The volcanic eruption of Cumbre Vieja in La Palma, 2021

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Introduction

The island of La Palma is located in the westernmost part of the Canary Islands in the northwestern sector of the island chain. It measures 708 km^2 and has a geological age of 1.7 million years, resting on a 4-million-year-old Pliocene submarine foundation (**Carracedo *et al.*, 2001**). The island is volcanic in origin, built up by a succession of eruptions differing in their degrees of violence and intensity, including such powerful episodes as the eruption of the Caldera de Taburiente. In recent times there have been eight eruptions since the fifteenth century, including the latest, the eruption of the Cumbre Vieja Volcano in 2021 (**Table 1**).

Date	Name	Days	Lava area (Ha)	Volcano height (m)	Diameter of base (m)
1430-40	Tacande	--	474	153	710
1585	Tehuya	84	454	140	1110
1646	Tigalate	82	450	--	--
1677-78	San Antonio	66	351	193	1100
1712	El Charco	56	568	--	--
1949	San Juan	47	422	--	--
1971	Teneguía	24	302	273	697
2021	Cumbre Vieja	85	1190	181	690

Table 1. Historical eruptions on the island of La Palma.
Source: Continuous geological map, IGME [Spanish Geological Survey]. (https://info.igme.es/visor/ and **Carracedo *et al.*, 2001**).

Predicting volcanic eruptions

From the day the series of seismic shocks on La Palma began on 11 September 2021, the Instituto Geológico y Minero de España (IGME in Spanish) – CSIC [*Spanish Geological Survey – Spanish National Research Council*] put the Unidad de Respuesta Geológica de Emergencia (URGE in Spanish) [*Geological Emergency Response Unit*] on standby footing to continuously monitor what was happening and give advance warning of a possible eruption on the island. Based on the series of eruptions in the historical record (**Table 1**), what might be coming was a Strombolian eruption, with the emission of lava flows potentially covering more than 700 ha. The maximum recorded duration up to that point was 84 days, and the mean duration was 59 days, roughly two months.

After the earthquake swarm, as the earthquakes quickly became shallower (earthquake focus depth less than 8 km), the IGME joined the Scientific Committee of the Plan de Emergencias Volcánicas de Canarias [Canary Island Volcano Emergency Plan] (PEVOLCA in Spanish), a subsidiary body of the Dirección General de Seguridad y Emergencias [*Emergency and Safety Bureau*] of the Government of the Canary Islands and placed URGE on an emergency footing (**Figure 1**).

Starting on 15 September, IGME – CSIC sent a field team composed of volcanologists and drone pilots with the Servicio de Trabajos Aéreos (STA in Spanish) [*Aerial Drone Service*] out to perform reconnaissance. The team reconnoitred the area between Jedey and Tacande on the western part of the island. That area was selected based on the high concentration of shallow earthquakes (depth less than 8 km, **Figure 2**) there and on the findings of previous geological studies carried out by IGME's VOLTEC National Park Research Project (**Rodríguez-Pascua *et al.*, 2018; Sánchez-Jiménez et al., 2019**). That same day, 15 September, the URGE coordinator contacted the Intelligence Section of the Unidad Militar de Emergencias (UME in Spanish) [*Spanish Emergency Military Unit*] (**Figure 1**) and forwarded to it all the data pointing to an impending eruption in the southwestern region of the island. Based on the historical eruption record, the most likely scenario was a Strombolian basaltic eruption with the formation of a monogenetic cinder volcano emitting lava over hundreds of hectares for approximately or more than one month.

