REPORT

VOLCANICA

Towards rapid integrated data acquisition and management during a volcanic crisis: the 2021 Tajogaite eruption of Cumbre Vieja (La Palma, Canary Islands)

Fátima Rodríguez*[α,β], Beverley Coldwell[α,γ], Alba Martín-Lorenzo[α], Daniele Andronico[δ], Costanza Bonadonna[ε], Elisabetta Del Bello[ζ], Marco Pistolesi[η], Jacopo Taddeucci[ζ], Sebastien Biass[ε], Jorge E. Romero[θ,ι], Marija Voloschina[η], Piergiorgio Scarlato[ζ], William Hernández[α], Luca D'Auria[α,γ], and Nemesio M. Pérez[α,γ]

[α] Instituto Volcanológico de Canarias (INVOLCAN), 38400, Puerto de la Cruz, Tenerife, Canary Islands, Spain.
[β] Gestión y Planeamiento Territorial y Medioambiental, S.A. (GESPLAN), 38005, Santa Cruz de Tenerife, Tenerife, Canary Islands, Spain.
[γ] Environmental Research Division, Instituto Tecnológico y de Energías Renovables (ITER), 38611, Granadilla de Abona, Tenerife, Canary Islands, Spain.
[δ] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Osservatorio Etneo, Sezione di Catania, 95125 Catania, Italy.
[ε] Department of Earth Sciences, University of Geneva, Geneva, Switzerland.
[ζ] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Sezione Roma 1, 00143 Roma, Italy.
[η] Department of Earth Sciences, University of Pisa, Pisa, Italy.
[θ] Department of Earth and Environmental Sciences, University of Manchester, Manchester, United Kingdom.
[ι] Instituto de Ciencias de la Ingeniería, Universidad de O'Higgins, Rancagua, Chile.

Abstract

The 2021 eruption of Cumbre Vieja in La Palma (Canary Islands) provided a unique opportunity for the international scientific community to collaborate and provide multidisciplinary data to civil protection authorities during a rapidly evolving volcanic crisis. Here we present data gathered and analysed as a package during the eruption, with a focus on a stratigraphic framework for tephra deposits. This consensus effort across multiple research teams was coordinated by the Instituto Volcanológico de Canarias (INVOLCAN). Teams were deployed strategically to compile comprehensive tephra stratigraphy through field mapping (depending on plume direction records and real-time tephra-fall observations). Tephra production was nearly continuous during the eruption, and the resulting stratigraphic framework, chronology, and distribution form a robust link between temporally resolved observations of eruption style, plume dynamics, changing chemistry of volcanic products, and geophysical records registered during this highly accessible yet destructive eruption. This article is focused on the scientific coordination effort and on the value that collaborative data streams had during the crisis (for the volcano emergency response teams), as well as on the processes that contributed to the creation of these successful and multidisciplinary data sets.

Resumen

La erupción de Cumbre Vieja en La Palma (Islas Canarias) de 2021 brindó una oportunidad única de utilizar el conocimiento científico internacional para proporcionar datos multidisciplinares a las autoridades de protección civil durante una crisis volcánica que evolucionaba rápidamente. Aquí presentamos datos recopilados y analizados durante la erupción, con énfasis en el marco estratigráfico de los depósitos de tefra. Este esfuerzo de consenso entre múltiples equipos de investigación fue coordinado por el Instituto Volcanológico de Canarias (INVOLCAN). Se desplegaron estratégicamente equipos de respuesta para llevar a cabo mapeos de campo de estratigrafía de tefra (según la dirección del penacho volcánico y las observaciones de caída de tefra en tiempo real). La producción de tefra fue casi continua durante la erupción, y el marco estratigráfico, la cronología y la distribución resultantes forman un vínculo sólido entre algunas observaciones como el estilo de la erupción, la dinámica del penacho, la química cambiante de los productos volcánicos y los datos geofísicos que se registraron durante esta erupción, tan altamente accesible como destructiva. Este artículo aborda el esfuerzo de coordinación científica y el valor que tuvo la transferencia de datos durante la crisis (para los equipos de respuesta a la emergencia volcánica), así como en los procesos que contribuyeron a la creación de estos conjuntos de datos multidisciplinares.

Keywords: Tajogaite; Tephra stratigraphy; Cumbre Vieja 2021; Volcanic emergency management; Institutional collaboration.

1 Introduction

The eruption of Cumbre Vieja volcano (La Palma, Canary Islands, Spain), which occurred between September 19 and December 13, 2021, took place 50 years after the last subaerial eruption of this system (Teneguía, 1971). This eruption lasted for 85 days, marking it as the longest of all historic eruptions on La Palma. It was a fissure-type eruption, creating a multi-vent cone that produced approximately 217.4 ± 6.6 million cubic meters of lava over an area of ~12 km^2 [Civico et al. 2022a; b], along with ~20 million cubic meters of tephra [Bonadonna et al. 2022]. Ash from the eruption reached other Canary Islands, including Tenerife and Gran Canaria, up to

* fatima.rguez83@gmail.com

Submitted: 2022-12-01 | Accepted: 2024-07-24 | Published: 2024-12-05

Editor: H E Gaunt | Typesetter: C Harnett

200 km away. The new volcanic edifice was subsequently named “Tajogaite.”

The eruptive products from Tajogaite constitute the largest deposit footprint among all historic eruptions on the island. This intense Strombolian eruption, rated VEI 3, emitted significant quantities of volcanic gases. An estimated 28 ± 14 Mt of CO_2 was released during the 2021 eruption [Burton et al. 2023], and the total SO_2 discharge during the eruption is estimated to have been 2.4 ± 0.4 Mt [Dayton et al. 2024]. Due to the extensive SO_2 emissions and the severe damage from lava and tephra, this event is considered the most significant European eruption since Vesuvius in 1944. It caused extensive destruction, burying 2800 buildings and 1000 hectares of farmland and plantations under lava and tephra deposits [Carracedo et al. 2022] and displacing hundreds of families.

2 Scientific response

The Tajogaite eruption represented a challenge from a civil protection point of view and a turning point in the research management of volcanic crises in the Canary Islands. Continuous lava emission, volcanic tremor (including up to magnitude Ml 4.3 earthquakes), cone collapses, gas emission, and tephra deposition posed a potentially long-term threat to towns, transportation, and agricultural resources. The geographical accessibility of the Tajogaite eruption heralded an opportunity for the scientific community to provide real-time data and assessment of hazard across all disciplines. The Instituto Volcanológico de Canarias (INVOLCAN) used the potential of the international scientific community to provide multidisciplinary support and expertise to civil protection authorities. INVOLCAN coordinated a network of 241 researchers (62 from Spain and 179 from other countries) across 79 institutions (9 from Spain and 70 from other countries) from 20 different countries, both in the field and remotely. This coordination strategy is aligned with volcano observatory best practices (VOBP) [Pallister et al. 2019], and with the more recently published ‘Guidelines for volcano-observatory operations during crises’ [Lowenstern et al. 2022]. IAVCEI’s International Network for VOLcanology Collaboration (INVOLC) engagement protocols for international collaboration from 2022*, which promote the integration of multidisciplinary knowledge, data sharing, and effective hazard communication, among others, are also aligned with the ethos deployed during the Tajogaite eruption. IAVCEI-INVOLC’s Guidelines for Best-Engagement Protocols in International Collaboration establish an ideal collaboration model. We report here a novel implementation of this model in a real-time volcanic emergency in the Canary Islands, which enabled a more rapid, broader understanding of the physical processes, fed into forecasting of pre- and syn-eruption signals, and in turn could be fed into management decisions by the local crisis coordination committee (PEVOLCA—acronym for Plan de Emergencia VOLcánica en Canarias or Plan for Emergency Response due to volcanic risk in the Canary Islands). International scientific collaboration is important during volcanic emergencies because: (i) volcanic emergencies pose scientific questions requiring a wide range of expertise which is unlikely to be fulfilled entirely at a local level, (ii) summing up the know-how available at an international level allows for a better management of volcanic emergencies, and (iii) both volcanic emergency management and scientific benefit.

Cumbre Vieja is the most active volcano in the Canary Islands, with 8 eruptions over the last 600 years, and an inter-eruptive average of 75 years. Therefore, the population is not familiar with the activation of protocols for this type of natural phenomenon, given the relatively low frequency of volcanic eruptions. This criticality, combined with the rapid evolution of the anomalous seismic activity that culminated in the Tajogaite eruption after only a week, made the first moments of the eruption very challenging for emergency management. Moreover, it was the first time that PEVOLCA was put into practice for a subaerial eruption in the Canary Islands, with some emergency management protocols being established or needing to be modified spontaneously. This is important from the point of view of civil protection, but it is also reflected in the scientific strategy.

A 2.5 km exclusion radius around the emission centres was established for most of the eruption duration to minimise the risk of pyroclastic (tephra and bombs) impact and exposure to volcanic gases. Thus, previous authorization from PEVOLCA was necessary to access the restricted area. Concerning the protocol for researchers’ access, an authorization to enter and work within this area had to be requested beforehand under the auspices of a local institution. Researchers granted access under this authorization were required to report any relevant information to the management of the volcanic emergency. Data and information sharing was carried out under a formal statement: the data did not need to be shared with the whole community, but with the PEVOLCA scientific committee for the sole purpose of managing the volcanic emergency. An example of using scientific data streams for decision-making during the emergency was the first ash isopach map made during the eruption [Romero et al. 2022] and displayed in PEVOLCA daily meetings (see Section 4.3). Between this work and the estimation of the amount of tephra emitted, the overall VEI of the eruption was increased from 2 to 3, on November 20, 2021.

This contribution focuses on real-time tephra fallout linked to physical and geophysical changes observed during the eruption. Physical and geophysical parameters are treated more extensively in Bonadonna et al. [2022], D’Auria et al. [2022], Romero et al. [2022], and Taddeucci et al. [2023], as an example of these coordinated activities led by INVOLCAN during the eruption. We present data streams produced by individual collaborative teams throughout the crisis, which was compiled by INVOLCAN and presented to PEVOLCA in order to provide a picture of the broader impacts of the eruption as well as aid in forecasting eruption evolution. By bringing together expertise from different disciplines, INVOLCAN aimed to develop a representative real-time strategy to help manage the major evolving hazards of an urban eruption. Primary teams and roles involved in this contribution were as follows:

*https://involc.iavceivolcano.org/engagement-protocols-for-international-collaboration-2/

1. INVOLCAN, Canary Islands: scientific coordination, volcanic tremor, daily tephra station collection, and sample cataloguing.

2. INGV, Italy: tephra fallout measurements, tephra station implementation with INVOLCAN, tephra station collection, tephra isopach mapping, tephra stratigraphy compilation during and after the eruption, physical observations of the eruptive activity, petrology.

