Littoral activity in the lava deltas of 2021 eruption on Cumbre Vieja Volcanic Rift, La Palma (Canary Islands): constraints on explosive water-magma interaction

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Abstract

Tephra jets are a characteristic explosive phenomenon of lava deltas built by pāhoehoe or ʻaʻā lava flows. Field observations made during the growth of the 2021 South Lava Delta (La Palma island), emplaced under a 100–150 m high marine cliff, show tephra jets driven by penetration of seawater through the external lava breccia into the interior of ʻaʻā lava flows entering the ocean. However, this littoral explosive activity was weak and very scarce throughout the entire period of delta emplacement, a circumstance that seem to have concur in other ʻaʻā lava deltas also emplaced under high marine scarps. Main constraint to explosive activity in these coastal settings seem to be the slow penetration into the ocean of ʻaʻā lava flows, which is clearly induced by coastal morphology, as lava abruptly slows and accumulates on the flatter abrasion platform after flowing on ramps of lava debris down the marine cliff.

Resumen

Los *tephra jets* son un fenómeno explosivo característico de los deltas de lava pāhoehoe o ʻaʻā. Las observaciones de campo realizadas durante el crecimiento del Delta Lávico Sur (2021), emplazado bajo un acantilado marino de 100–150 m de altura, muestran *tephra jets* originados por la penetración de agua de mar a través de la capa externa de brechas autoclásticas en el interior de coladas 'a'ā. Sin embargo, esta actividad explosiva litoral fue débil y muy escasa durante todo el periodo de emplazamiento del delta, circunstancia que parece haber concurrido en otros deltas de lava similares. La principal limitación a la actividad explosiva en estos entornos costeros parece ser la lenta velocidad de penetración en el océano de las coladas 'a'ā, fenómeno claramente inducido por la morfología costera, ya que las lavas, después de fluir sobre el acantilado marino, desaceleran abruptamente y se acumulan en la plataforma de abrasión.

1 INTRODUCTION

Lava deltas originated from pāhoehoe or ʻaʻā lava flows entering the ocean are a common feature at oceanic island volcanoes (Skilling 2002; Ramalho et al. 2013; Smellie et al. 2013). These coastal emerged platforms are built on volcanic shores of very different morphology, both on low-lying coastal areas and at the base of marine cliffs from a few meters to >100 m high.

When hot lava and much colder sea water mix in active lava deltas, littoral explosive activity can occur. The hazard associated with these phenomena is usually limited to the nearest surroundings (several hundred meters; Poland and Orr 2014). Nonetheless, there have been events in which several people have been killed or seriously injured by inhaling harmful gases or being hit by ballistic projectiles (Johnson et al. 2000; Soule et al. 2021). Hydrovolcanic explosions are widely documented in lava deltas built on flat coasts, but not in their counterparts under high marine scarps, where lava flows from vents located above the cliff edge experience collapsing or pouring from considerable height.

A monogenetic fissure eruption began on 09/19/2021 at Cumbre Vieja Volcanic Rift, La Palma (Canary Islands). It started at an approximate height of 925 m a.s.l. with amphibole-bearing tephrite lavas and tephra emitted along a main NW-SE eruptive fissure with multiple vents, soon developing in a single large cone. Magma emission abruptly stopped for a few hours in the early morning of September 27 (Figure 1A). Activity resumed in the late afternoon with lava fountains, Strombolian explosions and fast lava flows of pyroxene-olivine-rich basanite, which persisted until the end of the eruption on 12/13/2021 (Day et al. 2022). Two ʻaʻā lava deltas were formed when some of these basanitic lava flows descended over a marine cliff about 100–150 m high (Sáez-Gabarrón et al. 2024;

Figure 1B). The southernmost delta (~0.76 km^2), whose leading edge is approximately 1.7 km long, is much larger than the northern one (~0.06 km^2).

This report describes the occurrence of at least one episode of low-intensity littoral explosive activity in the South Lava Delta of the Cumbre Vieja 2021 eruption. Main characteristics of the littoral activity and lava flow conditions during the episode are described, followed by a brief assessment of the role that coastal morphology plays in restricting explosive activity in ʻaʻā lava deltas built at the foot of high marine cliffs.

2 GEOLOGICAL BACKGROUND

The marine cliff under which the two lava deltas were built is the result of wave erosion on the hard volcanic rocks of the western flank of the active Cumbre Vieja Rift. Cumbre Vieja is a N-S trending volcanic edifice ~20 km long and of 1949 m of maximum height above sea level. This volcanic rift constitutes the southern and younger portion of the island of La Palma (Ancochea et al. 1994; Klügel et al. 2017). The age of the subaerial part of the rift spans from ~123 ka and present day (Carracedo et al. 2001). Lavas and pyroclastic deposits cut by the escarpment were emplaced before the last glacial maximum, when the sea level was >100 m below the current one, and therefore are >20 ka in age. The lavas aged <20 ka that reached the coastline, including those emitted by seven of the eight eruptions of historical age in the rift (from 15 century CE to present; Figure 1A), built deltas at the foot of the scarp (Carracedo et al. 2001).

