Palma (Canary Islands), we quantified the species most affected and their fate during the 85-day eruption from September to December 2021 (Nogales *et al.*, 2022). Our primary objective was to monitor biodiversity under critical stress during this volcanic eruption. We found that all biodiversity within a 2.5 km radius was severely affected within the first two weeks (Medina *et al.*, 2025). It is difficult to determine whether volcanism can influence the evolutionary traits of insular organisms. Exam-

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ples include the adaptation of an endemic conifer to high temperatures, the selection of functional plant types («secondary woodiness») (Beierkuhnlein *et al*., 2023), the effects of the disappearance of invertebrates on trophic networks, and the influence of vertebrate trophic plasticity (Guerrero *et al*., 2023). However, our data suggest that these evolutionary changes may have favoured the resilience of these species during the eruption. This eruption provides a valuable opportunity to assess the extent to which periodic volcanic catastrophes may create temporary windows of opportunity for the evolution and speciation of oceanic island biota. Lastly, to our knowledge, this is the only study of the status of terrestrial biodiversity in the immediate vicinity of a limited-duration volcanic eruption.

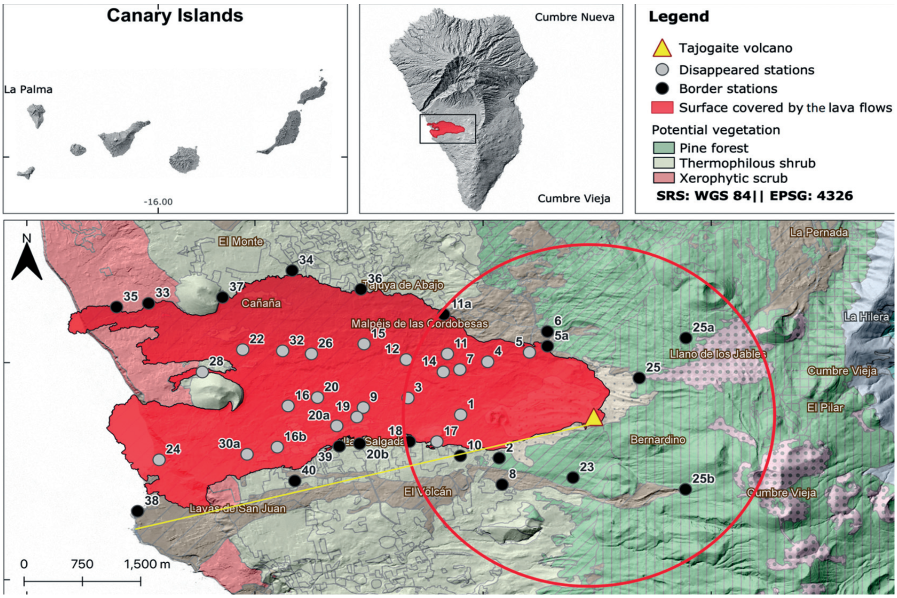

Fig. 1. Location of the volcano (at Hoya de Tajogaite) on La Palma (Canary Islands, Spain). General map of the crater and lava flows, showing the three main habitats and the study stations. The red circle (2.5 km in radius) around the eruptive center represents the zone of most severe biodiversity affectation, where the tephra deposition and toxic gas concentrations were the highest. The yellow line represents the tephra thickness transect measured from the crater to the coast. The map has been created with QGis 3.22.2 from Copernicus (https://emergency.copernicus.eu/mapping/list-of-components/EMSR546) and IDE Canarias (Infraestructura de Datos Espaciales de Canarias) (https://www.idecanarias.es/listado_servicios)

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SPATIO-TEMPORAL BIODIVERSITY PATTERNS ALONG THE ALTITUDINAL CLINE OF TAJOGAITE VOLCANO

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Rafael García Becerra[2], Félix M. Medina[3], Manuel Nogales[4]

Abstract

The eruption of the Tajogaite volcano began on 19 September 2021 on the Cumbre Vieja ridge in La Palma (Canary Islands). The initial eruptive fracture rapidly evolved into a series of volcanic cones that emitted extensive lava flows, which ultimately reached the sea, along with intense tephra fall and toxic gases (Rodríguez-Pascual *et al*., 2024). Three natural habitats were substantially damaged: Canary pine forests, thermophilous shrublands, and xerophytic scrub (Fig. 1) (Nogales *et al*., 2022). Following the elevational gradient from the main crater (at approximately 1120 m a.s.l.) to the cost along both sides of the lava flows, we established study plots where we conducted flora and fauna inventories, estimated vegetation cover and phenology, and censused invertebrates (mainly insects) and vertebrates (reptiles, birds, and bats) within these ecosystems. This integrated approach allows to assess the impact of the eruption on the richness, composition, and distribution dynamics of biodiversity throughout the three years after volcanic event. We used an extensive dataset to create updated distribution maps of flora and fauna, estimate spatiotemporal diversity patterns, evaluate the resilience capabilities of different organism groups, and assess the recovery of the ecosystems. We also applied statistical models to analyse how distance from the crater and ash thickness affect ecology dynamics following the eruption. The overall results indicate that the edges of the lava flows show evident recovery signs, unlike the areas near the crater, where the post-eruptive process, characterized by reduced gas emissions and temperature, is slower.

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This variation in the recovery rate is observed not only among different biodiversity groups but also among species within those groups. Our findings reveal that certain species have begun to recolonize these habitats more rapidly than others, indicating differing levels of resilience. For instance, while some plant species have adapted quickly to the altered conditions, certain vertebrate populations, such as reptiles, exhibit a slower recovery rate, likely due to their specific habitat requirements. These results highlight the complexity of volcanic environments and emphasize the need for further investigation (Guerrero-Campos *et al*., 2023).

Fig. 1. Lava flows from the Tajogaite volcano (in the background) affecting three habitats, Canary pine forests, thermophilous shrublands, and xerophytic scrub, along an altitudinal gradient

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ECOLOGICAL RESILIENCE OF BIRD POPULATIONS TO A VOLCANIC EVENT

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Abstract

The severe and immediate loss of habitats as a consequence of a volcanic eruption, likely led to the disruption of the ecosystem functioning and food web stability in the impacted ecosystems. Birds, with a greater overall ability to escape, can survive by moving away from affected areas (Nogales *et al.*, 2022, Guerrero-Campos *et al.*, 2023). However, their return would depend on the new environmental conditions (Fig. 1). In this study, we assessed the resilience capability of birds three years after the 2021 eruption throughout the analysis of the changes in species richness and community composition along an elevational gradient to evaluate the effects of volcanic disturbance. We conducted standardised point-count surveys in Canary Islands pine forests, thermophilous shrublands, and xerophytic scrub, complemented by detailed assessments of vegetation and invertebrates, as well as measurements of tephra deposition. Data analysis involved estimating temporal changes in bird populations using distance sampling methods and comparing these results across different altitudinal ranges and habitats. By integrating spatial mapping of volcanic damage with avian and habitat data, we also applied statistical models to disentangle the influence of elevation from volcanic impact. In particular, we evaluated the effects of invertebrate abundance, distance from the crater, and tephra thickness on the presence of insectivorous passerines. Overall, our results indicated a weak trend suggesting that other environmental parameters may have a more significant impact on bird populations (Dals-

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gaard *et al*., 2007; Blanco *et al*., 2024). However, it would be beneficial to analyse this relationship at the species level because some bird species might exhibit different responses to the availability of specific insect taxa.

Fig. 1. Common ravens (*Corvus corax*) on tephra deposition during the eruption of the Tajogaite volcano

Understanding these dynamics is important, as it may reveal specific ecological interactions that contribute to community structure (del Moral & Grishin, 1999).

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CHANGES IN THE DYNAMICS OF INVERTEBRATE COMMUNITIES AFTER A VOLCANIC ERUPTION

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Abstract

The collapse of invertebrate communities observed after the volcanic eruption of Tajogaite (2021, La Palma) not only resulted in a dramatic loss of biodiversity and biomass (Nogales *et al*., 2022; García Becerra & Medina, 2023), but also triggered a breakdown of fundamental ecosystem functions in the affected habitats (Canary pine forests, thermophilous shrublands, and xerophytic scrub). Since invertebrates are key components in plant pollination, nutrient cycling, and food webs, their sudden disappearance could have caused a cascading effect on ecosystems. In this study, we examined the composition, richness and distribution of invertebrates in study plots established along an altitudinal gradient from the crater to the coast on both sides of lava flows during the three post-eruptive years. Our main aim was to examine the ability of different invertebrate orders to colonise these new environments (Vandergast *et al*., 2004). Firstly, we sampled three microhabitats (surviving plants, ground or volcanic ash, and air) to identify and evaluate the density of insect species with diverse habits. In this way, we were able to record the various ecological roles of invertebrates within these ecosystems. Using the resulting dataset, we applied statistical methods to assess spatiotemporal diversity patterns, and generated models to analyse the effects of vegetation cover, distance from the crater, and ash thickness on insect abundances (see del Moral & Grishin, 1999). Furthermore, we constructed bipartite networks to examine the relationships between insect orders and the dominant plant species in each

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habitat, allowing us to better understand the ecological interactions in recent volcanic environments (Guerrero-Campos *et al*., 2023).

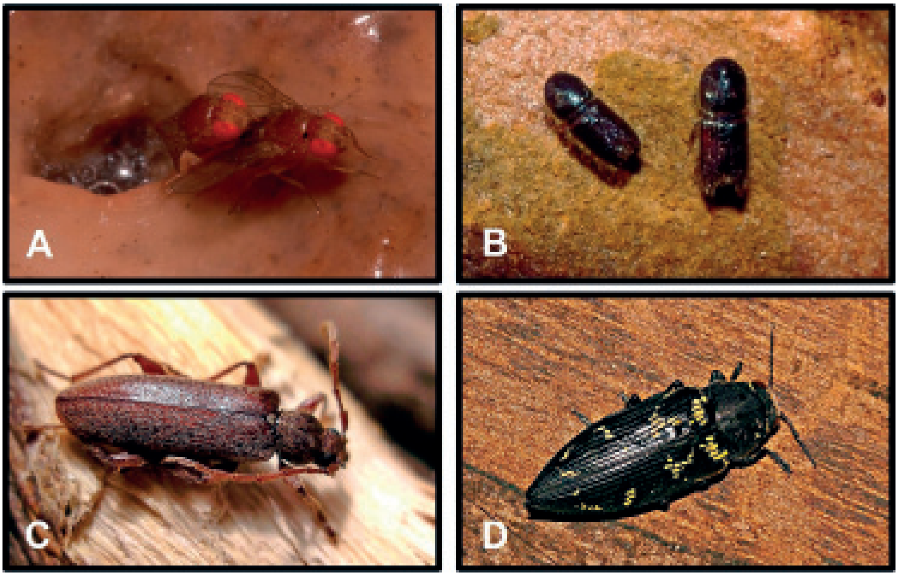

Fig. 1. Opportunistic species that took advantage of the collapse and death of pine trees: A) *Drosophila melanogaster* Meigen, 1830. B) *Orthotomicus nobilis* (Wollaston, 1862) and xylophagous species that took advantage of pine collapse and death: C) *Oxypleurus nodieri* Mulsant, 1839, D) *Buprestis bertheloti* Laporte & Gory, 1837

Our main results revealed that eruption caused significant changes in biodiversity. A noticeable example of this variation was the increase in saprophytic and xylophagous species (Fig. 1) exploiting dead vegetation and pine trees, alongside the important absence of pollinators, particularly in areas closest to the crater. In conclusion, our study highlights the complex ecological dynamics observed after a high-impact volcanic eruption, with destruction and system collapse in the initial phases of the event, followed by the emergence of advantages for specialist and opportunistic insects that exploit the new conditions to thrive in the post-eruption stages.

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HIGH-THROUGHPUT MOLECULAR CHARACTERISATION OF SOIL AFFECTED BY LAVA DEPOSITION FROM THE TAJOGAITE VOLCANO

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Abstract

The 2021 eruption of the Tajogaite volcano (Cumbre Vieja, La Palma) dramatically reshaped the island's landscape, covering extensive areas of forest and agricultural land with lava (Troll *et al.*, 2024). While the visible consequences of lava deposition are well documented, its hidden effects, particularly soil health remain poorly understood. This study explores how extreme volcanic heating alters soil properties and soil organic matter (SOM) composition by examining the molecular fingerprint of buried soils. We conducted high-throughput molecular characterisation of three buried soil profiles beneath a lava flow from Tajogaite eruption using ultra-high-resolution mass spectrometry (UHRMS, Orbitrap Q-Exactive Focus), combining Electrospray Ionisation (ESI) and Atmospheric Pressure Chemical Ionisation (APCI) in positive mode. To assess the impact of lava deposition, we employed a classical comparative design, analysing both lava-affected and unaffected soils. The molecular composition of distinct soil horizons was visualised using van Kre-

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velen diagrams (Fig. 1), enabling classification into key biochemical families based on atomic H/C and O/C ratios, and the modified aromaticity index (AI_{mod}; Kim *et al.*, 2003; Jiménez-Morillo *et al.*, 2018). Results revealed a clear vertical stratification in soil physico-chemical properties and SOM composition. In the uppermost buried horizons, lava deposition led to increased pH and aggregate stability, mainly due to thermal alteration of clay minerals. Related to molecular composition, the uppermost horizons showed a noticeable loss of thermolabile biomolecules (lipids, polysaccharides) and a relative enrichment of thermally resistant compounds (condensed).