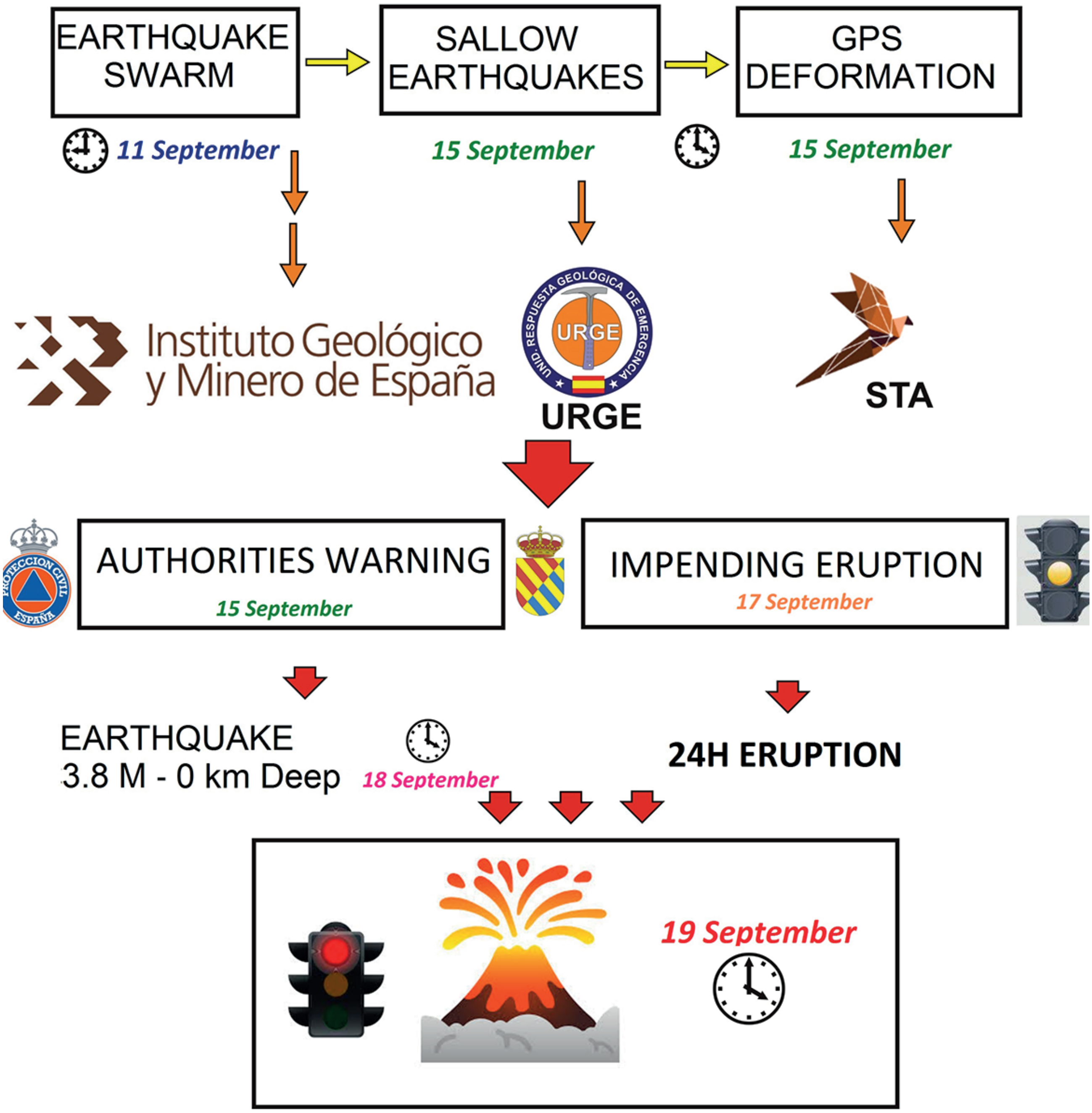

Figure 1. Graphic representation of events and IGME – CSIC decision-making during the pre-eruption stage of the Cumbre Vieja Volcano on the island of La Palma (2021).

