

Feature

The 2021 eruption of the Cumbre Vieja volcanic ridge on La Palma, Canary Islands

Almost exactly half a century after the eruption of the Teneguía Volcano on La Palma (26 October to 28 November 1971), a new eruption occurred on the island and lasted for 85 days from 19 September until 13 December 2021. This new eruption opened a volcanic vent complex on the western flank of the Cumbre Vieja rift zone, the N-S elongated polygenetic volcanic ridge that has developed on La Palma over the last c. 125 ka. The Cumbre Vieja ridge is the volcanically active region of the island and the most active one of the Canary Islands, hosting half of all the historically recorded eruptive events in the archipelago. The 2021 La Palma eruption has seen no direct loss of human life, thanks to efficient early detection and sensible management of the volcanic crisis by the authorities, but more than 2800 buildings and almost 1000 hectares of plantations and farmland were affected by lava flows and pyroclastic deposits. Satellite surveillance enabled accurate mapping of the progressive buildup of the extensive and complex basaltic lava field, which together with monitoring of gas emissions informed the timely evacuation of local populations from affected areas. Lava flows that reached the sea constructed an extensive system of lava deltas and platforms, similar to events during earlier historical eruptions such as in 1712, 1949 and 1971. Long-term challenges in the aftermath of the eruption include protection of drainage systems from potential redistribution of tephra during high rainfall events, the use of the large surplus quantities of ash in reconstruction of buildings and in agriculture, and the crucial concerns of where and how rebuilding should and could occur in the aftermath of the eruption. Finally, there remain strong financial concerns over insurance for properties consumed or damaged by the eruption in the light of future volcanic hazards from the Cumbre Vieja volcanic ridge.

Volcanic activity on La Palma has been exclusively centred on the southern part of the island in the last 125 ka, especially along the Cumbre Vieja volcanic ridge (Fig. 1). This most recent stage of La Palma's evolution has produced a 20 km long, 1950 m high N-S-trending rift volcano, with a surface area of 220 km². Along this ridge, eruptive vents and fissures align with the volcano's crest to form a characteristic ocean island rift zone, locally known as a 'dorsal' (Fig. 1a). The majority of the volcanism on the Cumbre Vieja rift volcano comprises silica undersaturated basaltic and alkali basalt, although volumetrically minor

evolved differentiates such as phonolites are also found along the ridge. Most of the recent and historical volcanic emission centres concentrate along the Cumbre Vieja rift, which continues offshore for another 20 km beyond the southern tip of the island, forming a chain of young and recently active submarine volcanoes.

Previous eruptions of the Cumbre Vieja include seven out of the 14 historical (witnessed and documented) eruptions recorded in the Canary Islands, making the Cumbre Vieja rift zone statistically the most probable site for future volcanic activity in the archipelago (Table 1). The sketch in Fig. 1(b) shows



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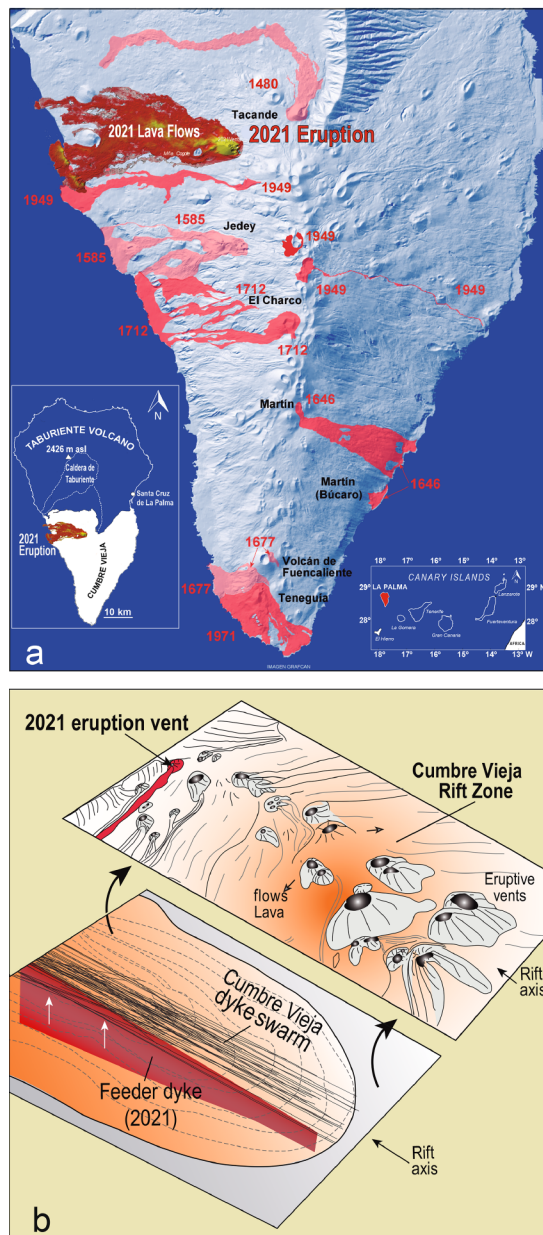


Fig. 1. a. The Cumbre Vieja rift zone forms the southern half of the island of La Palma (see inset) and is the volcanically most active region in the Canary Islands. It produced more than half of all the archipelago's historical eruptions (i.e. over approximately the last 500 years; see Table 1). b. The Cumbre Vieja volcanic ridge was constructed in the last 125 000 years and is composed of a densely packed, N–S aligned cluster of cinder cones and their corresponding lava flows that are predominant on the ridge flanks. The internal structure below the cinder cones is composed of a dense dyke swarm, many of the dykes representing the feeder conduits of past eruptions.

the internal structure of the Cumbre Vieja rift zone as has been envisaged by Carracedo and coauthors in 2001, on the basis of eroded rift systems on the older island of Tenerife. Below the aligned cinder cones and their associated deposits on the surface, the core of the rift zone is made up by a tightly packed dyke swarm that represents the feeder conduits to the surface vents and cinder cones. Intrusion of one such dyke, or possibly a series of dykes, in early September 2021 led to the opening of an eruptive vent at a few minutes after 1400h local time on 19 September 2021 in the Cabeza de Vaca area on the western flank of the Cumbre Vieja ridge (Fig. 2).

The 2021 eruptive activity occurred almost exactly 50 years after the 1971 Teneguía eruption that took

place at the southern tip of the Cumbre Vieja ridge and near the western lava flows and vents of the preceding 1949 eruption (see Fig. 1a). The most recent 2021 eruption was preceded, since 2017, by relatively deep (25–35 km) but low magnitude seismic activity, with the eruption itself taking place after a week of intense seismic unrest and ground deformation in mid-September 2021, leaving only a very limited time window for coordinated disaster mitigation and civil protection measures. The area affected by the 2021 eruption consists of a gently sloping plain on the lower flanks of the Cumbre Vieja, at an altitude of ~1000 m asl, in an area that is relatively densely populated. This topography resulted from previous voluminous pre-historic eruptions, such as the Birigoyo Volcano (dated at 6 ± 2 ka) that smoothed the local terrain, contrasting with the steeper slopes of the southern part of the Cumbre Vieja ridge (Fig. 2). In addition, the northern region of the Cumbre Vieja preserves a shallow-marine abrasion platform that is absent in the southern part of the ridge. This platform is connected to the Last Glacial Maximum (LGM), which occurred ~20 ka. The LGM corresponds to the stage when the continental ice sheets reached their maximum total mass during the last ice age, and the global sea level was 120–135 m lower than at present, allowing the shallow fringe of this coastal abrasion platform to form. This was discussed in detail by Carracedo and coworkers in 2001, realizing that in the marginal portions of the Cumbre Vieja, the LGM abrasion platform now provides a shallow submarine substrate on which recent lavas can form characteristic lava deltas or platforms, such as the 1712, 1949 and 1971 eruptions, and now also the most recent 2021 eruption.

