The 2021 La Palma eruption; social dilemmas resulting from living close to an active volcano

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Summary

Damage and destruction caused by the 2021 eruption of the Tajogaite volcano on La Palma was unprecedented relative to other historical eruptions of the last century (1909, 1949, 1971, 2011) in the Canary Islands. The devastation caused by the eruption was not a result of eruption magnitude, which was only marginally larger than other historical events, but instead of increasing vulnerability due to population growth and increasing rural land use on the slopes of the volcanically active Cumbre Vieja Ridge. Since future eruptions along the Cumbre Vieja are inevitable, it is imperative that actions are taken to ensure the safety of the island's growing population. While civil protection and emergency services managed to avert loss of life from direct volcanic impacts in 2021, loss of property for many people in the affected area remains a grave issue and requires targeted measures to safeguard against human suffering from similar future events.

Introduction

With an increasing number of people on the planet and growing urban population centres, it is estimated that currently some 14.3% of the global population (ca. 1 billion people) reside within 100 km of a potentially active volcano and that at least 600 million people are exposed to direct volcanic hazards worldwide. The concern by authorities and civil protection and emergency services over volcanic risk, especially in densely populated urban areas (Naples, Mexico City, Seattle, Yogyakarta, etc.) is thus growing. The consequences of volcanic eruptions in urban environments are particularly problematic, posing significant threats such as loss of human lives, disruption of critical infrastructure, and disturbances in energy and resource supply chains as discussed in e.g. Freire and others in 2019 and Mani and colleagues in 2021. Over the past few decades, although the number of fatalities from volcanic activity declined, the expansion of human settlements near active volcanoes has led to a fivefold increase in global financial losses due to volcanic activity, soaring from $1 billion in the 1990s to $5 billion in the 2000s, as evident by comparing the data in e.g. Annen and Wagner from 2003 with those by Mani and colleagues in 2021. Furthermore, the risk associated with active volcanoes has been further amplified by volcano tourism, as reported by Brown and coworkers in 2015 and 2017, with the unfortunate demise of over 1,000 volcano tourists in eruption incidents over the previous decade, and most recently exemplified by the 2019 White Island disaster in New Zealand.

Recent and historical volcanic activity on the island of La Palma (Canary Islands, Spain) has been exclusively centred along the Cumbre Vieja Ridge (CVR) in the southern part of the island. The CVR has been expanding over the last ca. 125 ka as a result of magmatic activity and runs N-S, with a maximum elevation of 1950 metres a.s.l, an onshore length of ca. 20 km, a surface area of 220 km^2, and a southward offshore continuation of > 20 km (see Carracedo et al., 2001, 2021, 2022 for full details). On the CVR, cinder cones and eruptive vents align, usually along ridge-parallel fissures, to form a characteristic ocean island rift zone that is usually fed from dyke intrusions that are emplaced along the rift zone. Intrusion of one of such dykes, or possibly a series of dykes, initiated the eruption on the western flank of the CVR on September 19th, 2021. The majority of volcanism along the CVR (including the 1949, 1971, and 2021 eruptions) involved silica-undersaturated basanite and tephrite lavas, although small volumes of evolved phonolite have also been produced, and details on these have been reported by e.g. Klügel and coworkers in 2017. Eruptions on the CVR represent about half of the historical (i.e. witnessed and documented) eruptions in the entire Canary archipelago (**Fig. 1**) making the CVR the most volcanically active region in the Canary Islands (Carracedo et al., 2022).