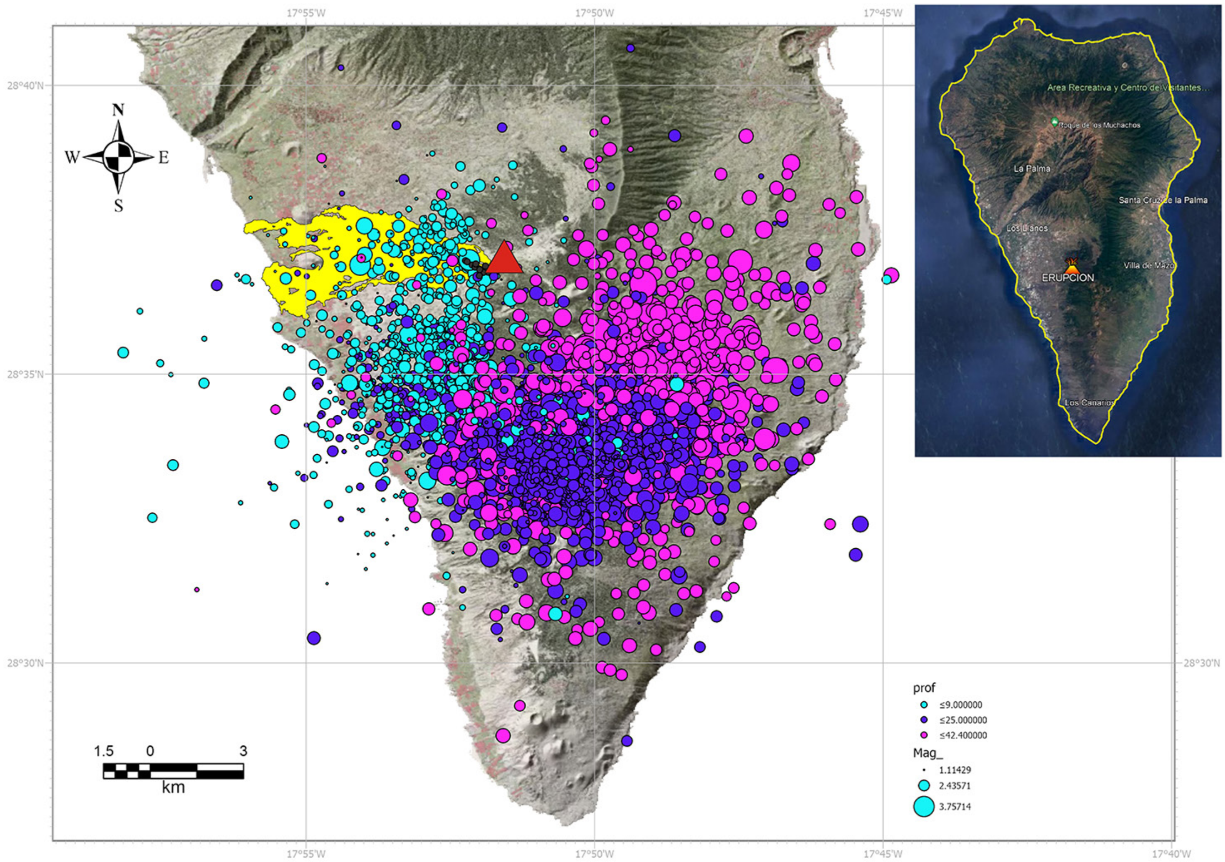

Figure 2. Map of earthquake epicentres recorded by the IGN [*Spain's National Geographic Institute*] (available at www.ign.es) from 11 September to 23 December 2021. More than 9,000 earthquakes were detected in all. Earthquakes whose hypocentres were located at a depth of less than 9 km are shown in light blue, earthquakes with hypocentres between 9 and 25 km deep are shown in purple, and earthquakes whose hypocentres were located at depths of more than 25 km are shown in pink. Circle size has been scaled to magnitude. The maximum magnitude recorded was 5.1. The red triangle marks the location of the Cumbre Vieja monogenetic volcano. The area shown in yellow is the expanse of the lava flow issuing from the volcano during the eruption. The black circles next to the red triangle are the various eruption mouths that opened over the 85 days the eruption lasted.

The strongest earthquake up to that time, magnitude 3.8 at a depth of less than 2 km, was recorded on 18 September. We then notified the authorities, the Scientific Committee, and the UME that the eruption would take place within the next 24 hours (**Figure 1**). The Cumbre Vieja Volcano officially erupted at 3:03 p.m. local Canary Island time (the same as UTC time) on 19 September 2021.

The course of the eruption is described below:

1. Magma emplacement

On 11 September the IGN recorded several dozen earthquakes at depths of 10 km in the southwestern part of the island of La Palma. Several earthquakes with magnitudes of less than 3.5 took place on 11 and 12 September, with more than 300 earthquakes on a single day on 14 September (**Figure 2**). At the same time, the IGN's network of GPS stations detected ground surface deformation several centimetres in height (**Figure 1**), clearly indicative of magma emplacement at depths of between 10 and 13 km (the depth where the earthquakes were taking place). That is the depth where scientists place the mechanical boundary between the lithosphere and the mantle (Moho), where part of the magma from below rose and accumulated, beginning to generate stress and ground surface deformation on La Palma (also known as "The Beautiful Island").

2. Rising up through the Earth's lithosphere

Once the magma had collected at between 11 and 13 km in depth, the Earth's crust began to fracture from below because of the magma's high gas content, chiefly water vapour and carbon dioxide (CO_2), which were causing the magma to rise to the surface. The question was to know where the magma would come up and where the eruption was most likely to take place. The high magma gas pressure is the ultimate cause of volcanic eruptions.

On 15 September nearly 1,000 earthquakes were detected at depths between 0 and 19 km (**Figure 2**). The earthquakes were beginning to take place at shallower depths closer to the Earth's surface. At this point, vertical ground surface deformation of 22 cm had reached high values after 4 days of volcanic seismic activity and exceeded the level recorded during the El Hierro eruption in 2011, which was around 7 cm. All these signs indicated that the crust was fracturing quickly and that the magma that was rising had high gas pressure inside. The Spanish Geological Survey (IGME) activated the URGE team, composed of scientists and technicians specialising in volcanology and earthquakes plus geologist drone pilots from the IGME's Aerial Drone Service (STA) to try to determine how imminent the eruption was, where it was located spatially, and the degree of intensity that could be expected.

The high number of earthquakes/day (on the order of hundreds), their rapid climb up to shallower depths in three days (they were becoming increasingly shallower), and the high ground surface deformation (peaking at 8 cm in 24 h) were all indicators that the eruption was imminent. The urgent studies we carried out suggested that some 6 million m^3 of magma had accumulated at a depth of 11-13 km, all in the span of just 4 days, and that it was rapidly rising towards the surface. Based on recent work on the critical volume of magmatic stoping in basaltic magma preceding an eruption (**Townsed and Huber, 2020**), we were close to the lower limit, suggesting that the volcano could erupt at any time (10 million m^3, depending on the magma's water content). We conveyed this information to the competent authorities and the Scientific Committee, which had formed when the PEVOLCA emergency plan was activated. In line with the cooperative agreement between the IGME and the UME, we also notified that unit for coordination in view of the impending eruption of unknown size. The IGME and the UME have had an agreement to cooperate in the event of natural disasters in place since 2011. Our models suggested peak likelihood of a Strombolian eruption within 7 days of 15 September.