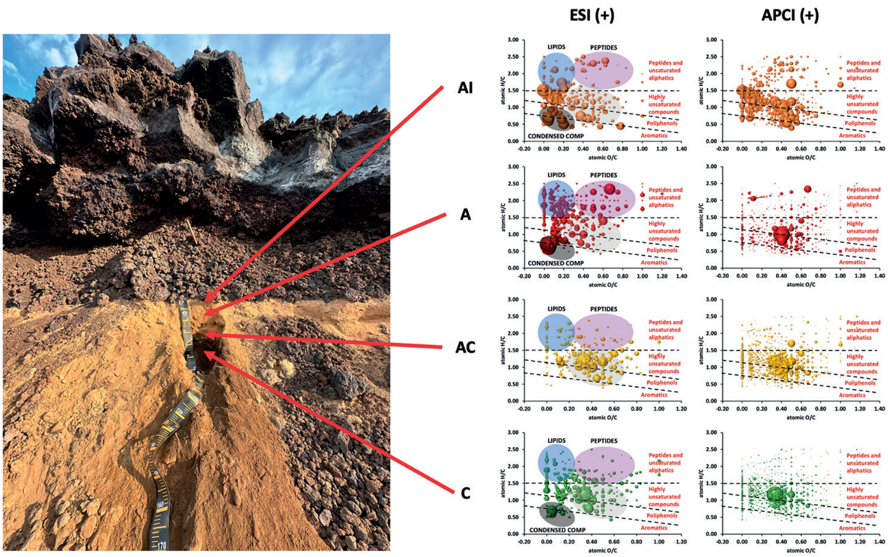

Fig. 1. van Krevelen diagram of the main molecular compounds, obtained in positive mode (+) using an Electrospay Ionisation (ESI) and an Atmospheric Pressure Chemical Ionisation (APCI), present in the different horizons from a soil affected by lava deposition. The diameter of each bubble is related to the relative intensity of each compound. The main molecular families are represented with coloured circles using the modified aromaticity index (AImod) and the rules outlined by Kim *et al.* (2003).

Deeper horizons retained more reduced, bioavailable molecular classes, suggesting partial preservation of the pre-eruption SOM profile. Across all horizons, molecular diversity and intensity declined markedly near the lava interface, reflecting pronounced thermal and oxidative stress. In control samples, uppermost horizons show a predominance of lignins and lipids (biomass deposition), while in deeper horizons the SOM is more humified, mainly composed by aromatics and proteins. This integrative molecular fingerprinting approach provides novel insights into the resilience and transformation of SOM following volcanic events. The results give valuable information for the development of post-eruption soil recovery and nutrient cycling models. The study demonstrates the power of combining chemometrics with UHRMS to track C dynamics in extreme geological contexts.

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ECOLOGICAL RESILIENCE AND BIODIVERSITY DYNAMICS OF AN ISLAND FOREST FOLLOWING A VOLCANIC ERUPTION

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ABSTRACT

Volcanic eruptions constitute complex and extreme disturbances, with multifaceted impacts on biodiversity and ecosystem dynamics. The 2021 Tajogaite eruption (La Palma, Canary Islands), which lasted for 85 days, provided a unique opportunity to study early successional processes across taxonomic groups in an insular forest ecosystem. This study investigates the spatio-temporal patterns of biotic recovery within the Canary Island pine (*Pinus canariensis*) forest through a two-year monitoring effort encompassing flora and

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fauna across a 7 km gradient from the eruption crater. Using twelve 30 × 30 m plots subjected to varying tephra deposition, we analyzed species richness, abundance, regeneration capacity, and ecological interactions. Vegetation surveys revealed a progressive increase in plant diversity with distance from the crater, with endemic woody species exhibiting significant resilience (Beierkuhnlein *et al*., 2023), while *P. canariensis* generated epicormic resprouting even under sustained exposure to volcanic stress. However, long-term survivorship near the crater was limited by sustained high soil temperatures, gas emissions, and disruption of water availability. Herbaceous species and seedling recruitment were largely absent within 400 m of the crater, with seed bank viability affected by tephra thickness (Medina *et al*., 2025).

Fig. 1. Early resprouting response of *Pinus canariensis* after the Tajogaite eruption. Epicormic shoots emerged predominantly from mechanically damaged trunks exposed to pyroclastic impacts, gasses, and tephra accumulation

Arthropod communities were shaped by vegetation structure and host plant availability: Hemiptera and Coleoptera dominated vegetated zones, while Diptera proliferated in proximal areas with high organic matter, forming necromass-based food webs near the crater. Reptiles (particularly *Gallotia galloti*) were confined to a few refugia and showed minimal recolonization. Avian communities exhibited divergent responses: insectivorous passerines recolonized the landscape rapidly post-eruption, while corvids and raptors persisted throughout the impacted area, exploiting abundant food resources. Bat activity, assessed through ultrasonic monitoring, remained nearly absent, reflecting delayed recovery of nocturnal insect prey and shelter conditions. This study highlights the intricate, taxa-specific trajectories of ecosystem resilience following volcanic disturbances. Our findings emphasize the ecological filters imposed by volcanic ash, the differential recovery of biotic groups, and the significance of pre-existing functional traits in determining post-eruptive survival. The Tajogaite case represents one of the few early-stage, integrated biodiversity assessments conducted in an oceanic island context, offering valuable insights for ecological theory, conservation planning, and future disturbance scenarios in volcanic archipelagos (Crisafulli *et al.*, 2015; Nogales *et al.*, 2022).

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EARLY MICROBIAL ECOSYSTEMS IN NASCENT LAVA TUBES: ASTROBIOLOGICAL AND BIOTECHNOLOGICAL POTENTIAL

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ABSTRACT

The 2021 Tajogaite eruption on La Palma (Canary Islands) generated an extensive system of lava tubes, providing an unprecedented opportunity to study microbial life emerging in one of Earth's youngest volcanic subterranean environments. These newly formed tubes, marked by thermal extremes, limited nutrient availability, and stable microclimates, offer a valuable analog for Martian lava tubes and a natural laboratory to explore early ecosystem development. Here, we combined high-throughput 16S rRNA gene sequencing, culture-based techniques, mineralogical analyses, and isotopic profiling to characterize initial microbial colonization within the newly formed lava tubes (Fig. 1A,B). We identified extremophilic bacteria from the phyla *Actinomycetota*, *Bacillota*, and *Pseudomonadota*, as well as chemolithotrophic archaea (*Euryarchaeota*), adapted to thrive under the harsh geochemical conditions of the volcanic subsurface. Host-associated taxa such as *Staphylococcus* sp., *Sphingomonas* sp., and *Filibacter tadaridae* were also detected, pointing to an exogenous organic matter input from animals (e.g., rodents and seabirds) near cave entrances. Additionally, taxa involved in nitrogen fixation, sulfur oxida-

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tion, and carbon cycling were detected, indicating the rapid formation of functional metabolic networks, similar to those previously reported in older lava tubes from the Canary Islands (Gonzalez-Pimentel *et al*., 2018; Gutierrez-Patricio *et al*., 2024; Palma *et al*., 2024), Mount Etna (Nicolosi *et al*., 2023) and the Galapagos (Miller *et al*., 2020).

Biofilm-like structures associated with sodium sulfate minerals (e.g., thenardite) revealed microbial participation in incipient mineral weathering and biogeochemical cycling (Fig. 1C,D).Our results demonstrate that early colonization is governed by both selective environmental pressures imposed by extreme abiotic conditions and stochastic biological seeding through airborne particles, animal vectors, and rainwater runoff, reflecting a complex interplay of endogenous and exogenous drivers. In addition to their ecological relevance, the extremophilic bacteria isolated from these lava tubes exhibit remarkable biotechnological potential. Several bacterial strains were successfully cultured, which are known for their metabolic plasticity, psychrotolerance, or halotolerance. We are currently investigating the extraordinary potential of these extremophiles to produce novel bioactive compounds through antimicrobial activity assays and advanced metabolomic profiling. The unique adaptations of these microorganisms to thermally dynamic, nutrient-poor environments may hold the key to the discovery of next-generation antibiotics, offering promising solutions to the global antimicrobial resistance crisis. These findings provide novel insights into geomicrobiological succession in nascent lava tubes and advance our understanding of biosignature formation, micro-

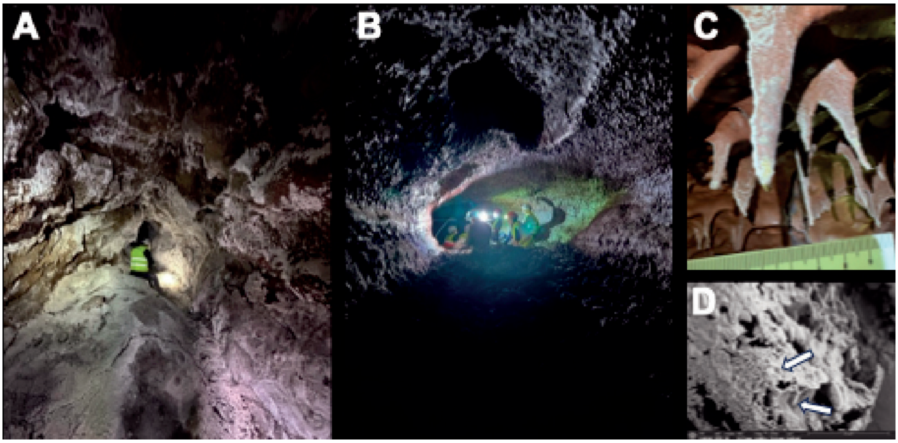

Fig. 1. Newly formed lava tube systems from the Tajogaite eruption. A,B) Field images of the interior of the lava tubes; C) Sodium sulfate minerals coating the host lava; D) Field Emission Scanning Electron Microscopy image showing biofilm-like structures (arrows)

bial resilience, and potential life-supporting conditions in planetary analog environments. They also highlight the importance of lava tubes as natural laboratories for astrobiological research and biotechnological innovation.

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LIFE AFTER LAVA: MOSS-ASSOCIATED PROKARYOTIC COMMUNITIES IN POST-ERUPTION VOLCANIC SUBSTRATES

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Abstract

Volcanic eruptions represent major natural disturbances that transform landscapes and initiate primary ecological succession. The 2021 Tajogaite eruption on La Palma (Canary Islands) was one of the most significant volcanic events in recent European history. Over a period of 85 days, it released more than 200 million cubic meters of lava and pyroclastic materials, destroying infrastructure and agricultural land. Despite its destructive impact, the eruption provides a unique opportunity to study the initial stages of biological colonization in a newly formed volcanic environment, providing an ideal natural laboratory for investigating how life re-establishes itself under extreme conditions (Carracedo *et al*., 2022; Ferrer *et al*., 2023; Handland *et al*., 2024). In this study, we investigated pioneer microbial communities associated with mosses growing on tephra in this nascent volcanic landscape. Samples were collected from two sites within the exclusion zone of the volcano, located near both active and inactive fumaroles. These samples were analysed using high-throughput DNA sequencing of the 16S rRNA gene to characterise the prokaryotic diversity and identify the main metabolic pathways present. Our results reveal that the prokaryotic community was dominated by the *Pseudomonadota phylum*, represented by genera such as *Methylobacterium*, Rhizobium, and Pseudomonas, which are known

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for their metal adsorption capabilities, plant growth promotion, antibiotic production and biodegradation potential (Fig. 1).