Before the emplacement of the 2021 South Lava Delta, a coastal platform of erosive-sedimentary origin and variable width extended at the foot of the cliff (Figure 2). In the northern and central sectors of the coastline invaded by the lava, the coastal platform consisted of a sand and cobble beach (Playa de la Galería) ~20 m wide at medium tide, and a submerged abrasion platform ~30 m deep and ~500 m wide; the offshore limit of this submerged platform is the steep slope of the island submarine flank. However, in the southern sector, an accumulation of cobbles and blocks extended backshore for ~100 m of maximum width between the foot of the escarpment and the existing sandy beach, called Playa de los Guirres. This beach was adjacent to an older delta, built by lavas from the northernmost vents of the 1949 CE eruption of the San Juan volcano (Figure 2).

3 METHODS AND MATERIALS

The field observations of the eruption on which this report is based have been complemented with video images (including thermal videos) obtained in drone flights that several public and private entities performed for PEVOLCA (Volcanic Emergency Plan of the Canary Islands), the administration body responsible for the management of the eruptive crisis. These videos, which cover virtually every day of the eruption, are available on the websites https://riesgovolcanico-lapalma.hub.arcgis.com/pages/multimedia and https://info.igme.es/eventos/Erupcion-volcanica-la-palma/videos. Additional data have been obtained from lava cartography performed daily by Cabildo de La Palma and Instituto Geológico y Minero de España (IGME-CSIC), which can be consulted through the IGME online viewer at https://info.igme.es/visor/?Configuracion=Enjambre-Terremotos-La-Palma&Extension=-17.93,28.57,-17.82,28.65,4326. Other on-line resources also used as photographs and reports can be consulted in https://volcanico-lapalma.hub.arcgis.com/pages/multimedia; https://info.igme.es/eventos/Erupcion-volcanica-la-palma and https://www.ign.es/web/vlc-serie-palma.

4 RESULTS

4.1 The development of the South Lava Delta

The tephritic and first basanitic lava emissions produced unconfined flows of ‘a‘ā or blocky lava that moved at velocities <1 m/min and stopped even on steep slopes (Carracedo et al. 2022). However, from at least October 2, a more complex lava flow behavior could be observed from the aerial video footage. This behavior induced the development of a braided system of lava channels and tubes, with advancing and branching ‘a‘ā lava flows and occasional pāhoehoe flows, mainly from overspills of lava channels. This system thermally insulated the lava flows, thus allowing a rapid transport to the coastline located 4.5 km away, with velocities exceeding 30 km/h (~8 m/s) in some lava channels. Vent reorganization and repeated episodes of overflow of lava channels led to the development of many flow fronts that gradually widened the lava field.

Once the lava flows reached the top edge of the marine cliff, they began to fall down over the scarp, experiencing a variable amount of fragmentation. Soon the lava debris built a complete ramp whose slope was about half the original slope of the cliff (~80º to ~40º), connecting the foot and the top of the scarp. Once this ramp was developed, the lava flowed in an almost continuous mode over it and started to spread over the submerged abrasion platform, expanding forward and laterally in a subaerial fan.

The evolution of the delta is depicted in a simplified way in Figure 3. The first of the lava falls down the cliff occurred on September 28 at 24:00 UTC (https://www.youtube.com/watch?v=6qgA3ZMYEto&list=PLJtsQppXs2YncCal7GP24nYUMLKiE9wf-&index=58), only one day after the eruptive pause. This first episode was followed by many other discontinuous arrivals of basanitic lava flows. Some of the later lavas originated new ramps on the cliff; other flowed down previous ramps and on the surface of the growing lava delta before reaching the ocean. These successive episodes originated a composite structure, result of the coalescence of three littoral lava platforms that grew separately, expanding laterally to finally merge (Figures 3A, 3B and 3C). Delta-forming lava flows widened and thickened considerably when they reached the foot of the marine cliff. The emerged portion of active flow fronts reached up 5 to 10 m in height at the edge of the delta; maximum emerged thickness of the delta is 35–40 m. At the same time, they experienced a remarkable deceleration. The maximum subaerial penetration of lava flows into the ocean was about 500 m. The growth of the South Lava Delta was maintained until the end of the eruption.

4.2 Littoral explosive activity in the South Lava Delta

Viscosities as low as 10 to 160 Pa·s have been experimentally estimated for some near-vent lavas emitted around mid-November (Castro and Feisel 2022). These figures were assessed as an underestimation by Gisbert et al. (2022), who estimated the minimum effective viscosity of lavas emitted during the 2021 eruption in 168–253 Pa·s. Regarding the apparent viscosity of distal lava flows reaching the top of the marine cliff, from video and field observations the apparent viscosity of the less mobile flows can be crudely estimated between $1 \cdot 10^5$–$1 \cdot 10^6$ Pa·s using Jeffrey's (1925) method. The arrival to that point of lavas of viscosity in the range estimated by Gisbert et al. (2022) for proximal flows seems to be an exceptional event throughout the 85 days of eruption. In fact, from our own observations and the review of the available data we document only one occasion when this circumstance occurred, coincidently on November 16, although some other similar episode cannot be ruled out. The video of that day's drone flight from Cabildo de La Palma, shot at 13:00 UTC (https://youtu.be/jxMSeHhvG6A), shows the presence of very fluid and hot lavas, with a yellow to red incandescent liquid surface and with only a very incipient and discontinuous solid crust, flowing westward from the base of the main volcanic edifice through a complex system of large tubes and channels. Above the top of the marine cliff, overflows or totally inactive flows of these lavas showed pāhoehoe morphologies once solidified. Near the southern fringe of the lava field, at a point situated 1.6 km from the upper edge of the cliff (UTM 28R 215820, 3168528; 285 m above sea level), two lava spills occurred, from what seems to be the lower end of two volcanic tubes (https://youtu.be/jxMSeHhvG6A?t=706). In the southernmost of these spills began a braided flow, whose main channel was about 15–20 m of maximum width. According to our field observations made at 15:00 UTC from a nearby (~2 km away) point on the coastline (213992, 3167808; point 1 in Figure 3D), this high-mobility lava flowed down the scarp over a well-developed ramp (214451, 3167808; point 2 in Figure 3D), drifting northward through an open channel about 10 m wide, at a speed of approximately 5 m/s. Therefore, if a rectangular section and a depth of 1–2 m are assumed for the open channel, the volumetric rate can be estimated at 50–100 m^3/s (Figure 4A; see also Supplementary Video 1).