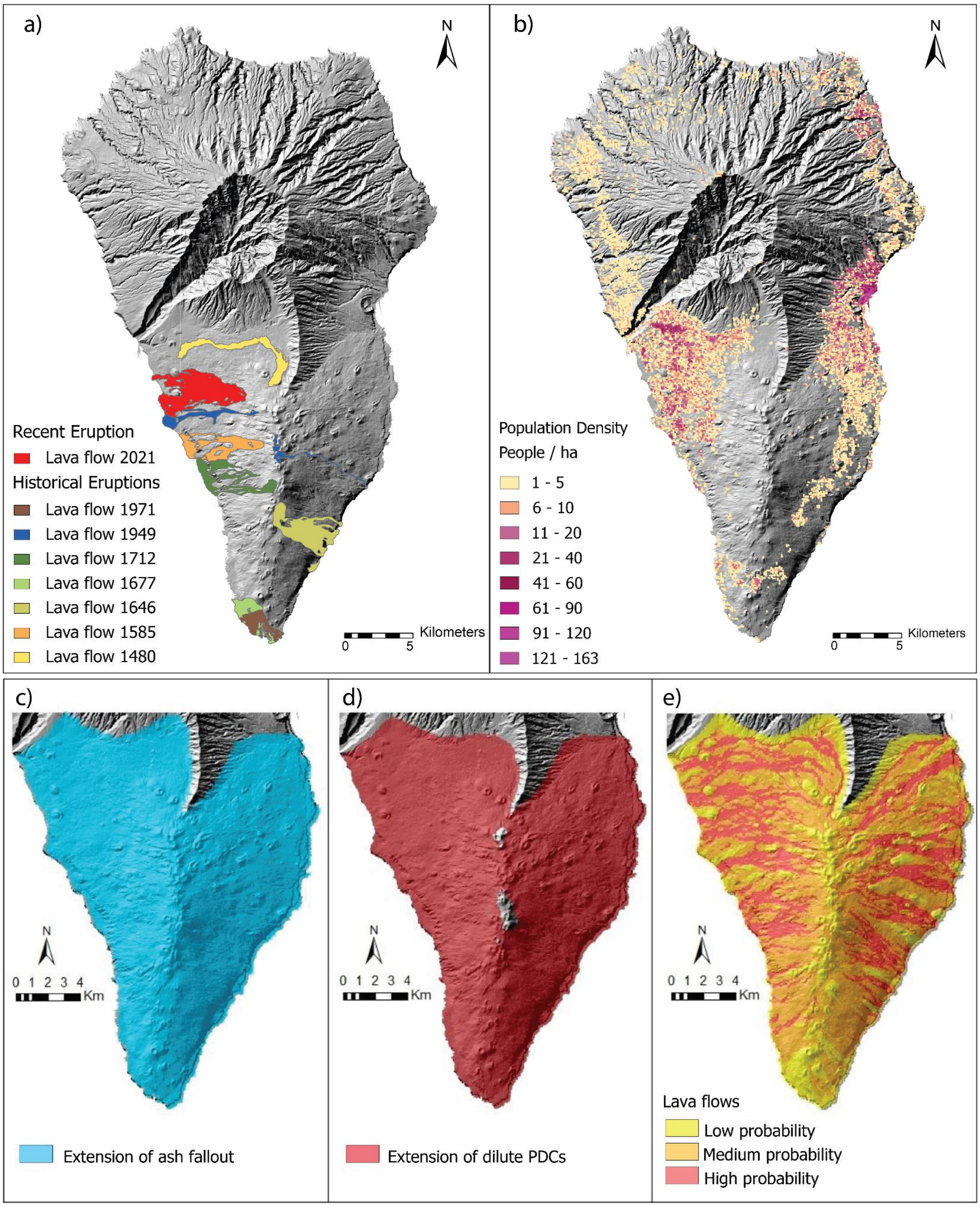


Figure 1. *a) The Cumbre Vieja rift zone forms the southern half of the island of La Palma. It records more than half of the eruptions occurring in the Canarian Archipelago in the last 500 years including eruptions in 1646, 1677, 1712, 1949, 1971 and 2021 (lava fields of historical eruptions are shown in colour). b) Population density of La Palma (data source: Pesaresi and Politis 2022) c-e) Volcanic risk zones for the Cumbre Vieja region (from Martí et al., 2022).*

The 2021 La Palma eruption was the largest, longest, and most destructive eruption on the island in recorded history. As noted by Carracedo and colleagues in their 2022 article, this is the most recent in a series of historical eruptions that emanated from the active Cumbre Vieja volcanic ridge in AD 1585, 1646, 1677-1678, 1712, 1949, and 1971. Although the 2021 eruption resulted in no direct loss of life, it led to evacuation of several thousand people and caused significant destruction, including loss of ~3000 buildings, >70 km of road network, and ~12 km^2 of crops (1237 hectares). Consequently, the eruption caused human suffering due to loss of livelihoods, homes, essential infrastructure, disruptions to vital traffic systems and public services, and truncation of energy, food, and resource supply chains as outlined by e.g. the Spanish Red Cross in 2023 . The 2021 eruption on La Palma therefore ranks as one of the most destructive volcanic eruptions in the history of Spain. This was not so much due to an unusually large eruption volume or a large explosive eruption, but mainly because of increased societal vulnerability in this part of the island. Here we review the combined geological and societal aspects that led to the high impact of the 2021 eruption and present our views on what measures could be taken to ensure that human suffering and material losses can be minimised when the next eruption on the Cumbre Vieja occurs.

Precursors and eruption

Historical eruptions on the Cumbre Vieja Ridge (CVR) represent about half of the historical eruptions in the Canary Islands (**Fig. 1**). The 2021 eruption lasted 85 days and was preceded by close to a decade of precursor signals, which exponentially increased one week prior to eruption. Differential interferometric synthetic aperture radar (DInSAR) data showed mild surface deformation compatible with emplacement of small volumes of magma as early as 2009/2010, some of it as shallow as 8 to 10 km beneath the CVR as reported by Fernández and coworkers, in 2021. This was coupled with increased CO_2 emissions and higher (magmatic) helium isotope ratios in spring water as described by Padrón and collaborators in 2015 and 2022. Seismic precursors were also recorded in multiple events (seismic swarms) during the 10 years before the eruption, the first one in 2011–2012. Larger seismic events (magnitude 1 to 2) were recorded in October 2017 and February 2018 at approximately 15 to 30 km depth, as was reported by the 'Instituto Geográfico Nacional' (IGN) and by Torres-González and colleagues in 2020; and by D'Auria and coworkers in 2022, which were also linked to changes in helium isotopes in spring waters and increased CO_2 emissions before and after the seismic swarms. Six further seismic swarms were recorded between summer 2020 and spring 2021, mainly pointing to activity at upper mantle depths. Between October 2017 and June 2021, earthquake hypocenters generally deepened from 20 to 35 km, returning to 20 to 25 km in August 2021 as detected by the IGN and described by Longpré in 2021. From the 8th to the 11th of September there was a pronounced shallowing of earthquake depths from initially 8-14 km to 6 km depth. On the 11th of September unrest accelerated and seismicity became more intense and of higher magnitude, increasingly shallow, and was accompanied by increasing levels of surface deformation. Finally, the magma reached the surface on 19th of September 2021.