3. Universities of Geneva (Switzerland) and Pisa (Italy): tephra fallout measurements, tephra stratigraphy compilation during and after eruption, tephra isopach mapping, tephra sedimentation, eruption dynamics, petrology.

4. University of Manchester, UK: volcanic cone observations, physical eruptive parameter quantification, tephra isopach mapping.

The overarching philosophy of the coordinated teams was that data and samples of volcanic products (tephra, lava) would be available upon request, to foster scientific collaboration after the crisis. Requests pertaining to physical products were directed towards a single team member in charge of an online user-managed (i.e. anyone can edit with a link) "sign-up" sheet, to register their details and main interest areas. This was designed as a straightforward and transparent solution to enable cross-communication between collaborators, and the best possible outcome of avoiding duplication of effort and maximising sharing. This sheet included a statement of the philosophy of the style of coordination and vision for an open-access "*Litoteca*" (rock library). The most immediate and tangible assistance during the eruption was to help with daily tasks such as tephra station collection and resetting, active lava flow sample collection, which typically involved several hours of driving. This alleviated INVOLCAN staff time for other tasks and provided staff with occasional rest days. Active stratigraphic logging, tephra sampling, and physical volcanological analyses were conducted mainly by collaborators. The collaborative effort also increased the opportunities for scientific crisis training for visiting and local scientists.

3 2021 Cumbre Vieja crisis and eruption

The 2021 Tajogaite eruption was preceded by ~5 years of low-magnitude seismicity, with at least 10 earthquake swarms [D'Auria et al. 2022], accompanied by chemical and isotopic changes in groundwater compositions [Amonte et al. 2022]. Significant changes in the ^{3}He/^{4}He ratio in the years before the eruption are considered early geochemical precursory signals of magma emplacement and movement through the crust [Padrón et al. 2022]. Accelerated pre-eruptive seismicity, related to a dike intrusion toward the surface, began just one week before the 19th September eruption [D'Auria et al. 2022]. Initially, seismicity was concentrated about 5 km SE of the future eruption site. Then, in a few days, it rapidly shifted toward NW and ground deformation was detected in the same area. Then the seismicity started migrating upward, reaching the surface only a few hours before the eruption [D'Auria et al. 2022]. The eruption took place at an elevation of 1080 m a.s.l., in the upper reaches of the populated Aridane valley (Figure 1). Climatic conditions and trade wind directions acting on the tephra jets and volcanic ash plume varied due to the position of the typical atmospheric thermal inversion layer around 1000 m a.s.l., with changes depending on season and Atlantic cyclonic systems [Herrera et al. 2001]. Winds at ground level in the Aridane valley dominantly blow from the NE, while above the thermal inversion winds are more variable.

The eruption started on Sunday 19th September at 15:11 local time, forming an ash-rich eruption column (Figure 2A) which rapidly evolved into a multi-vent explosive lava fountaining complex along a ~NW–SE fissure of several hundred metres. Subsequently, the explosive activity focused on the SE section and constructed a 200 m-high cone centred on the initial vent location, while the NW section produced lava and strong degassing. The summit of the cone hosted at least 3 co-active vents throughout the eruption, with variable explosive activity, lava fountaining, and jetting [Figure 2B Bonadonna et al. 2023; Taddeucci et al. 2023]. The NW vent produced lava and gas, often observed as a light-coloured plume. Over time, a cone complex developed, which hosted several vents that shifted in position and activity on a time scale of hours to days, producing tephra (Figure 2C) and lava (Figure 2D). Taddeucci et al. [2023] reported a description and physical parameterization of the explosive activity of the eruption. Eruptive activity was continuous except for two pauses on 27th September and 17th November, which lasted a few hours each. Average volcanic plume heights were ~3 km a.s.l., although the eruption column reached 8.5 km a.s.l. during a set of large explosions on 13th December, i.e. the last day of the eruption (Figure 2E, volcanic plume heights reported by the civil protection authority PEVOLCA*). Bonadonna et al. [2022] reported a complete series of the tephra plume heights during the three months of the eruption, obtained from PEVOLCA reports and compiled by the Instituto Geográfico Nacional [IGN; Felpeto et al. 2022].

4 Syn-eruptive and post-eruptive data streams

4.1 Tephra deposits

Tephra deposits preserve a record of processes that occur during magma storage, ascent, eruption, transport and deposition. Tephra stratigraphy is, therefore, necessary to decipher and characterize explosive eruptions. Time-series analyses of tephra sampling during long-lasting eruptions are also crucial to constrain eruptive dynamics and evolution. Tephra sampling was performed in dedicated containers throughout the whole eruption, while stratigraphic studies were carried out both during and after the eruption. The combination of the two strategies allowed for the temporal constraint of individual units and layers.

4.1.1 *Tephra sampling strategy*

INVOLCAN co-ordinated with visiting scientific teams to extensively study the evolving tephra deposits during the eruption. This included collection of tephra fallout samples during

*https://www.gobiernodecanarias.org/infovolcanlapalma/pevolca/

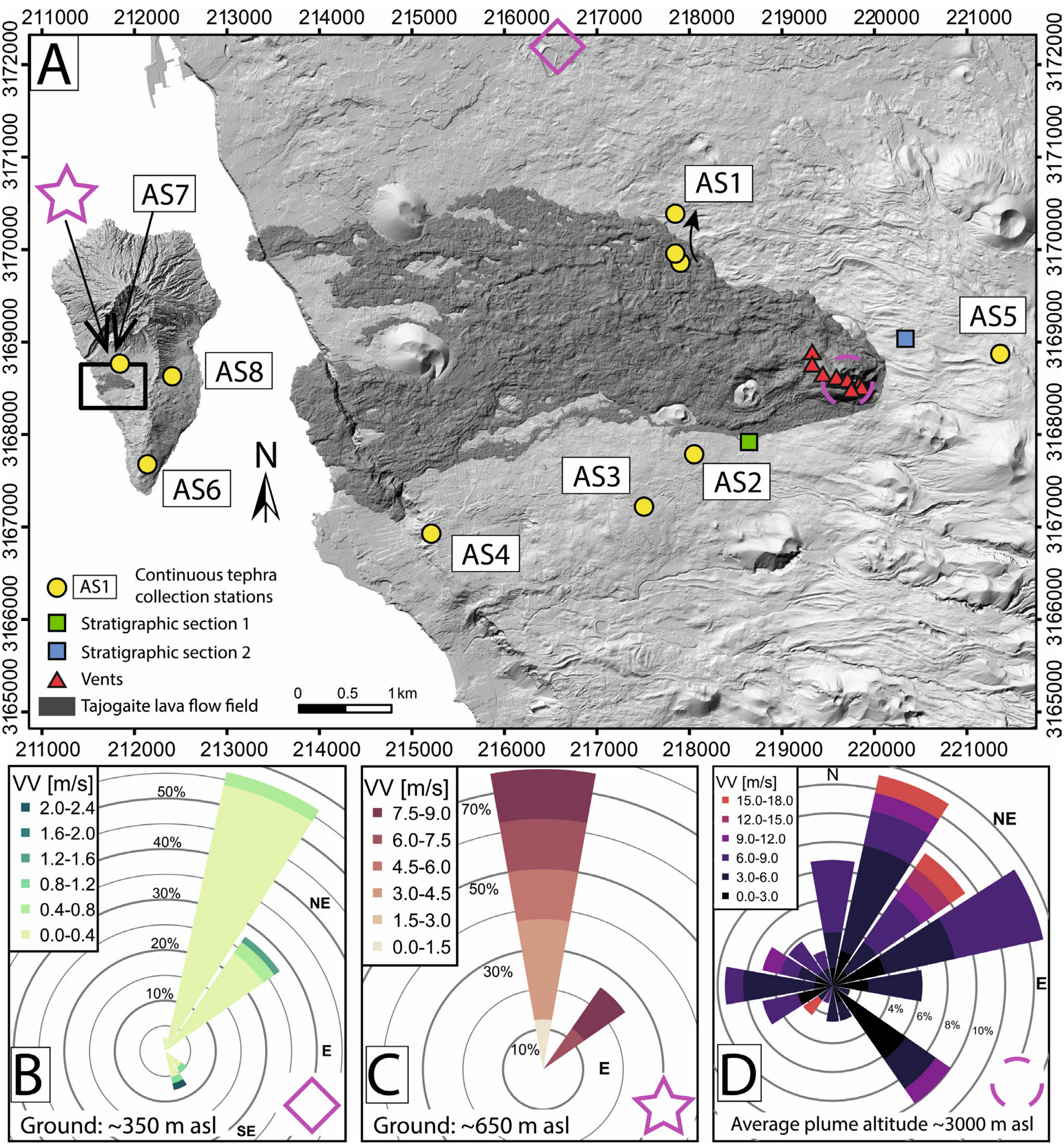

Figure 1: [A] Location of eruptive vents, stratigraphic log sites and continuous tephra-sampling stations. Ground-based and atmospheric meteorological stations (to measure wind velocity) are shown with a purple diamond, star, and dashed circle. [B]–[D] Rose diagrams of composite daily ground- and medium-altitude-based wind direction (orientation) and strength (colour) measurements for the duration of the eruption (% of time in each direction is quantified by radial markers). Direction is shown as the direction from which the wind originates by meteorological convention rather than the direction that it is moving. [B] Los Llanos mobile ground station ~350 m a.s.l. (location approximate), [C] El Paso ground station ~650 m a.s.l., [D] volcanic plume-focused meteorological data, at an average of 3 km a.s.l. Ground-level observations are from https://www3.gobiernodecanarias.org/medioambiente/calidaddelaire/datosHistoricosForm.do, atmospheric-level observations are from AEMET (www.aemet.es) via internal communication within the PEVOLCA committee.