Timeline of the 2021 eruption

The 2021 La Palma eruption classifies as a basaltic fissure type eruption, dominated by strombolian activity and with episodic phreatomagmatic pulses. The eruption, opened several vents as it progressed, ultimately building up a sizable cinder cone and an extensive lava flow field. This newly formed volcanic structure is about 200 m high from its base, with a total altitude of 1131 m asl and six major craters on its top define the main ~560 m long NW–SE eruptive alignment (Fig. 3).

Throughout the eruption, the intensity of the explosive activity was reflected through the eruptive column that was typically around 3500 m asl, although peaks of higher column height occurred, with a maximum height of 8500 m recorded on December 13. The plume height together with a volume of emitted pyroclastic material of about 45 million m^3 (total pyroclastic deposits and lavas together exceeded 200 million m^3), and the characteristics of the eruption define the event as a VEI3 on the Volcanic Explosivity Index.

During the eruption, fine lapilli and ash were an almost constant eruption product and thickly man-

Table 1. Some features of Canary Islands historical eruptions (last 500 years)

Year	Island	Eruption	Seismic precursors	Duration onset-end	Days
1492	Tenerife	Boca Cangrejo ^a			
1585	La Palma	Jedey/Tajuja	~50 days	19 May–10 Aug	84
1646	La Palma	Martin/Tigalate	~1 day	1 Oct–21 Dec	82
1677–1678	La Palma	Fuencaliente	~4 days	17 Nov–21 Jan	66
1704–1705	Tenerife	Siete Fuentes	~1 month	31 Dec–5 Jan	66
		Fasnía		5–15 Jan	10
		Arafo		2 Feb–27 Mar	53
1706	Tenerife	Garachico	~1 year	5 May–13 Jun	39
1712	La Palma	El Charco	~5 days	9 Oct–3 Dec	56
1730–1736	Lanzarote	Timanfaya	~6 years	1 Sep 1730–2 Apr 1736	2041
1798	Tenerife	Chahorra	~3 years	9 Jun–15 Sep	99
1824	Lanzarote	Tao	~11 years	31 Jul–1 Aug	2
		Nuevo		29 Sep–5 Oct	7
		Tinguatón		16–24 Oct	9
1909	Tenerife	Chinyero	~2 years	18–27 Nov	9
1949	La Palma	San Juan	>2 years	24 Jun–30 Jul	37
1971	La Palma	Teneguía	>1 month	26 Oct–18 Nov	24
2011–2012	El Hierro	Tagoro ^b	>4 years	10 Oct–15 Feb	129
2021	La Palma	Cabeza de Vaca	~4 years	19 Sep–13 Dec	85

^aThe eruption reported by Christopher Columbus.

^bSubmarine eruption.

tled the western flank of the Cumbre Vieja ridge, but during westerly wind periods, ash fall also affected the eastern side of the island reaching the airport and the island's capital Santa Cruz (Fig. 4). Lapilli, finely fragmented lava particles (>2 to <64 mm) of basanite composition, were the typical emitted material. Because basanite magmas are generally of low viscosity, volatiles effectively degas, commonly leading to lava fountains (Strombolian-type) and very fluid lava flow (Hawaiian-type) eruptions. Basanitic strombolian

eruptions are mildly explosive, producing rhythmic pyroclastic bursts of fluid lava that usually solidifies in flight, creating fragments of hardened lava of a few mm to a few cm in size, but occasionally also reaching metres in size (known then as volcanic bombs). Bombs and lapilli usually follow ballistic trajectories falling in proximal areas (generally less than 1 km) from the vent (Fig. 4). Finer ash particles (<2 mm in size) originate in more explosive phases of Strombolian eruptions and are frequently dispersed for greater distances from the eruptive centre. The 2021 La Palma eruptive column dispersed falls of fine-fragmented ash hundreds of kilometres away from the volcano. In addition to fine ash, volatiles such as SO₂ may also travel for thousands of kilometres and fine ash and volatile components from La Palma have not only been detected on the neighbouring islands of El Hierro and Tenerife, but as far afield as the Caribbean and Central Europe (Fig. 4f).

Another important aspect of the 2021 eruption was that the lava flows had relatively high eruption temperatures (max. 1140°C) and were consequently very fluid at times (Fig. 5a), with velocities of some channelized lava flows exceeding 30 km/h. However, upon cooling, the viscosity of lavas increased (Fig. 5b–d), producing slower-moving blocky lava flow facies beyond the major channels and, as a result, breakout tongues and overflow frequently stopped even on relatively steep slopes, a characteristic of non-Newtonian fluids. Resulting from these viscosity changes were a range of lava flow forms, from minor, relatively thin and often channelized pahoehoe-type flows, to major a'a blocky lava flows that moved at less than 1 m/min, and locally produced accretionary balls at the leading edges of the flow fronts. La Palma 2021 a'a lava flows show a rough, scoriaceous and highly fractured surface, unlike the pahoehoe lavas (which do not usually reach more than 1 m thickness), a'a lava lobes reach several metres in thickness. During the course of the eruption, the changing topography and lava flow dynamics led to a complex range of temporally distinct anastomosing lava tongues and channels, with



Fig. 2. The area affected by the 2021 eruption, the Los Llanos de Aridane zone ('Llanos' means 'plains' in Spanish), is an essential part of the population and economic resources (banana plantations, tourism) of La Palma. The area consists of a gently inclined flatland on the north-western flank of the Cumbre Vieja ridge (at an altitude of ~50–1000 m asl). This comparatively smooth topography, the result of voluminous pre-historic eruptions such as the Birigoyo Volcano (dated at 6 ± 2 ka), contrast the steeper slopes of the southwestern part of the Cumbre Vieja ridge, where erosion is predominant. In addition, an extensive shallow marine abrasion platform formed during the last glacial maximum (c. 20 ka), which allows the Holocene lava flows to form coastal platforms and lava deltas to the NW of the Cumbre Vieja ridge, as exemplified in the 2021 volcanic event. Image Credit: European Union, Copernicus Sentinel 2 satellite image from 3 January 2022.



Fig. 3. a. View of the new volcano cone from the West (from El Paso), showing the open western crater and extensive sulfur deposits that formed after the termination of the eruption from degassing of sulphur rich vapours. b, c. Views of the new volcano edifice from the East, showing an ash covered crater landscape. A total of six major craters developed during the three-month eruption, which is typical for the multi-vent eruption style of many of the historical volcanic events on La Palma and in the Canary Islands in general.

younger flows often covering older flows and generating a maximum accumulation thickness of 70 m in the centre of the lava field and an average lava thicknesses of 12 m.

Lava flows travelled distances beyond 6.5 km onshore and up to 1.1 km under the sea. Lavas reached the sea for the first time on 28 September in the area of Playa de los Guirres, forming a lava delta. The successive arrivals of the lava flows to the sea, some of them drained through lava tubes, resulted in the formation of a second lava delta. The main delta, located to the south, represents the amalgamation of three temporary deltas initially separated from each other but progressively expanded to make the main delta. The total area lava claimed from the sea during the eruption is c. 50 ha, and thus the island of La Palma grew by this surface area during the 2021 eruption events.

Notably, the tephrite to basanite lavas that erupted are compositionally similar to historical eruptions in La Palma (see Fig. 6), fitting the overall chemical pattern of the Cumbre Vieja volcanic system. The 2021 La Palma lavas sampled until early December are porphyritic, variably vesiculated, and with a phenocryst content of subhedral and compositionally zoned clinopyroxene as the main mineral phase and lesser amounts of olivine crystals in early erupted lavas. The phenocrysts are immersed in a very fine-grained groundmass. Interestingly, brown amphibole phenocrysts are present in the earliest lavas emitted by the

volcano, with clear reaction textures indicating disequilibrium with the carrying melt. As the eruption proceeded into late October and November, no more amphibole was present and olivine increased in abundance instead.