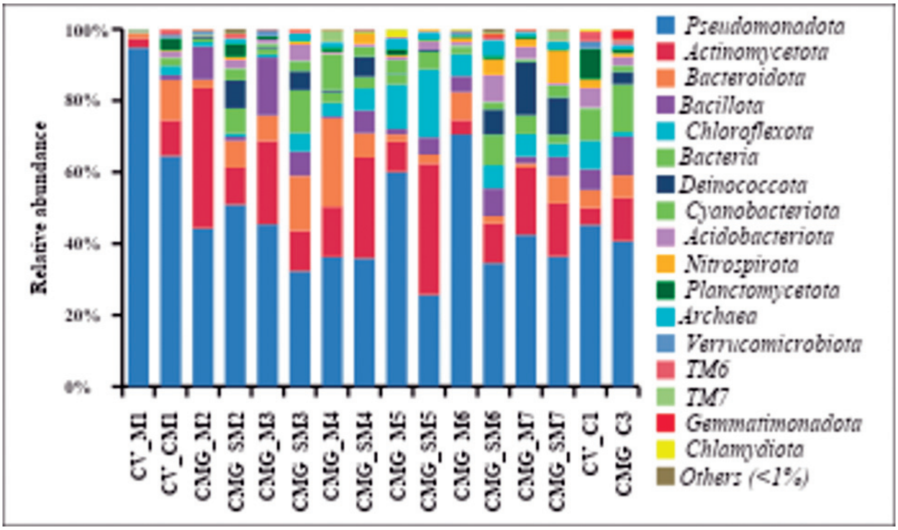

Fig. 1. Prokaryotic community composition associated with moss samples and tephra at the phylum level

Actinomycetota, particularly of the genus Arthrobacter, were abundant in the volcanic substrates and may play a role in rock weathering and initial soil formation (Gutiérrez-Patricio *et al*., 2024). Notably, extremophilic taxa belonging to the phylum *Deinococcota* were found exclusively in moss samples collected from steam-emitting fumaroles, highlighting the impact of environmental stress on microbial community composition. Functional predictions indicated that key metabolic pathways were primarily related to carbon and nitrogen cycling, as previously reported in other volcanic environments from the Canary Islands (Palma *et al*., 2024). Overall, our findings emphasize the crucial role of microorganisms in primary ecological succession and ecosystem recovery following volcanic eruptions. Understanding these pioneer stages is essential for unravelling the key biological processes that drive ecosystem regeneration in the aftermath of such natural disturbances.

ACKNOWLEDGEMENTS

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DE NOVO TRANSCRIPTOME ASSEMBLY AND FUNCTIONAL ANNOTATION OF THREE CO-OCCURRING SPECIES OF THE CANARY ISLANDS PINE FOREST AFFECTED BY THE 2021 TAJOGAITE VOLCANIC ERUPTION

María Guerrero-Campos[1,2], Tania Domínguez-Flores[3], Oliver Gailing[3], Patricia Marrero[1], Félix M. Medina[4], José Carlos Miranda[5], Manuel Nogales[2], Víctor Chano[3,*]

Abstract

The Tajogaite eruption on La Palma (Autumn, 2021) deeply impacted the Canary Island pine forest habitats, including the dominant tree species *Pinus canariensis* and the co-occurring endemics *Cistus symphytifolius* and *Erica canariensis* (Nogales *et al*., 2022). The ecology of these species has been shaped under recurrent volcanism, with woody plants often persisting above ash layers while seed banks and seedling recruitment were strongly disrupted by tephra burial (Beierkuhnlein *et al*., 2023; Medina *et al*., 2025). The main goal of this work is to provide genetic tools to uncover the molecular mechanisms underlying the survival and adaptation of these species in a volcanic environment. Previous transcriptomic work in *P. canariensis* has characterized key traits for persistence in volcanic landscapes like wound healing and resprouting (f.i., see Chano *et al*., 2023). This eruptive event provides a unique opportunity to investigate transcriptomics for these endemic species under a real volcanic scenario, linking ecological resilience and evolutionary

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history to gene-expression responses (Keagy *et al.*, 2025). Total RNA was extracted from leaves/needles samples collected from individuals at different distances from the eruption point and also at different time points for *P. canariensis*. *De novo* assemblies of each species were evaluated by analysing N50 and L50 parameters, transcript length distributions, and GC content. For *P. canariensis*, the assembly yielded 68,871 transcripts identified as unigenes, while 69,170 and 55,300 unigenes were identified for *C. symphytifolius* and *E. canariensis*, respectively.

To better understand the functionalities of these genes, particularly those related to stress responses and recovery, we compared them against well-characterised genes from public databases and assigned standardised Gene Ontology (GO) terms linked to biological processes and molecular functions. The functional annotation revealed high cross-species homology. In *P. canariensis*, 70.55 % of transcripts matched database genes, with 42.68 % receiving GO terms; in *E. canariensis*, 80.0 % had homologues and 64.23 % were GO-annotated; and in *C. symphytifolius*, 85.9 % showed sequence homology and 65.7 % were GO-annotated (Fig. 1). These reference transcriptomes are valuable resources for future differential gene expression analyses and the identification of genes involved in eruption response and subsequent recovery of the endemic flora of the Canary Islands.

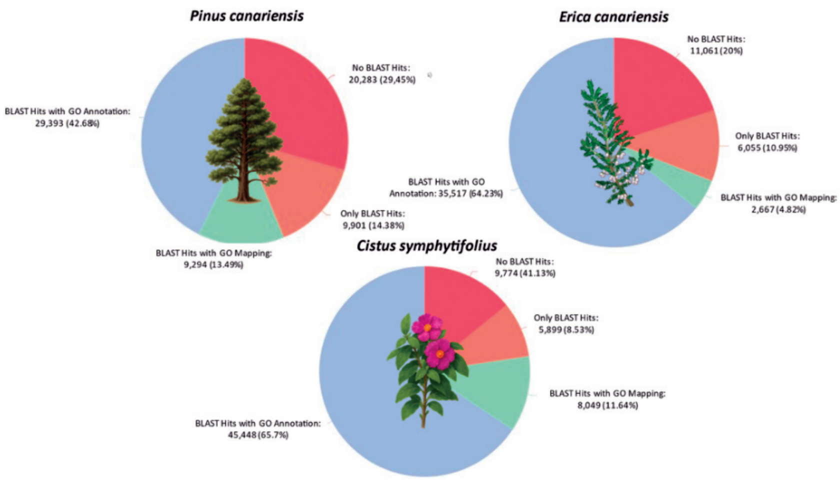

Fig. 1. Functional Annotation and BLAST Hits distribution across three Canary Islands endemic species

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Topic 13

New resources opportunities

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EDUCATION AND SCIENTIFIC OUTREACH: UNDERSTANDING VOLCANIC GEOMORPHOLOGY, GEOHERITAGE, AND VOLCANIC HAZARD THROUGH TAJOGAITE ERUPTION 2021 (LA PALMA, SPAIN)

Rafael Becerra-Ramírez[1,2], Rafael U. Gosálvez[1,2], Estela Escobar[1,2], Elena González[1,2], Darío Guevara[1], Adrián Navas[1], Beatriz Morales Pérez[1]

Abstract

The 2021 Tajogaite volcano eruption has been monitored from the precursors to the beginning of the eruptive process, its development hour by hour and its end, thanks to scientists from different universities and leading scientific institutions and through the media worldwide. The interest that this eruption has aroused in the population is an opportunity and a resource for developing university training courses specialising in volcanic geomorphology, geoheritage, volcanic hazards and geotourism, and other training and scientific outreach activities aimed at the public and primary and secondary school students (workshops, talks, documentaries, photographic exhibitions...), based on the science of Geography. This work presents the different activities carried out by geographers of the GEOVOL-UCLM group, scientific collaborators of INVOLCAN, on the Tajogaite eruption between 2021 and 2025, in the field of university, secondary and primary education, and scientific outreach. These activities have been:

- Technical report of the eruption and an interpretation guide of the volcanic landforms of La Palma (González *et al*., 2023 a, b).
- Practical course on Volcanic Geomorphology, Biogeography and Natural Hazards on La Palma (UCLM, 2023).
- *Geotaller de Geografía y Volcanes*.

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- —Scientific talks in secondary and primary schools.
- —European Volcanoes' Night.
- —Exhibition *Bajo el Volcán: La Geografía en La Palma* (UCLM, n.d.).
- —Museum *Ciencia por un Día*.
- —*Ciencia en la Calle* (Casa de la Ciencia, n.d.).
- —*Ciencia con² Ciencia* conference.
- —Interviews in local, regional, national and international press.

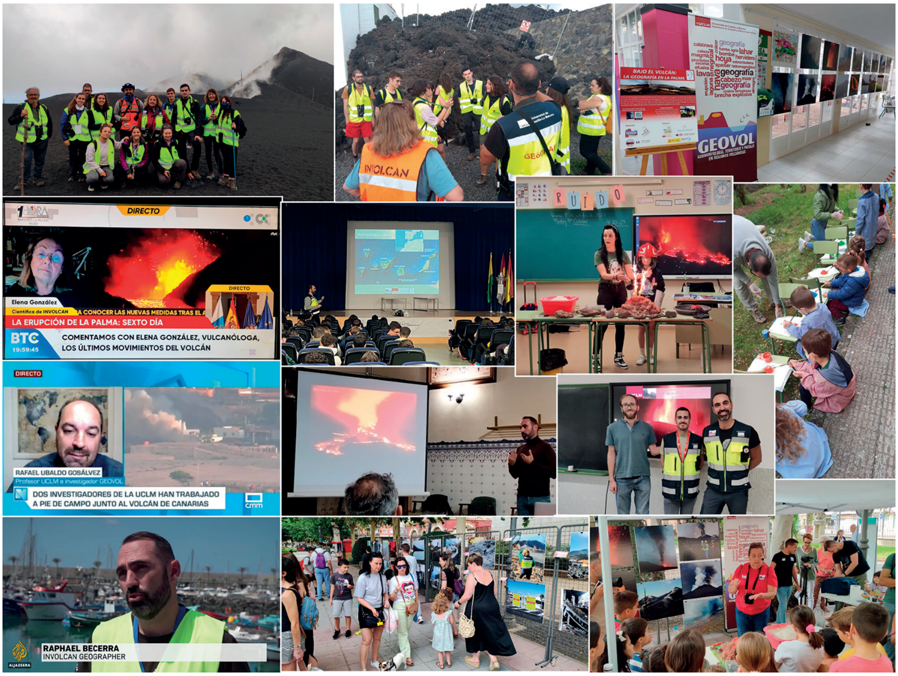

Fig. 1. Several university education and scientific outreach activities on volcanic geomorphology, geoheritage and volcanic hazards

The implementation of these activities, from the perspective of Geography, is vital for the training of university students in such a specific and interesting phenomenon as volcanism: landforms built on a human scale, a phenomenon that reorganises the landscape and land uses, and the associated hazards. Related to the opportunities that volcanic landscapes have for territorial planning, the creation of protected natural areas and the geoconservation of volcanic landscapes, their interest as geoheritage and a resource for geotourism.

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FEASIBILITY OF PRODUCING MORTARS FROM 100% VOLCANIC MATERIAL FROM THE TAJOGAITE ERUPTION

Andrés Caño[1], José A. Suárez-Navarro[2], José F. Mediato[3], Pablo Martín-Rodríguez[1], Inés García Lodeiro[1], Ana Fernández-Jiménez[1], María del Mar Alonso[1]

Abstract

Four years after the eruption of the Tajogaite volcano on the island of La Palma, there is still a lot of recoverable material from the eruption that is in landfills or occupying lands (Mediato *et al.*, 2023). In this work, we have studied the possibility of developing mortars prepared 100% using materials from the volcanic eruption. The mortars were prepared from alkaline-activated Tajogaite volcanic fly ash (FAT) and volcanic aggregates (VA) of the same origin. Mortars composed by 100% Portland cement (OPC) and by 70% OPC and 30% FAT were also prepared, in order to compare their feasibility (Martín-Rodríguez *et al.*, 2024). All types of mortars were also prepared with a siliceous aggregate (SA) (used as a reference). Both types of aggregates have been studied from the physical, chemical, mineralogical and radiological safety point of view. The use of volcanic aggregate produced a decrease in the mechanical strength of the 100% OPC and 70/30% OPC/FAT mortars, while in

Fig. 1. Morphological aspect of FAT, SA and VA

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the 100% FAT mortars there was an increase in the mechanical strength. The radiological safety of both FAT and VA materials has also been proven (Caño *et al*., 2025). Therefore, it demonstrates the feasibility of using mortars made with 100% volcanic material.