The 2021 eruption on La Palma eventually began at ~14:11 UTC on the 19th of September and lasted until ~22:21 UTC on 13th December 2021. A series of successive vents opened as the eruption progressed, ultimately building up a sizable cinder cone and an extensive lava flow field that reached the coast in several places, as outlined in 2022 by e.g. Day and colleagues, Muñoz and others, and Romero and coworkers (**Fig. 2**). The newly formed volcanic cone is almost 300 m high from its pre-eruption base, and six major craters are present on its top that follow a >550 m NW-SE alignment. The 2021 La Palma eruption represents a typical Canarian basaltic fissure type eruption that was dominated by lava emission and strombolian fountaining from a multi-crater vent complex, with episodic phreatomagmatic pulses as was pointed out in 2022 by Carracedo and coworkers and by Bonadonna and collaborators. Seismic activity showed two main magma storage levels during the eruption: a deep zone between 35 and 45 km, and a shallower zone between 10 and 15 km, as was determined by del Fresno and team in 2023. The deeper region has been placed at only ca. 20 to 25 km depth by D'Auria and collaborators in 2022, based on a different velocity model, which seems consistent with equilibration pressures obtained by Dayton and coworkers in 2023 from fluid inclusion data from olivine crystals contained within tephra. During the eruption, the largest earthquakes occurred in the deeper storage region, reaching up to magnitude 5 in late October and in December 2021. The 2021 Tajogaite eruption is the longest historical eruption on La Palma (85 Days) with an emitted volume of 0.2 km^3. When compared to the previous historical eruptions on the island, the Tajogaite volcanic eruption was of similar magnitude, but the Tajogaite lavas covered an area equivalent to 50% of the area covered by the six earlier historical eruptions on the island. The large area affected was influenced by the preexisting topography, presenting a wide valley with gentle slopes, which favoured the high population density and agricultural activity in the Valle de Aridane area. This resulted in high financial losses for the island population due to a locally very high population density and thus high economical vulnerability (see also below).

Figure 2. *Photographs of the 2021 Tajogaite lavas that covered some 350 hectares of land and destroyed close to 3000 man-made structures, public services facilities, and crops, as well as truncated over 70 km of roads.*

Eruption magnitude and damage caused

The material destruction caused by the 2021 eruption on La Palma is amounting to nearly 1 billion € in damages, as summarised for example by the Copernicus European Union Earth Observer Program and Carracedo and colleagues (2022). Throughout the three-month eruption, the explosive intensity was highly variable, as described by Bonadonna and others in 2022. Although a sustained eruptive column with a height of typically around 3,500 metres a.s.l. was fairly constant, temporary peaks in activity resulted in column heights up to 8,500 metres a.s.l. in December 2021 as reported by the IGN in 2021. The plume height together with the volume of emitted pyroclastic material (ca. 45 million m^3) define the event as a VEI 3. Onshore, pyroclastic deposits covered ca 12 km^2 (1237 hectares) and lava flows covered over 350 hectares of farmland. The lavas travelled downslope, reaching the shore at ca. 6.5 km, and continued for over 1 km underwater. Successive arrivals of the lava flows to the sea resulted in the formation of two lava deltas with an area of approximately 50 ha of new land.

During the eruption, almost 8000 people were evacuated for several months, and some evacuations are still ongoing at the time of writing (September 2023) due to high gas risks in certain areas (e.g. Puerto Naos), leaving several hundred residents unable to return to their properties. In material terms, the eruption produced extensive damage in the affected area and volcanic deposits completely buried or severely covered over 950 hectares of farmland (over 350 by lava, some 600 by thick pyroclastic deposits) (**Figs. 2, 3 & 4**). Lava flows also truncated roads along the western flank of the island, severely disrupting transport. In total, between 70 and 90 km of roads were destroyed, including the important North-South traffic connection LP-2. According to the reports published by the 'Comisión Mixta Para La Reconstrucción, Recuperación y Apoyo a La Isla de La Palma' (CMRRA) and the 'Gestión y Planeamiento Territorial y Medioambiental of the Canarian Government' (GESPLAN) in 2022, lava flows also damaged almost 3000 man-made structures, of which most were homes (including some 270 tourist holiday homes), but also auxiliary buildings (e.g. garages, sheds, swimming pools), and 1000 buildings linked to industry, manufacturing and agricultural processing, as well as public service facilities (e.g. schools, religious buildings and local sports facilities). The government reports that 85% of the almost 3000 devastated or damaged buildings are registered in the cadastre, while 561 buildings that were damaged or destroyed were not registered.

Figure 3. *Tephra covered some 1200 hectares of settlements and agricultural land with variably thick layers of coarse to fine lapilli layers, with entire houses disappearing beneath the tephra blanket near the vent sites of the Tajogaite volcano.*

Figure 4. *Enormous clean-up efforts have been underway since December 2021, with tephra being removed from public spaces and private properties (top images) and piled up in large storage mounts, like those near San Nicolás and Las Manchas cemetery (bottom images).*

These widespread and severe damages have led to the economic paralysis of the affected areas. The most important economic sectors of the island are the primary sector (agriculture, livestock, fishing) and tourism. Significant crop destruction and the prohibition of fishing in the Tazacorte area had severe economic impacts, since this is the primary sector that generates almost 50% of the economy of La Palma, with banana production being the dominant agricultural product and source of income. La Palma is the second largest producer of bananas in the Canaries (32% of the total production in the Canary Islands in 2021) after Tenerife, bringing annual revenues of ca. 135 million Euro according to the 'Asociación de Organizaciones de Productores de Canarias' (ASPROCAN) in 2022. The total of 2,757 hectares dedicated to banana production on La Palma in 2019 was reduced by ca. 600 ha due to the 2021 eruption. According to the 'Department of Agriculture, Livestock and Fisheries of the Government of the Canary Islands' (DALF) in 2022, the economic losses in the agricultural sector amounted to 100 million € and the Spanish and Canarian Governments contributed ca. 29 million € to offset economic losses in the primary sector between September 2021 until June 2022, of which ca. 50% were direct subsidies, as reported by CMRRA in 2022.