In trying to locate the place where the eruption would occur, both the areas with the maximum number of earthquakes and the areas with maximum GPS deformation were prime candidates. However, geological models constructed by **Rodríguez-Pascua *et al.*, 2018** suggested that there was an extensional deformation zone further north of the above-mentioned areas where the magma would meet less resistance when rising to the surface in combination with the presence of extensional fractures running in a NW-SE direction might result in basaltic dikes[1].

3. Eruption on 19 September 2021

After the volcano had erupted, it quickly built up a monogenetic volcanic edifice (edifice produced by a single eruption) from cinder and spatter[2] accumulating on its flanks while a jet of gas and magma shot up nearly 300 m into the air from the centre of the volcano.

(1) A dike is a planar intrusion of igneous rock (thin and wide) within earlier rock, breaking that rock.
(2) Spatter of blobs of still molten lava that forms a conglomerate.

Figure 3. 1. Initial stages of genesis of the Cumbre Vieja Volcano a few days after the eruption started. The lava fountain reaching 100 m in height is visible in these initial stages along with the first lava fields in the Tacande area at km 2 of the LP-212 highway. The lava appears to be directed by lateral movement and cooling. 2. UME members (Environmental and Technology Emergency Intervention Group, GIETMA in Spanish, reconnaissance unit) collecting hot lava fragments and lapilli. 3. 200 m-high gas, magma, and spatter jet of a typical Strombolian eruption and main *pahoehoe*[3]-type river of lava. 4. Greater Strombolian explosivity with a more vigorous lava fountain responsible for higher lava emission rates throughout the eruption. 5. Increase in Strombolian intensity and genesis of a second Strombolian jet combined with emissions of Hawaiian basaltic lavas. 6. Shot of night-time activity with lava bombs shooting out.

(3) *Pahoehoe*, from the Hawaiian, smooth. Lava flows with a smooth, glassy surface and highly characteristic ropy structures.

The Cumbre Vieja eruption began with the formation of a monogenetic cinder cone (**Figures 3 and 4**) several dozens of metres high with sonic explosions and emission of gases at speeds of more than 330 m/s. The volcano spewed out different types of material (**Figure 4**): (a) ash less than 2 mm in diameter; (b) lapilli, fragments of volcanic glass ranging from 2 mm to 6.4 cm; and (c) lava bombs greater than 6.4 cm and ranging up to 1.5 m in diameter ejected from several hundred metres inside the main crater.