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LA PALMA VOLCANIC ASH AS A NEW RESOURCE FOR MAKING LOW CARBON CEMENTITIOUS BINDERS

Inés García-Lodeiro*, Pablo Martín-Rodríguez, Andrés Caño, María del Mar Alonso, Ana Fernández-Jiménez

Abstract

The eruption of the Tajogaite volcano on La Palma island destroyed buildings, roads, and infrastructure. To this day, large quantities of volcanic material are still accumulated in landfills. In this work, the fly ash from the Tajogaite volcano (FAT) has been used for the preparation of Low-Carbon cementitious binders (Fig. 1). For that the FAT, once grinded, have been characterised

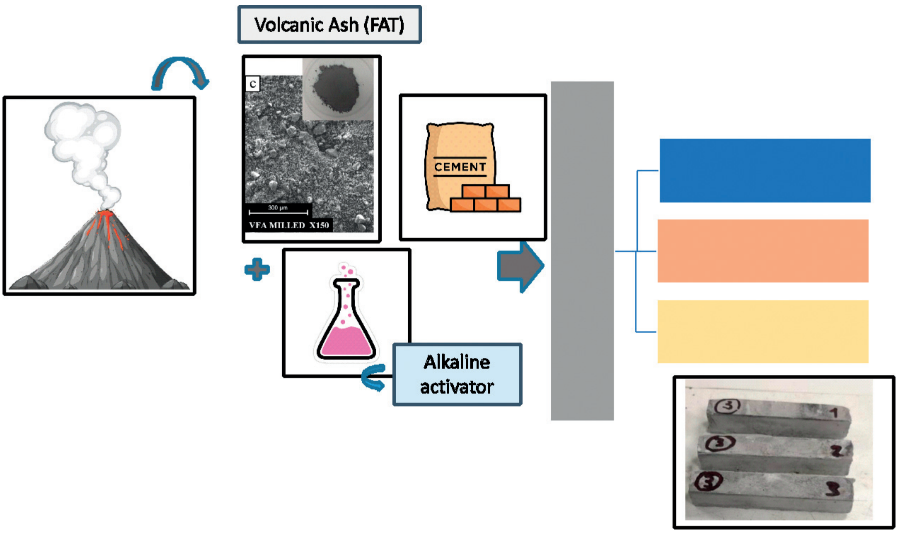

Fig. 1. Preparation of Low Carbon Cementitious Binders using volcanic ash as a precursor

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from the chemical and mineralogical point of view (XRF and XRD). Three types of cements have been prepared: blended cements (BC = 30 % FAT + 70 % Portland cement (PC)), Hybrid Alkaline Cement (HAC = 70 % FAT + 30 % PC + Activator), and Alkaline Cements (100 % FAT + liquid alkaline activator) (Martín-Rodríguez *et al*., 2024). With these cements, pastes were prepared and cured at different conditions and the compressive strength development was tested at 2 and 28 days. In all cases, compressive strengths overpass 20 MPa at 2 days and 40 MPa at 28 days. The kinetic reaction was determined by isothermal conduction calorimetry and the reaction products formed were characterized by XRD, TG/DTG and BSEM/EDX. Results indicate that FTA has a high potential to be used as both SCMs and precursor in the elaboration of low CO_2-cements.

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METAPHORS OF LOSS AND RESILIENCE: A COGNITIVE-SEMIOTIC PERSPECTIVE ON LANDSCAPE RECONSTRUCTION AFTER THE ERUPTION OF TAJOGAITE VOLCANO IN LA PALMA

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Abstract

The eruption of Tajogaite in 2021 irreversibly transformed the landscape of La Palma, generating a radically new volcanic territory with significant tourism potential (Gkoliomyti & Tsukamoto, 2021). Since the end of the event, urban planning has prioritized policies aimed at the recovery and reconstruction of pre-eruptive conditions. However, the absence of in-depth, community-oriented studies that inform planning decisions is adversely impacting the post-eruptive lava field landscape. This lack of contextualized knowledge has led to missed opportunities for developing an integrated infrastructure that harmonizes tourism development with the unique characteristics of the volcanic landscape (ICOMOS & UNESCO, 2020; Gkoliomyti & Tsukamoto, 2021). After eruption, La Palma faces not only material reconstruction but also the challenge of recovering intangible heritage, emotional ties, and the fractured narratives of its communities (Pallasmaa, 2025). Our interdisciplinary project, combining cognitive linguistics, semiotics, and architectural research, examines how affected residents conceptualize the volcanic landscape, the loss of homes and land, and the ongoing recovery process (Kövecses, 2020). Through interviews with local inhabitants and analysis of their narratives, we identify recurring conceptual metaphors and image schemas that structure how people talk about the eruption, aid distribution, land use, and identity (Wachowiak *et al*., 2022). These metaphors—such as the island as a body, the lava as an intruder, or home as rootedness—reveal how trauma, belonging, and perceived injustice shape responses to institutional interventions and spatial proposals (Kövecses, 2020). By mapping these metaphorical structures and embo-

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died experiences, we aim to support more context-sensitive planning decisions. This includes recognizing emotional geographies, the value of informal networks and senior residents' knowledge, and the role of storytelling in preserving memory (ICOMOS & UNESCO, 2020; Gkoliomyti & Tsukamoto, 2021). Our approach offers a transdisciplinary toolkit to better align architectural and touristic strategies with the lived experiences of those most affected.

Fig. 1. Earth moving worksite on Tajogaite lava field

Rather than promoting tourism as a generic opportunity, we argue for practices that integrate memory, emotional reconstruction, and symbolic continuity, fostering a form of slow, participatory, and sustainable tourism more aware of the material and geological value of the lava field as living testimony of Tajogaite eruptive event. Our findings can inform future decisions about interventions on volcanic terrain by involving affected communities more deeply and aligning planning strategies with their lived narratives, needs, and emotional times to the land.

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FROM WASTE TO SUSTAINABLE RESOURCE: UTILISING CUMBRE VIEJA VOLCANIC ASH AS PRECURSOR IN ALKALINE ACTIVATED TECHNOLOGY

Silvia Portale[1,2], Roberta Occhipinti[2], Gabriele Lanzafame[2], Domingo Gimeno[3], Germana Barone[2], Paolo Mazzoleni[2]

Abstract

The three-months lasting eruption of the Cumbre Vieja volcano (La Palma, Canary Islands, Spain), in 2021, released large volumes of volcanic ash. This ash extensively covered the island causing severe damage to residential areas and agricultural lands, especially in the closest areas to the eruptive vent. According to the European law, this volcanic ash is classified as wastes, representing a disposal challenge. However, recent studies have demonstrated its suitability as a precursor for producing Alkali-Activated Materials (AAMs) (Barone *et al.*, 2021; Occhipinti *et al.*, 2024). In this study, the feasibility of using pyroclastic material from the Cumbre Vieja eruption as a raw material for AAMs production is presented. The utilization of waste for producing new and greener materials aligns with circular economy principles, promoting sustainable construction practices. Ash samples, collected from various locations across the island, were firstly characterised from a chemical-mineralogical point of view.

Alkaline activated binders were tested using the volcanic ash both as a standalone precursor, and then in binary mixtures with metakaolin. Sodium hydroxide and sodium silicate solutions were used as alkali activators. Foaming agents were also added to test lightweight formulations of AAMs. The resulting AAMs were comprehensively characterised using X-ray diffractometry (XRD), Fourier-transform infrared spectroscopy (FT-IR), scanning electron microscopy (SEM), and uniaxial compressive strength testing, also comparing

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the final materials with the original precursor. Additionally, 3D microstructural analysis was conducted via synchrotron-based X-ray microtomography, providing detailed insights into distribution, morphology, and connectivity of the pore systems of AAMs. Cumbre Vieja volcanic ash was demonstrated to be a viable raw material for AAMs production, offering a sustainable solution with promising applications in the construction industry.

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ARCHITECTURE AND INFRASTRUCTURE IN THE VOLCANIC SPACE BASED ON THE VISUAL AND PERCEPTUAL TRANSFORMATIONS OF THE ERUPTION OF THE TAJOGAITE VOLCANO ON LA PALMA

ESTELA RODRÍGUEZ CADENAS*, MANUEL PÉREZ TAMAYO*

ABSTRACT

The result of the eruption of the Tajogaite volcano in La Palma has profoundly transformed both the natural and built environment, opening new ways to understand heritage, landscape, and architectural intervention in volcanic contexts. This study investigates the visual and spatial consequences of the eruptive phenomenon, with special attention to the transformation of the landscape landmarks that defined the cultural identity of the area. Based on the analysis of the territory, it proposes how the volcanic flow acts as a new layer that generates a virgin landscape, which, far from representing only destruction, also offers the possibility of rethinking the edges, boundaries, and connections between the lava and the pre-existing territory. This research work understands that the main geomorphological values of the volcanic landscape caused by the Tajogaite volcano must be preserved and protected against human activity to avoid its disappearance. This research work understands that the main geomorphological values of the volcanic landscape caused by the Tajogaite volcano must be preserved and protected from human activity to prevent their degradation, enhancing them as an additional attraction within the geotourism circuit of the island of La Palma, contributing to the economic revitalization of La Palma (Hernández *et al*., 2022). In this context, this work investigates the new visual perspectives for observing the volcanic landscapes of the Tajogaite volcano, the interactions between the architectural heritage and its lava flow, and the infrastructures that cross this new landscape. The objective is to establish the criteria for action and necessary corrective measures to enhance the visual perspectives of the Tajogaite volcano as a tourist attraction from a geotourism perspective, understanding this type of tourism as a sustainable economic activity. It also achieves the preservation

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and conservation of the geomorphological values of these new volcanic landscapes. The methodology used is based on identifying, classifying, and characterizing the visual perspectives, the edges of the lava flow, and the new interventions generated after the Tajogaite volcano.

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VOLCANIC TUBES AS A GEOTOURISM RESOURCE: PROTOCOLS FOR RADON MEASUREMENT

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Abstract

The volcanic caves of the Canary Islands are an important natural heritage resource that attracts a wide variety of visitors (Júnior & Lobo, 2012). The recent volcanic eruption on the island of La Palma in 2021 generated many volcanic tubes that represent an important natural resource, with interesting prospects for future tourist exploitation. Given the loss of significant agricultural land and many buildings, buried by lava, which were part of the island's productive fabric, the volcanic tubes present an opportunity to partially compensate for the economic damage caused by the eruption. However, the exploitation of these underground resources requires the study of the natural hazards that affect this type of structure. Among these hazards is radon gas (Padilla *et al*., 2013). This is a radioactive gas that accumulates in underground environments and poses a significant occupational health risk, especially for workers who spend long periods of time inside the caves (Sainz *et al*., 2007). Short-term exposure may be harmless for most visitors, but long-term inhalation can cause DNA damage and increase the risk of lung cancer. This paper proposes a comprehensive protocol for studying and controlling radon exposure in people who visit or work in volcanic tourist caves. It is based on current European and Spanish safety standards for the control of ionizing radiation. The protocol includes radon measurement campaigns in several phases using passive and active detectors, the classification of radon levels using a color-coded system (Fig. 1), spatial mapping of homogeneous radon zones, and

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the implementation of mitigation strategies adapted to each area of the cave. Organizational measures such as staff rotation, restricted access to areas with high radon levels, and regular health monitoring are also taken into account to ensure worker safety. This work involves the managers of volcanic tourist caves so that they not only comply with safety standards but also participate in educational initiatives to raise awareness of geological risks, spreading the truth about radon gas.

Fig. 1. Traffic light for assessment of radon concentration

This work provides a replicable, science-based model for managing radon risks in volcanic tourist caves, ensuring user safety while promoting sustainable tourism practices that protect both public health and the unique underground environments of the Canary Islands.

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WATER AS A STRUCTURING AGENT: NEW TERRITORIAL STRATEGIES AFTER THE TAJOGAITE ERUPTION

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Abstract

The 2021 eruption of the Tajogaite volcano radically disrupted La Palma's hydrological and territorial systems (Fig. 1), revealing the fragility of a model built on inherited flows, fragmented technical solutions, and a growing disconnection between water and landscape (García Rodríguez, 2024). This article proposes a re-reading of water not only as a resource, but as a structuring, symbolic, and cultural agent capable of generating new opportunities for territorial reconstruction in post-volcanic contexts. From a landscape-architectural perspective, the article examines the historical role of water in shaping La Palma's territory, from traditional infrastructures (such as acequias, dulas, washhouses, galleries, and storage tanks) to the transformations induced by modernization and the progressive abandonment of hydraulic heritage (Pais Pais, 2018). By analyzing the improvised emergency responses -such as floating desalination plants or aerial pipelines over lava flows- the study highlights the limitations of interventions disconnected from place and memory (GESPLAN, 2023). The text outlines design strategies based on the active recovery of historical infrastructures, the symbolic revaluation of the water cycle, and the incorporation of hybrid, visible solutions adapted to the new volcanic landscape. It explores techniques such as atmospheric water harvesting, runoff slowdown systems, and semi-buried reservoirs with landscape expression (Suárez Moreno, 2011), alongside the proposal for a pedagogical center integrating local knowledge and contemporary technologies. The research follows a transdisciplinary methodology combining historical cartography, GIS analysis, and case study, supported by theoretical frameworks that conceive landscape as a cultural and identity-based construction (Nogué & Prats, 2007). This approach enables both the diagnosis of changes in the island's water system and the projection of place-sensitive design criteria. Ultimately, the article advocates for a water architecture that articulates territory, techno-

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logy, and culture. Lava is proposed as a projective surface, and water as a narrative capable of reconstructing the bond between community, identity, and landscape.