Another notable feature of the 2021 eruption is the presence of xeno-pumice fragments, a type of frothy xenolith that occurred during approximately the first half of the La Palma eruption (Fig. 7). Two main types have been identified, a white one and a grey xeno-pumice. The white type resembles those previously identified in El Hierro by Troll and co-workers in 2011/2012, whereas the grey xeno-pumice bears similarities with frothy phonolitic xenoliths in some earlier eruption on La Palma as has been recorded by, for example, Carracedo & Troll in 2016. Notably, xeno-pumice was commonly found amongst the tephra in the first half of the eruption, but stopped being present amongst the tephra deposits in the later weeks of November, so that during the second half of the eruption an almost complete absence of xeno-pumice was noted. Xeno-pumice fragments are not uncommon on La Palma and in other Canary Island eruptions and are known from the eruption of Timanfaya on Lanzarote in 1730–1736, San Juan in 1949 and Teneguía in 1971 on La Palma, and from Montañón Negro on Gran Canaria c. 3000 years BP, as has been discussed by Carracedo and colleagues in 2015. This list now also includes the 2021 event and preliminary major element analysis

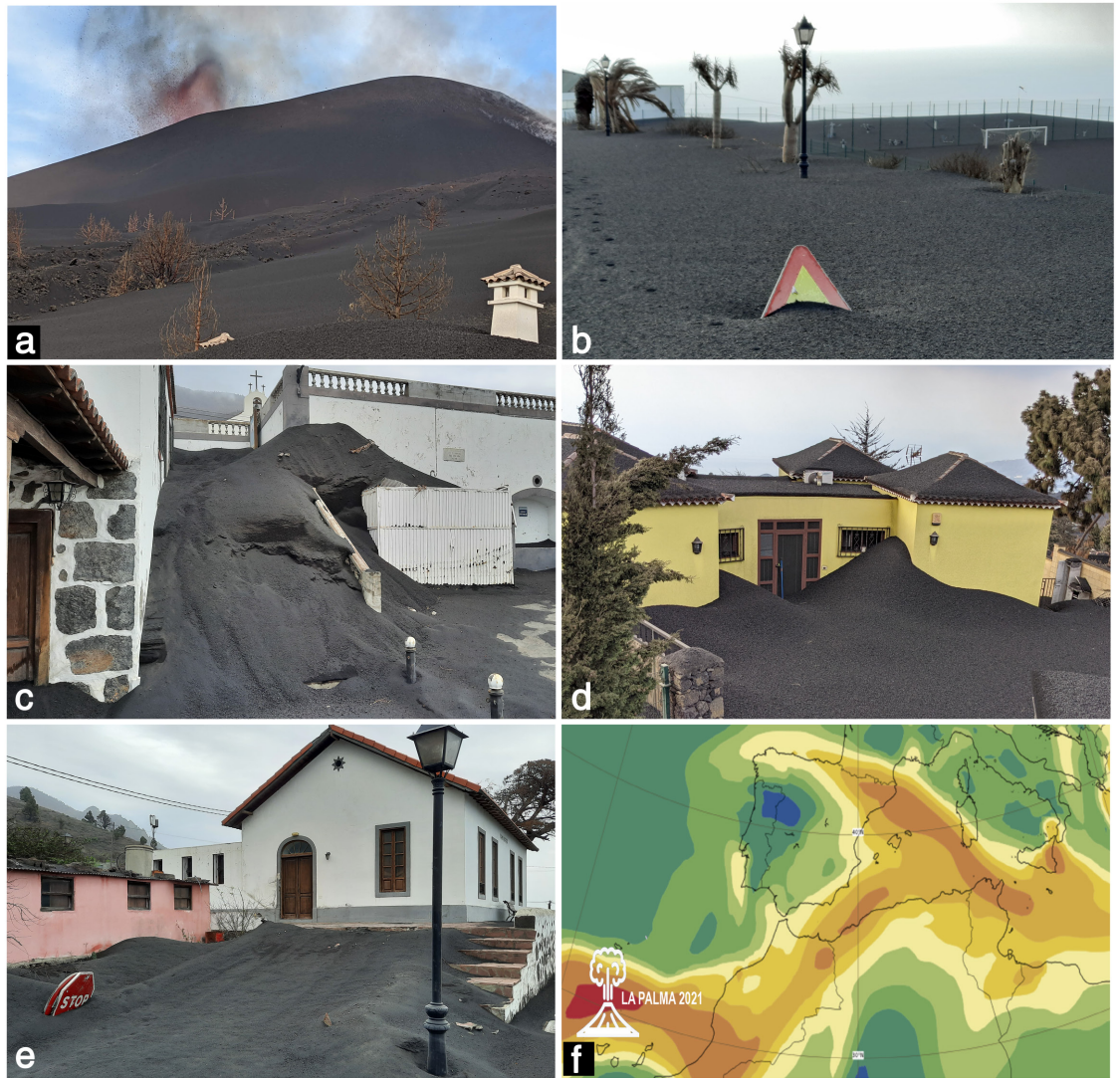


Fig. 4. **a.** The 2021 La Palma eruption classifies as a monogenetic basaltic Strombolian-type fissure eruption, opening several vents as the eruption progressed to ultimately build up a sizable cinder cone. **b–e.** Lapilli deposits thickly mantled roads and houses in the Valle de Aridane area. The almost constant lapilli airfall strongly affected the western flank of the Cumbre Vieja ridge, but also reached the airport and the island's capital Santa Cruz on the eastern side during periods where winds were flowing in from the West. **f.** Aerosols of fine particles and of volcanic gasses, such as SO_2 , and fine ash particles reached Central America and also Western and Central Europe. (Image credit: CAMS Forecast of total column of sulphur dioxide for Thursday 23 September 2021, Copernicus Atmosphere Monitoring Service/ECMWF.)

for sodium, potassium and silica content shows that the white La Palma 2021 xeno-pumice has a rhyolitic composition (see white star in Fig. 6), likely representing frothed up fragments of sedimentary materials from the ocean crust similar to the white xeno-pumice material from El Hierro that were analysed by Troll and colleagues and by Zaczek and coworkers in 2015. The grey xeno-pumice type that occurred in the 2021 La Palma eruption is akin to the composition of typical phonolites from the Cumbre Vieja volcano. The grey phonolitic xeno-pumice type was also observed in some historical eruptions such as in the 1585 Jedey eruption on La Palma, and thus represents dominantly older phonolite intrusive materials. Notably, unlike at El Hierro in 2011, where initial misunderstanding of xeno-pumice as precursors to potentially explosive eruptions of high silica magma prompted authorities to repeatedly evacuate the village of La Restinga, the La Palma 2021 xeno-pumice samples were correctly interpreted as relatively harmless xenoliths that are more of

a scientific curiosity than a signal for an increase of the eruption's hazard potential.

Early detection, monitoring and management of the 2021 eruption

Effective hazard management is clearly a remarkable triumph, resulting from the 2021 La Palma eruption. The implemented measurements and policies avoided any direct human fatalities from volcanic activity by securing the eruption site and limiting damage as much as possible due to evacuations and rapid emergency repair efforts inside the exclusion zone. This was possible through early detection using seismic arrays, deformation analysis, satellite-based geodetics, and gas monitoring carried out by several organizations (e.g. IGN, CSIC and INVOLCAN) that were coordinated by the Volcanic Emergency committee PEVOLCA. This management effort led to the evacuation of almost 8000 people, a significant part of the

Fig. 5. Lava flows were one of the most destructive features during the 2021 La Palma eruption. **a, b.** Rivers of lava were emitted from the central cone system and flowed downhill at enormous speed during several episodes of the eruption as the lava temperature commonly exceeded 1100 °C near the vent (max. 1140°C). These channelized (thermally insulated) lava flows allowed rapid and efficient lava transport all the way to the sea (see below). **c, d.** Frontal lava tongues and overbank facies, in turn, cooled rapidly and became blocky lava flows that advanced in caterpillar mode, slowly progressing towards buildings and destroying all man-made structures in their way, like this house in the Las Manchas area. **e.** If the supply of lava at the vent ceases, lava fronts and tongues stop and freeze irrespective of topography, like here in La Laguna village showing the edge of a lava tongue that entered the town. This shift to a 'a'a' style emplacement, acting similar to a huge bulldozer at their front, can sweep away everything in their path and demolish anthropogenic structures such as houses with great ease, and contrasts the mode of thinner lava emplacement at higher temperatures that was frequently flowing around houses (**f**), thus creating islands of relict infrastructure (kipukas) within the main lava field.