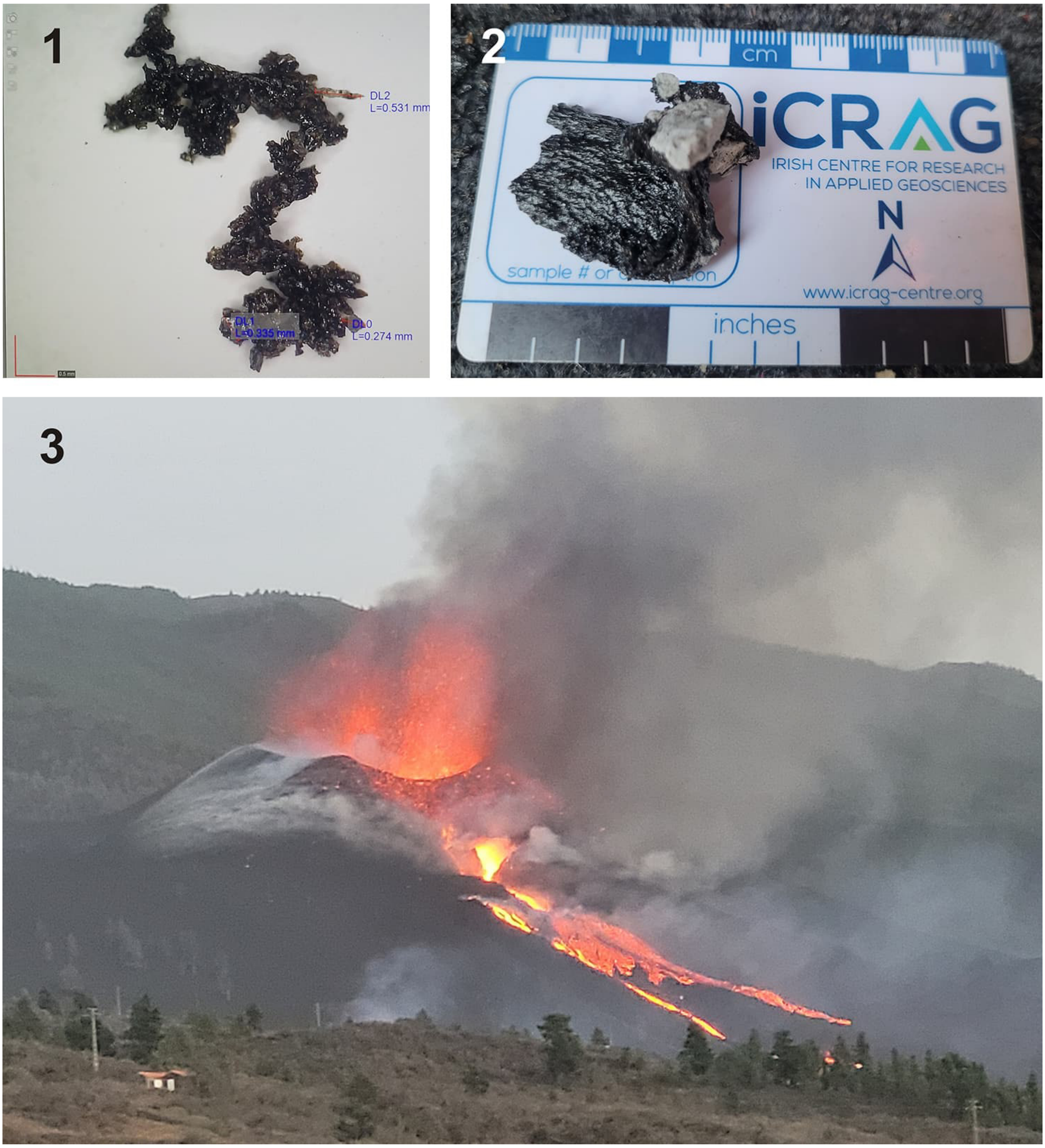

Figure 4. 1. Detail of agglomerated volcanic ash caused by wet aggregation. 2. Fragments of lapilli with lava globules (white lithic fragments) collected in the vicinity of Fátima Viewpoint, Jedey. 3. Explosivity and ejection of ash, lapilli, and bombs by the Cumbre Vieja Volcano.

Early in the eruption work focused on finding the lava emission vents and using probability models devised by the IGN to the areas affected by lava flows. The IGME also carried out real time mapping using drones piloted by the drone pilots. The advantage of doing this was that the IGME's drone pilots are geologists, and this helps make better use of flight time to locate lava emission points and in estimating lava flow rates along valley floors. The IGME conducted a series of flights, and the live images transmitted helped in decision-making by the Scientific Committee regarding evolution of the eruption stage, by the emergency services, and in this case also by the Canary Island Government.

4. Singular episodes

Various singular episodes took place during the Cumbre Vieja eruption associated with increasing intensity and volcanic vigour, for instance, lava debris avalanches with partial collapse of the volcanic edifice and increases in lava effusion rates (**Figure 5**).

Figure 5. Detail of a lava debris avalanche in October in the region around Tacande de Arriba on La Palma. Blocks of erratics associated with partial collapse of the volcanic edifice are visible along with volcanic ash build-up covering nearby buildings. This phenomenon took place in the space of a matter of minutes.

The first large lava debris avalanche took place in the vicinity of Tacande de Arriba (northern flows) on 9 October, when the main cone partially collapsed and another collapse of the secondary cone caved in on the lava fountains, causing them to spill over in an avalanche that tore off large erratic boulders (tens of metres in size and weighing in the tonnes), which were carried along at high speed on top of the river of lava (**Figure 5**). By that time large amounts of ash can be seen to have been deposited around the volcano, reaching heights of up to 1.2 m in thickness hundreds of metres distant from the eruption in the western portion of the island.

The blanket of ash mainly affected the towns of Jedey and Las Manchas and the area around Caños de Fuego, west of the volcano, under the influence of the prevailing trade winds. More than 700 flights were cancelled because of the effect on the air space, and the ash column ejected reached heights of more than 6 km and had an average height of 3 km.

5. Lava flow maps

Working in combination with the Canary Island Government's Emergency and Rescue Services [*Grupo de Emergencias y Salvamento*] (GES in Spanish), the IGME - CSIC Aerial Drone Service used a range of drones equipped with optical and thermal sensors (**Figure 6**) to conduct dynamic mapping of the advancing lava field. The data were then included on maps that the La Palma Government and PEVOLCA's Scientific Committee could then use. Besides cooperating with the Emergency Services, the drone services also worked actively with UME drones and the National Police Force (CNP in Spanish) drones. This is the first eruption in history in which drones have been used extensively, and they demonstrated their worth and versatility for emergency management tasks.

Figure 6. Mario Hernández, IGME drone pilot and specialist with the Geological Hazard and Climate Change Department, piloting a flight from the Virgen de Fátima Viewpoint in the midst of the explosive eruption stage with the ash column collapsing in the east. The Cumbre Vieja eruption was the first time drones have been widely used to help monitor the eruption in urban enclaves.