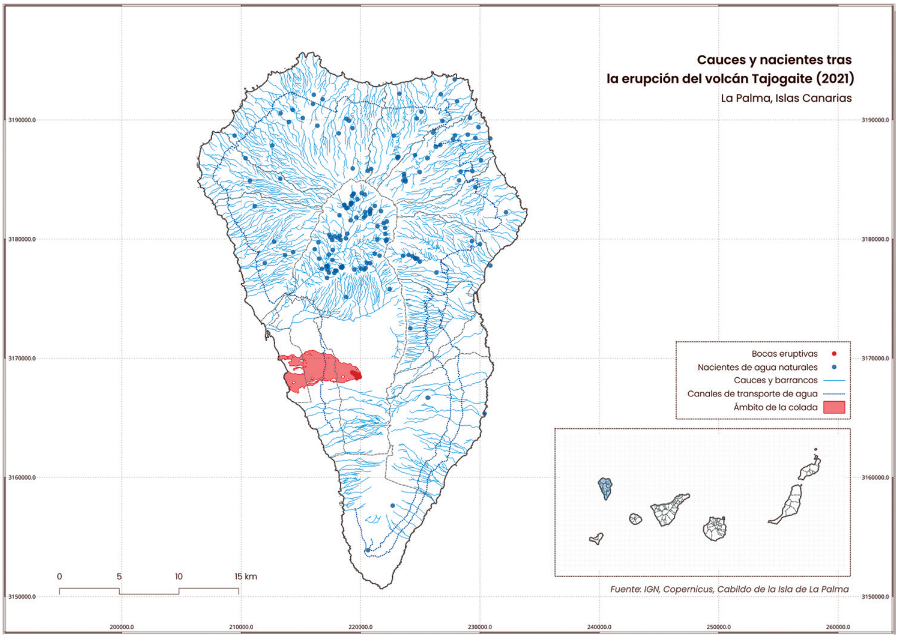

Fig. 1. Watercourses and springs after the 2021 eruption of the Tajogaite volcano. Source: Own elaboration

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LEVERAGING TAJOGAITE VOLCANIC ASH FOR DIRECT AIR CAPTURE AND CO_2/H_2O CONVERSION

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Abstract

An integrated experimental investigation is underway to explore four complementary pathways for atmospheric CO_2 removal and valorization, leveraging local volcanic resources. First, direct air capture (DAC) of CO_2 and H_2O is being evaluated in a fixed bed temperature swing adsorption (TSA) system using commercial zeolites 13X, 4A and JLMP3 under realistic conditions (~400 ppm CO_2, 1-4 % RH). Zeolite JLMP3 is showing the highest CO_2 uptake with stable cyclic performance when regenerated at 100 °C, while zeolite 4A is demonstrating superior H_2O/CO_2 selectivity and is serving as a critical dehumidification stage to protect CO_2 adsorption sites. Ongoing work focuses on minimizing thermal stress through optimized internal heat exchange and evaluating long term adsorbent stability. Second, a zeolite synthesis route from Tajogaite volcanic ash is being developed via alkaline fusion followed by hydrothermal crystallization over varying durations. Preliminary characterizations (XRD, BET, TGA) will assess microporosity, cation exchange capacity and framework integrity to tailor sorbent properties for DAC applications. Third, a laboratory scale «air to fuel» system is being developed that integrates: (i) electrolytic H_2 production from DAC derived water, (ii) reverse water gas shift (RWGS) or chemical looping RWGS for CO generation, and (iii) Fischer-Tropsch synthesis to produce liquid hydrocarbons. Finally, accelerated mineralization of CO_2 in basaltic rocks and volcanic ash is under investigation in high pressure reactors. Early trials are monitoring Ca^{2+}, Mg^{2+} and Fe^{2+} release and carbonate precipitation rates. Collectively, these ongo-

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ing experiments are establishing a comprehensive laboratory infrastructure for CO_2 capture, adsorbent development, e fuel synthesis and permanent carbon mineralization, laying the groundwork for regionally adapted, circular economy approaches to climate mitigation.

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EVALUATING THE GEOTHERMAL POTENTIAL IN LA PALMA ISLAND (CANARY ISLANDS) THROUGH GEOPHYSICAL TECHNIQUES

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ABSTRACT

Over the past few years, the island of La Palma has been the subject of various studies aimed at examining its internal structure using different methodologies. All these studies, to some extent, were directly helpful in evaluating the geothermal potential of the island (Fariña-González *et al.*, 2025). In this work, we compare the 3D models of La Palma, obtained using different techniques, with the island's geology and discuss their implications for assessing its geothermal potential. Specifically, we focus on seismic ambient noise tomography (ANT). This technique enabled us to highlight the seismic velocity anomalies in the shallow crust of Cumbre Vieja volcano, located in the southern part of the island, with unprecedented resolution (Cabrera-Pérez *et al.*, 2023). In this context, the seismicity associated with the 2021 Cumbre Vieja eruption enabled, for the first time, a detailed local earthquake tomography up to a depth of approximately 20 km (D'Auria *et al.*, 2022). Recently, we also applied an innovative methodology that enables the determination of seismic attenuation, a parameter strongly influenced by fluid-saturated rocks (Cabrera-Pérez *et al.*, 2024). We compare seismic properties with the resistivity inferred by magnetotelluric soundings (Di Paolo *et al.*, 2020) and gravity survey (Camacho *et al.*, 2009). In summary, our findings indicate:

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- The presence, in the northern part of the island, of a large, high-velocity, low-attenuation, high-resistivity, and high-density body, which is geologically linked to the Taburiente volcanic complex, an inactive, prominent volcanic edifice on the island.

- The southern part of the island, with the active volcano Cumbre Vieja, exhibits radically different characteristics, including lower seismic velocities, densities, and resistivity, as well as higher seismic attenuation.

- In particular, we evidence two volumes, located respectively on the western and eastern sides of Cumbre Vieja volcano, characterised by very low S-wave velocity and resistivity, low density and very high seismic attenuation. These two volumes extend to a depth range of 0-2 km and have volumes of 25 and 6 km^3, respectively. We interpret these two bodies as liquid-saturated reservoirs that have the potential to host geothermal reservoirs.

In conclusion, we demonstrate how the application of modern geophysical exploration techniques provides a crucial tool for accurately assessing the geothermal potential in La Palma.

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MULTI-SCALE SURFACE GEOCHEMICAL SURVEYS FOR GEOTHERMAL RESOURCE EXPLORATION IN THE SOUTHERN SECTOR OF THE TAJOGAITE LAVA FLOWS (LA PALMA, CANARY ISLANDS, SPAIN)

Gladys V. Melián[1,2], Nemesio M. Pérez[1,2], María Asensio-Ramos[1], Sttefany Cartaya[1,2], Eleazar Padrón[1,2], Germán D. Padilla[1,2], Pedro A. Hernández[1,2]

Abstract

Geochemical surveys are crucial in the early stages of geothermal exploration. While water and gas sampling from natural discharges are common in known geothermal fields, soil and soil-gas surveys become essential where surface manifestations are scarce or the extent of the system is unknown. These methods help identify permeable zones, potential upflow or boiling areas, and delineate the boundaries of geothermal systems. They also complement geophysical surveys, especially where interpretation is complicated by topography. Soil-gas surveys are particularly valuable on volcanic islands such as La Palma (Canary Islands, Spain), where obvious geothermal surface features are absent. By detecting surface geochemical anomalies linked to deep-seated degassing, soil-gas surveys significantly aid in locating promising geothermal areas (Padrón *et al*., 2013; Rodríguez *et al*., 2015a, 2015b, 2021; Martín-Lorenzo *et al*., 2024). This study presents soil gas survey results from western La Palma aimed at identifying geothermal potential. The surveys included in-situ measurements of soil CO_2 efflux and radon (222Rn and 220Rn) activity, alongside soil gas sampling at 40 cm depth for subsequent chemical (He, H_2, CH_4, CO_2) and isotopic (δ13C-CO_2) analyses. The investigation comprised two phases. The first phase involved a broad survey of ~25 km^2 using a moderately dense network (~40 sites/km^2) to detect permeable structures and potential upflow zones indicative of geothermal systems (Fig. 1). Based on these

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findings, a second high-resolution survey (~5,000 sites/km^2) was conducted over a focused 0.84 km^2 area to refine the geochemical and structural characterization of anomalous zones. This detailed analysis provided deeper insights into gas origins, migration pathways, and transport mechanisms. The spatial correlation of major geochemical anomalies with fault-controlled degassing structures suggests strong structural control and a direct link to underlying geothermal reservoirs. These findings highlight the value of geochemical tools in early geothermal exploration and support their integration in prioritizing areas for exploratory drilling on La Palma.

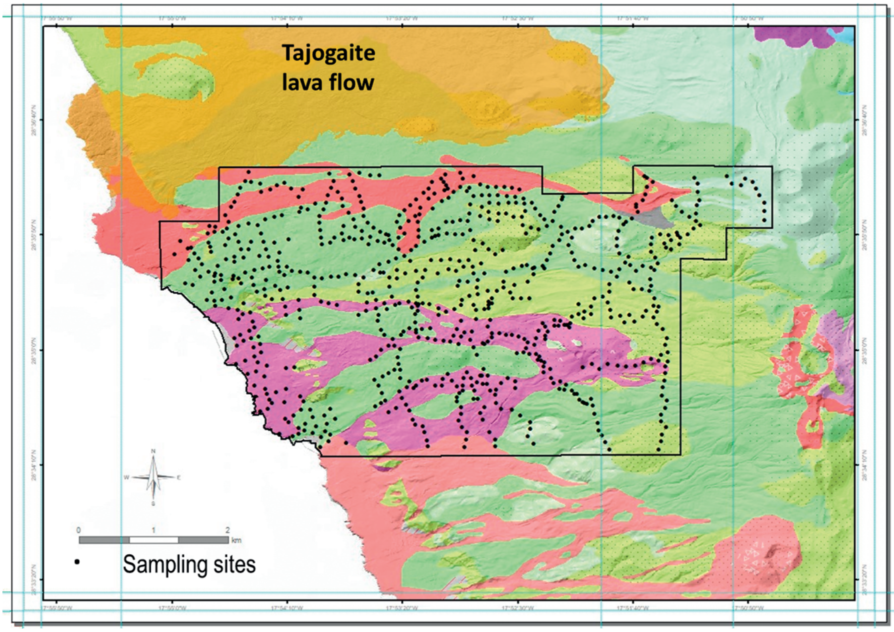

Fig. 1. Distribution of sampling sites during the first phase of the soil gas survey for geothermal exploration in the northwestern sector of Cumbre Vieja volcano, La Palma (Canary Islands)

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SITES OF GEOTURISTIC INTEREST FROM 2021 TAJOGAITE ERUPTION (LA PALMA, SPAIN)

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Abstract

The Canary Islands (Spain) are an oceanic, subtropical, and active volcanic area located in the African Plate. In the past 500 years, sixteen historical eruptions were documented in Lanzarote, Tenerife, El Hierro, and La Palma. The latest eruption, the Tajogaite, occurred in 2021 in La Palma and the richness and diversity of the natural and cultural heritage associated with this eruption can be a valuable resource for attracting visitors and tourists (Dóniz-Páez *et al*., 2022, 2024a). The main aim of this work is to select sites of geotourist interest (SGIs) in order to create for in-person and virtual geo-itineraries. The methodology used is based on fieldwork during the years 2021 to 2024 and drone flight videos (DJI Mavic 2 Pro with camera Hasselblad) and photos taken during and after the eruption. Sixteen SGIs have been selected and studied. Eleven sites represent the geo-heritage of the Tajogaite eruption and six sites are related to the surrounding natural and rural landscapes (Dóniz-Páez *et al*., 2022, 2024a). SGIs in this study include the geoheritage of the Tajogaite volcano (scoria cones, hornitos, fissures, lapilli and ash fields, lava fields, lava deltas, lava tubes, lava channels, jameos, paleo-cliffs, gullies, slopes, sedimentary deposits, cliffs, beaches (Fig. 1) and natural (lava field and pine forest) and rural elements (traditional houses, stone walls, crops, and livestock). This study highlighted the rich and varied heritage associated with the eruptive event at Tajogaite and the current tourist demand that exists to visit the volcano along with its territorial impacts (Dóniz-Páez *et al*., 2024b). It is necessary to propose the creation of virtual or real geo-itineraries, taking advantage of the selected SGIs, to show the exceptional volcanic heritage created through this eruption. This development undoubtedly enriches the geotourism sector, not only in the area affected by the eruption but throughout the island of La Palma.