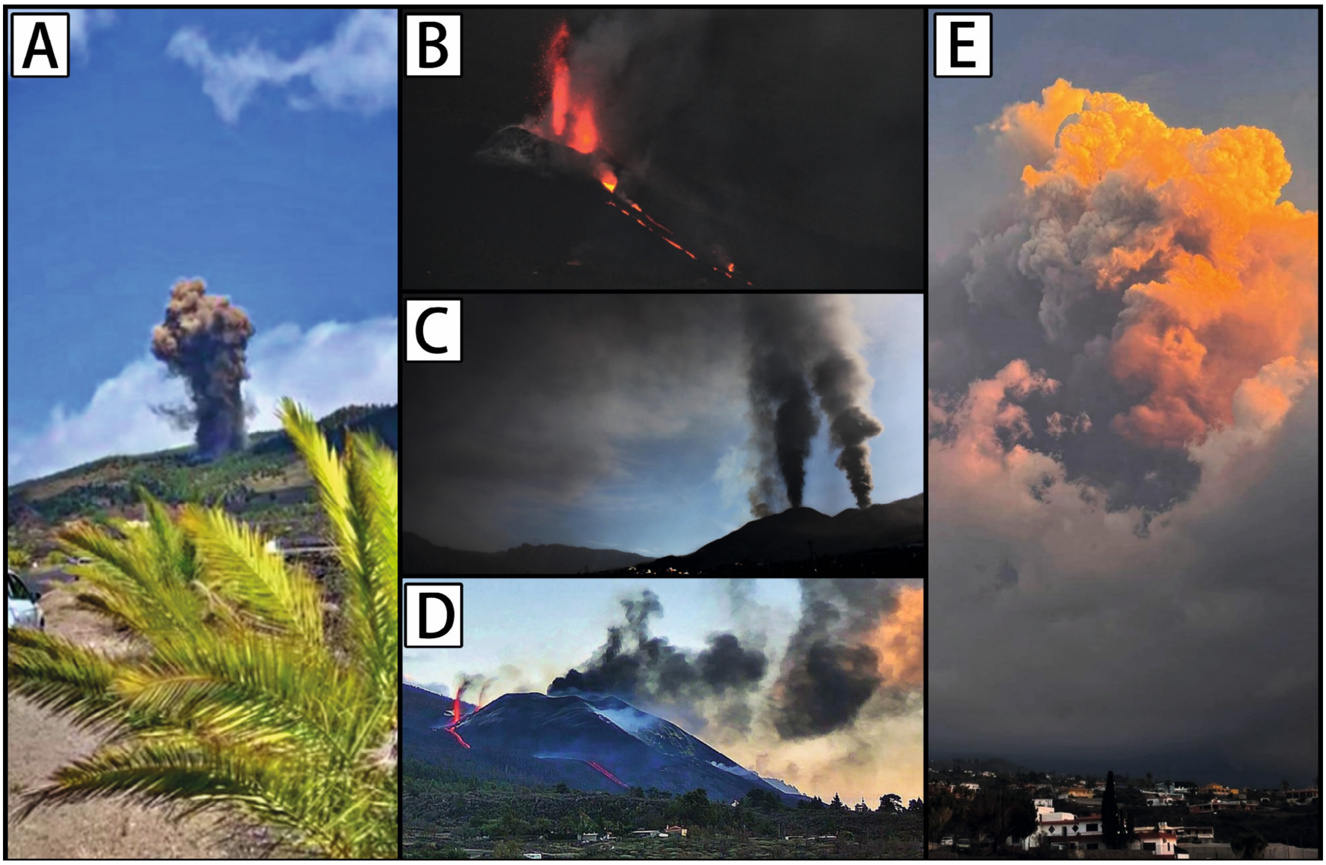

Figure 2: The eruptive activity of Tajogaite volcano. [A] Explosive onset of the eruption on 19th September. The image captures the location on the NW slope of Cumbre Vieja (Photo: Alba Martín-Lorenzo). [B] Picture of the eruption on 2nd October (looking towards the SE), showing vigorous explosive activity at two summit vents on the cone complex (Photo: Jorge Romero). The lowermost vent on the NW flank sources the lava flow towards the west. [C] Opening of an explosive vent on 14th October, located ca. 200 m SE of the cone complex (Photo: Jorge Romero). [D] Opening of satellite vent on the N flank of the cone complex, sourcing a ca. 30 m-high lava fountain and a lava flow (Photo: Mike Burton). [E] Column of the 13th December explosion reaching ca. 8.5 km a.s.l. (Photo: Catherine Hayer).

the 85 days of eruption to create the *Litoteca* sample library for multi-disciplinary study. Initial tephra-fall collection onto plastic sheets and paper containers transitioned rapidly into using a network of plastic box collection stations (Figure 3A; Table 1), from which tephra samples were collected almost daily (every 1–2 days, conditioned by the approval of daily access for scientists to the exclusion zone under strict safety measures; Figure 3B). The containers were placed in open spaces, away from roads (between 20–50 m away), secured to stable surfaces with straps, and protected from aeolian remobilisation as best as possible by being attached to elevated structures and featuring high sides (Figure 3A). Real-time observations of plume behaviour were recorded and complemented by extra tephra sampling using plastic sheets (Figure 3C). Tephra thickness measurements were made at the whole range from proximal (1 km from fissure) to distal (5–10 km from fissure) locations (Figure 3D) on flat, undisturbed surfaces. In addition, pyroclastic bombs were sampled near the active vents (Figure 3E). This high sampling rate was facilitated by the dense road network around the eruption site. Tephra stations AS1 and AS5 (Table 1; Figure 1) were located within a safety exclusion zone, while tephra stations AS2, AS3, and AS4 were in the proximal–medial–distal sites, respectively, along the main tephra dispersal axis (NE–SW). Tephra stations AS1 and AS5 were situated for occasional off-axis and reversal of wind directions (winds from S or W), respectively. Three additional stations were positioned outside the exclusion zone to support full coverage (AS6–8; Figure 1). All the stations shown on the map were sampled under the same methodology.

Tephra station AS1 was moved twice, hours ahead of lava inundation (see Figure 1). Meteorological ground station measurements demonstrate consistent low-level wind behaviour during most of the eruption period (Figure 1B, Figure 1C), with some variability in direction recorded at different plume altitudes (Figure 1D). Tephra fall was mostly dispersed both NE and SW of the vents, while the lava field expanded towards the west.

Stratigraphic logging of tephra deposits was carried out during and after the eruption by INGV, University of Geneva, and Manchester University teams (Section *4.1.2*). Periodic assessment of tephra fall layer thicknesses (University of Manchester, INGV) produced isopach maps (Section 4.3), used to obtain bulk tephra volume estimates (INVOLCAN, INGV; Section 4.4).

Table 1: Continuous tephra collection stations and coordinates.

Continuous tephra collection station ID	Location	Easting (UTM 28 R)	Northing (UTM 28 R)	Installation date (DD/MM/YYYY)
AS1	Tajuya	217952	3169790	21/09/2021
AS1–new1	Tajuya new1	217884	3169882	26/09/2021
AS1–new2	Tajuya new2	217929	3170222	11/10/2021
AS2	Corazoncillo	218089	3167790	26/09/2021
AS3	Caños de Fuego	217550	3167233	26/09/2021
AS4	Puerto Naos	215246	3166942	26/09/2021
AS5	Mirador del Jable	221403	3168887	27/09/2021
AS6	Fuencaliente	221507	3155359	09/10/2021
AS7	Dos Pinos	216422	3172191	01/10/2021
AS8	Montaña La Breña	227997	3170445	23/10/2021

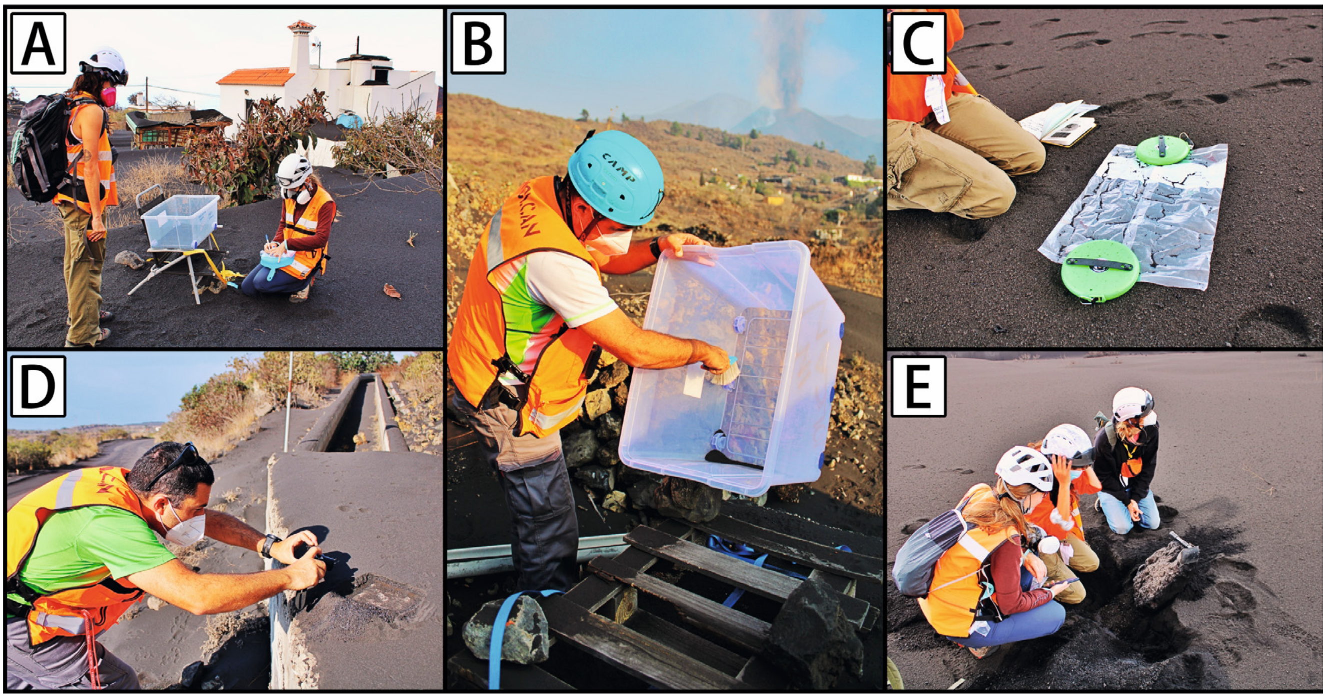

Figure 3: Active stratigraphic assessment and tephra sampling. [A] Continuous tephra collection stations were located in open spaces and fastened to heavy objects to prevent disturbance or removal. [B] Systematic sampling of tephra from the stations involved collection of every visible particle and resetting in the same position. [C] On-site collection of tephra fall using plastic sheets provided highly precise temporal resolution but was not feasible to conduct in a continuous manner for the entire eruption. [D] Thickness measurement of the total deposit on flat undisturbed surfaces. [E] Sampling of pyroclastic bombs near the active vents (<1.3 km). Photos by Jorge Romero.

4.1.2 *Tephra stratigraphy*

Based on field observations, available wind direction and speed changes, and deposit characteristics, two locations were selected as representative of the entire tephra eruptive sequence (locations in Figure 1). These reference stratigraphy sections were characterized during January and February 2022, after the end of the eruption. However, hundreds of observation points were made both during and after the eruption around the eruptive centres at different distances. These detailed observations in combination with syn-eruptive and post-eruptive sampling allowed us to acquire a comprehensive understanding of the chronology for the composite stratigraphic framework. Section 1 was located ~1 km SW of the vents and has a total thickness of 182 cm; Section 2 was located ~0.5 km NE of the vents and has a total thickness of 167 cm (each section is provided in Supplementary Material 1 Figures S1–S3). From these observations, a basic composite stratigraphy was built, that served as a framework and has provided nomenclature for post-eruption studies by all scientific teams. An absolute chronology of layer deposition was formed (Section 4.2) from real-time observations and syn-eruption logging, cross-checked between stratigraphic sections and with samples collected from a proximal tephra sampling station (AS2, SW of the cone complex; Supplementary Material 2 Table S1 and Table S2).