The lava reached temperatures of 1,200 °C, within the range for lavas with a basaltic chemical composition, consisting of trachytes and basanites, mainly composed of volcanic glass, together with olivines and clinopyroxenes, amphibole, titanium oxides, and magnetite. The presence of titanium and magnetite was a source of considerable difficulty for the drones, because the metallic ashes affected their mechanical parts and the magnetic fields generated by the lava field and the volume of ash in suspension also interfered with communications and guidance systems.

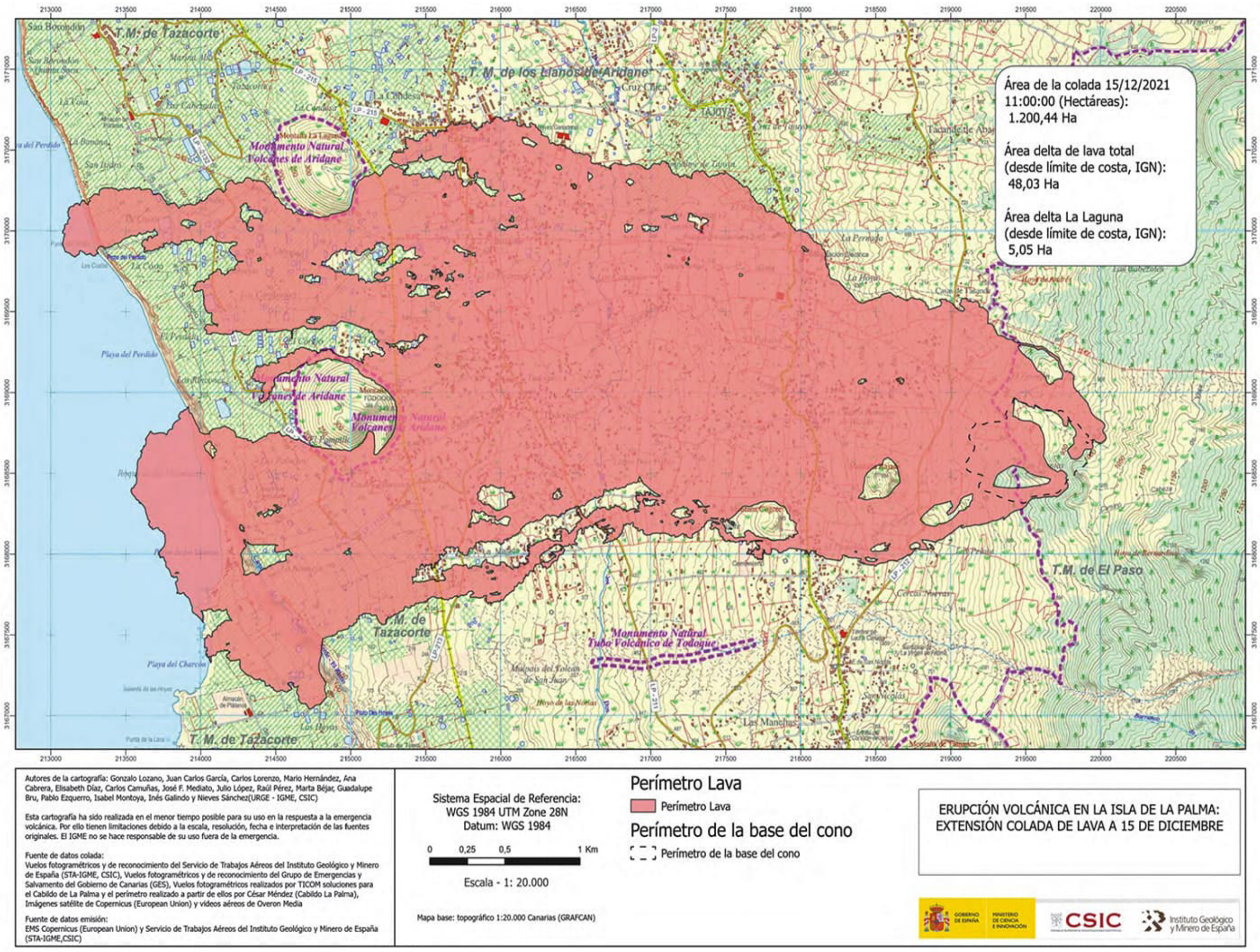

Figure 7. Final map drawn up by the IGME - CSIC Aerial Drone Service based on a number of drone flights and field work. The total area affected came to 1,200 ha. Two lava maps were produced every day from the beginning of October. They were used for decision-making by the Director of Emergency Services.

Figure 7 depicts the final map of the lava field that was formed over the 85 days the eruption lasted, nearly 1,200 ha (**Table 1**). The formation of lava deltas is visible in the area around the town of Tazacorte and in the vicinity of Perdido beach, which can be seen to be surrounded by two deltas, one to the north and the other to the south. Lava thickness ranged from a couple of metres to tens of metres. The lava filled up valleys and changed the topography. Those very changes to the topography are what caused the lava to spread out sideways to the north and to the south of the first lava field laid down at the beginning of October.