Until 2019, tourism brought on average 62.4 million € to La Palma annually (2.5 million tourists per year by air). Due to the Covid-19 pandemic, tourism revenues on the island fell by around 68% in 2020 and the number of tourists dropped by 56%. The tourism sector recovered again in 2021 with an increase of 35% over the previous year, but still well below pre-pandemic levels. While the Canary Islands as a whole experienced a 118% increase in visitor numbers in 2022 compared to the previous year and 11% higher revenue relative to pre-pandemic levels, as reported by the Instituto Canario de Estadística ('Canary Institute of Statistics' ISTAC) in 2022, on La Palma this growth was limited to 32%, with tourism revenues in 2022 of around 34 million €, and was thus far below pre-pandemic values.

Along with the material and economic damages, the volcanological crisis also impacted the health of the island citizens, especially those from volcanically affected areas. Respiratory, ocular, and dermatological diseases cause short and long-term harmful health effects associated with inhalation and contact with volcanic ash and gases emitted during a volcanic eruption, as considered by the European Environment Agency (EEA) and by e.g. Ruano-Ravina and team in 2023. In addition, the uncertainty and anguish of the inhabitants during and after the volcanic eruption resulted in mental health problems amongst some of the population, demonstrated by the numerous testimonies in media and newspaper reports at the time (see summaries by Escolà-Gascón and coworkers and Navarro and colleagues in 2023).

Growing population of La Palma and pre-eruption perception of volcanic risk

Populations in the Canary archipelago and La Palma have undergone rapid expansion over the last 200 years. During the 20th century, the region experienced an increase of over 450%, representing phenomenal growth compared to the ca. 100% population increase experienced in mainland Spain. This expansion of the resident population in the Canary Islands is due to a higher number of births than deaths, the arrival of immigrants, and to settlement of 'peninsulars' (people from mainland Spain) in the Canaries. However, through the last century the relative percentage of children has decreased and the number of those over 65 increased to 11.8% of the total population in 2000, as recorded by Alcaide and coworkers in 2007, and is over 20% at present.

At the beginning of the 20th century the population of La Palma was at 44,856, increased to 78,800 people at the end of the 20th century, and to almost 85,000 at present. This represents an increase of 175% during the 20th century (**Figures 5, 6, 7**) and La Palma currently has the third highest population density in the archipelago (220/km^2 relative to 94/km^2 in Spain overall) with two of the four municipalities affected by the 2021 eruption having population densities in excess of 400/km^2 (i.e. Los Llanos de Aridane and Tazacorte).

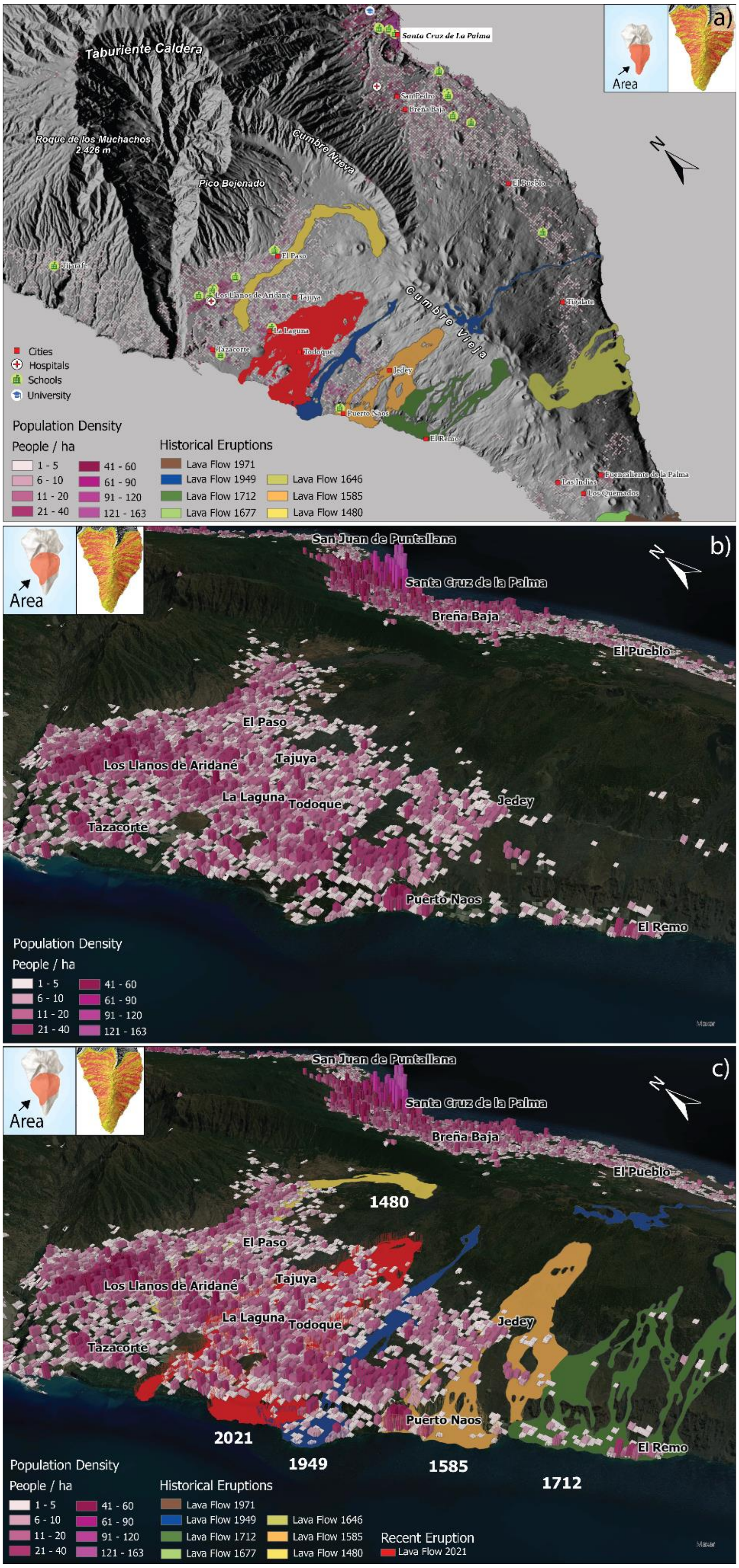


***Figure 5.a** Map view of central La Palma (top panel) and (**b & c.**) oblique views from the West (central and lower panel). **a & c.** panels are showing the historical lava flows and link these to present day population density (data source Pesaresi and Politis, 2022)*. *The region affected by lava flow hazard (after Marti et al., 2022) is shown as inset in all three panels. The population along the CVR is at risk from future lava flow eruptions, which includes the larger population centres of the island in the NE and NW of the Cumbre Vieja Ridge.*