Based on deposit appearance, componentry, and textural features (e.g. grain size, grading, sorting) three main stratigraphic units were identified (Lower, Middle and Upper Units; Figure 4).

The Lower Unit (LU) is dominated by lapilli-size clasts, with intercalations of fine to coarse ash layers, and was divided into three layers (LU1–3) (Figure 4). Due to its brownish colour, LU1 is easily identified at both proximal and medial outcrops. The contact between LU1 and LU2 is defined by a marked colour change of the deposits, shifting from brown to black. The base of LU2 is defined by coarse, moderately sorted subtly stratified dark silvery iridescent lapilli. Intercalations of thin layers of fine to coarse-grey ash are present in LU2. LU3 is characterised by a poorly sorted gold-coloured coarse ash to lapilli, with elongated shapes.

The Middle Unit (MU) is dominated by fine to coarse ash, with intercalations of lapilli to coarse lapilli layers, and consists of six layers (MU1–6) (Figure 4). The transition from LU to MU is marked by a decrease in average grain size, with a massive layer of fine to coarse black ash as MU1. Above MU1, MU2 is represented as a mm-thick layer of fine to coarse ash, rich in red, oxidised lithics. This horizon is identifiable in proximal, medial, and distal sections and is a marker horizon for the 2021 Tajogaite eruption. After this stratigraphic marker, scattered red lithic fragments are present in subordinate proportions throughout layers MU3–6, which. Layers MU3, MU4 and MU5 are characterised by alternating black lapilli and black, coarse-grained ash layers. MU6 is characterised by a sequence of alternating moderately to poorly sorted, grey to black coarse ash layers. The upper section contains iridescent ash and lapilli.

The Upper Unit (UU) is a lapilli-dominated unit, which in proximal areas, is overlain by a decimetric to metric-bomb field, reflecting the last explosive stage of the eruption of 12–13 December (Figure 4). The transition between MU and UU is marked by a normally graded, poorly sorted, grey coarse ash to lapilli layer, with distinct red and (less frequently) whitish mm-size lithic clasts. This grades into lapilli with elongated shapes, which progressively become more angular in morphology as the eruption reaches its final stages.

The entire tephra sequence rapidly thins away from the cone [Bonadonna et al. 2022; Romero et al. 2022; Bonadonna et al. 2023]. In proximal areas (<3 km from the vents), the 3 units and most of their individual layers can be identified and correlated, whereas at medial-distal sites (>3 km from the vents) distinction between only the principal units is possible. The maximum clast sizes provided are those of the most proximal sections.

4.2 Temporal constraints of tephra layers

Samples from the continuous tephra collection station AS2 (INVOLCAN, collected near-daily) were correlated with stratigraphic layers in the tephra sections to the SW of the cone (Supplementary Material 2 Tables S1 and S2). Together with the identification of specific tephra features across the net-

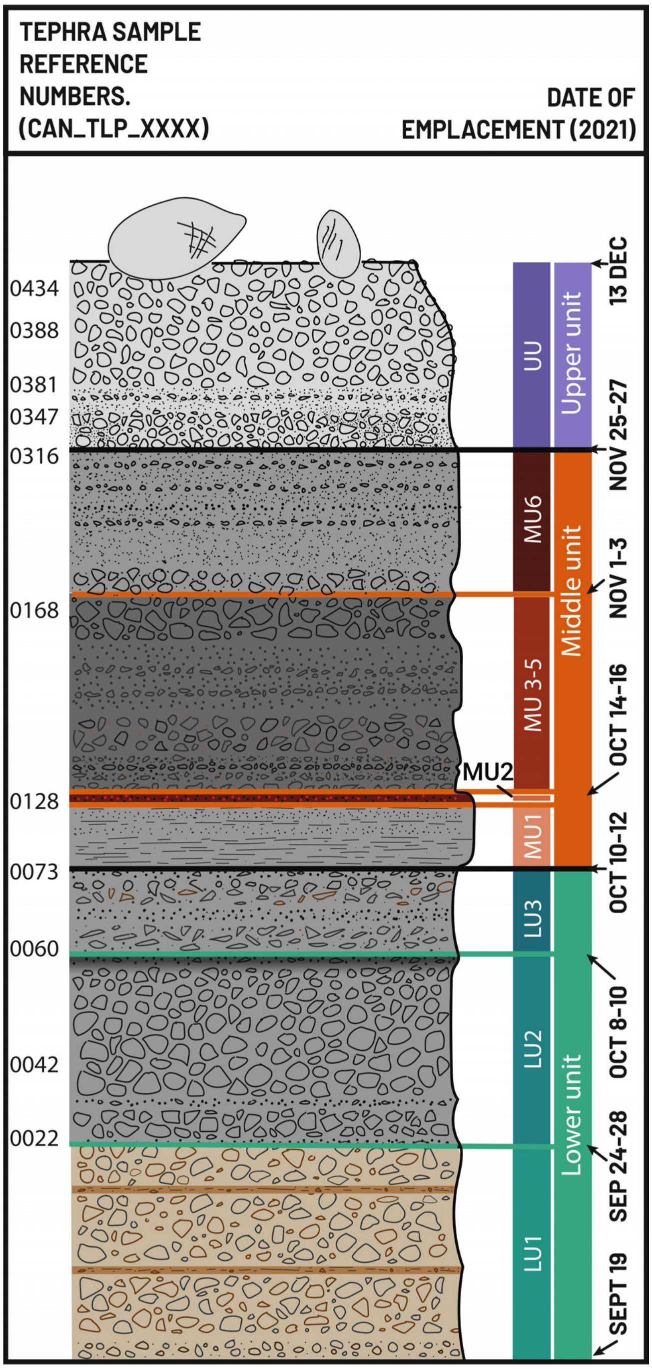

Figure 4: General tephra stratigraphy of the Tajogaite 2021 eruption of Cumbre Vieja volcanic system, La Palma (adapted from Bonadonna et al. [2022]). Deposit logs recorded during the eruption have been combined to form a composite reference log without an absolute scale (see Supplementary Material 1 Figures S1–S3 for raw observations). Absolute chronology (Section 4.2) is marked using samples verified between the in-situ deposits and collection station AS2. Note that bombs were found in proximal vent areas throughout the eruption, although they are most prevalent at the end of the eruption (top of section).

work (e.g. the appearance/disappearance of a peculiar component or specific pyroclast type), physical observations of the erupting activity (INGV), a compilation of PEVOLCA daily reports on eruption characteristics*, and real-time geophysical data (volcanic tremor; INVOLCAN; Section 4.6), an absolute chronology for the composite stratigraphic framework could be determined with an uncertainty of ±2 days (Figure 4). From eruption onset (19th September), LU was emplaced during 23 ± 1 days, during which the cone experienced a ∼ 5 Mm^3 lateral collapse towards the west on 25th September [boundary between LU1 and LU2; Bonadonna et al. 2022; Romero et al. 2022]. Following LU deposition, MU was the result of eruptive activity from 10–12 October until 25–27 November, lasting for 46 ± 2 days. A stratigraphic marker layer of distinctive red ash was deposited on 14–16 October, characterised by abundant subangular oxidised lithics. The UU was emplaced by activity from 25–27 November, until the end of the eruption on 13th December 2021, with a duration of 17 ± 1 days [Bonadonna et al. 2022].

4.3 Isopach maps and volume calculations

Tephra volume estimations were carried out using `AshCalc v.1.1` [Daggitt et al. 2014] through Exponential [Pyle 1989] and Weibull [Bonadonna and Costa 2013] integration of data. Tephra depth data collected during the eruption (until 11th October) was used to draw eight isopach curves, from which the integrated volume was calculated at 8–9 × 10^6 m^3 of bulk tephra (51 field points; Figure 5A). Four points from the initial campaign were then inundated by lava flows, preventing repeat measurements in these areas, thus these points represent a minimum thickness. The isopach map drawn on 21st November was based on 70 field measurements, with none of these affected by lava flows (Figure 5B), and the estimated integrated volume was 12–22 × 10^6 m^3 of bulk tephra. Field data collection was subsequently disrupted by the destruction of the road by lava inundation; research teams then had to drive around the island to reach the south from north (up to 2 hours with traffic) to obtain measurements. In order to monitor continuous tephra deposition, it is necessary to revisit predetermined control points on a regular basis to consistently measure thicknesses throughout the eruption. For example, one location had 61 cm of deposition by 11th October (Figure 5C), then had accumulated 120 cm by 18th November (Figure 5D). The repetitiveness of field measurements was made available by coordinated efforts among the different scientific groups, extensive road networks, and access permissions granted to researchers which allowed rapid interactions with local authorities during the fieldwork.

4.4 Sedimentation rate

Together with isopach thicknesses, cumulative sedimentation rate aids in understanding the dynamics of the volcanic plume, eruption column behaviour, dispersal of volcanic materials in the atmosphere, and can help in formulating eruption models for a particular volcanic system. Cumulative sedimentation rate during the Tajogaite eruption was facilitated by the implementation of fixed tephra stations (Table 1). The 5 most proximal stations were included in the cumulative daily sedimentation rate (AS1–5, black line; Figure 6). Cumulative weight using only AS1, 2, and 5 was also calculated (red line; Figure 6), as these stations were at similar distances from the cone in different directions (Figure 1) and should capture the same order of tephra despite significant changes in wind/tephra dispersal during the eruption (assuming similar wind intensity, column height, and eruptive style). Two time periods show significant deviations in the patterns of cumulative curves (Figure 6), 27–30 October and 4–6 November. As the accumulation patterns during the eruption are remarkably similar except for these periods, the deviations represent changes in eruptive style (explosivity) and plume dynamics, which are then captured by an increase in tephra deposition in the more distal stations (Figure 6). The distinctive red stratigraphic marker unit emplaced from 14–16 October also shows an increase in sedimentation rate in distal stations. In this way, active eruptive dynamics can be recorded in the tephra sedimentation patterns and stratigraphy, and with a regular monitoring schedule, tephra sedimentation can be used in hazard assessment and risk management plans.