The observation of this flow on the delta was greatly impeded by the steam plume emitted from the entry point of lava into the ocean (213872, 3167997; point 3 in Figure 3D); this point, along with the lava down flow in the scarp, were the only flow sectors visible from the observation point at the coast. It was evident, however, that the lava flow changed direction on the delta to the west following a path of almost 400 m until it entered the sea. During the movement on the delta the flow widened and presumably thickening, and also developed an auto-brecciated crust. Flow deceleration was patent at the ocean entrance; despite this, the seaward advance of the lava was still perceptible to the naked eye. Flow speed at that point can be very roughly estimated at 2–10 m/min. Lava penetrated into the ocean as a massive ‘a‘ā flow ~100 m width (Figure 4B), although the littoral explosive activity were only visible in a reduced sector of the flow section (<25 m in width). Unfortunately, we do not have surficial temperature measurements of this lava flow. From the measuring range of the thermal camera that recorded a non-published additional aerial drone thermal video of the South Lava Delta at 13:00 UTC on November 16 (Figure 5), we can only state that the surficial temperature of the lava flowing down the ramp was higher than 850ºC.

The ocean entrance of the lava was accompanied by the formation of a large gas plume in which vertical steam jets containing dark particulate matter was observed (Figure 4C; see also Supplementary Video 2). These jets, up to 10 m high, included lava fragments of diameter >10 cm that were projected to a maximum of 10–15 m away, following ballistic trajectories until falling into the sea and often leaving traces of white steam behind them. Some lava fragments showed very slow flight speeds, suggesting that their density was low, but nevertheless they sank immediately upon reaching the water. Gas and lava fragments jets had a pulsating character, with an observed duration of a few seconds to 12–13 seconds of sustained activity. The height reached was directly proportional to duration of the jets.

Offshore of the entry point, an area of anomalous coloration and turbidity of seawater was observed. The location of the observation point, 225 m away the entry point, did not allow a clear appreciation of the shape and extent of this body of colored seawater. However, it is clearly visible as an ample heated water mass in the aforementioned thermal video, which shows that the hot water plume extended more than 400 m offshore (labelled 1 in Figure 5). An area of darker water was apparent just in front of the entry point (labelled 2 in Figure 5), surrounded by two diffuse plumes of greenish-brown water, whose innermost edge produced a large amount of steam (Figure 4B).

From our own observations and the checking of the abundant published footage, the occurrence of other possible episodes of weak littoral explosions seems to have been very scarce during the growth of the two lava deltas of the 2021 eruption. This situation of no littoral explosivity was recorded even when there were several active flows of incandescent lava flowing down the escarpment and entering the ocean, as illustrated by the aerial drone videos recorded by Instituto Español de Oceanografía (CSIC-IEO) on October 2 (https://youtu.be/k7sxyaWxr_k;

https://youtu.be/noCxXfztnrg; https://youtu.be/pZH_WBqVaYM) and IGME on November 10 (https://youtu.be/HZKp7YBWZ_0). A similar but slightly weaker explosive phenomenon, consisting of the aerial projection of lava fragments wrapped in steam, seems to be recorded by a later drone flight around 13:30 UTC on November 22 (https://youtu.be/cfuupnMEL78), which records the first moments of the development of the North Lava Delta. However, the resolution of this video published by Cabildo de La Palma does not allow to appreciate the process clearly. Hyaloclastites less than 1 mm in size were reported 1.5 km onshore the same day. These hyaloclastites were blown inland by the wind together with large steam plumes. In general, aerial dispersion of these particles seems to have been limited.

5 DISCUSSION

Only weak and very infrequent littoral explosive activity was observed during the emplacement of the two ʻaʻā lava deltas of the 2021 La Palma eruption. Similarly, no littoral activity was reported in the well-monitored eruption of Teneguía in 1971 CE (Figure 1A), in which analogous ʻaʻā lava deltas were emplaced at the foot of the ~200 m high marine cliff in the southern tip of the W flank of Cumbre Vieja Rift (Afonso et al. 1974).

Moreover, littoral explosive edifices and deposits in deltas built at the foot of high marine cliffs by ʻaʻā lavas flowing down the scarp seem to be rare not only in La Palma and the rest of the Canaries, but also in other volcanic islands. In Açores, for example, where such lava deltas are relatively common, very few examples of littoral explosive activity are known, the littoral cone in Ponta da Ferraria lava delta (Sao Miguel island) being the best preserved (Lima et al. 2017). Our observations suggests that the scarcity of examples is due not only to the poor conservation of explosive littoral deposits in the unfavorable coastal environment, but also to the fact that the conditions for littoral explosions are rarely achieved in this kind of deltas.