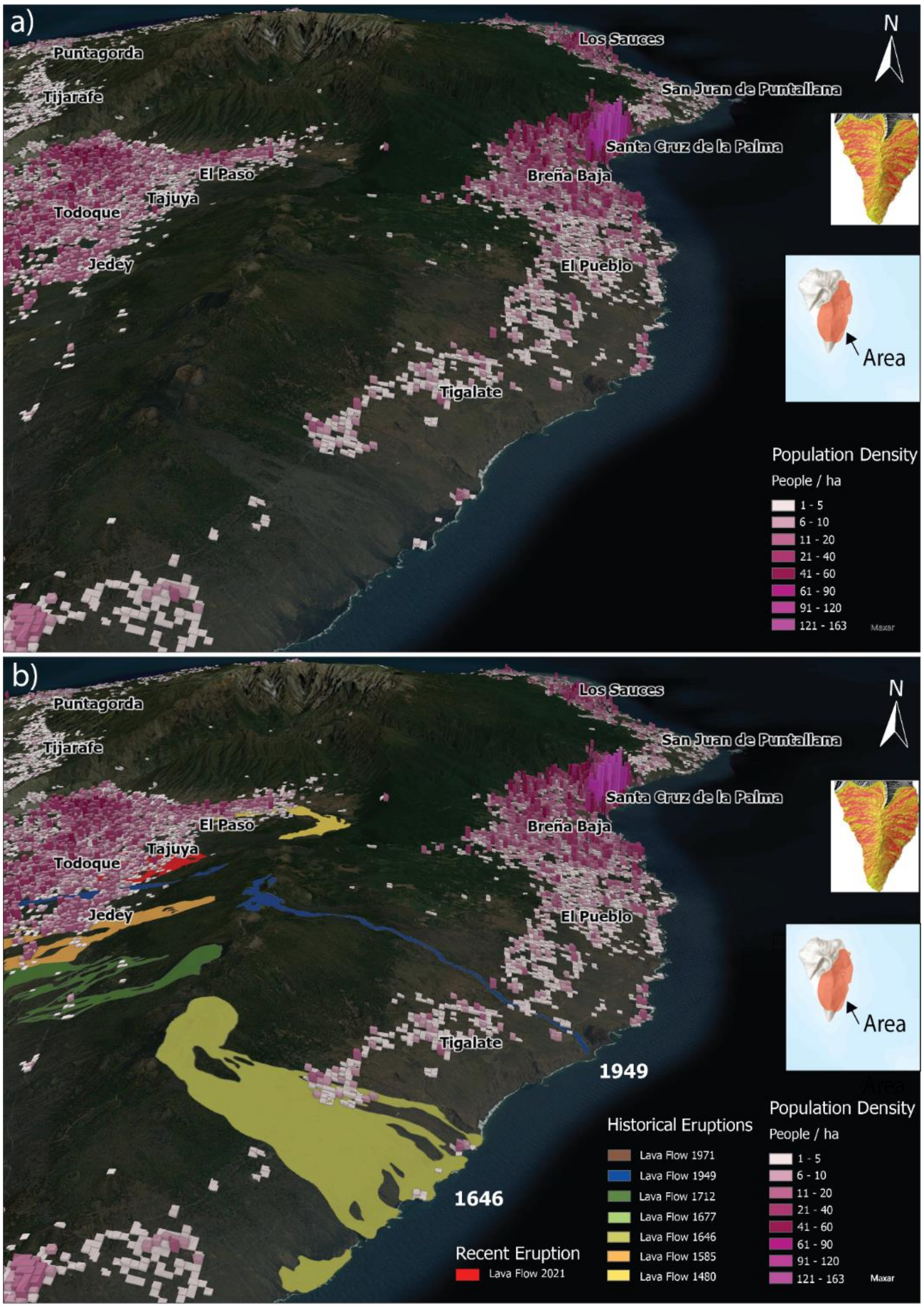
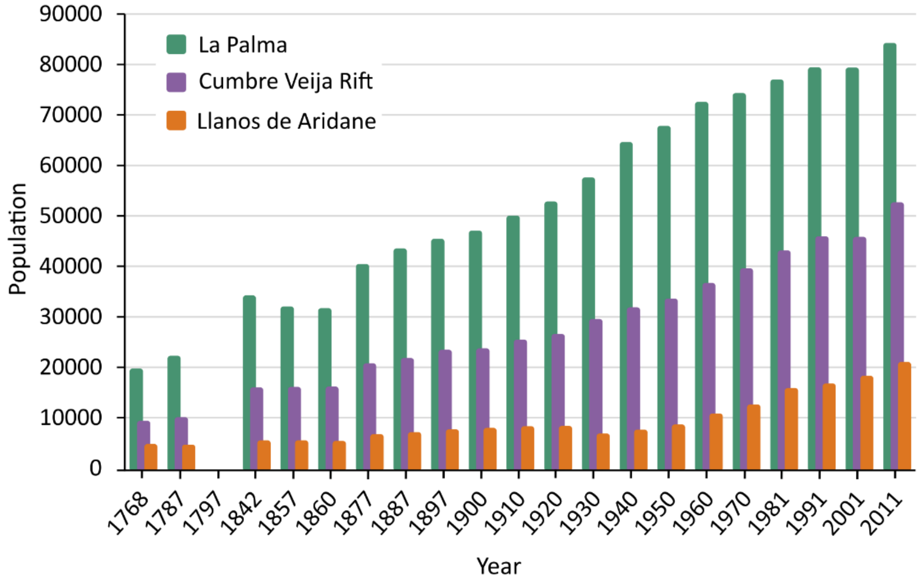