population of the Aridane Valley, the main settlement area on the western side of La Palma (see Fig. 2). The analysis of seismic activity and ground deformation was of critical importance, not only in the early detection of the unrest that led to the eruption and in predicting its most likely location, but also as principal elements for monitoring the entire eruptive event and the continued supply of magma to the vent site from depth. Seismically grouped hypocentres defined two zones beneath the surface: a deeply located hypocentre zone between 30 and 40 km, and a shallower hypocentre region between 10 and 15 km (Fig. 8). Crucially, in the days just prior to the eruption, swarms of earthquakes made it possible to trace the journey of the rising magma towards the surface (blue dots in Fig. 8a), indicating an increasing probability of volcanism sur-

facing at the NW end of the Cumbre Vieja ridge. The diagram in Fig. 8(b) differentiates both pre-eruptive and subsequent eruptive activity from a seismic perspective, and in the latter one, part of the progressive increase of activity and the waning stage towards the end of the eruption on 13 December. Moreover, a series of consecutive INSAR images of the Cumbre Vieja area taken by the Copernicus satellite detected millimetre scale differences in the terrain and this ground deformation indicated the zone of maximum deformation in the area where the eruptive centre would eventually open (Fig. 9).

Volcanic gases, mainly CO₂, SO₂ and H₂O, that were dissolved in the ascending magma exsolved when the magma approached shallower levels during ascent, increasing the gas pressure within the conduit sys-

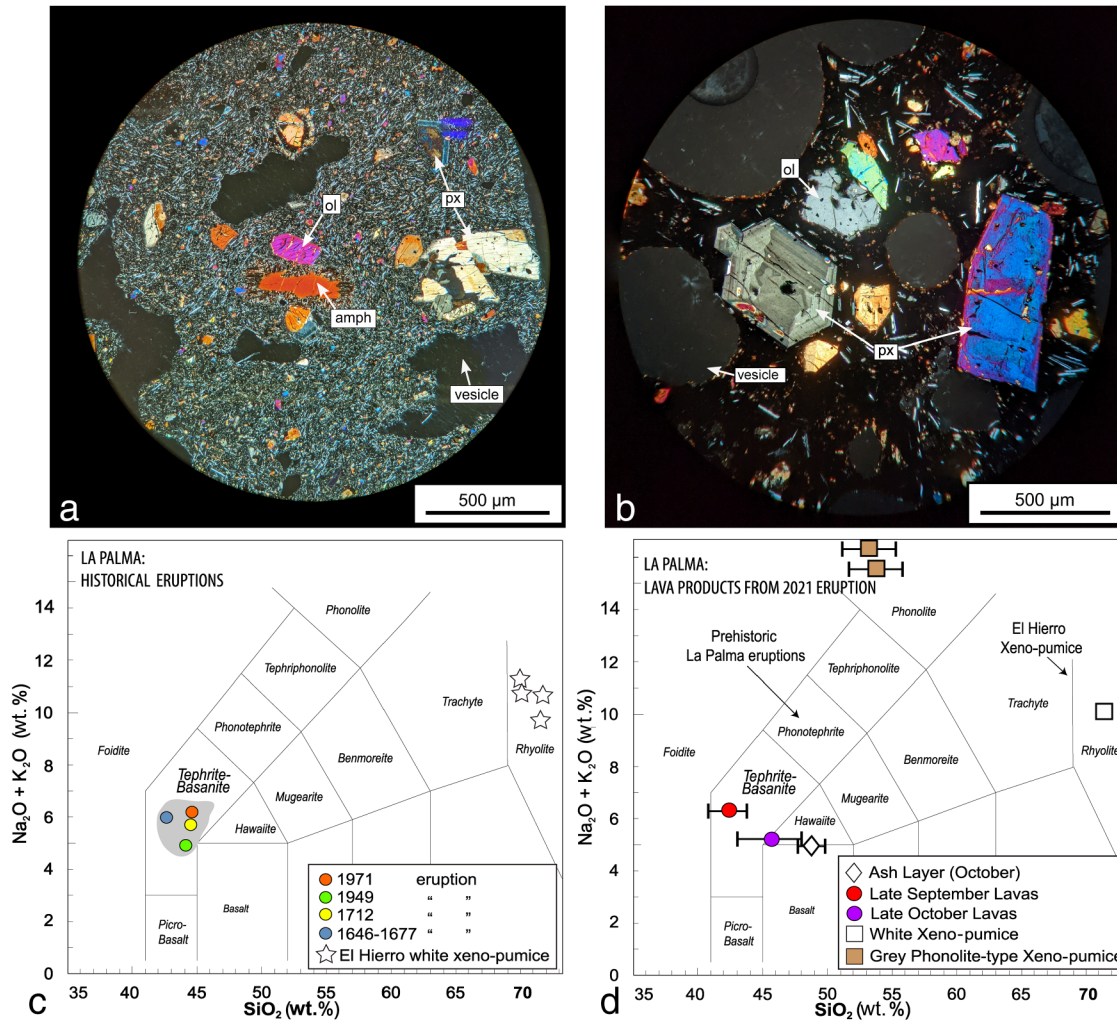


Fig. 6. a. Thin section image of a lava sample erupted on 22 September in crossed-polarized light, showing amphibole with a reaction rim as well as pyroxene set in a microlitic groundmass. b. Thin section image of lava sample erupted on 25 November, also in cross-polarized light, showing complex zonation and a cloudy core in larger pyroxene and some small clots of olivine and pyroxene. The larger grey areas are vesicles in both images. Note the larger grain size of the main phenocrysts later in the eruption, signaling that different magmatic source regions have likely been tapped during different episodes of the eruption on La Palma. c. Major element analysis for sodium, potassium and silica content of historical eruptions on La Palma (grey area with specific examples as coloured dots). The data define a mafic array in the basanite section of the diagram. White xeno-pumice samples from El Hierro, in turn, show a high-silica rhyolite composition (see also Fig. 7). d. The tephrite to basanite lavas that erupted in 2021 are compositionally similar to historical eruptions in La Palma, thus they broadly fit the overall chemical pattern of the Cumbre Vieja volcanic system. The 2021 La Palma lavas show, however, a compositional difference between early and late erupted lava samples that reflects a progressively more mafic character of the eruption products with ongoing eruptive duration and indicates different source regions to be involved. The white 2021 La Palma xeno-pumice (see text and Fig. 7) is similar in composition to the 2011 El Hierro white xeno-pumice, implying a dominantly sedimentary ocean crust origin for this inclusion type. The grey xeno-pumice found in the 2021 La Palma tephra, in turn, represents frothed up intrusive phonolites, similar to what has been seen previously in older La Palma eruptions. For instance, the 1585 Jeday eruption was fed through a vent that intersected an older phonolite spine complex, entraining considerable amounts of older phonolite intrusive materials that are now found as frothy phonolite xeno-pumice in the 1585 lavas.

tem, and ultimately, acting as a propellant for magma to feed the surface eruption (Fig. 10). When reaching the surface, these volatiles commonly generate an eruption column driven by expanding gas bubbles, as exemplified by the sustained eruption column during the La Palma events, causing the magma to fragment and to be thrown out of the vent as tephra (bombs, lapilli, or ash). These particles travel initially with ballistic trajectories and the eruptive column is sustained by the upward thrust of the gas jet at high pressure and temperature, constituting the kinetic sector of the column. The ingestion of cold atmospheric air, known as entrainment by the eruptive column, lowers its temperature and pressure, creating a convective regime until it reaches a height where the rising hot air equals the density of the cold air outside the column, ultimately establishing a level of neutral buoyancy (Fig. 10). The finer particles are then transported horizontally by the prevailing winds until they finally rain out if overcome by gravity, which can lead to dispersion distances of hundreds to even thousands of kilometres (see Fig. 4a). Incandescent pyroclasts of >64mm size ejected from

active volcanoes known as 'bombs' are commonly considered to fall ballistically, so the extent of the area affected by this volcanic hazard can be easily mapped, and was limited to a 1 km-radius from the vents. However, an intriguing type of bomb was recognized by our team to form by initial ejection from the volcano followed by transport down the volcano flank during the 2021 La Palma eruption (Fig. 11). These bombs were observed to spall hot material during transport on the soft, lapilli and ash covered substrate or on impact with pre-existing hardened lava flows, leading to fragmentation into incandescent pieces that posed a significant fire and impact hazard, and they have therefore been termed 'spallation bombs' by our team.