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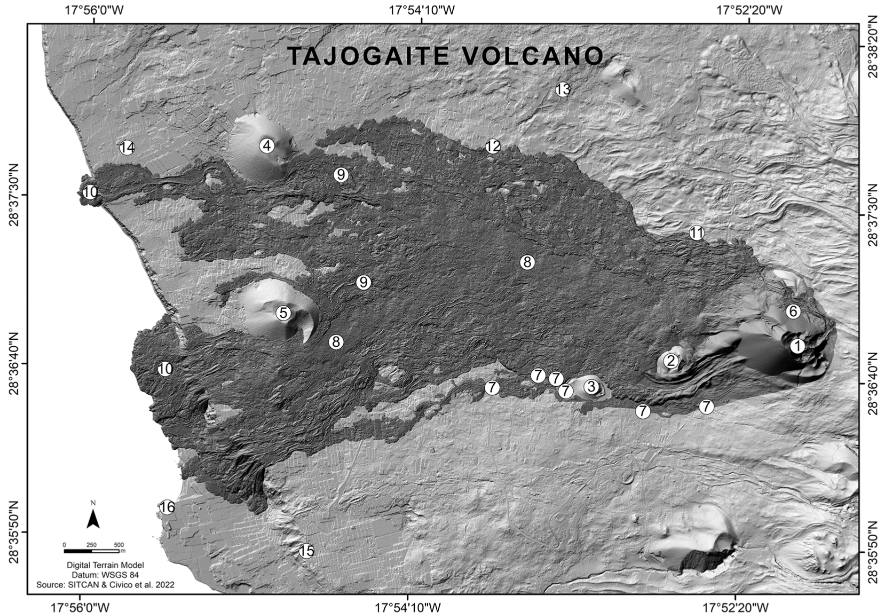

Fig. 1. Location of the SGIs associated to the Tajogaite volcano: 1-Tajogaite cone 2021. 2-Rajada Mountain. 3-Cogote Mountain. 4-La Laguna Mountain. 5-Todoque Mountain. 6-Hornitos 2021. 7-Fissures 2021. 8-Pahoehoe lavas 2021. 9-Aa lavas 2021. 10-Lava delta 2021. 11-Tacande viewpoint. 12-Campitos viewpoint. 13-Tajuya Church. 14-San Isidro viewpoint. 15-Hoya viewpoint. 16-Bombilla lighthouse. Source: IDE-Sitcan. Self-elaboration.

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SOIL AND SOIL-GAS SURVEYS FOR GEOTHERMAL EXPLORATION AT CUMBRE VIEJA VOLCANO (LA PALMA, CANARY ISLANDS, SPAIN)

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Abstract

The most common geochemical surveys conducted in known geothermal areas typically involve sampling of thermal waters and gases from natural surface discharges such as hot springs, fumaroles, and steam vents. However, in regions where such manifestations are absent or sparse, and where the spatial extent of the geothermal field is not well-defined, soil and soil-gas surveys become essential tools. These surveys provide critical information on subsurface gas migration patterns, helping to identify permeable zones, potential upflow areas, and regions of near-surface boiling. Moreover, they are highly complementary to geophysical surveys, particularly in complex volcanic terrains where interpretation of geophysical data alone can be limited by structural or topographic complexities. In this context, a soil and soil-gas geochemical survey was carried out across the Cumbre Vieja volcano (La Palma, Canary Islands), a volcanic region with no surface evidence of hydrothermal alteration or visible gas emissions. This work aimed to investigate the geothermal potential of the area using indirect indicators of subsurface fluid movement and degassing. The Cumbre Vieja soil and soil-gas geochemical survey corresponds encompassing 1,200 sampling sites over an area of 220 km^2, ~5.5 sites/km^2 (Fig. 1), in line with similar investigations across the Canarian archipelago (Padrón *et al*., 2013; Rodríguez *et al*., 2015a, 2015b, 2021). At each sampling location, in-situ measurements of soil CO_2 efflux and 222Rn activity were taken. Soil gas samples were collected at a depth of 40 cm for laboratory analyses, including chemical composition (e.g., He, H_2, CH_4, CO_2) and isotopic characterization (δ13C-CO_2). Concurrently, soil samples

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were collected from the base of the B-horizon (30-50 cm), dried, sieved to 80 mesh, and leached to quantify volatile elements (Hg0, As, B, NH_3) retained in the organic-clay fraction. This study presents preliminary results that highlight the utility of soil and soil-gas surveys in identifying geothermal signatures in areas lacking surface indicators. These findings contribute to the broader effort of geothermal resource assessment in volcanic island settings.

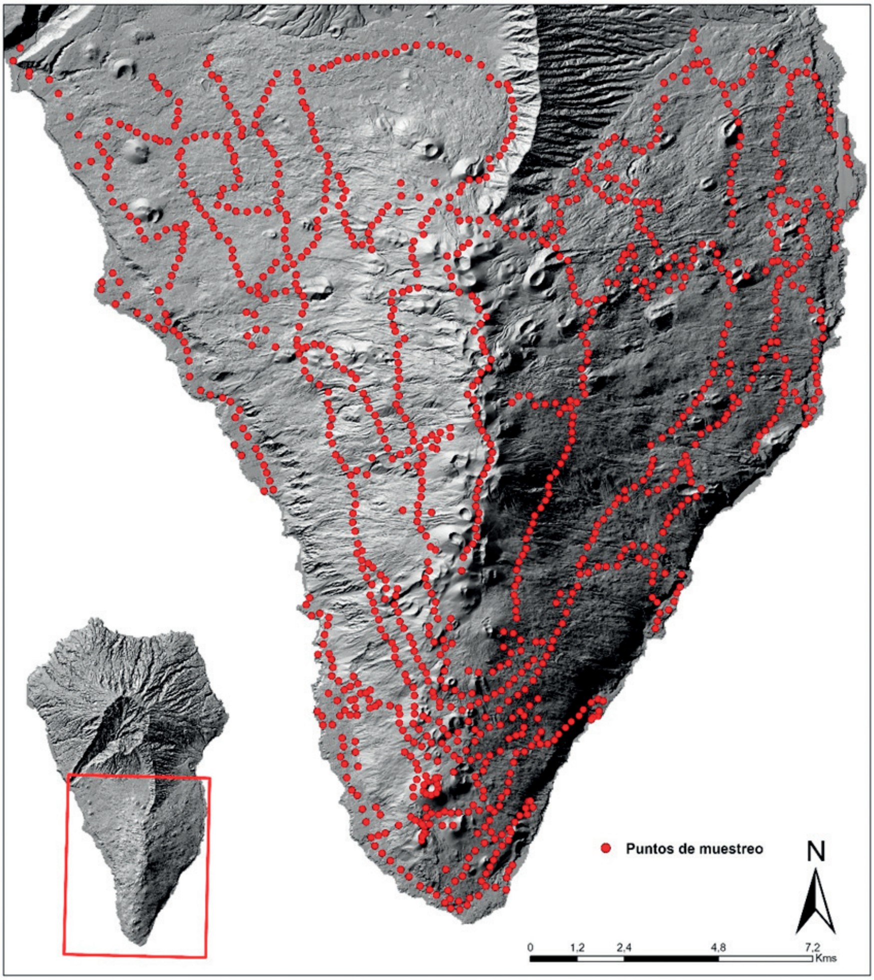

Fig. 1. Sampling site distribution of the soil chemistry and soil gas physical-chemistry survey for geothermal exploration at Cumbre Vieja volcano, La Palma (Canary Islands) 1.200 sites · 220 km^2 · 5,5 sites/km^2

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INHABITING THE VOLCANIC COASTLINE. STATIONS FOR PROJECTING THE LANDSCAPE OF THE TAJOGAITE LAVA DELTA

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Abstract

«This new punctum, which is no longer of form but of intensity, is Time [...] its pure representation.» Roland Barthes in Camera Lucida. The new lava delta resulting from the Tajogaite eruption is an exceptional event for the comprehensive understanding of the island of La Palma as part of a constellation of unique island geoanthropological features. The coastline, with its rich history and cultural significance, offers a unique perspective on the special bond between the people and the sea. This new layer of volcanic seascape offers the possibility of approaching and inhabiting the delta as a witness to comprehensible and measurable geological time. To inhabit a place is to gradually conquer it and participate in the evolution of the territory. By interfering with existing reality, we transform it to a greater or lesser degree; we domesticate it. By strengthening our ties with the surrounding space, we become part of the life cycles of the inhabited, colonised landscape. This work explores essential formal structures that improve the experience of perceiving the qualities of the delta. It proposes inhabiting the place through architecture situated between the extreme environment and the person contemplating it. This approach enhances the meaning of the place through careful actions, fostering frameworks and horizons for understanding, celebrating uniqueness and creating spaces for shared experiences. The architecture is immersed in an extreme and demanding landscape, allowing it to be conquered while preserving it. This living architecture of the coastal landscape is heritage worthy of continued updating. Thanks to the project, we become aware of temporality as a spatial presence. The landscape then takes on meaning. The project identifies potential, recognises unique qualities, and finds ways to make them more visible. Interventions of this nature offer an opportunity for social development in La Palma (VVAA, 2011). Both tourists and residents can enjoy the emo-

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tional benefits of living on the volcanic coastline, which is designed to promote human well-being and environmental awareness of the area's fragile balance between materials and energies. A subjective, existential and symbolic enjoyment of man with his environment, where senses, thoughts and emotions are refined with respect to the place.

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ABORA EXPEDITIONS: REGENERATIVE TOURISM AND ECOLOGICAL RESTORATION IN POST-ERUPTION VOLCANIC LANSDCAPES

DESIRE IZQUIERDO*

ABSTRACT

Abora Expeditions is a pioneering initiative in the Canary Islands that redefines tourism as a force for regeneration (Fig. 1). Rooted in the principles of ecological restoration, scientific collaboration and cultural resilience, it offers transformative expeditions where visitors become active participants in the recovery of vulnerable territories. Unlike conventional tourism models that often extract more than they give back, Abora designs experiences where science, nature, and local identity converge, creating measurable positive impact. Each expedition is co-developed with local communities and scientific partners, combining storytelling, citizen science, and field-based activities that connect travellers with the ecological and cultural processes shaping island landscapes (Iniciativa Global de Turismo Regenerativo, 2025). The Tajogaite volcano —a site marked by destruction but also by resilience (INVOLCAN, 2025)— is now a central axis of Abora's work. Its recent eruption created a mosaic of new geological formations, redefined forest boundaries, and initiated complex processes of marine-terrestrial recolonization. Abora leverages this unique setting as a living laboratory, offering activities such as ecological monitoring, volcanic ecology workshops, and field expeditions designed to interpret and actively support the regeneration of post-eruption ecosystems (PLOCAN, 2025). Abora's regenerative model includes reinvestment of expedition income into local restoration projects, supporting native biodiversity, sustainable livelihoods, and the circular economy (Gobierno de Canarias, 2025) Its approach is grounded in collaboration with local scientists, guides, artists, and elders —ensuring that knowledge exchange is mutual and that the impact extends beyond the visit. Strategic pillars include:

- Citizen science in disturbed and recovering ecosystems.
- Revalorization of geocultural heritage through immersive learning.

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- Integration of Blue-Green Tourism in coastal and terrestrial zones.
- Strengthening local-global alliances for long-term stewardship.