One of the best documented examples of the explosive interactions of ocean water and lava were described in the Kamoamoa delta, built in 1992-1994 by pāhoehoe lavas fed by volcanic tubes during the eruption of Pu'u 'Ō'ō in the East Rift Zone of Kīlauea Volcano, Hawaiʻi (Mattox and Mangan 1997). Four types of explosive events were described: tephra jets, lithic blasts, lava bubble bursts and littoral lava fountains. Tephra jets were the most common and the most similar to that observed on November 16 in South Lava Delta of Cumbre Vieja 2021 eruption. The phenomenon consisted of the violent expulsion of jets of tephra and steam ≥40 m high. They were produced when the collapse of the leading edge of the delta, or the detachment of part of its shallow submerged crust, caused a sharp increase in the contact surface between waves-driven water and lava flowing inside a tube, and their mixing in unconfined environmental conditions (open mixing). Tephra jets in the South Lava Delta also took place in an unconfined environment. However, the explosive interaction in the South Lava Delta seems to have occurred when seawater penetrated through the external layer of loose autoclastic breccia, perhaps partially removed by the impact of the waves, to the much hotter interior of the ‘a‘ā lava flowing in an wide open channel.

It is generally assessed that conditions for lava-water interaction generated during these entries into the ocean of ‘a‘ā lava flows fed by open channels favour higher-intensity explosive activity compared with those generated by tube-fed pāhoehoe lavas (Macdonald 1972, Jurado-Chichay et al. 1996a). The generation of littoral explosions in ‘a‘ā lava flows could be enhanced by the fragmentary nature of their surface, since they allow water an easy access to the hot interior of the flow (Macdonald 1972). It could also induce a more efficient water-magma premix (Mattox and Mangan 1997).

Mattox and Mangan (1997) suggested tephra jets of long persistence and high explosive energy as the formation mechanism of littoral cones of historical age in Hawai‘i produced by transitional and ‘a‘ā lava flows (Moore and Ault 1965; Fisher 1968; Macdonald et al. 1981). These cones can reach considerable sizes (450 m in diameter and 100 m in height) and contain a high percentage of fragments of fine size (minor lapilli and bombs and up to 90% volume of coarse ash; Holt et al. 2021). The high energy of the hydrovolcanic explosions needed to build those large littoral cones in ‘a‘ā flows has been linked with their high flow volumetric rate and flow velocity into the sea (Jurado-Chichay et al. 1996b), which has been estimated from data compiled by Rowland and Walker (1990) at one to two orders of magnitude greater than the pāhoehoe flows at Kamoamoa delta (≥4 m^3/s from tubes with an average diameter of 3 m, which implies flow velocities ≥0,57 m/s; Mattox and Mangan 1997).

This roughly coincides with our estimations for the lava flowing down the ramp on November 16 in the South Lava Delta (velocity of 5 m/s and flow rate of 50–100 m^3/s). From the morphology and thermal signature of the flow on the delta, it can be assumed that this high volumetric rate was approximately the same at the entry point in the ocean and in the underwater portion of the lava flow. This is also suggested by the observed abnormal coloration and the steam emission due to high temperature ocean water offshore the entry point, including the darker water area produced by the convective rise of heated water from the seafloor (see Realmuto et al. 1992). However, flow velocity seems to have been much lower at the ocean entrance along the section where littoral activity was observed (≤0,17 m/s). This implies that the amount of hot lava newly exposed to the water (i.e. the rate at which heat was transferred from lava to water) at any time in any point of the flow front was also more reduced than those estimated for historical ‘a‘ā lava flows entering the ocean at Hawai‘i coast.

In fact, the even slower penetration into the ocean most frequently observed in the ‘a‘ā lava flows that built the South Lava Delta seems to be the main constraint to explosive lava-water interaction in these coastal settings. In part this fact can be the result of increased cooling rate at the flow fronts due to water ingestion, but is also clearly induced by coastal morphology, as lava abruptly slows and accumulates on the low-slope abrasion platform after a rapid flowing on ramps of lava debris down the marine cliff. Except for highly mobile flows like the one observed on November 16, the seaward advance on the coastal platform is usually so slow that the amount of hot lava newly exposed to the water within a small area at any instant is insufficient to generate an explosive interaction, so only variable amounts of saturated steam are emitted passively into the atmosphere.

Other lava entry styles that can trigger littoral activity were not observed by us or have been reported during the growth of the South Lava Delta. It is the case of events in which large amounts of molten lava suddenly come in contact with seawater by the exposing of a lava conduit interior during a seaward collapse of the lava delta bench (Poland and Orr 2014, Neal and Anderson 2020). ‘A‘ā lava deltas seem to be much less prone to collapse than their pāhoehoe counterparts. ‘A‘ā lava flows penetrating into the water maintain their structure and cohesion more so than pāhoehoe lavas. They are not subjected to much quenching as pāhoehoe, and their greater thickness and flow rates slow the freezing effect of rapid cooling, allowing them to travel further below the waterline (Stevenson et al. 2012; Smellie et al. 2013, Bosman et al. 2014). ‘A‘ā lava flows also show consistently lower underwater dips than submarine pāhoehoe lava or hyaloclastite sets in pāhoehoe lava deltas (Skilling 2002; Smellie et al. 2013), and they construct deltas by aggradation rather than progradation (Ramalho et al. 2013). Thus, the structure of deltas built by ‘a‘ā lava flows is much more stable, particularly on low-slope abrasion platforms.