Detailed satellite imagery depicting the progression and growth of the lava field was possible through the European Union Copernicus Programme, where dedicated satellites (the Copernicus Sentinel family) provided a constant stream of information that was validated by data collected on the ground. The map in Fig. 12(a) shows the different lava flows branching downslope from the vent towards the ocean at pro-

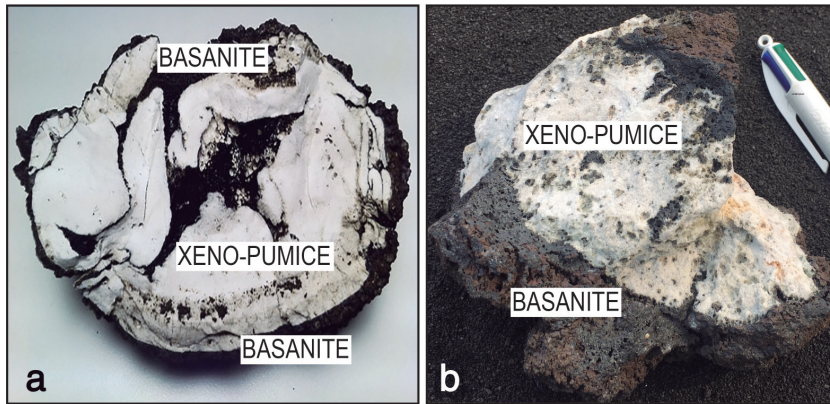


Fig. 7. Comparison of **a.** 'coconut-type' rhyolitic xeno-pumice from the 2011–2012 submarine eruption of El Hierro, and **b.** white xeno-pumice of the 2021 subaerial eruption of La Palma. These samples consist of white, frothy, high-silica material mantled by dark, basanite, host magma. Sample in **(a)** is c. 5 cm across. Sample in **(b)** has a pen for scale. The El Hierro 2011 xeno-pumice specimen were determined to represent frothed up fragments of sedimentary materials from the ocean crust due to their high-silica rhyolite composition, their high oxygen isotope ratios, and their considerable content of nannofossils and abundant quartz. The 2021 La Palma xeno-pumice samples overlap in major element composition with the El Hierro examples, and we can hypothesize that they are likely of oceanic sedimentary origin as well.

gressive stages defined by Copernicus satellite data. Figure 12(b) shows the thickness of lava flows on 1 January 2022, with a total volume of 188 000 000 m³ covering an area of a little over 12 km², equivalent to a time-average discharge rate of 27 m³/s. Lava flows arrived close (80 m) to the coastal cliff on 17 and 21 October, 24 November and 5 December. Flows reached the sea on several occasions during the eruption, forming a series of lava deltas (Figs 12 and 13), the most extensive one just north of the previous 1949 lava delta and a smaller one resting on the 1949 flows. The interaction of these incandescent lava flows with the ocean water led to plumes of steam, local explosive interactions and distinct volcanic forms from those that occurred on land, including submarine pillow structures and local hyaloclastite layers.

The eruption—its dangers and its effects

The area affected by the lavas of the 2021 eruption was the extensive sloping plain of Los Llanos de Aridane, one of the most populated and most prosperous agricultural and tourist areas of La Palma. This circumstance, together with the unexpected magnitude of the 2021 eruption, made this episode the most disastrous in the recorded history of the island.

A notable aspect of the fissure eruptions in the Canary Islands is the formation of several, often aligned, eruptive vents. During the 2021 La Palma eruption, as in the 1712 El Charco eruption, eruptive vents aligned at about 45° against the slope. This arrangement causes the venting to occur at different altitudes, operating through an arrangement that produces a 'chimney' effect. The arrangement favours the vent system to mainly degas through the upper (higher altitude) vents while the lava flows usually erupt from the lower altitude vent openings. Very hot (1140°C), dense and fluid lava flows advanced along a front of more than 3 km, sweeping away over 2800 buildings, leaving over 350 ha of productive farmland (banana plantations, avocado plantations, vineyards) covered by lava, and buried over 70 km of vital roads,

including the main North–South connection (LP-2) of the Western side of the Island. This severely disrupted the crucial transport system in that part of La Palma, forcing traffic and supply transportation to take the much longer route around the Eastern side of the Cumbre Vieja with considerable addition of costs and a severe reduction of transport efficiency in the entire southern part of the island. The destructive advance of 'a' lava, despite obstacles, is because lava flows constitute, for the most part, a non-Newtonian fluid, i.e. a fluid that offers resistance to movement, and so their advance requires that a lava flow continues to be fed from an eruptive centre. If this contribution is steady state, the lava flows act like 'bulldozers' at their front that sweep away everything in their path, demolishing houses and roads with ease (Figs 5 and 14). If the supply of lava at the vent ceases, however, lava fronts and tongues stop and cool irrespective of topography. The change in the environment before and after the passage of the lava flows is overwhelming and gives a clear idea of the power of this process.

Volcanic gases also caused severe disruption, forcing confinement of the population and the cessation of public activities (e.g. school attendance) in certain areas. This 'unfavourable air condition' was particularly severe during the final stages of the eruption, when SO₂ emission rates were exceptionally high (over 50 000 tonnes), likely from degassing of primitive magma stuck inside the plumbing system emitting gas from decompressive exsolution. Alone or in combination with high concentrations of dangerous gases, ambient concentrations of fine particulate volcanic matter forced repeated confinement of communities exposed to volcanic emissions beyond the area of direct impact of the 2021 eruption. Fine particulate matter PM10 describes all airborne particles with diameters less than 10 μm, a grain size not detectable during breathing and which will cause fine material to be lodged deep in the respiratory system. Episodes of high PM10 concentration of for example 225 μg/m³ at the Los Llanos station on 2 November dramatically exceeded the threshold set at 50 μg/m³, causing 'extremely unfavourable air quality'. This forced population confinement in the Valle de Aridane area and although people tried to maintain normal activities as much as possible under these conditions, questions remain about long-term health risks from prolonged or chronic exposure to even moderately elevated PM10 values, based on the now well-recognized morbidity and mortality effects (asthma, chronic bronchitis and emphysema) from epidemiological studies (cf. EEA, 2012).