Figure 8 shows various examples of how the lava affected homes and buildings in the Paraíso district in the town of Los Llanos.

Figure 8. Different views of buildings affected by the lava during the Cumbre Vieja eruption in 2021. 1. and 2. Detail of the destruction of a home, engulfed by an *a'a*[4] lava flow with a temperature of 1,010 °C and a frontal zone height of 6 m. 3. The La Laguna lava flow just opposite the church. 4. Advancing *a'a* lava flow constrained by the street with the Disa petrol station on one side and a bank branch on the other in La Laguna. 5. Lava field at the beginning of December covering parts of homes in Las Manchas. 6. Detail of a home where lava spewed forth from a vent under the front porch. All that can be seen of the house is the attic.

(4) *A lava flow with an uneven surface made up of clinkers ranging from decimetres to metres in size.*

The lava fields have done grave damage to large numbers of homes. Not only did the lava wreck homes as it went along (**Figures 8.1, 8.2**), it was also channelled along the streets in the towns, destroying everything in its path (**Figures 8.3, 8.4**), at a speed of several metres per hour and lava flow frontal zone heights of up to 8 m. Temperatures of between 800 and 1200 °C were measured in the molten lava. Different lava flows came in waves throughout the eruption, unlike what happened during the San Juan eruption in 1949, which only released lava at the end, forming the Caños de Fuego Natural Park with lava tubes and pahoehoe flows. Lava emissions during this eruption were continuous from the very outset (19 September) up to the final day of the eruption (13/14 December 2021). The lava flows were thick enough to cover houses completely (**Figure 8.5**). Several houses were affected by effusions that came up through vents under their porches after they had been evacuated, as can be seen in **Figure 8.6.** The only part of the house still visible is the attic, 5 m above ground level at the top of the house, where a vent erupted on 24 November.

6. Maps of volcanic ashes

Ash falls are one of the features of Strombolian eruptions that have the most effect. The ash consists mainly of volcanic glass smaller than 2 mm in size and in the main submillimetric in size (**Figure 4.1**). From the start of the eruption the IGME - CSIC put together a task force in the framework of "Operation Cinderella". The task force's main job was real-time mapping of ash layer thickness and classification by lithological type.

Figure 9. Different ash deposits during the Cumbre Vieja eruption in 2021. 1. Homes covered by ash in the area around Caños de Fuego towards Puerto Naos. 2. Detail of a vehicle partially covered by ash in Las Manchas. 3. Measuring ash layer thickness on the path coming down from the Mirador del Jable towards Jedey. 4. Volcanic bomb collected from on top of a blanket of ash on the foothills to the north of the volcano. Ash depth in that area reached 40 cm.

On that mission IGME - CSIC scientists used portable equipment to take readings of the ash thickness at different measurement sampling points to draw up a final ash thickness map. They also checked particle sizes as a measure of the volcanic explosivity index. One method used to preserve stratigraphic records of the ash falls was by taking peels, i.e., by solidifying the ash sample using an epoxy resin solution (**Figure 10**). Various ash measurement campaigns were carried out all over the island for mapping purposes.

Figure 10. 1. Javier Martínez, a IGME - CSIC scientist, preparing a chemical solution for a peel from an ash deposit laid down during the final eruption stage. 2. Detail of a sampling point to record the stratigraphic column of an ash layer, taking samples to measure particle size and for geochemical analysis.

Risks associated with studying active volcanoes

During our study IGME - CSIC scientists, technicians, and drone pilots had to cope with a series of hazards inherent to volcanic eruptions. The first and most obvious was the danger posed by lavas at a temperature of 1,200 °C, which gave off extremely hot thermal fields with a risk of suffering burns up close. This hazard was met by wearing antistatic fire resistant suits and safety footwear with a heat resistance of up to 300 °C. This allowed us to approach cool lavas (between 100 and 700 °C) to collect samples for study. For hotter temperatures we turned to the UME for help; they had suits that could withstand temperatures of up to 1,000 °C. The high temperatures limited the time we could work in hot lava fields (T > 800 °C) environments. Dehydration was another hazard. Another inherent hazard when walking on active lava fields is the existence of lava tubes with incandescent lava flowing inside. Scientists walking on the more fragile cooler surface above faced the danger of breaking through and falling in.

Being in range of pyroclastic bombs was yet another hazard. For this reason, a safety perimeter of 1 km was established around volcanic ejection zones, particularly around Strombolian vents, which ejected bombs measuring metres wide (see, for example, the bomb in **Figure 9.4**).