6 CONCLUSIONS

Following observations made in Cumbre Vieja 2021 eruption, weak littoral explosive activity of the type known as tephra jets can occur in ‘a‘ā lava deltas built under high marine cliffs when seawater penetrates through the external layer of loose autoclastic breccia, perhaps partially removed by the impact of the waves, to the much hotter interior of the lava flows. However, this process is greatly impeded by the immediate deceleration of the lava on the low-slope abrasion platform after flowing down the marine scarp, which increases the section and substantially reduces the velocity of the flows entering the ocean. Littoral activity driven by sudden exposing of active lava flow interiors to the water is precluded by the higher stability of these ‘a‘ā lava deltas, which makes them much less prone to collapse than pāhoehoe lava deltas. In these conditions, littoral explosive activity is not expected in ‘a‘ā lava deltas built under high marine cliffs, except if very hot and mobile flows, with also a high volumetric rate, are able to reach the foot of the coastal escarpment.

In basic/ultrabasic subaerial fissure eruptions on oceanic island environments, lava flows can produce physical phenomena (e.g. infrastructure demolition and burial) which pose widespread hazards of much concern for emergency planners and managers. However, this is not the case for explosive activity in this type of lava deltas, which foreseeable mechanical effects are strictly local and extend only a few tens of meters around the entry points of active flows into the ocean.

Author contributions

All authors contributed to the study conception and design. Data collection and geological observations were performed by J.J. Coello-Bravo, R. Herrera, E. Ancochea, and I. Galindo. Data analysis were performed by all authors. The first draft of the manuscript was written by J.J. Coello-Bravo and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The authors declare that the observational data supporting the conclusions of this study are available within the article and the supplementary material, and they can be freely accessed through the web pages referred in the text. Supplementary Video 1 and Video 2 can be viewed and downloaded in Zenodo open access repository at https://doi.org/10.5281/zenodo.12583727 .

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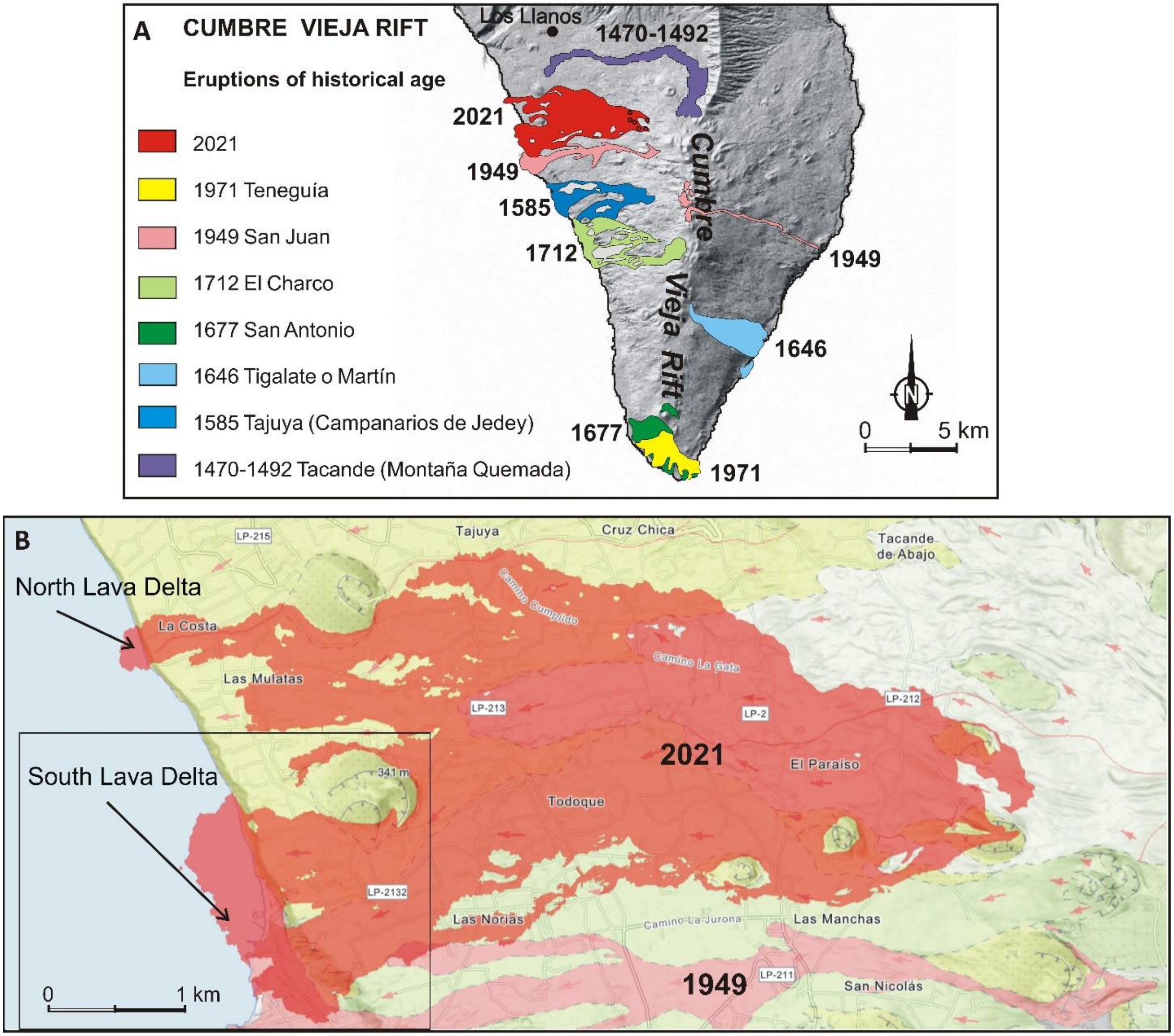

Figure 1: Volcanic setting of 2021 eruption at Cumbre Vieja Rift. [A] Map of historical (from 15 century CE to present) eruptions of Cumbre Vieja. Modified from Hernández-Pacheco and Valls (1982) and Longpré and Felpeto (2021). [B] Map of the lava field of 2021 eruption (in red), including the two lava deltas formed. The box corresponds to the area depicted in Figure 2 and 3.