Crucial lessons learned from the 2021 eruption

A positive lesson from this eruption is that effective crisis management protocols are now in place in the Canary Islands, as reflected in the absence of direct volcano casualties, apart from one fatality that

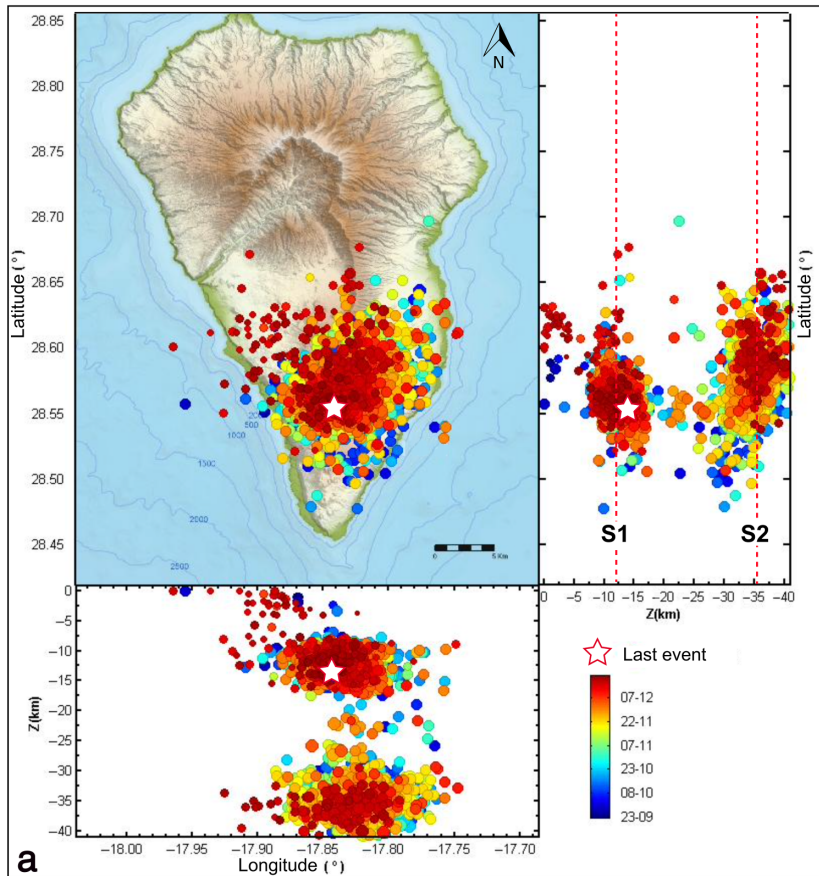
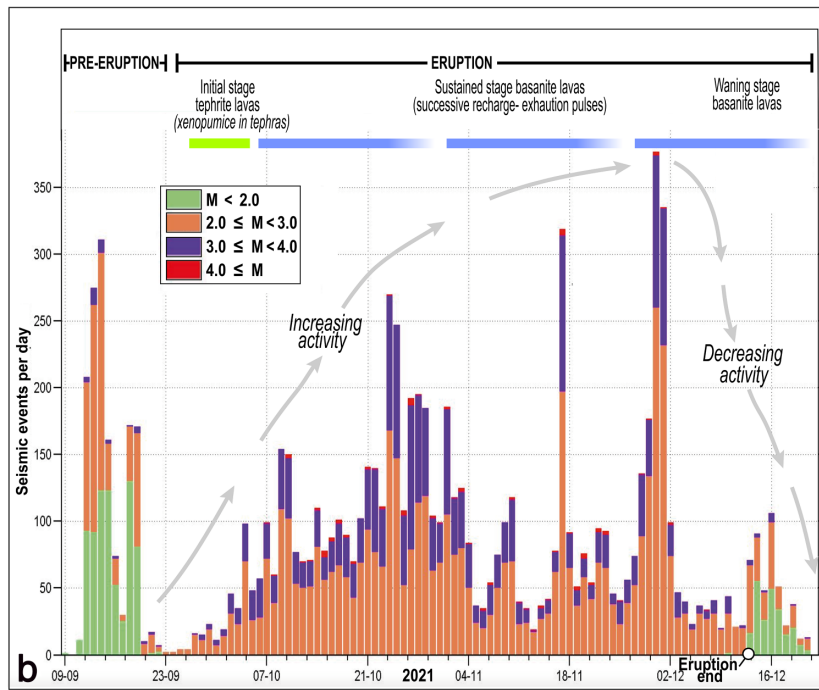


Fig. 8. Seismic unrest data from La Palma. **a.** Beneath the surface of La Palma, the 2021 eruption hypocentres defined a deep (between 30 and 40 km) and a shallower zone (between 10 and 15 km). In the days just prior to the eruption, swarms of seismic activity allowed the journey of the rising magma towards the surface (blue dots) to be traced, which indicated that volcanism would be surfacing at the NW end of the Cumbre Vieja ridge. **b.** The timeline diagram differentiates both pre-eruptive and subsequent eruptive activity from a seismic perspective, and shows the progressive increase of seismic activity before and during the eruption and the waning of seismic intensity towards its end in the middle of December 2021. (Source: Instituto Geográfico Nacional; IGN.)



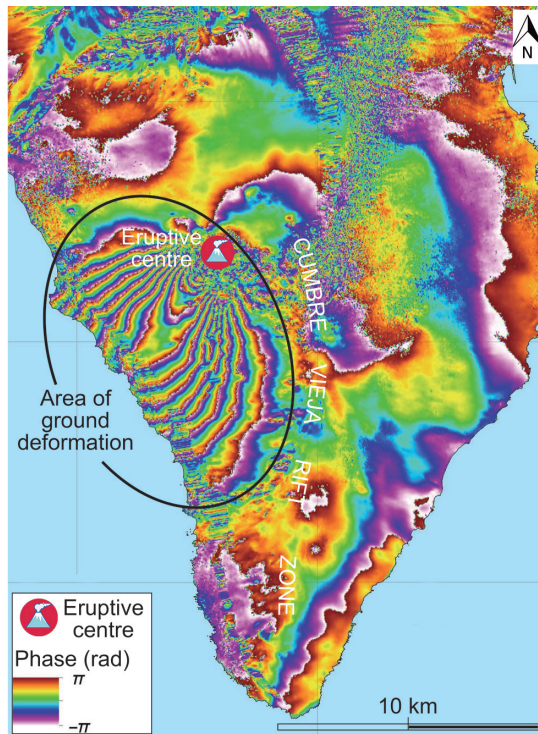
resulted from indirect causes. Indeed, crisis management policies and protocols worked highly effectively on La Palma in 2021 and marks a clear improvement in comparison to previous volcano crisis handling (cf.

discussion in e.g. Perez-Torrado *et al.*, 2012 and Carracedo *et al.*, 2015). Contrasting with the poorly monitored 1971 Teneguía eruption on the southern tip of the onshore Cumbre Vieja ridge, the 2021 event is by far the best monitored volcanic crisis in the Canary Islands. The advanced technical surveillance available now provides valuable scientific information and a sound basis for civil protection measures that will serve as a model for future volcanic crises on the Cumbre Vieja ridge and likely for other ocean island volcanoes worldwide. Specifically, surveillance of the lava flows with UAV (Unmanned Aircraft Vehicle) equipped with optical and thermal cameras was crucial to follow the lava lobes advances and allowed timely evacuations and emergency preparations to be carried out. The 2021 crisis has given us the knowledge that adverse effects from future eruptions in the Canaries can be mitigated if properly monitored, forecasted, and managed, despite the high population density of the Canary Islands and the relatively long inter-eruptive periods between major volcanic events.

After the end of the eruption on 13 December and the 10-day safeguard extension by the managing authorities for its official announcement, ahead lies a challenging, laborious and costly period of reconstruction of the areas affected by the eruption. This includes (re-)building of houses and utility buildings to replace the over 1300 homes and *c.* 1500 utility buildings destroyed by the eruption (Fig. 15). Challenges will include the assessment of which remnants can be reconstructed and which may need to be entirely demolished before being reconstructed. Building on the new lava will have to adapt to the new topographic conditions of up to 70-m-thick lava flows and assessment will be required if lava tunnels exist below certain spots on the lava field, probably making rebuilding directly on the lava a costly exercise. Removal of lava, in turn, will require blasting and intense labour to break the lava rock and pave the ground for new constructions. Crucially, the reconstruction of the lost road connections will be vital and will thus see investment of considerable effort and time, especially as it offers the opportunity for a re-planning of the road

network to accommodate the needs of the growing population in the western part of the island.