4.5 Petrological evolution

INVOLCAN sampled lava and tephra on a daily basis, with the aim of providing petrological data (mineralogy, texture, chemical composition) as a real-time tool to interpret the state of the magmatic plumbing system [Pankhurst et al. 2022]. Collected samples were distributed through collaborative partners with analytical instrumental availability (EPMA, QEMSCAN, XRF, XRD, ICPMS), and only three weeks after eruption onset, petrological data could be incorporated into the datastreams presented to the disaster committee. Samples were also catalogued into the *Litoteca*, ensuring availability and collaborative strategies into the future.

Mineralogy of lavas over the first 6 days of the eruption included amphibole (together with plagioclase feldspar, clinopyroxene, magnetite, ilmenite, and biotite mica). On day 6, the vent complex entered a new explosive phase, and <<1 cm pieces of white/grey material (frothy, pumice-like appearance) were ejected with the tephra. After 24–28 September, the amphibole component decreased rapidly and was difficult to find in hand specimens (or was almost reacted out), and bulk lava MgO was increasing [Pankhurst et al. 2022]. These petrological changes were marked in the tephra stratigraphy by a distinct colour change at the LU1/LU2 boundary (Figure 4). LU1 represents the first, opening phase which tapped shallower magmas, with the transition to a deeper magma feed reflected in the geochemistry and mineralogy/componentry. The changes in the eruption parameters were reflected by increased tremor, an explosive phase, decreasing amphibole mineralogy, pumice material presence, and tephra stratigraphy changes.

4.6 Volcanic tremor

INVOLCAN operates the Red Sísmica Canaria (C7), whose stations in La Palma recorded the volcanic tremor during the eruption as well as the pre-, syn-, and post-eruptive earth-

*https://www.gobiernodecanarias.org/infovolcanlapalma/pevolca/

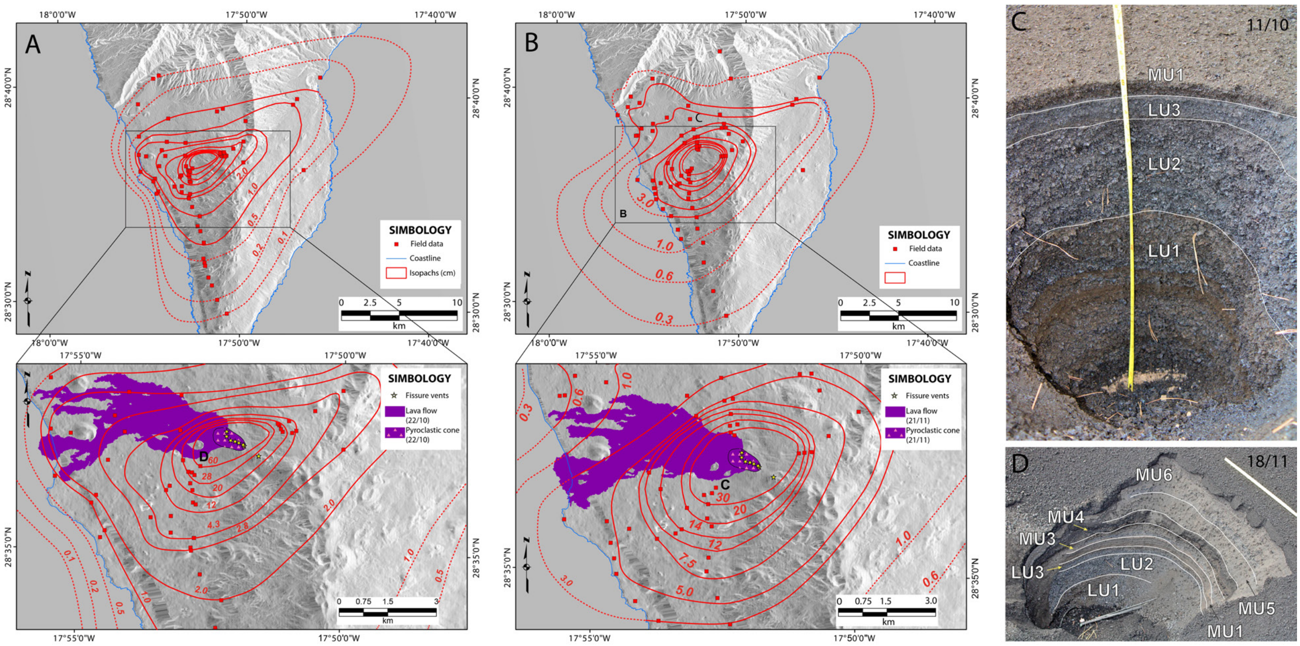

Figure 5: Isopach maps. [A] 11th October 2021, based on 51 field measurements and [B] 21st November 2021, based on 70 field measurements. [C] and [D] show the same location and the change in volume of tephra between 11th October and 18th November 2021.

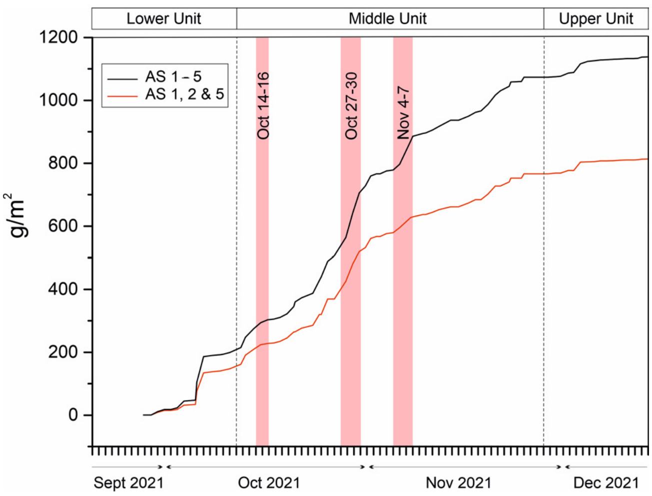

Figure 6: Normalised cumulative mass of tephra captured by fixed stations. Black line: AS1–5 stations; red line: AS1. 2 and 5 stations.

quakes [D'Auria et al. 2022]. Bonadonna et al. [2022], then analysed the volcanic tremor, separating the signal into two distinct frequency bands: Long Period (LP, 1–5 Hz) and Very Long Period (VLP, 0.4–0.7 Hz). Considering the local S-wave velocity model [D'Auria et al. 2022] and assuming the tremor wavefield to be composed mainly of Rayleigh waves, the LP tremor component can be related to explosive activity at the vent, while VLP tremor is potentially associated with deeper parts of the conduit and therefore to the gas flow through it. Using this perspective, the ratio between the amplitude of the two components can provide an indication of the eruptive style [Bonadonna et al. 2022].

Since the volcanic tremor amplitude is highly variable, the time series of the ratio is quite 'noisy'. To clean up the signal, we used the Independent Component Analysis [ICA; Hyvärinen and Oja 2000] to relate the variability of the two components. After normalising the data (assuming a log-normal distribution), we applied ICA, obtaining two components that we call ICA1 and ICA2.

We observe that ICA1 is related to the amplitude of the tremor and, therefore, to the intensity of the explosive activity (Supplementary Material 1 Figure S4 shows scatter plots of the normalised data coloured according to the component value). Conversely, ICA2 shows variations similar to the ratio between LP and VLP used in Bonadonna et al. [2022]. Therefore, we relate it to the eruption style at the vent, modulated by near-surface processes. This post-eruption data treatment allows us to more easily see the relation between the recorded tremor and eruptive activity (source to surface; Figure 7), which is helpful in showing how the changes in the Cumbre Vieja volcanic system affected the type of volcanic tephra emitted. This type of information is then directly applicable to future eruptions in the Canaries.

Increased sedimentation of tephra (Figure 6) and changes in the stratigraphic column (Figure 4) can be linked to changes in tremor parameters recorded (Figure 7). Prominent examples include:

- 24–28 September, extreme and rapid fluctuations in ICA1 reflected rapid changes in the intensity and explosivity of the eruption. This culminated on 27th September, coincident with the highest value of ICA2 recorded during the eruption, demonstrating a massive change in eruption style at the vent (while ICA1 recorded a minimum). These signals were recorded as the initial volcanic cone collapsed [Romero et al.

2022], plume heights reached 6000 m [Bonadonna et al. 2022] and the chemistry of the lavas began to change [Ubide et al. 2023], indicating changes in the magma source. The ICA data for this period show that the volcanic system was undergoing rapid fluctuations in the subsurface portion, culminating in a big change at the surface.

- During 14–16 October, the stratigraphic marker bed was emplaced across La Palma. In the tremor data, LP and VLP signals are similar with only a slight decrease in both. The ICA signals show a brief increase, then decrease (ICA1), while ICA2 rises suddenly on the 14th and then is constant, indicating the Tajogaite system was in a vent-activity dominated phase. This phase deposited the highly visible, oxidised (recycled?) fragments as the stratigraphic marker bed (MU2).

- There are two periods (27–30 October and 4–7 November) where the tephra sedimentation rate shows a distinct increase in the distal stations over the proximal ones (Figure 6). These two periods fall just either side of the peak ICA1 values (peak intensity and explosivity; smoothed red line) during the eruption, with no major fluctuations in ICA2 values. These two periods of significantly increased sedimentation further from the cone represent subsurface volcanic system changes/inputs, e.g. gas content or magma recharge, which served to increase the energy (and therefore the distance travelled) of the erupting tephra, while the vent complex remained relatively stable.

5 Discussion

5.1 Integrating data in real-time during a volcanic crisis

Integration of tephra stratigraphy, tephrochronology, isopach maps, sedimentation rate, and macroscale petrological changes, related to volcanic tremor during the 2021 Tajogaite eruption allowed ongoing direct comparison of physical and geophysical characteristics of the eruption to best monitor the evolution of the eruption dynamics. Examples include:

- A change in tephra deposition before and after a cone collapse event, on 25th September [Romero et al. 2022]. From eruption onset until the cone collapse event, tephra comprised brown ash and lapilli, forming unit LU1. Cone collapse was marked by a spike in ICA2, after rapid changes in explosivity (ICA1). The tephra stratigraphy shows a colour change visible across proximal to distal deposits. Concurrently, the first white/grey xeno-pumice fragments appeared in tephra, amphibole began to disappear and the MgO content of the volcanic products began to increase. These changes, taken separately, all had significance, but together, they indicated a change from the magmatic source and then throughout the system, from subsurface to vent.

- The red marker bed visible in all tephra sections (MU2) was deposited between 14–16th October, and was a result of the opening of a transient vent to the southeast of the main cone complex.

- The two greatest deviations in cumulative sedimentation rate between the distal and proximal tephra stations were related to a high ICA1 signal, reflecting subsurface processes that caused significant increases in ash emission. During these periods, the plume was controlled by normal trade winds from the NE, so increased tephra sedimentation can be linked directly to volcanic system changes.