Figure 6. a) *Oblique view of La Palma from Southeast showing population density (data source Pesaresi and Politis, 2022).* ***b)*** *hand panel and historical lava flows and population density. The region affected by lava flow hazard (inset after Marti et al., 2022) is shown in the upper inset in both panels. The population in these areas is at risk for future lava flow eruptions from the CVR, including some of the larger population centres of the island.*

During the 2021 eruption, the debate about suitability of living in active volcanic areas, where eruptions can lead to a disaster, was reopened. During volcanic crises the risk-benefit balance is usually disturbed (the risk increases noticeably). What, then, makes a significant part of the global population live close to active volcanoes? There are people who cannot afford to live elsewhere or even have to live there, forcibly, but many others find sufficient benefits to live and prosper near volcanoes, both personally and professionally. Geothermal resources, soil fertility, tourism and mineral resources are some of the main benefits that volcanoes offer, and on which the economic pillars of these areas are based. This is also the case in La Palma, which has an economy largely based on agriculture and tourism, making use of the fertile volcanic soil and volcano tourism as outlined in Erfurt-Cooper and others (2015) and Troll and co-workers in (2017). Moreover, the sense of belonging to a place, often driven by history, culture or religion, also influences people's decision-making. It is not surprising that many of those affected by the 2021 eruption of La Palma expressed their desire to start again and recover their way of life in the same place where they had lost everything as described by Wei-Haas in 2022, although ‘attachment to the place’ did generally drop during the crisis as noted by e.g. Escolà-Gascón and coworkers in 2023.

A key issue at La Palma is that the perception of residents and those affected by the eruption did not fully correspond with those in charge of developing the emergency and evacuation plans, as summarised by e.g. Wei-Haas in 2022. While a volcanic emergency plan was in place, the four-colour traffic light system designated to inform the public of possible evacuations and other protective actions was not fully utilised. On September 13th, code yellow was called out, which alerts of an increased eruption risk and advises the population to pay attention to official communication channels. However, the next stage of the emergency plan (code orange), which calls for a general preparedness for an imminent evacuation, was not utilised. This mismatch between planning and execution has been criticised by the population and has shown possible flaws of such a system (see Wei-Haas, 2022). While escalation of an emergency plan to a full evacuation without the immediate onset or the complete absence of an eruption can cause loss of trust in authority emergency actions, a more cautious approach can leave the population unprepared for an actual volcanic crisis. Since governmental actions contained in volcanic emergency plans are usually based on data provided by a scientific advisory committee, the burden of possible false alarms and the resulting backslash also rests with scientists. This issue is not unique to La Palma. Studies carried out in other active volcanic areas, such as in Iceland highlight the need for better communication between the scientific community, government authorities (at all levels) and the population before, during, and after a volcanic crisis, as discussed by e.g. Jóhannesdóttir and Gísladóttir already in 2010. In these cases, socio-community support, real time information, and the fulfilment of institutional promises are essential to create a framework of trust between different actors involved, as outlined by Wisner and coworkers in 2012 and by Gaillard and Mercer in 2013.



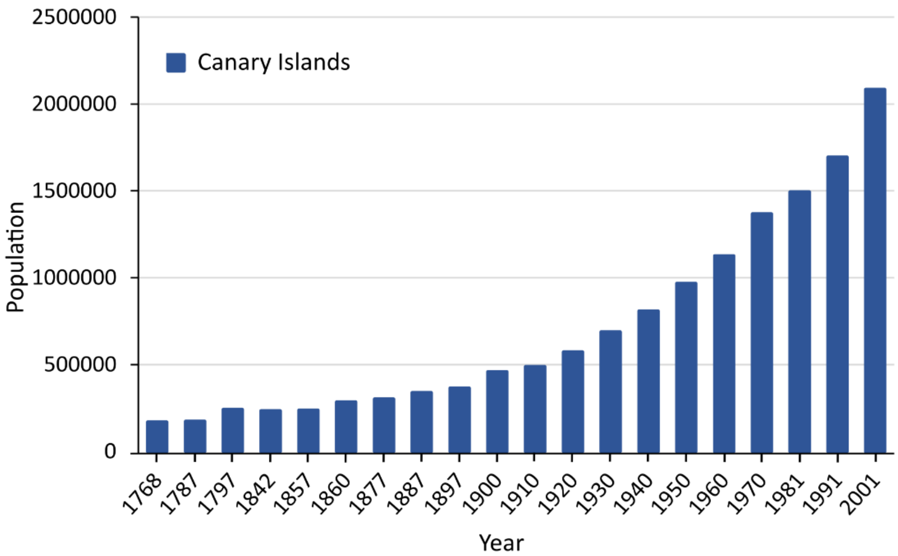


Figure 7. *Population growth in the Canary Islands, in La Palma, on the Cumbre Vieja Ridge (CVR) and in one of the largest settlements in the region, Los Llanos de Aridane (data source:* Instituto Canario de Estadística , ISTAC, 2022). *Population growth on the CVR since the last eruption in 1971 is stronger than on La Palma overall, adding to rapidly increasing vulnerabilities in this volcanically active region.*