Fig. 9. Intense ground deformation near the eruption site at La Palma, localized by Copernicus Sentinel 1 between 14 and 20 September 2021. Deformation affected the NW flank of the Cumbre Vieja ridge all the way to the coastline. Ground deformation indicated a zone of maximum uplift in the area where the eventual eruptive vents opened.



A commodity not easily replaced, however, is the significant portion of the fertile and agriculturally highly productive land of the Aridane Valley (chiefly banana and avocado plantations, but also wine and pineapples etc). These lands have disappeared, covered by lava flows and/or thick lapilli beds. The future use of this new territory as farmland will require costly and laborious investment in the process of 'sorribado', a local term meaning to prepare the land for farming by adding new soil on top of the fresh lavas, a process recently described by Troll *et al.* (2017) and which has already been successfully applied to the 1949 and 1971 lava flows and especially their lava deltas (see Fig. 2).

Moreover, reconstruction will need to take much care to at least in part preserve the natural beauty of the newly formed volcanic landscapes in a way to ultimately favour preservation of crucial volcanological features, while simultaneously allowing for nature-based tourism, the most significant economic resource of this part of the island. It is important to note that article 132.2 of the Spanish Constitution stipulates that any new land reclaimed from the sea in case of a volcanic eruption becomes governmental property. The new lava deltas that formed in 2021 are now governmental lands by definition, which raises the possibility of saving this new lava delta sequence as a valuable educational and touristic resource. This could take the form of a nature park (e.g. a Volcano Park) or even a demarcated nature reserve, perhaps with a visitor centre and marked footpaths to allow visitors to enjoy the beauty of the volcanic features while ensuring minimal impact on these landforms from large numbers of visitors.

One problem remains, however, regardless of the enormous improvements in the early detection and use of scientific monitoring instrumentation. This is to create a system that guarantees provisions that can alleviate the costs associated with the losses that occur to local populations in such natural disasters that are of foreseeable recurrence. Models from other

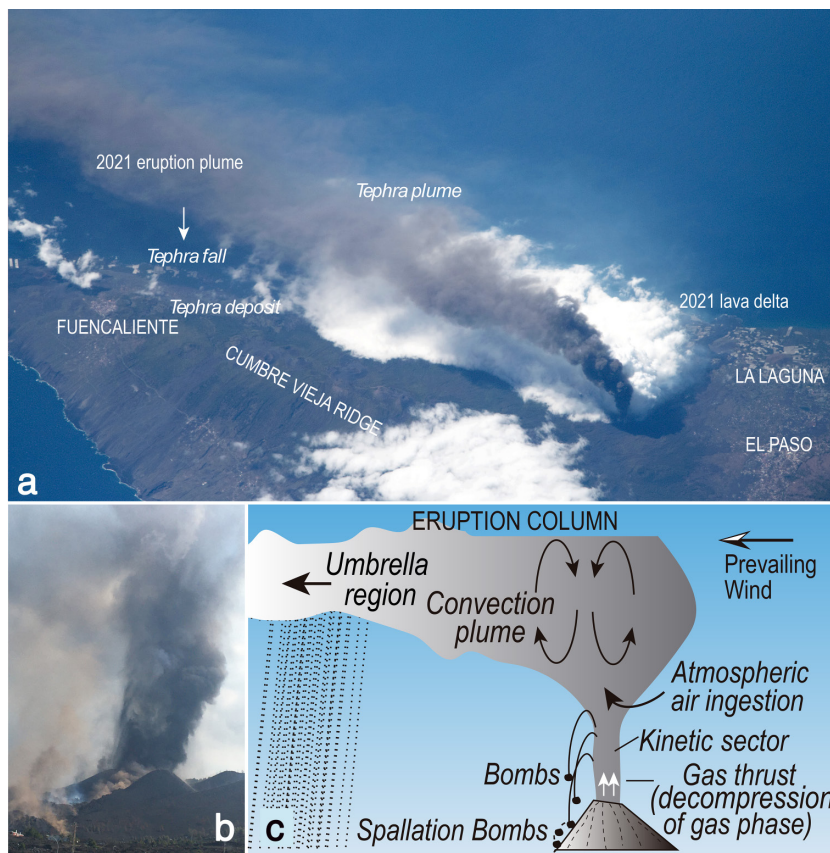


Fig. 10. **a.** Photograph of the south end of La Palma from the International Space Station taken on 4 October 2021. The oblique camera angle provides a 3-dimensional view of the volcanic plume rising over low-level clouds. The north to south wind direction moves the plume away from the airport, located further down the lower right of the image. **b.** The lower volcanic plume as seen during the eruption from the ground (viewed from the SW). Wind blowing towards the NE led to cancellation of air traffic, leaving the ferry as the only feasible connection to and from the island. **c.** Particles travel with ballistic trajectories and the eruptive column is initially sustained by the upward thrust of the gas jet at high pressure and temperature, constituting the kinetic sector of the column (more explanations in the text). Larger and denser particles then fall out, whereas finer and lighter particles can be transported further from the vent by wind and air currents.

Fig. 11. A large volcanic bomb that was observed being ejected from the volcano and to roll down the volcano's slopes on tephra beds down the lower volcano flanks near the evacuated settlement of Las Manchas during the 2021 La Palma eruption. The bomb shows an incandescent inner core with partial vitrophytic coating. Hammer head is 19 cm in length. This one and similar bombs were observed to spall hot material during transport on the soft, lapilli and ash-covered substrate or on impact with pre-existing hardened lava flows, thus representing a considerable fire and impact risk in the vicinity of the active volcanic cone.



active volcanic areas very similar to the Canary Islands (e.g. the Hawaiian Islands) may need to be investigated and perhaps adopted. On the Big Island of Hawaii volcanic hazards are more frequent than in the Canary Islands and therefore the population is more aware and volcanic phenomena are taken into account in urban planning, specific housing design, and in road construction techniques, and, importantly, there are compensation options via insurance premiums that are especially designed for volcanic eruptions. In the case of Hawaii, most standard insurances cover damage to houses and property directly caused by a vol-

canic eruption, including damage caused outdoors by lava flows or falling tephra (volcanic bombs, pyroclasts) and fires that may result from, for example, hot spallation bombs or lava incinerations. Damage insurance can even cover appliances such as TV sets, furniture, clothing, and possible acts of looting. The costs for living elsewhere until the volcanic risks have subsided can also be included, as can the maintenance and repair costs that may arise until a dwelling is habitable again.

A significant aid to premium assessment is the best possible knowledge of the expected volcanic hazards and associated risks, i.e. the foreseeable frequency of eruptions in a given area, and the anticipated estimation of the type and distribution of destructive elements, particularly lava flows (Fig. 15a). Luckily, all recorded (historical) eruptions in the Canary Islands are of the same fissure fed cinder cone and lava flow type, making assessment of future volcanic hazards from eruptions in the archipelago at least qualitatively achievable within this framework of previous knowledge. In particular, the maximum damage caused by a possible eruption of the kind expected in the Canary Islands (fissure fed basaltic cinder cones and lava flows) can be analysed with methods similar to those used for large floods, where the decisive factor is the existing topography. As in the estimation of flood areas, there are programmes based on geographical information systems (GIS) and digital terrain models (DTM), optimizable with the use of satellites and lidar points, which can cross-reference data from the terrain, roads, houses and other properties, with the projection of the lava flow for given volumes, i.e. successive stages during eruption progress (see Fig. 16b). Employment of this method on islands such as El Hierro, Tenerife, Lanzarote and La Palma would yield a detailed analysis to draw up a potential hazard map for each island that would enable estimation of the expected damage for the various areas of the volcanically active ridges and valleys alike.