Volcanic tremor has been successfully linked to the three main stratigraphic units [Bonadonna et al. 2022] which in turn are correlated to physical phases of the eruption, both in duration and to transitional episodes. Here, we have shown the possibility that all the volcanological disciplines can contribute to a central, neutral purpose. This contribution is focused on monitoring tephra deposition, and collaborative processes allowed rapid network development and coordinated implementation during a volcanic eruption. The data streams produced during and after the Tajogaite eruption are leading to a detailed understanding of the Canarian systems and are applicable to other ocean island settings. Of course, international collaboration in volcanology is not unique to the case of the 2021 Tajogaite eruption. Similar collaborative approaches have been successfully implemented at active volcanoes around the world. For instance, Lautze et al. [2013] and Gurioli et al. [2014] and Andronico et al. [2021] shared data and methods from Stromboli volcano (Aeolian Islands), improving our understanding of eruptive dynamics. Similarly, Andronico et al. [2009] applied a multidisciplinary approach (seismic data, live camera observation, and tephra sampling and study) to monitor the explosive activity of Etna (Sicily). Also, during the 2010 Eyjafjallajökull eruption in Iceland, an international collaborative effort enabled rapid data collection and analysis that were crucial for crisis management and minimising disruption to air traffic [Bonadonna et al. 2011; Cioni et al. 2014]. These studies underscore the importance of international collaboration in advancing volcanological knowledge. In the case of the 2021 Tajogaite eruption, for the first time the international collaboration significantly expanded the resources available to scientists and civil protection and were coordinated beforehand by a local volcanological institution, enhancing the accuracy of forecasting the evolution of the volcanic system during the emergency. Of particular relevance is the combination of real-time volcanic emergency scientific management and an open-door scientific collaboration philosophy. Comprehensive real-time observations, syn-eruptive deposit logging, continuous tephra collection, weather records, and post-eruption field studies, and stratigraphic logging, have allowed the definition of a reference stratigraphy and a unified consensual nomenclature of the deposits, linked to specific date/times throughout the eruption (Supplementary Material 2 Tables S1 and S2). This framework represents a robust foundation for studies aiming to correlate eruption processes (physical, geochemical, petrological and geophysical).

5.2 Collaboration strategy—reviewed

Once the eruption period was over, individual scientific teams could develop their prioritised data streams, resulting in extensive analysis of pre-, syn-, and post-eruptive processes in the Cumbre Vieja system [e.g. Bonadonna et al. 2022;

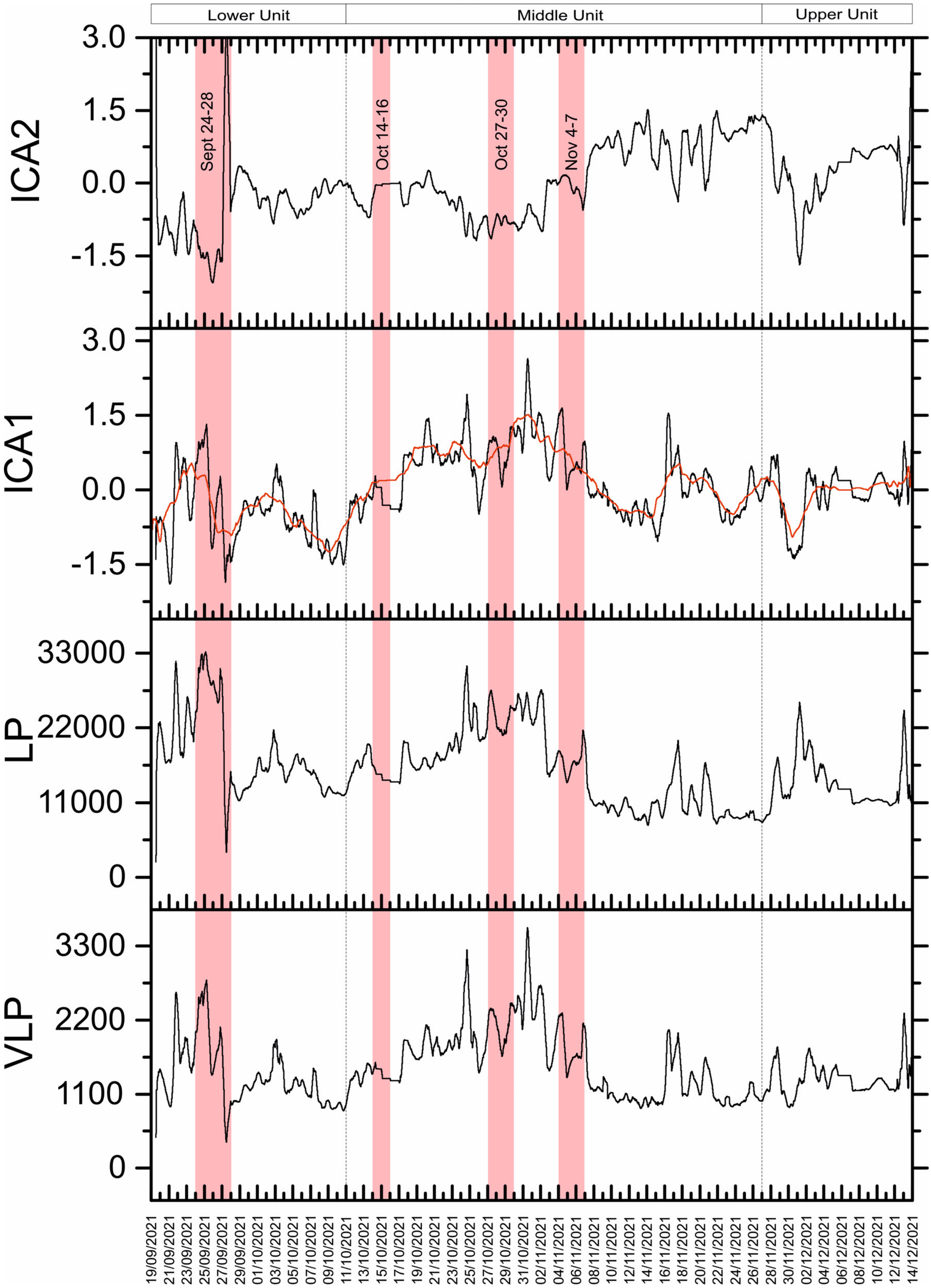

Figure 7: Volcanic tremor throughout the eruption, recorded as LP and VLP signals. Principal component analysis of the signals shows the relation between gas content of the erupting magma (ICA1) and surface conduit processes (ICA2). The principal tephra stratigraphic units are marked with a discontinuous line, and four example events that can be correlated across volcanological disciplines (marked in red) are discussed in the text.

D'Auria et al. 2022; Romero et al. 2022; Bonadonna et al. 2023; Taddeucci et al. 2023]. These insightful contributions began as part of a coordinated effort, designed to maximise potential and minimise duplication of effort during a crisis period. An obvious benefit to scientific coordination was linking groups and forming new collaborations between volcanological disciplines. INVOLCAN now hosts a catalogue of >130 lava samples and >450 tephra samples in a *Litoteca* (samples are available on request through the email address involcan@gmail.com). Other studies published within the framework of the Tajogaite national and international collaboration through INVOLCAN include: Wadsworth et al. [2022], Birnbaum et al. [2023], Burton et al. [2023], Butcher et al. [2023], Cabrera-Pérez et al. [2023], Di Fiore et al. [2023], Piña-Varas et al. [2023], Sandoval-Velasquez et al. [2023], Wertheim et al. [2023], Biass et al. [2024], Bonechi et al. [2024], Dóniz-Páez et al. [2024], Ericksen et al. [2024], Ortega-Ramos et al. [2024], Przeor et al. [2024], Reyes-Hardy et al. [2024], Sandoval-Velasquez et al. [2024], and Zanon et al. [2024]. More articles are in preparation on a variety of subjects.

In the Canary Islands, international scientific collaboration represents a path to significantly increase the resources available to scientists and civil protection agencies. With such wide resources available, forecasting of the evolution of the volcanic system is more accurate during the crisis, rather than solely applied retrospectively. To streamline the collaborative process, it is important to maintain an open access database of which teams are performing which tasks, and to promote collaboration for data. To aid civil protection authorities, all data should be easily available with a specialist from each team to explain the relevance of their work to volcanic hazard management. In this way, scientists can be part of the civil protection decision processes including the organisation and level of restrictions in volcanic hazard zones.

The 2021 Tajogaite eruption is an example of scientific crisis management from a 'standing start'. The eruption had immediate impacts on the local population, so the style of activity was relevant on very short spatial and temporal scales. In order to improve what happened during the eruption, the promotion of best practices or a protocol for volcanic emergency response including international scientific collaboration specifically, would be beneficial.

This successful collaborative effort has also highlighted strengths and weaknesses in the scientific management of a volcanic crisis. We have identified some important key lessons learned from this crisis such as: i) Scientific collaboration at both national and international levels is crucial for better understanding volcanic processes during an emergency, providing valuable information for the management of the crisis, and forecasting short-term evolution scenarios based on volcano dynamics, ii) Regulating access to the eruptive area is essential. However, scientists, being usually more expert on volcanic hazards than civil protection authorities, should be part of the decision-making process to avoid unnecessary restrictions, iii) Data collected during a volcanic emergency should be readily available to the civil protection authorities, even if not made available to the general public or to the wider scientific community, iv) Local coordination is required to prevent overlapping between team's activities on the field or laboratory, ensure safety of scientists, and promote productive collaborations; and v) A clear data and sample sharing policy among different teams should be clearly defined beforehand to avoid misunderstandings.

As some final considerations, we highlight that the 2021 eruption of Tajogaite in La Palma stands out as the most significant volcanic event in Europe for 75 years, necessitating the evacuation of thousands and causing extensive destruction. The eruption bore similarities in style with historic eruptions of the Cumbre Vieja system [Longpré and Felpeto 2021], therefore a thorough multidisciplinary understanding of the 2021 eruption will lead to a deeper understanding of those eruptions that were not recorded by modern monitoring networks or physically sampled in real-time, yet can be investigated using their deposits. These data can also be used to better understand similar systems worldwide, especially at volcanoes without robust geophysical monitoring where tephra deposits can be studied. In this context, the scientific collaboration model led by INVOLCAN played a crucial role during the Tajogaite eruption, and provides an example based on best practice for handling scientific input during future volcanic emergencies.

Author Contributions

F.R., B.C., A.M-L., D.A., C.B., E.D.B., M.P., J.T., S.B., J.E.R., M.V. and P.S. contributed to writing the manuscript, preparing figures, conducting fieldwork and processing samples. W.H. undertook the cartography. L.D. contributed to writing the manuscript and preparing figures. N.M.P. initiated the study and was responsible for funding acquisition.