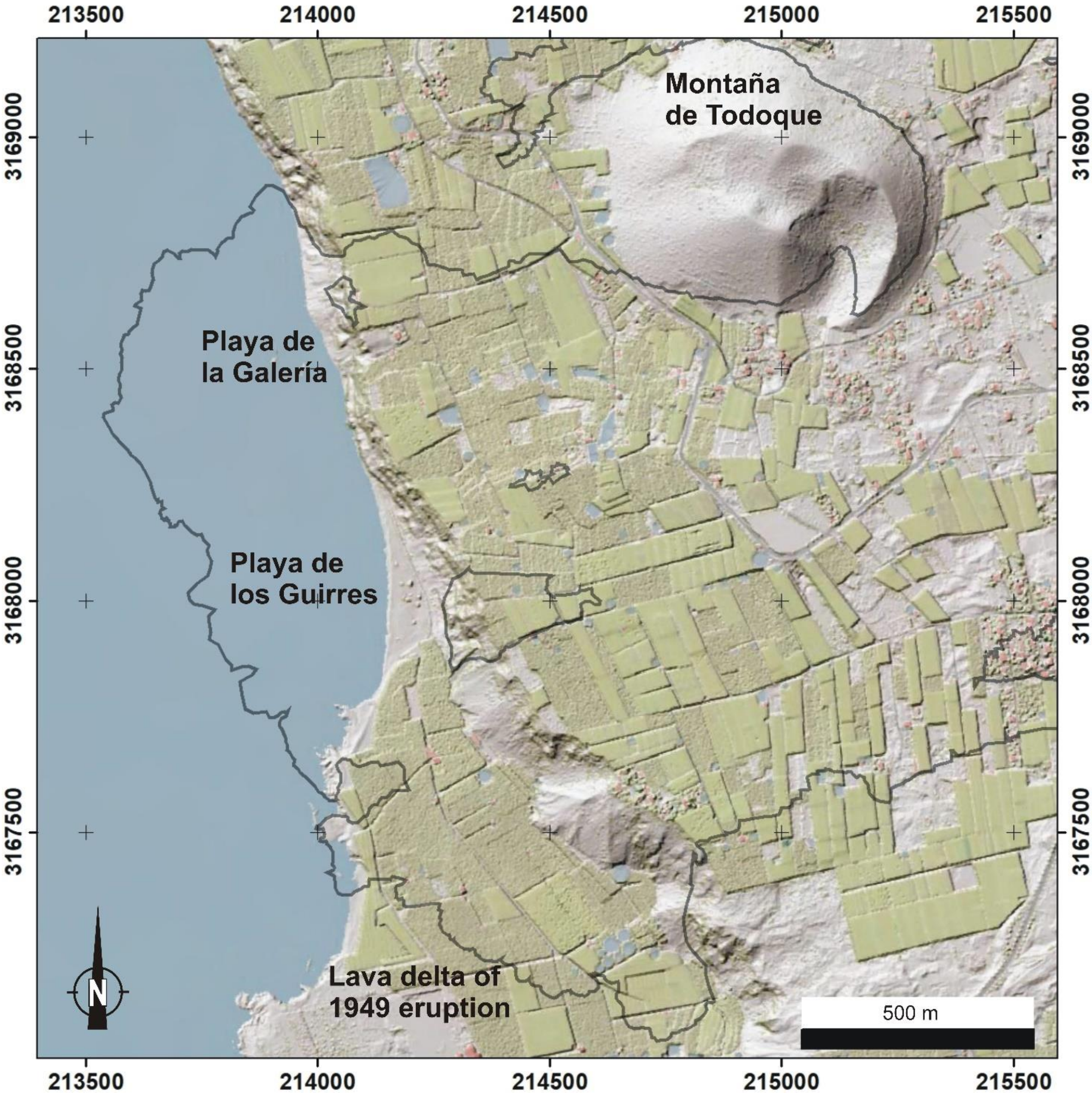

Figure 2: LiDAR-derived shaded relief image of the pre-eruptive littoral setting where the 2021 South Lava Delta developed, with indication of places referred to in the text. Solid line is the South Lava Delta final contour.