In summary, the 2021 event was a typical strombolian fissure fed cinder cone eruption with lava emissions, characteristic of the recent activity of the Cumbre Vieja Volcano Ridge and also of histori-

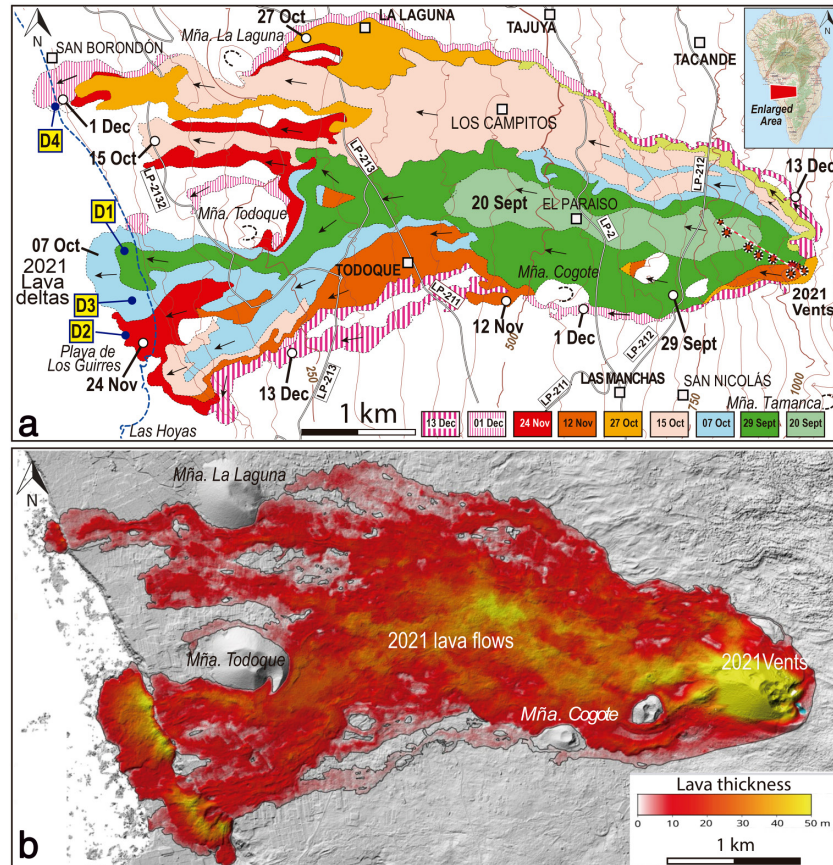


Fig. 12. **a.** Successive stages of growth of the lava field during the 2021 La Palma eruption as determined by Copernicus Satellite information (<https://emergency.copernicus.eu/mapping/list-of-components/EMSR546>). Temporally distinct lava lobes are separated by colours and patterns. Also indicated are the eruptive vents (marked by stars) and the successive lava deltas that formed in the coastal area west of the volcano (D1–D4). The pre-eruption coastline is marked by the blue stippled line. **b.** Extent of lava flows on 1 January 2022, totaling a volume of 194 000 000 m³, and covering an area of 12.35 km², equivalent to a time-average discharge rate of 27 m³/s. (Data and credit: JMC Belart from the elevation differential LiDAR 2016 (IGN, Spain) and Pléiades, 1 January 2022.)



Fig. 13. Flows reached the sea on several occasions during the eruption forming a series of lava deltas (see Figs 2 and 12), including an extensive one that in part overlaps with the older 1949 lava delta and a later smaller one that occurs to the north of the main delta. **a**, **b**. Impressions of the northern smaller lava delta showing the cliffs and the cascaded lavas as well as the delta that extended the coast. **c**. Photo of 2021 lava that overlies the 1949 lava delta (which hosts extensive banana plantations by now).



Fig. 14. **a**. Lava field in late October (28th) viewed from the older La Laguna cinder cone. **b**. Lava field in January 2022 showing lava flows that migrated around plantation walls near La Laguna village. **c**. The extensive lava field in January 2022 viewed from its NW edge (near Los Llanos) looking East. **d**. Lava incursion into a banana plantation near Los Llanos.



Fig. 15. Cleaning the thick lapilli deposits and reconstruction are the primary tasks after the eruption. **a–d.** Houses need to be cleaned and safety checked for structural damage and gas pockets and traps before populations can return to the properties that were not swallowed up by lava or collapsed under the weight of the ash. **e, f.** Transport of lapilli to temporary pile-up sites allow storage of large amounts of ash before being hopefully redeployed as concrete supplements, aggregates in road construction, and soil supplements in agriculture. Images are from San Nicolás and the Las Manchas region.

cal volcanism in the Canary Islands in general. While the 2021 eruptive event on La Palma was of unusually large volume and duration, it is of great value to realize that the fundamental volcanological pattern is identical to those observed in the historical record. It is now up to us to reconcile the eruptive style of Canary fissure type basaltic eruptions with the possibility that their location might be in very populated and prosperous areas (agriculture, tourism, infrastructure). The lessons learned at La Palma give the potential for inhabitants of the Canary Islands to prepare for, and mitigate against, future human and economic losses caused by volcanic activity on La Palma and the other islands in the Canary archipelago in the decades to come.

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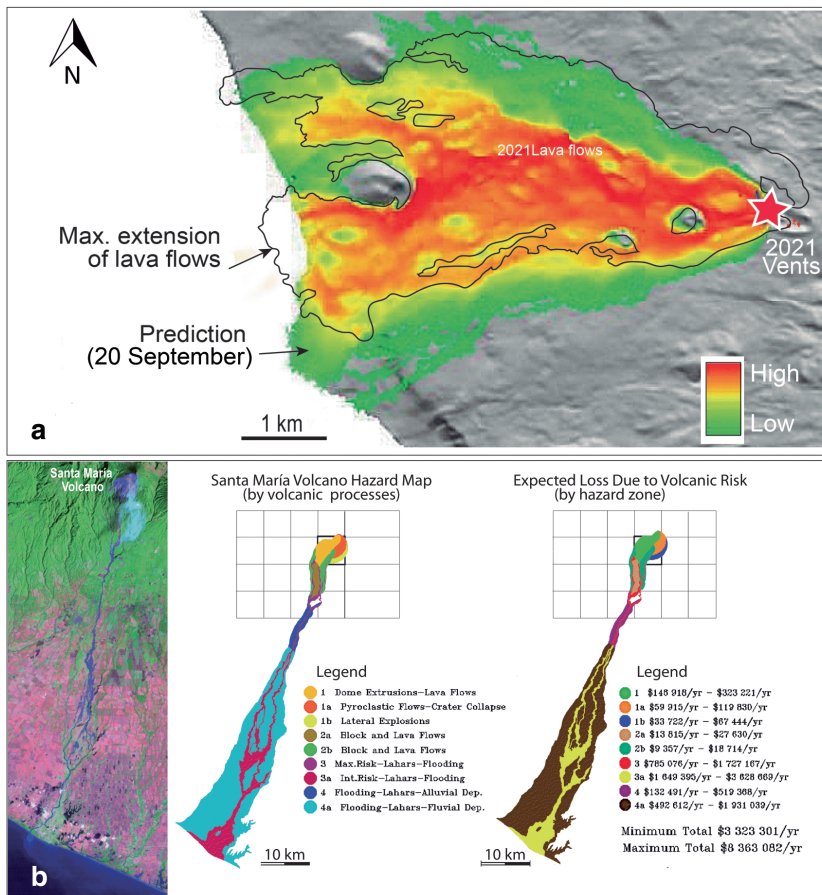


Fig. 16. a. Probabilistic map from the initial stage of the 2021 eruption in La Palma (produced in late September) that shows the results of a simulation of the possible paths the lava would travel from the specific emission zone of the 2021 volcano. Increasing eruptive lava thickness is shown from green to red, with red areas being the most probable lava paths that would also produce the thickest lava flow deposits. In the model, all the coloured zones are attainable by lava flows. (Image from A. Felpeo, IGN.) **b.** Geographic Information System (GIS) maps compiled for the Santa María Volcano (Guatemala) and its surroundings that combine volcanic hazard zonations with four layers of economic and population data (population, infrastructure, land use and standard of living) following from work by Green & Rose in 1999). This single map presents the risks from volcanic activity and could be a basis for assessing insurance premiums in volcanically active areas such as the Canary Islands.

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