Acknowledgements

We would like to sincerely thank all the colleagues who kindly carried out the tephra sampling and/or cataloguing work. We are especially grateful to Dr. Kristi Wallace and two anonymous reviewers for their contribution and help to improve this paper. This research was financially supported by the projects (i) VOLRISKMAC (MAC/3.5b/124) and (ii) VOLRISKMAC II (MAC2/3.5b/328), financed by the Program INTERREG V A Spain-Portugal MAC 2014-2020 of the European Commission; (iii) Cumbre Vieja Emergencia, financed by the Science and Innovation Ministry, Spanish Government; (iv) TFassistance, financed by the Cabildo Insular de Tenerife and (v) LPvolcano, financed by the Cabildo Insular de La Palma. INGV president C. Doglioni and INGV-OE director S. Branca, are acknowledged for supporting the field surveys of the INGV personnel. INGV has also benefited from MIUR project Premiale Ash-RESILIENCE (FOE 2015). This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101005611 for Trans-National Access conducted at INGV-RM1-FESEM/EMPA. University of Manchester fieldwork was financed through NSFGEONERC-funded project DisEqm (NERC Reference: NE/N018575/1; NE/N018443/1) and V-PLUS projects. University of Geneva fieldwork was supported by Swiss National Science Foundation (Grant #200020-188757).

Data Availability

Supplementary Material provided alongside the online version of this article.

- Section photos
  - Figure S1. Photograph of stratigraphic section 1.
  - Figure S2. Photograph of stratigraphic section 2.
- Figure S3: Correlated section logs.
- Figure S4: Values of the two Independent Components (ICA1 and ICA2). a) Values of ICA1 represented as a shade of colours on the scatter plot of Normalized VLP vs. Normalized LP. The corresponding palette is displayed on the right of the graph. b) Same as for (a) but for ICA2.
- Table S1: Detailed chronological correlation of AS2 samples with key stratigraphic units.
- Table S2: Correlation of AS2 samples with principle stratigraphy.

Copyright Notice

References

Amonte, C., G. V. Melián, M. Asensio-Ramos, N. M. Pérez, E. Padrón, P. A. Hernández, and L. D'Auria (2022). "Hydrogeochemical temporal variations related to the recent volcanic eruption at the Cumbre Vieja Volcano, La Palma, Canary Islands". *Frontiers in Earth Science* 10. DOI: 10.3389/feart.2022.1003890.

Andronico, D., E. Del Bello, C. D'Oriano, P. Landi, F. Pardini, P. Scarlato, M. de'Michieli Vitturi, J. Taddeucci, A. Cristaldi, F. Ciancitto, F. Pennacchia, T. Ricci, and F. Valentini (2021). "Uncovering the eruptive patterns of the 2019 double paroxysm eruption crisis of Stromboli volcano". *Nature Communications* 12(1). DOI: 10.1038/s41467-021-24420-1.

Andronico, D., S. Scollo, A. Cristaldi, and F. Ferrari (2009). "Monitoring ash emission episodes at Mt. Etna: The 16 November 2006 case study". *Journal of Volcanology and Geothermal Research* 180(2–4), pages 123–134. DOI: 10.1016/j.jvolgeores.2008.10.019.

Biass, S., M.-P. Reyes-Hardy, C. Gregg, L. S. Di Maio, L. Dominguez, C. Frischknecht, C. Bonadonna, and N. Perez (2024). "The spatiotemporal evolution of compound impacts from lava flow and tephra fallout on buildings: lessons from the 2021 Tajogaite eruption (La Palma, Spain)". *Bulletin of Volcanology* 86(2). DOI: 10.1007/s00445-023-01700-w.

Birnbaum, J., E. Lev, P. A. Hernandez, J. Barrancos, G. D. Padilla, M. Asensio-Ramos, D. Calvo, F. Rodríguez, N. M. Pérez, L. D'Auria, and S. Calvari (2023). "Temporal variability of explosive activity at Tajogaite volcano, Cumbre Vieja (Canary Islands), 2021 eruption from ground-based infrared photography and videography". *Frontiers in Earth Science* 11. DOI: 10.3389/feart.2023.1193436.

Bonadonna, C. and A. Costa (2013). "Plume height, volume, and classification of explosive volcanic eruptions based on the Weibull function". *Bulletin of Volcanology* 75(8). DOI: 10.1007/s00445-013-0742-1.

Bonadonna, C., R. Genco, M. Gouhier, M. Pistolesi, R. Cioni, F. Alfano, A. Hoskuldsson, and M. Ripepe (2011). "Tephra sedimentation during the 2010 Eyjafjallajökull eruption (Iceland) from deposit, radar, and satellite observations". *Journal of Geophysical Research* 116(B12). DOI: 10.1029/2011jb008462.

Bonadonna, C., M. Pistolesi, S. Biass, M. Voloschina, J. Romero, D. Coppola, A. Folch, L. D'Auria, A. Martin-Lorenzo, L. Dominguez, C. Pastore, M.-P. Reyes Hardy, and F. Rodríguez (2022). "Physical Characterization of Long-Lasting Hybrid Eruptions: The 2021 Tajogaite Eruption of Cumbre Vieja (La Palma, Canary Islands)". *Journal of Geophysical Research: Solid Earth* 127(11). DOI: 10.1029/2022jb025302.

Bonadonna, C., M. Pistolesi, L. Dominguez, V. Freret-Lorgeril, E. Rossi, A. Fries, S. Biass, M. Voloschina, J. Lemus, J. E. Romero, V. Zanon, C. Pastore, M.-P. Reyes Hardy, L. S. Di Maio, P. Gabellini, A. Martin-Lorenzo, F. Rodriguez, and N. M. Perez (2023). "Tephra sedimentation and grainsize associated with pulsatory activity: the 2021 Tajogaite eruption of Cumbre Vieja (La Palma, Canary Islands, Spain)". *Frontiers in Earth Science* 11. DOI: 10.3389/feart.2023.1166073.

Bonechi, B., M. Polacci, F. Arzilli, J. Romero, J. Fellowes, and M. Burton (2024). "Magma residence time, ascent rate and eruptive style of the November ash-laden activity during the 2021 Tajogaite eruption (La Palma, Spain)". *Volcanica* 7(1), pages 51–65. DOI: 10.30909/vol.07.01.5165.

Burton, M., A. Aiuppa, P. Allard, M. Asensio-Ramos, A. P. Cofrades, A. La Spina, E. J. Nicholson, V. Zanon, J. Barrancos, M. Bitetto, M. Hartley, J. E. Romero, E. Waters, A. Stewart, P. A. Hernández, J. P. Lages, E. Padrón, K. Wood, B. Esse, C. Hayer, K. Cyrzan, E. F. Rose-Koga, F. Schiavi, L. D'Auria, and N. M. Pérez (2023). "Exceptional eruptive CO2 emissions from intra-plate alkaline magmatism in the Canary volcanic archipelago". *Communications Earth & Environment* 4(1). DOI: 10.1038/s43247-023-01103-x.

Butcher, A. R., R. Windmill, I. J. Corfe, S. Lim, E. M. Jolis, S. Lukkari, M. J. Pankhurst, O. A. Barbee, B. C. Coldwell, N. P. Rodriguez, L. F. White, A. Dunford, and M. Anand (2023). "Volcanic ash as a resource for future research on Earth and the Moon". *Geology Today* 39(4), pages 144–148. DOI: 10.1111/gto.12442.

Cabrera-Pérez, I., L. D'Auria, J. Soubestre, M. Przeor, J. Barrancos, R. García-Hernández, J. M. Ibáñez, I. Koulakov, D. M. van Dorth, V. Ortega, G. D. Padilla, T. Sagiya, and N. Pérez (2023). "Spatio-temporal velocity variations observed during the pre-eruptive episode of La Palma 2021 eruption inferred from ambient noise interferometry". *Scientific Reports* 13(1). DOI: 10.1038/s41598-023-39237-9.

Carracedo, J. C., V. R. Troll, J. M. D. Day, H. Geiger, M. Aulinas, V. Soler, F. M. Deegan, F. J. Perez-Torrado, G. Gisbert, E. Gazel, A. Rodriguez-Gonzalez, and H. Albert (2022). "The 2021 eruption of the Cumbre Vieja volcanic ridge on La Palma, Canary Islands". *Geology Today* 38(3), pages 94–107. DOI: 10.1111/gto.12388.

Cioni, R., M. Pistolesi, A. Bertagnini, C. Bonadonna, A. Hoskuldsson, and B. Scateni (2014). "Insights into the dynamics and evolution of the 2010 Eyjafjallajökull summit eruption (Iceland) provided by volcanic ash textures". *Earth and Planetary Science Letters* 394, pages 111–123. DOI: 10.1016/j.epsl.2014.02.051.

Civico, R., T. Ricci, P. Scarlato, J. Taddeucci, D. Andronico, E. Del Bello, L. D'Auria, P. A. Hernández, and N. M. Pérez (2022a). "High-resolution Digital Surface Model of the 2021 eruption deposit of Cumbre Vieja volcano, La Palma, Spain". *Scientific Data* 9(1). DOI: 10.1038/s41597-022-01551-8.

Civico, R., T. Ricci, P. Scarlato, J. Taddeucci, D. Andronico, E. Del Bello, L. D'Auria, P. A. Hernández, N. M. Pérez, M. Asensio-Ramos, J. Barrancos, D. Calvo, D. Martínez van Dorth, E. Padrón, A. Álvarez, and C. Doglioni (2022b). "2021 Cumbre Vieja volcano eruption (La Palma, Spain) SfM DSM, Jan 2022". *Distributed by OpenTopography*. DOI: 10.5069/G96971S8. [Dataset].

D'Auria, L., I. Koulakov, J. Prudencio, I. Cabrera-Pérez, J. M. Ibáñez, J. Barrancos, R. García-Hernández, D. Martínez van Dorth, G. D. Padilla, M. Przeor, V. Ortega, P. Hernández, and N. M. Peréz (2022). "Rapid magma ascent beneath La Palma revealed by seismic tomography". *Scientific Reports* 12(1). DOI: 10.1038/s41598-022-21818-9.

Daggitt, M. L., T. A. Mather, D. M. Pyle, and S. Page (2014). "AshCalc–a new tool for the comparison of the exponential, power-law and Weibull models of tephra deposition". *Journal of Applied Volcanology* 3(1). DOI: 10.1186/2191-5040-3-7.

Dayton, K., E. Gazel, P. E. Wieser, V. R. Troll, J. C. Carracedo, M. Aulinas, and F. J. Perez-Torrado (2024). "Magmatic Storage and Volatile Fluxes of the 2021 La Palma Eruption". *Geochemistry, Geophysics, Geosystems* 25(6). DOI: 10.1029/2024gc011491.