Tajogaite is reframed not as a wound, but as an open classroom and a catalyst for innovation in tourism and conservation. Abora Expeditions presents a replicable, scalable model of regenerative travel, offering a new paradigm where exploration becomes restoration, and every journey becomes part of a shared effort to heal and reimagine island territories. (UN Tourism, 2025)

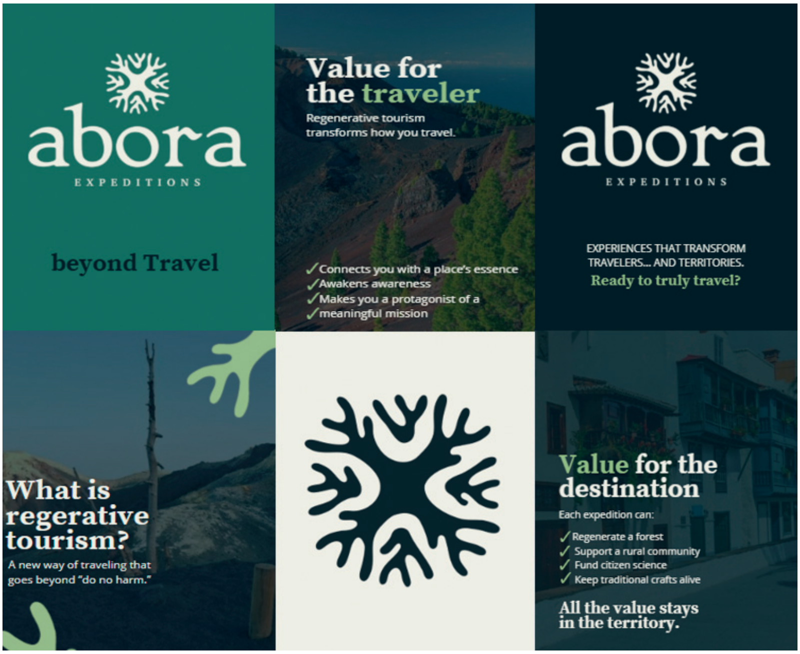

Fig. 1. Abora Expeditions

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Topic 14

Social-community framework

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LISTENING WHILE THE VOLCANO ROARS

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Abstract

A volcanic eruption always attracts a large number of people with scientific interests in its many manifestations, a constellation of disciplines that meticulously unravel each of its components. Tajogaite has been —and continues to be— a paradigmatic case, and even, for many analysts, a model of science working together to manage an episode that is enormously complex due to its multiple effects. The terrain was already being monitored and tracked long before the volcano erupted on September 19, 2021, and then there was a notable influx of research structures. The emergency and the rush to help those affected also came immediately, always with the anxiety of the extent of the damage. Who listened to the people involved at that time? Apart from the volcano, was attention paid to the thoughts and discourses of the people of the Valley? Perhaps the least known aspect of the volcanic process on La Palma in terms of its community impact (Zapata, 2023) is the early implementation of structured listening to investigate the situation of the people who were experiencing something unprecedented for a large part of the island's population, thus encouraging their conscious participation in the process of reflection and decision-making linked to the volcanic eruption and its effects, as has been recommended internationally for quite some time (UNDP, 2011; United Nations General Assembly, 2014). Now, four years later, it is a good time to analyze the initiative and reflect on its relevance and contributions, considering, moreover, that it was key in some of the decisions made since then, as well as influencing the effort to promote a strategic planning initiative with a view to defining new settlements once the eruption was over (González *et al.*, 2024). This paper aims to highlight the key aspects of this social hearing process (Fig. 1), which consisted of two consecutive actions that revealed the prevailing discourses of the Aridane Valley community (Zapata & Del Rosario, 2023), which has undergone one of the greatest transformations in the history of the island of La Palma.

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Fig. 1. Advertising for the training process to involve the citizens of the Aridane Valley in conducting the social hearing and holding a collective colloquium in Los Llanos de Aridane

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UNDERSTANDING ATTACHMENT TO PLACE IN THE CONTEXT OF THE 2021 VOLCÁN DE TAJOGAITE ERUPTION CRISIS AND RECOVERY, LA PALMA

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Abstract

Attachment to place describes the relationship between a person and a specific place, including, but not limited to, the 'interplay of affect and emotions, knowledge and beliefs, and behaviors and actions in reference to places' (Low & Altman, 1992). Previous research on place attachment and disasters has focused on its influence on risk perception, evacuation, relocation, and its re-establishment post-disaster (see Ruiz & Hernández, 2014; Jamali & Nejat, 2016; Domingues *et al*., 2021; Bukvic *et al*., 2022). However, consideration of place attachment in hazard management has hitherto been little studied. The 2021 eruption of Volcán de Tajogaite, La Palma, significantly damaged urban areas and some residents still wait to be rehoused or allowed to return to their homes. This study adopted a qualitative methodology with fifteen interviews collected during April and May 2023. Interview data was supplemented by thematic analysis of the PEVOLCA (2018) volcanic emergency management plan, to understand how place attachment was accommodated in the management of the crisis, to what extent it affected resident experience of the eruption, and how it has changed because of the eruption. Here I show that: (i) place attachment, particularly to the home, was largely neglected during the emergency evacuations yet strongly influenced resident experiences, and (ii) attachment to place is being re-established amongst the communities in temporary housing, encouraging people to stay on the island. Drawing on these findings, I make recommendations for 'place-based' hazard management with broad relevance to volcanic islands.

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FAITH IN THE FIRE: CHRISTIAN IMAGINARIES AND THE 2021 VOLCÁN DE TAJOGAITE ERUPTION

Rosie Frances Rice, Clive Oppenheimer*

Abstract

The relationship between volcanic eruptions and religion is long established; for example, throughout history volcanic disasters have long been described as 'Acts of God' or attributed to divine punishment. Nevertheless, there is still much to learn about the ways in which faith can shape individual and community resilience to such events. This interdisciplinary study brings together literature from Volcanology, and Practical and Trauma Theologies to understand the experience of Catholic communities in La Palma during the 2021 Tajogaite eruption, and their subsequent recovery. A qualitative methodology was adopted, with 20 interviews conducted in February 2025. Initial results indicate: i) faith shaped experience of the eruption to a large extent and ii) faith and faith communities have positively influenced recovery from the 2021 eruption and resilience. In summary, this research documents the lived experience of Catholic residents affected by the eruption and highlights how faith-based responses to disaster can offer valuable insights for enhancing resilience, even in secular contexts.

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HOW CAN PYROCLASTIC MATERIALS FROM THE TAJOGAITE ERUPTION AFFECT BANANA CROPS?

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ABSTRACT

Lava flows emitted by the Tajogaite volcanic eruption in 2021 devastated approximately 1,200 ha, including about 370 ha of cultivated surface (Gobierno de España, 2022) in one of the most productive banana plantations of the Canary Islands. That eruption emitted an estimated volume of 23,000,000 m^3 of pyroclastic ashes and more coarse-grained particles (Shatto *et al*., 2024), whose unique physical and chemical properties have highlighted their potential use in agriculture (Troll *et al*., 2017). These pyroclasts can be catalogued as growing medium, following legal requirements (RD 865/2010). However, nutrient leaching from these tephric materials presents a challenge and requires comprehensive studies, considering crop requirements and water management. Around 40 % of La Palma's cultivated land is dedicated to banana production, making it the second-largest producer in the Canaries (ISTAC). Considering the role of banana plantations within the island's economy, environment, and social context, this study carried out a laboratory experiment to evaluate leachates from lapilli (64-2 mm) and volcanic ash (<2 mm), under irrigation conditions relative to the nutritional requirements of banana plants. For this purpose, seven cumulative samples were taken from Novem-

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ber 2021 to July 2022 in four different locations (El Jable, San Nicolás, Paraíso, and Tacande). After measuring the particle size, bulk density, and saturated hydraulic conductivity, the crystal columns (with a volume of 363 cm^3) were packed using the same bulk density as the *in situ* samples. Synthetic water, like that of the closest aquifer, was applied, simulating local irrigation management practices, and soil leachates were collected for analysis. To characterise these leachates, the concentrations of K, Na, Ca, Mg, B, Cl, F, SO_4, NO_3, and SiO_2 were determined.

The results show that the pyroclastic material emitted during the eruption has the capacity to retain K, Mg, NO_3, and SiO_2 and to contribute Cl and F to the soil solution. Other nutrients, such as Ca, Na, SO_4, and B, do not exhibit a consistent pattern. Thus, the nutrients added to the soil are insufficient to guarantee normal crop development, and the retention of macronutrients must be considered in future fertilization programs.

Aknowledgements

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EXPLORING PAST HUMAN RESPONSES TO VOLCANIC EVENTS IN THE CANARY ISLANDS THROUGH TRADITIONAL MEDIA USING TOPIC AND SENTIMENT ANALYSIS

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Carmen Solana, Pablo González

Abstract

Effective risk communication is essential for strengthening community preparedness and responses to volcanic hazards. There has been an unprecedented growth in the use of personal communication technologies in the last decade, including the use of social media platforms to assess public responses and perceived impacts during geophysical hazards. Social media platforms offer real-time insights into community needs, emotional reactions, and the effectiveness of official communications, making them a valuable tool for hazard monitoring and response. The recent 2021 Cumbre-Vieja eruption on La Palma has highlighted the opportunities offered by media sharing platforms based on the abundance of information disseminated by individuals and organisations (e.g. IGEO (CSIC-UCM) and Guardia Civil). However, much of the existing literature remains divided between qualitative approaches that explore narratives and experiences, and quantitative analyses that track trends or sentiment, with relatively few studies integrating both to offer a more comprehensive view of communication practices. This study addresses this gap through analysis of historical newspapers using natural language processing techniques, specifically sentiment analysis and topic modelling to trace how reporting on volcanism in the Canary Islands has evolved over time. Tracing shifts in volcanic hazard communication, highlighting changes in both language and reporting practices. It aims to inform the development of evidence-based risk communication strategies for the Canary Islands and comparable volcanic regions. This study highlights how the inherent infrequent nature of volcanic eruptions offers a rare opportunity to reflect and improve our approaches to risk communication and reduction by incorporating new and emerging technologies and platforms. These insights are crucial for developing targeted, evidence based risk communication strategies.

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THE DESIGN PRINCIPLES OF OPEN-ACCESS SCIENCE: VOLCANOSTORIES 4 YEARS IN

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ABSTRACT

Science communication is an interdisciplinary field of study that aims to learn the best ways to communicate complex information to the general public. This field emerged from the need to mitigate the systemic inaccessibility of academia and journal articles and to democratise science. VolcanoStories utilises a participatory, decentralised, accessible model of science communication. Drawing upon literature such as Lorke *et al*. (2024), we emphasise the limitations of the 'deficit model', where academics dictate science and what science is important to the community. VolcanoStories opens a dialogue with residents and stakeholders to prioritise their scientific curiosity and concerns, thus improving the reception of science. Most of the public have not attended university, resulting in a lack of skills to navigate the accessibility barriers of readability, paywalls, and hyperspecialisation of information (or 'siloing'). This can lead to misconceptions about science, fostering distrust in scientific findings and scepticism about scientists' expertise (König *et al.*, 2025). Thus, the scientific community must expand to create new pathways to communicate science and remediate the varying degrees of access to truth and scientific knowledge. By utilising GeoTenerife's 48,000 followers across Instagram, X, BlueSky, and TikTok through polls and questions aimed at resident engagement, GeoTenerife has proven a model of resident-science dialogue. VolcanoStories is a user-focused interface inviting the public into the sphere of research. The value of this platform in society is to provide resources designed upon literature review of effective science communication and citizen science; combining fieldwork with creative storytelling, utilising the 'bloggability' of the science content, non-traditional outputs published, shared on social media for discussion. By portraying science holistically and not 'siloed' into particular niches, which are abstract to the common person, we

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can bring together experts from various sciences to collaborate on innovative resources. For example, our interactive timeline illustrates the geological, political, and social evolution of the Tajogaite eruptive period. VolcanoStories sets a new benchmark for open-access science communication, blending fieldwork, desk-based research with accessible storytelling. It's free, multimedia resources, and design principles demonstrate a method of democratising science.

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ENGAGING COMMUNITIES IN VOLCANIC RISK AWARENESS: AN EDUCATIONAL INITIATIVE IN LA PALMA (CANARY ISLANDS)

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Abstract

Living in La Palma means coexisting with an active volcanic landscape, where the island's environment, history, and daily life are deeply shaped by past eruptions. The southern region is dominated by the Cumbre Vieja volcano, responsible for 8 of the 18 historical eruptions recorded in the Canary Islands (Romero-Ruiz *et al*., 2024). The most recent eruptions —San Juan (1949), Teneguía (1971), and Tajogaite (2021)— have all occurred within the last 60 years, highlighting the volcano's ongoing activity. Despite this well-documented history, the 2021 Tajogaite eruption revealed a significant social disconnect from the island's collective volcanic memory. Many younger residents have grown up without a clear understanding of volcanic hazards and risks. As a result, much of the population faced the eruption without adequate preparation, affecting both individual and community responses during the crisis. This gap in volcanic risk awareness underlines the urgent need for effective educational programs to improve public understanding and resilience. In response, scientists from ITER and INVOLCAN (Instituto Volcanológico de Canarias) have been promoting the program «Canarias: A Volcanic Window in the Atlantic» since 2008 (Rodríguez *et al*., 2016). The initiative has been implemented across all municipalities of La Palma as part of a broader strategy to strengthen the island's risk culture. The program includes a range of educational tools —outreach talks, engaging videos, and interactive volcanic-themed trivia games— designed to enhance knowledge of volcanic phenomena and promote a proactive attitude toward risk

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reduction (Fig. 1). The aim of this program extends beyond sharing information: fostering critical thinking, encouraging self-directed learning, and stimulating active citizen participation in disaster preparedness. These efforts align with Spain's Basic Guidelines for Civil Protection Planning against Volcanic Risk and contribute directly to the goals of the Special Civil Protection and Emergency Response Plan for Volcanic Risk in the Canary Islands (PEVOLCA). As such, this initiative plays a vital role in volcanic risk management and community resilience on La Palma.