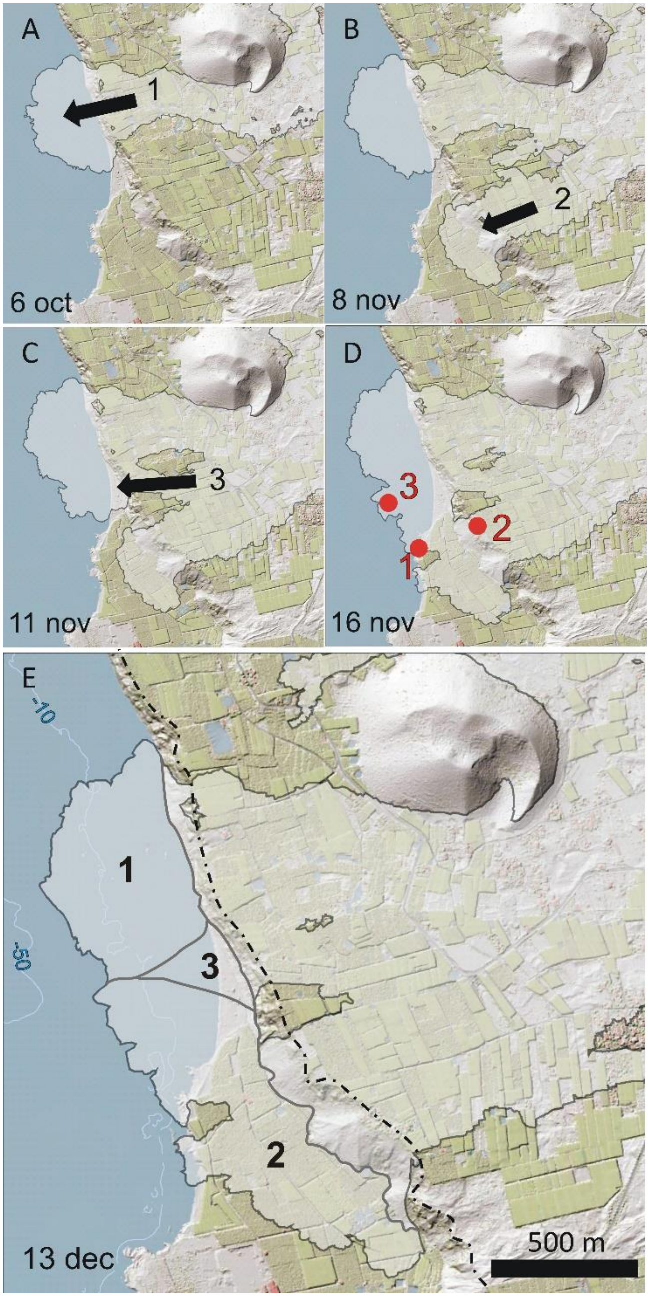

Figure 3: South Lava Delta growth reconstructed from IGME maps (https://info.igme.es/visor/). [A], [B], [C] Numbered arrows indicate the approximate provenance and trajectory of the different lava flows that successively built the three separate coastal lava platforms that finally merged in a single delta. [D] Numbered red dots are the observed locations on November 16 mentioned in the text: 1) point of observation; 2) point of fall of the active lava flow at the upper edge of the sea cliff; 3) entry point of the active lava flow into the sea. [E] Area of the South Lava Delta at the end of the eruption. The approximate final contour of the three lava platforms merged to build the delta

(labelled from 1 to 3 following the order of the date in which they began to grow) is shown. Dashed and dotted line marks the upper edge of the sea cliff; white lines are the -10 m and -50 m isobaths.

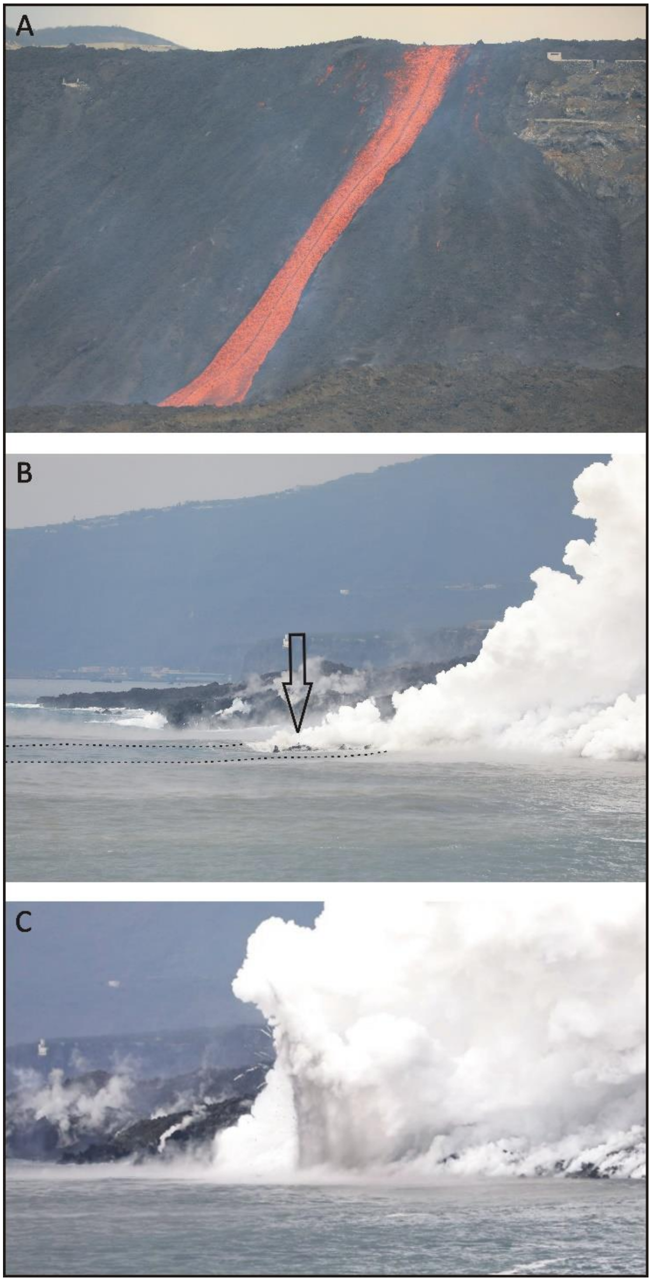

Figure 4: [A] Very low viscosity lava flowing down the sea cliff inside an open channel on November 16 (see also Supplementary Video 1). [B] Sea entry point of the same active lava flow. Note the large and dense aerial steam plume and the roughly circular area of anomalous coloration and turbidity of seawater around the entry point. In