However, the primary hazard that we had to face continuously over the 85 days the eruption lasted was the presence of toxic gases, acids (hydrochloric, sulphuric, nitric acids, etc.), and organic and inorganic vapours with boiling points above 65 °C that were capable of displacing oxygen. To cope with this danger we used gas masks with ABEK+Hg+P3 filters to protect against breathing in SO_2, SH_2, NH_3, HCl, mercury vapours, and such toxic substances as arsenic in the form of arsine (AsH_3). High levels of carbon monoxide (CO) were also detected. This made it necessary to wear self-contained breathing apparatuses (SCBAs) where exposure levels were high (**Figure 11**).

Figure 11. Detail of protection equipment during a reconnaissance at the crater of the Cumbre Vieja Volcano by a combined team of IGME – CSIC and UME GIETMA scientists. Full face ABEK P3+Hg masks and self-contained breathing apparatuses (SCBAs) were worn in areas where oxygen levels were less than 19% and large quantities of carbon monoxide were present.

Conclusions

The 2021 Cumbre Vieja eruption on the island of La Palma was the first eruption in urban areas in modern times in Europe since the Heimaey-Eldfell eruption in 1973, in Iceland, which affected 5,000 persons (**Williams and Moore, 1976**). The Cumbre Vieja eruption displaced 7,000 people, and nearly 2,000 people lost their homes to the lava. Nearly 3,000 homes were destroyed. Some 400 ha of banana farmland were destroyed. In all, around 20,000 people were exposed to the eruption and its effects. In the end, a new volcanic edifice nearly 200 m high and 700 m in diameter was built up on the upper slopes of the area known as Montaña Rajada. The edifice contained 6 Strombolian mouths issuing all at once, and in all there were 33 lava effusion vents. The maximum height of the gas jet was estimated at 300 m, with an eruption column reaching a maximum height of 6 km. The magma discharged was basaltic in chemical composition, according to preliminary analyses made up of trachytes and basanites. The Scientific Committee has put the volcanic explosivity index (VEI) at between II and III pending further assessments based on the total volume emitted. Nearly 1,300 ha of land was affected and covered by lava flows, and the entire island was covered in ash, which was recorded as far away as the neighbouring islands of Tenerife, El Hierro, and even Grand Canary Island.

Thanks to the prediction of the eruption performed by various government scientific agencies (IGME–CSIC, IGN, etc.), it was possible to activate the Canary Island Volcano Emergency Plan (PEVOLCA) and minimise the harm caused by the eruption, which was able to be limited to property damage only, damage that is unavoidable, such as the loss of homes, businesses, and crops under the lava field.

The combined work carried out by those agencies during the emergency made it possible for the Director of Emergency Services to have available first-hand information produced by experts in the field subsequent to prior deliberation by the Scientific Committee. The field work carried out jointly by URGE [*Geological Emergency Response Unit*] and GIETMA [*Environmental and Technology Emergency Intervention Group*] of the UME [*Spanish Emergency Military Unit*] successfully gathered worthwhile scientific data during the emergency. The real success of the work performed by the Spanish Geological Survey-Spanish National Research Council was being able to place at the disposal of the emergency services the most important scientific data on the volcanic eruption: when, how, new lava flow effusion vents, eruption stages, and so forth.

We will continue to be living in the shadow of volcanic eruptions in the Canary Islands and suffering their effects. Lest we forget, the Cumbre Vieja Volcano is at least monogenetic volcano number 69 in the southern part of the island and that eruptions of this kind have been going on for a million years. The lessons learned from this eruption should point us in the direction of responsible land planning, especially with regard to volcanic activity. It is highly likely that a Strombolian eruption of this kind will occur again at some future date, lasting three months or more, with lava fields that may spread out to the sides and lava flow thicknesses of tens of metres.

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Let us first of all thank the people of La Palma, especially all those whose lives have been touched during the 85 days this eruption lasted between 19 September and 13 December 2021. From these pages we would like to pay tribute to their strength, courage, and most of all, their cooperation with us. Special thanks go to the Spanish Emergency Military Unit (UME) (2nd Battalion and GIETMA) and to the lieutenant colonel commanding the 2nd Battalion and the lieutenant colonel commanding GIETMA for their disinterested help and unstinting cooperation. A special mention also goes out to the Canary Island Emergency and Rescue Services (GES), particularly their pilots Enrique and Juani, for their cooperation in the days leading up to the eruption and while the eruption lasted. Thank you for everything you taught us and for your patience. We thank Joaquín Quirós, Workplace Health and Safety Technician with the Spanish National Research Council, for everything he taught us about protection from noxious gases and toxic atmospheres and for all the sensors and PPE he made available to us for our field work. Thanks as well to the Director of the Canary Island Civil Defence Corps and his technical staff for making it possible for us to work in the exclusion zone. Lastly, our thanks to the Civil Guards, the National Police Force's Bomb Disposal Unit (CNP-TEDAX in Spanish), and to their drone services for working together with us. This article has been funded by the Spanish Ministry of Science and Innovation under the La Palma volcanic eruption emergency budget pursuant to Spanish Royal Decree 1078/2021 of 7 December 2021, No. 293 Section I. Page 150995.

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