Maybe in part because volcanism in the Canary Islands attracts tourism, its destructive potential is sometimes underestimated in political and economic decisions, even if scientific evidence for its hazard potential has always been there. In fact, the 2021 opinion poll carried out by the Canarian Institute of Statistics (ISTAC) showed that the priority concern in the Canaries during 2021 was unemployment. The volcanic eruption was the second main concern only on La Palma, whereas natural disasters occupied a subordinate position in the ranking of archipelago wide concerns, where immigration and healthcare were in the second and third place, respectively. Risk perception, i.e. how people viewed the risk from volcanic hazards, may have been somewhat distorted amongst the population, especially given the infrequent recurrence interval of volcanic eruptions in the Canary Islands, and the limited economic damage from eruptions on La Palma prior to 2021. The most recent historical eruptions on La Palma prior to the one in 2021 was in an area with very low population density in the South of the island. This is reflected in Copernicus data of current populations. These data record fewer than 30 people living on lavas of the 1971 eruption today (data from 2020). Similarly, only 63 people live on the 1677 and 191 people on the 1646 eruption deposits today, which are also located in the south of the island (see geographical distribution of historical lavas in **Fig 1.**). Although data for population prior to these eruptions are not available, a severe contrast is apparent with 1279 people that live presently on the 1949 lavas, and 1096 on the 1585 lavas, which erupted further north on the CVR. Yet further north, at the northern end of the CVR, we find 2464 people living on the lavas of the 1480s eruption, and over 7200 people that were registered in 2020 to have lived on the area covered by the deposits of the 2021 eruption. This distribution of eruptions, especially with the 1971 eruption in the low population areas of South La Palma, may have added to the view that La Palma eruptions are not particularly destructive and could so have led to an underestimation of the true risks posed by renewed volcano activity on La Palma (compare also discussions published in Wei-Haas in 2022 and by Escolà-Gascón and coworkers in 2023 and **Figures 5 & 6**). This distorted risk perception, coupled with an attachment to a place, is likely also reflected in ongoing post-eruption attempts to continue and rebuild, which is at least partly a reflection of a popular sense of safety or immunity against volcanic hazards. This is further exemplified by numerous individual testimonies and collective citizen initiatives (e.g. the 'Plataforma de Afectados por la Erupción del Volcán Cumbre Vieja 2021; PAEVCV in 2022) from during and after the eruption, with many of the people expressing that their wish to resume their lives in the same place or close to the place where the lava destroyed everything that they had.

Fundamental lessons learned from the 2021 La Palma Eruption

An important realisation from the 2011 El Hierro and 2021 La Palma eruptions, as well as from the two less well monitored eruptions in the last century, i.e. the 1949 and 1971 eruptions, is that we now know that crisis management protocols in the Canary Islands are sufficiently developed to ensure an absence of direct volcano casualties in basaltic fissure-fed eruptions. Apart from a small number of fatal accidents (two in 1971 and one in 2021), all of which were connected to unauthorised or unnecessarily risky behaviour by individuals, no fatalities from direct volcanic causes occurred. Indeed, crisis management policies and protocols on La Palma in 2021 built on the experiences from El Hierro in 2011/12 with large improvement compared to previous volcano crisis handling, as outlined in 2012 by Carracedo and coworkers in Geology Today and by Perez-Torrado and colleagues in Spanish in 'Estudios Geologicos'. Moreover, compared to the 2011/2012 El Hierro eruption, and also the 1971 Teneguía and 1949 San Juan eruptions during the last century on La Palma, the 2021 crisis was the technically best monitored volcanic crisis in the Canary Islands to date. This is due to the advanced and widely extended technical surveillance available now that provides valuable scientific information in near real-time, and to the now historically repeated type of eruption style from the Cumbre Vieja that can serve as a model for future volcanic eruptions along the CVR. Importantly, the 2021 crisis has, despite the intense material and economical damage, given us the knowledge that threats to human life from future eruptions in the Canaries can, in principle, be mitigated, forecasted and managed. This is despite the high population density of the Canary Islands and the relatively long inter-eruptive periods between major volcanic events (see Carracedo and others in Geology Today in, 2022). This realisation is of crucial importance beyond La Palma and is relevant for the entire archipelago, as La Palma only has the third highest population density (220/km^2) in the Canary Islands after Gran Canaria and Tenerife with 546 and 456/km^2, respectively. These numbers are relatively high compared to e.g. El Hierro with only 42/km^2 and 94/km^2 in Spain overall.

Reconstruction after the eruption

Now, some two years after the 2021 La Palma volcanic eruption, a challenging, laborious and costly period of reconstruction still lies ahead for the people of La Palma. This includes rebuilding or replacement of the over 1300 homes and over 1500 utility buildings damaged or destroyed by the eruption. Challenges will include assessment of which remnants can be reconstructed and which need to be demolished. Building on the new lava is not simple and will likely be avoided if possible for some time, especially in the portions of the lava field that have accumulated up to 70-m-thick lava flows and are expected to emit extra heat and gases for several years to come, as outlined by the 'Ministerio de Transporte, Movilidad y Agenda Urbana' (MITMA) in 2023. Moreover, assessment will be required if lava tunnels are present, which could destabilise any infrastructure above, making rebuilding on the new lava a costly exercise. Reconstruction of roads and houses requires blasting and rock removal to pave the ground, as well as careful testing of materials to ensure resistance against residual heat from underlying lava to comply with the 2023 MITMA recommendations. Crucially, reconstruction of vital road connections is a priority, and now offers the opportunity for re-planning the road network to accommodate the needs of the growing population in the western part of the island. Together with the new road crossing the lava field, new emergency roads and tracks can be constructed to optimise access for civil protection vehicles and for supplying areas that can become isolated by future ash fall and lava emissions.