Di Fiore, F., A. Vona, A. Scarani, G. Giordano, C. Romano, D. Giordano, L. Caricchi, A. Martin Lorenzo, F. Rodriguez, B. Coldwell, P. Hernandez, and M. Pankhurst (2023). "Experimental Constraints on the Rheology of Lavas From 2021 Cumbre Vieja Eruption (La Palma, Spain)". *Geophysical Research Letters* 50(4). DOI: 10.1029/2022gl100970.

Dóniz-Páez, J., R. Becerra-Ramírez, K. Németh, R. U. Gosálvez, and E. Escobar (2024). "Geomorfositios de interés geoturístico del volcán monogenético Tajogaite, erupción de 2021 (La Palma, Islas Canarias, España)". *Geofísica Internacional* 63(1), pages 729–746. DOI: 10.22201/igeof.2954436xe.2024.63.1.1731.

Ericksen, J., T. Fischer, G. M. Fricke, S. Nowicki, N. Pérez, P. Hernández Pérez, E. Padrón González, and M. Moses (2024). "Drone CO2 Measurements During the Tajogaite Volcanic Eruption". DOI: 10.5194/amt-2023-229.

Felpeto, A., A. J. Molina-Arias, F. Quirós, J. Pereda, L. García-Cañada, and E. A. Díaz-Suárez (2022). "Measuring the height of the eruptive column during the 2021 eruption of Cumbre Vieja (La Palma Island, Canary Islands)". *EGU General Assembly 2022*. Copernicus GmbH, EGU22–9419. DOI: 10.5194/egusphere-egu22-9419.

Gurioli, L., L. Colo', A. J. Bollasina, A. J. L. Harris, A. Whittington, and M. Ripepe (2014). "Dynamics of Strombolian explosions: Inferences from field and laboratory studies of erupted bombs from Stromboli volcano". *Journal of Geophysical Research: Solid Earth* 119(1), pages 319–345. DOI: 10.1002/2013jb010355.

Herrera, R. G., D. G. Puyol, E. H. MartÍn, L. G. Presa, and P. R. Rodríguez (2001). "Influence of the North Atlantic Oscillation on the Canary Islands Precipitation". *Journal of Climate* 14(19), pages 3889–3903. DOI: 10.1175/1520-0442(2001)014<3889:iotnao>2.0.co;2.

Hyvärinen, A. and E. Oja (2000). "Independent component analysis: algorithms and applications". *Neural Networks* 13(4–5), pages 411–430. DOI: 10.1016/s0893-6080(00)00026-5.

Lautze, N., J. Taddeucci, D. Andronico, B. Houghton, A. Niemeijer, and P. Scarlato (2013). "Insights into explosion dynamics and the production of ash at Stromboli from samples collected in real-time, October 2009". *Understanding Open-Vent Volcanism and Related Hazards*. Volume 498. Geological Society of America, pages 125–139. ISBN: 9780813724980. DOI: 10.1130/2013.2498(08).

Longpré, M.-A. and A. Felpeto (2021). "Historical volcanism in the Canary Islands; part 1: A review of precursory and eruptive activity, eruption parameter estimates, and implications for hazard assessment". *Journal of Volcanology and Geothermal Research* 419, page 107363. DOI: 10.1016/j.jvolgeores.2021.107363.

Lowenstern, J. B., K. Wallace, S. Barsotti, L. Sandri, W. Stovall, B. Bernard, E. Privitera, J.-C. Komorowski, N. Fournier, C. Balagizi, and E. Garaebiti (2022). "Guidelines for volcano-observatory operations during crises: recommendations from the 2019 volcano observatory best practices meeting". *Journal of Applied Volcanology* 11(1). DOI: 10.1186/s13617-021-00112-9.

Ortega-Ramos, V., L. D'Auria, J. L. Granja-Bruña, I. Cabrera-Pérez, J. Barrancos, G. D. Padilla, P. Hernández, and N. M. Pérez (2024). "Evidence of a Low-Velocity Zone in the Upper Mantle Beneath Cumbre Vieja Volcano (Canary Islands) Through Receiver Functions Analysis". *Geophysical Research Letters* 51(9). DOI: 10.1029/2023gl105487.

Padrón, E., N. M. Pérez, P. A. Hernández, H. Sumino, G. V. Melián, M. Alonso, F. Rodríguez, M. Asensio-Ramos, and L. D'Auria (2022). "Early Precursory Changes in the 3He/4He Ratio Prior to the 2021 Tajogaite Eruption at Cumbre Vieja Volcano, La Palma, Canary Islands". *Geophysical Research Letters* 49(18). DOI: 10.1029/2022gl099992.

Pallister, J., P. Papale, J. Eichelberger, C. Newhall, C. Mandeville, S. Nakada, W. Marzocchi, S. Loughlin, G. Jolly, J. Ewert, and J. Selva (2019). "Volcano observatory best practices (VOBP) workshops - a summary of findings and best-practice recommendations". *Journal of Applied Volcanology* 8(1). DOI: 10.1186/s13617-019-0082-8.

Pankhurst, M. J., J. H. Scarrow, O. A. Barbee, J. Hickey, B. C. Coldwell, G. K. Rollinson, J. A. Rodríguez-Losada, A. Martín Lorenzo, F. Rodríguez, W. Hernández, D. Calvo Fernández, P. A. Hernández, and N. M. Pérez (2022). "Rapid response petrology for the opening eruptive phase of the 2021 Cumbre Vieja eruption, La Palma, Canary Islands". *Volcanica* 5(1), pages 1–10. DOI: 10.30909/vol.05.01.0110.

Piña-Varas, P., J. Ledo, P. Queralt, D. M. van Dorth, A. Marcuello, I. Cabrera-Pérez, L. D'Auria, and A. Martí (2023). "Volcanic monitoring of the 2021 La Palma eruption using long-period magnetotelluric data". *Scientific Reports* 13(1). DOI: 10.1038/s41598-023-43326-0.

Przeor, M., R. Castaldo, L. D'Auria, A. Pepe, S. Pepe, T. Sagiya, G. Solaro, P. Tizzani, J. Barrancos Martínez, and N. Pérez (2024). "Geodetic imaging of magma ascent through a bent and twisted dike during the Tajogaite eruption of 2021 (La Palma, Canary Islands)". *Scientific Reports* 14(1). DOI: 10.1038/s41598-023-50982-9.

Pyle, D. M. (1989). "The thickness, volume and grainsize of tephra fall deposits". *Bulletin of Volcanology* 51(1), pages 1–15. DOI: 10.1007/bf01086757.

Reyes-Hardy, M.-P., S. Biass, L. Dominguez, L. S. Di Maio, C. Frischknecht, C. Bonadonna, and N. Pérez (2024). "Temporal evolution of roof collapse from tephra fallout during the 2021-Tajogaite eruption (La Palma, Spain)". *Frontiers in Earth Science* 11. DOI: 10.3389/feart.2023.1303330.

Romero, J. E., M. Burton, F. Cáceres, J. Taddeucci, R. Civico, T. Ricci, M. J. Pankhurst, P. A. Hernández, C. Bonadonna, E. W. Llewellin, M. Pistolesi, M. Polacci, C. Solana, L. D'Auria, F. Arzilli, D. Andronico, F. Rodríguez, M. Asensio-Ramos, A. Martín-Lorenzo, C. Hayer, P. Scarlato, and N. M. Perez (2022). "The initial phase of the 2021 Cumbre Vieja ridge eruption (Canary Islands): Products and dynamics controlling edifice growth and collapse". *Journal of Volcanology and Geothermal Research* 431, page 107642. DOI: 10.1016/j.jvolgeores.2022.107642.

Sandoval-Velasquez, A., F. Casetta, T. Ntaflos, A. Aiuppa, M. Coltorti, M. L. Frezzotti, M. Alonso, E. Padrón, M. Pankhurst, N. M. Pérez, and A. L. Rizzo (2024). "2021 Tajogaite eruption records infiltration of crustal fluids within the upper mantle beneath La Palma, Canary Islands". *Frontiers in Earth Science* 12. DOI: 10.3389/feart.2024.1303872.

Sandoval-Velasquez, A., A. Rizzo, F. Casetta, T. Ntaflos, A. Aiuppa, M. Alonso, E. Padrón, M. Pankhurst, A. Mundl-Petermeier, V. Zanon, and N. Pérez (2023). "The noble gas signature of the 2021 Tajogaite eruption (La Palma, Canary Islands)". *Journal of Volcanology and Geothermal Research* 443, page 107928. DOI: 10.1016/j.jvolgeores.2023.107928.

Taddeucci, J., P. Scarlato, D. Andronico, T. Ricci, R. Civico, E. Del Bello, L. Spina, L. D'Auria, M. Asensio-Ramos, D. Calvo, E. Padrón, P. A. Hernández, and N. M. Pérez (2023). "The Explosive Activity of the 2021 Tajogaite Eruption (La Palma, Canary Islands, Spain)". *Geochemistry, Geophysics, Geosystems* 24(6). DOI: 10.1029/2023gc010946.

Ubide, T., Á. Márquez, E. Ancochea, M. J. Huertas, R. Herrera, J. J. Coello-Bravo, D. Sanz-Mangas, J. Mulder, A. MacDonald, and I. Galindo (2023). "Discrete magma injections drive the 2021 La Palma eruption". *Science Advances* 9(27). DOI: 10.1126/sciadv.adg4813.

Wadsworth, F. B., E. W. Llewellin, J. I. Farquharson, J. K. Gillies, A. Loisel, L. Frey, E. Ilyinskaya, T. Thordarson, S. Tramontano, E. Lev, M. J. Pankhurst, A. G. Rull, M. Asensio-Ramos, N. M. Pérez, P. A. Hernández, D. Calvo, M. C. Solana, U. Kueppers, and A. P. Santabárbara (2022). "Crowd-sourcing observations of volcanic eruptions during the 2021 Fagradalsfjall and Cumbre Vieja events". *Nature Communications* 13(1). DOI: 10.1038/s41467-022-30333-4.

Wertheim, D., B. Coldwell, L. Miyashita, I. Gill, S. Crust, R. Giddens, N. M. Pérez, N. Petford, and J. Grigg (2023). "Confocal microscopy 3D imaging and bioreactivity of La Palma volcanic ash particles". *Science of The Total Environment* 899, page 165647. DOI: 10.1016/j.scitotenv.2023.165647.

Zanon, V., L. D'Auria, F. Schiavi, K. Cyrzan, and M. J. Pankhurst (2024). "Toward a near real-time magma ascent monitoring by combined fluid inclusion barometry and ongoing seismicity". *Science Advances* 10(6). DOI: 10.1126/sciadv.adi4300.