Fig. 1. INVOLCAN delivering the educational talk «Canarias: A Volcanic Window in the Atlantic» in the municipality of Breña Baja.

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THE VOLKIS: AN ADVENTURE IN LA PALMA

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ABSTRACT

Earth Sciences often receive less attention than other basic sciences, particularly among teenagers. Early childhood interests significantly shape future curiosity, and fostering enthusiasm for understanding our planet and environment during formative years is essential. To address this, developing engaging educational tools has become a pressing challenge. Comics, graphic novels, and illustrated books have proven increasingly effective in introducing scientific concepts to children and teens. One such initiative is *The Volkis*, a series of illustrated books and creative educational resources designed to teach young audiences about volcanoes, their origin, dynamics, impacts, and benefits. Following the success of the first volume, *The Volkis: A Volcanic Adventure* (Schamuells *et al*., 2023, 2025), the series now continues with a new title: *The Volkis: An Adventure in La Palma* (Fig. 1), inspired by the 2021 eruption of La Palma (Canary Islands, Spain). In this new adventure, the Volkis, a secret club of volcano enthusiasts, travel to La Palma to investigate the eruption and its aftermath. Along the way, readers are invited to explore the fascinating world of volcanoes through engaging illustrations, curious facts, and clear, accessible explanations. The book addresses where, how, and why volcanoes form, the precursory signals that may precede an eruption, volcanic hazards, and other fundamental aspects of volcanic activity. Focusing specifically on the La Palma 2021 eruption, the book highlights the scientific, environmental, and human dimensions of this

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recent volcanic event. It also contains a short description of the eruptive history of the Canary Islands, the geological evolution of La Palma and its most recent eruptions, among many other interesting chapters.

Fig. 1. Cover of the book *The Volkis: An Adventure in La Palma* (top left). Examples of two pages from the book are also shown: one illustrating the precursory signals of volcanic eruptions (top right), and another focusing on the hazards associated with the 2021 La Palma eruption (bottom)

Richly illustrated and designed to engage both readers and educators, the book combines storytelling with scientific knowledge. Supported by the interactive website https://descubrelosvolcanes.es, which offers videos, hands-on experiments, and printable activities, *The Volkis* aims to make science education entertaining, accessible, and interactive, fostering learning not only for children but also for the adults accompanying them.

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ADDRESSING COMMUNICATION GAPS IN LA PALMA'S ERUPTION AND RECONSTRUCTION TO STRENGTHEN VOLCANIC RESILIENCE

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Ajay Wynne Jones[1], José Marrero[2], Isabel Queay[1]

Abstract

The 2021 eruption of La Palma's Cumbre Vieja volcano marked a pivotal moment in Canary Islands crisis communication. The eruption occurred after nearly five decades of quiescence in a populated area and garnered unprecedented media attention. Melo López *et al*. (2023) analysed GeoTenerife's interviews with residents, politicians, emergency managers, and media professionals to ascertain how emergency communications impacted residents' volcanic resilience. We found systemic communication gaps that resulted in uncertainty due to the lack of easily available, reliable information. We made recommendations to the Public Communication strategy: improve the socio-scientific relationship, integrating psychosocial experts into emergency management, and a dedicated sci-comm unit bridging the information gap between volcanologists and the public. These recommendations complement the critiques of the Advicing and Scientific Communication Strategy of PEVOLCA by Marrero *et al*. (2015) post-El Hierro's 2011 eruption. Our current work aims to address communication deficits before the next eruption in the Canary Islands. VolcanoStories is an open-access, user-focused multimedia interface with accessible volcanic resilience resources. Dedicated science communicators review journals and news articles, databases, and perform novel research to formulate new accessible materials. We provide spaces for public and scientific engagement through social media polls and open discussions, hosting private screenings of our Lava Bombs docuseries for feedback from those we aim to give a voice, answering queries and concerns. GeoIntern students and staff perform annual assessments of Canary Island emergency pro-

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tocols to assess volcanic resilience through resident and tourist surveys and stakeholder interviews. The 2024 Vilaflor and 2025 Garachico resident surveys identify information deficit from official sources and a lack of trust in public officials as key barriers (Jones *et al.*, 2025).

We are working with IGN and the Santa Cruz Press Association to develop an ethics protocol for the press covering volcanic emergencies following a workshop at COV 2024, a communication event at the Etna Observatory, and a short survey of the Tenerife press. As featured in our documentary Lava Bombs 2, the lack of reliable syn and post-eruption information was the biggest concern for residents. It's essential to address systemic communication gaps to re-establish trust and better support affected communities.

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CANARY ISLANDS STRATEGY FOR VOLCANIC RISK REDUCTION: FACING A SOCIAL CHALLENGE

Óscar Rodríguez[1], Javier Páez-Padilla[1], Nemesio M. Pérez[1,2], Luca D'Auria[1,2], Pedro A. Hernández[1,2]

Abstract

The Canary Islands is an active volcanic region as evidenced by hundreds of eruptions over the past 10,000 years. In the last 600 years, 18 historical eruptions have been documented across La Palma, Tenerife, Lanzarote, and El Hierro (Romero-Ruiz *et al*., 2024). Meanwhile, human exposure to volcanic hazards has grown significantly due to rising population and expanding infrastructure. In this context, a comprehensive volcanic risk reduction strategy is essential to protect lives, infrastructure, and the economy. Such a strategy must enhance early warning systems, improve emergency response capabilities, and promote public awareness and inter-institutional coordination. The 2021 Tajogaite eruption should mark a turning point for volcanic risk management in the Canary Islands, despite major advances over the past 25 years. This new direction should be implemented through a Canary Islands Strategy for Volcanic Risk Reduction; an operational framework designed to effectively address and respond to the unique challenges posed by volcanic risk in the region. This strategy should act as a driving and coordinating force across various sectoral policies, while also promoting greater awareness and preparedness among citizens, businesses, and public institutions. It will rest on three core pillars: Citizen Participation, Scientific Knowledge, and Broad Consensus (Pérez *et al*., 2022; 2023; Páez-Padilla *et al*., 2025). To strengthen citizen participation, twelve specialized workshops on volcanic risk management will be conducted (Fig. 1), involving a wide range of social sectors and promoting shared responsibility in risk reduction. INVOLCAN leads the scientific outreach, informing participants about volcanic hazards, regional volcanic features, and international recommendations from organizations such as IAVCEI and UNESCO. Each workshop employs SWOT analysis —a strategic tool used to

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identify strengths, weaknesses, opportunities, and threats— facilitating open dialogue and ensuring only consensus-based conclusions are recorded. Each workshop will help diagnose the current situation and define strategic actions for reducing volcanic risk through inclusive, collaborative processes.

Fig. 1. Participants of the workshop #02: Public and Political Representatives Sector.

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A UNIQUE AND UNPRECEDENTED SCIENTIFIC COLLABORATIVE RESPONSE TO THE TAJOGAITE ERUPTION (LA PALMA, CANARY ISLANDS)

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Abstract

The 2021 Tajogaite eruption holds historical significance as the most destructive volcanic eruption affecting Europe in the past 75 years. Despite the significant losses, this eruption brought valuable opportunities for scientific research. Furthermore, this crisis presented a remarkable opportunity to highlight the indispensable role of scientific and technical collaboration during volcanic emergencies (Rodríguez *et al.*, 2024). During the Tajogaite eruption, Instituto Volcanológico de Canarias (INVOLCAN) spearheaded efforts to engage a myriad of national and international scientific institutions, thereby optimising the scientific management of the unfolding eruption. A total of 93 dedicated researchers, comprising 14 from Spain and 79 from abroad, represented 42 scientific institutions, including seven Spanish and 35 foreign entities. Their collaborative efforts spanned various domains, encompassing the analysis of gas geochemistry, geophysics, and petrology. The experience gained through the management of this vast collaborative effort can be summarised into five points:

1. Scientific collaboration at the national and international levels is fundamental for a better understanding of volcanic processes during an emergency, providing helpful information for crisis management and short-term forecasting of volcanic dynamics.

2. Regulation of access to the eruptive area is essential. However, since scientists are usually more expert than civil protection authorities on volcanic hazards, they should be part of the decision process to avoid unnecessary and suffocating restrictions.

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3. Data collected during a volcanic emergency should be readily available to civil protection authorities, even if not made available to the general public or the general scientific community.

4. Each team's activities on the field or in the laboratory should be publicly known to the rest of the scientific community to avoid duplication of efforts and promote fruitful collaborations.

5. Data and samples sharing policy among different teams should be clearly defined «a priori» to avoid misunderstandings and «conflicts».

In conclusion, we can boldly state that the Tajogaite eruption marked a historic milestone as the first instance of such extensive scientific collaboration during a volcanic event of this scale. This exemplifies a paradigm shift in scientific management strategies for future volcanic crises, illustrating the potential for enhanced preparedness and response through international cooperation and knowledge sharing.

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SOCIAL AND ECONOMIC RECONSTRUCTION IN PUERTO NAOS AND LA BOMBILLA DUE TO THE TAJOGAITE VOLCANO

Héctor Izquierdo Triana

Abstract

Both Puerto Naos and La Bombilla are affected by intense volcanic-hydrothermal degassing of CO_2. Sánchez *et al*. (2023) point out that it can infiltrate buildings through hydraulic and electrical conduits, as well as due to their vertical structural design characteristics, affecting around 1,350 homes and a hotel with 1,100 rooms as a materialization of volcanic hazards (Sanz *et al*., 2023). While measures were being taken to recover the homes, the following package of measures was carried out (Chase *et al*., 2009) which started with a review of procedures (Ballesté & Nogueras, 2018) temporary employment regulation files, temporary cessation of activity for the self-employed, bonuses on social security contributions, income compensation based on pre-Covid-19 benefits, rents for those affected who had their first home in those neighbourhoods, exemption from the property tax and the economic activities tax and moratoriums on mortgages and agricultural loans, among other measures. The objective was to create a social shield that would protect those affected and reduce their income losses and expenses while the situation lasted. The Budget and the economic costs are explained in this presentation and the consequences of these actions, which are allowing for the gradual and safe recovery of homes, have led to a series of economic and social improvements in employment, the mental health of those affected by a situation of uncertainty in their life scenario, compensation, recovery of activity and income generation, hotel investment, social security, tax matters and family reunification. The lessons learned from the Tajogaite volcano (Pérez, 2021) will not only serve to improve procedures in future eruptions in the Canary Islands, but could also serve as an experience for CO_2 management in highly polluted environments such as large metropolitan cities.

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CRITICAL DECISIONS AND CONSEQUENCES: THE LACK OF PREVENTIVE EVACUATION IN THE 2021 ERUPTION ON LA PALMA

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ABSTRACT

The Tajogaite (Cumbre Vieja) volcanic eruption on La Palma, which began on 19 September 2021, caused one of the most significant geological emergencies in recent European history, forcing the evacuation of more than 7,000 people and destroying over a thousand homes. However, beyond the absence of direct victims as an official positive outcome, there remains a profound social debate about the management of the emergency in its early hours, especially regarding the decision to keep the alert level at yellow until the very beginning of the eruption. This paper, the result of the work of the Tierra Bonita Association (2023), unravels how, despite the availability of scientific information and unequivocal signs of the imminent nature of the eruption, the authorities did not activate a generalised preventive evacuation. Maintaining the yellow alert, instead of raising it to orange, prevented the early evacuation of the most exposed population and the orderly protection of essential goods, pets and vulnerable people. Testimonies collected from scientists who are members of the PEVOLCA Scientific Committee reveal that the imminence of the eruption was known several hours in advance, but the administrative decision remained unchanged. This forced hasty evacuations in situations of real danger and with little information for those affected. The investigation highlights the lack of effective protocols for the evacuation of people with reduced mobility and the absence of clear systems for communication and citizen participation in the process. In addition, it highlights the refusal to make public the minutes and deliberations of scientific and political management bodies, hindering transparency and institutional learning. In conclusion, the experience of La Palma highlights the urgent need to review volcanic response protocols under the precautionary principle, prioritising anticipation and transparency as pillars of citizen protection in the face of natural emergencies.

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