front of it, an area of darker water is surrounded by a greenish-brown body of water whose inner edge (indicated by the dashed line) emits abundant steam. Large autoclastic fragments in the partially submerged top of the lava flow penetrating the sea, pointed by the arrow, are also visible. [C] Tephra jets of steam and lava fragments at the entry point. Note the ballistic projectiles with traces of white steam behind (see also Supplementary Video 2). All pictures taken from the south of the entry point.

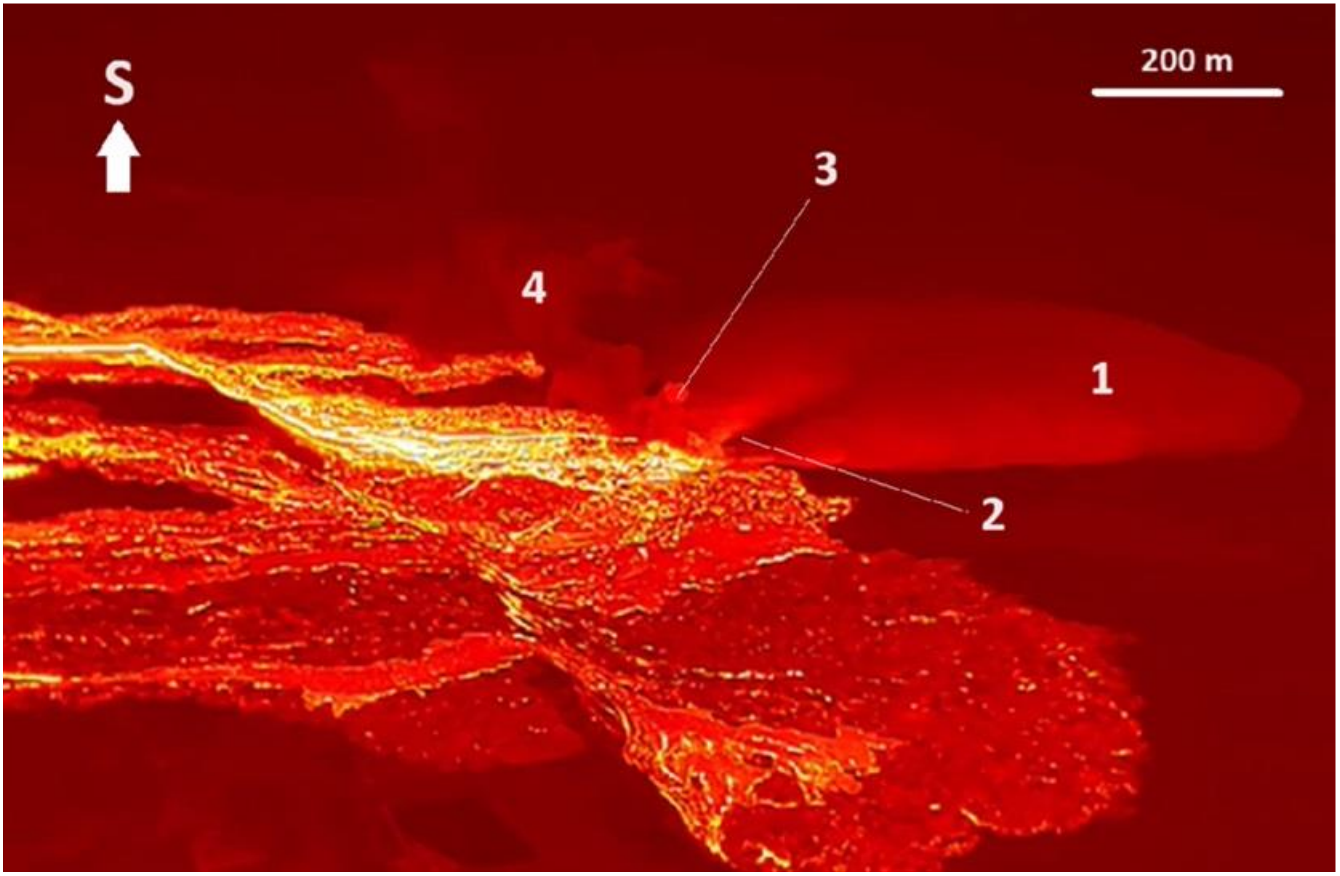

Figure 5: Aerial thermal image of South Lava Delta from a drone video recording on November 16 at 13:00 UTC. High mobility lava flowing down the marine cliff and on the delta inside an open channel is visible as a high-temperature (yellowish) elongated area. 1) Heated ocean water plume offshore the entry point of the lava flow. 2) Colder water area near the entry point in the central part of the plume. 3) Steam and tephra jets emitted at the ocean entry point. 4) Steam plume.