However, significant portions of the fertile and agriculturally highly productive land of the Aridane Valley (bananas, avocado, pineapples, and wine) have been covered by lava flows and/or thick lapilli beds and so will be unproductive for some time to come. The future use of former farmland covered by lavas will require costly and laborious investment to prepare the land for farming by adding new soil on top of the fresh lava (a process locally called "sorribado", which was described in detail by Troll and coworkers in Geology Today in 2017) and which has been previously applied to lava platforms of the 1585, 1712, 1949, and 1971 eruptions. Moreover, reconstruction will need to take much care to at least in part preserve the natural beauty of the newly formed volcanic landscapes and discussions are underway to preserve crucial volcanological features, while simultaneously allowing for nature-based tourism, as discussed in Carracedo and colleagues and by Wei-Haas in 2022. The new lava deltas that formed in 2021 are now, by definition, governmental lands. Although population pressure exists to make these lands agricultural areas, another possibility is to develop the new lava deltas as an educational and touristic resource, perhaps in the form of a volcano park or a demarcated nature reserve (compare with discussion in Carracedo and others in 2022). A visitor centre and marked footpaths would allow large numbers of visitors to enjoy the beauty of the volcanic features, yet ensuring minimal impact on the landforms.

Preventing loss of livelihoods in future CVR eruption

The most important problem that remains, however, is to create a system that guarantees alleviation of costs associated with losses that occur to local populations in case of a recurrent volcanic disaster. Models from other active volcanic areas similar to the Canary Islands (e.g. the Hawaiian Islands) may need to be investigated and adopted (compare with the work of Houghton and coworkers in, 2021). In this respect, it is important to realise that only ca. 50% of affected properties on La Palma were fully insured, and that this is the main factor for the complete loss of livelihood for many of the worst affected citizens. 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, housing design, and road construction. Importantly, in Hawaii there are insurance premiums that are especially designed for volcanic eruptions that cover damage to houses and property caused by such events. These include damages caused by lava flows and/or volcanic bombs and by fires that may result from incineration by lava flows or glowing projectiles. Similar to the mandatory car insurance, volcano damage insurance can be further extended. It can include repair costs that may arise from lack of maintenance in case of longer evacuations as well as damage to furniture, clothing, appliances and possible acts of looting, and even the costs for temporary accommodation until the volcanic risks have subsided (see also the article by Carracedo and others in Geology Today in 2022). While insurance adds extra financial burden, and may not be immediately popular with local populations, mandatory insurance for the Cumbre Vieja region seems to be the only real long-term protection against loss of livelihoods, especially as volcanic risk is widespread for almost all of the CVR, as pointed out by e.g. Carracedo and coworkers and Martí and colleagues in 2022. Aversion against financial cover by insurance companies may in part stem from many buildings not being constructed to required building standards, or may even be unregistered (illegal), such as garages converted into living spaces that were never registered as living quarters. To circumvent issues with substandard or non-approved buildings, insurances could consider employing levels or grades for building quality, with lower refund values for poorly built or not registered buildings. This is a practice that is for instance in use in Scandinavia, where DIY renovations of homes, that often fall short of fully professional workmanship, can nevertheless receive a degree of insurance cover, albeit lower than a fully certified equivalent. An initial assessment by an insurance inspector would in no way be unusual when buildings are bought and sold or assessed for value and standard of construction and repair. Refusal to have at least basic insurance cover in the areas at risk could still be permitted, but might then lead to non-eligibility for governmental emergency support in case of future volcanic disaster, thus ensuring high participation rates by populations along the CVR.

In addition, insurance premiums are based on assessment of the volcanic risk, which in turn is based on the foreseeable frequency of eruptions in a given area, and the anticipated type and distribution of volcanic emissions. All recorded (historical) eruptions in the Canary Islands are of the same fissure-fed cinder cone and lava flow type, which makes prediction of the probable future volcanic hazards from eruptions in the archipelago qualitatively achievable. Among the possible volcanic hazards, bouncing spallation bombs described in detail by Day and coworkers in 2022, should now also be considered in future volcanic risk assessment. They have been proven to significantly increase the volcanic hazard and require recognition of an expanded hazard area on steep-sided volcanoes with ballistic tendencies such as was the case for the Tajogaite eruption. Indeed such proximal as well as the distal damages expected by a possible volcanic event of this eruption type can in principle be assessed based on lava flow and pyroclastic eruption simulations in the framework of for instance Geographic Information Systems (GIS). These can be utilised to model damage areas in case monogenetic fissure fed cones emerge in higher altitude areas on islands such as El Hierro, Tenerife, Gran Canaria and La Palma. Such model calculations, as initiated by Marrero, and coworkers in 2019 and Marti and others in 2022 for La Palma, and similar to the work of Prieto-Torrell and colleagues in 2021 for El Hierro, and the maps shown in **Figures 5 and 6**, would permit a detailed hazard and infrastructure damage classification for each island and so enable estimation of the expected financial damage for the various areas of the volcanically active ridges and valleys alike. Such maps would not only allow to identify the financial risk and inform insurance premium estimates, but would moreover permit identifying areas of heightened risk to vital structures and large population numbers. This will be especially important as our modern society is more vulnerable to volcanic hazards due to increase in population density and interconnected infrastructure, which is in fact one of the key reasons why the 2021 eruption was more disastrous than most historical eruptions in the Canary Islands to date, with perhaps the exception of the 1706 Garachico eruption on Tenerife or the 1730-36 Timanfaya eruption on Lanzarote, which were described in considerable detail in Carracedo and Troll in 2016.

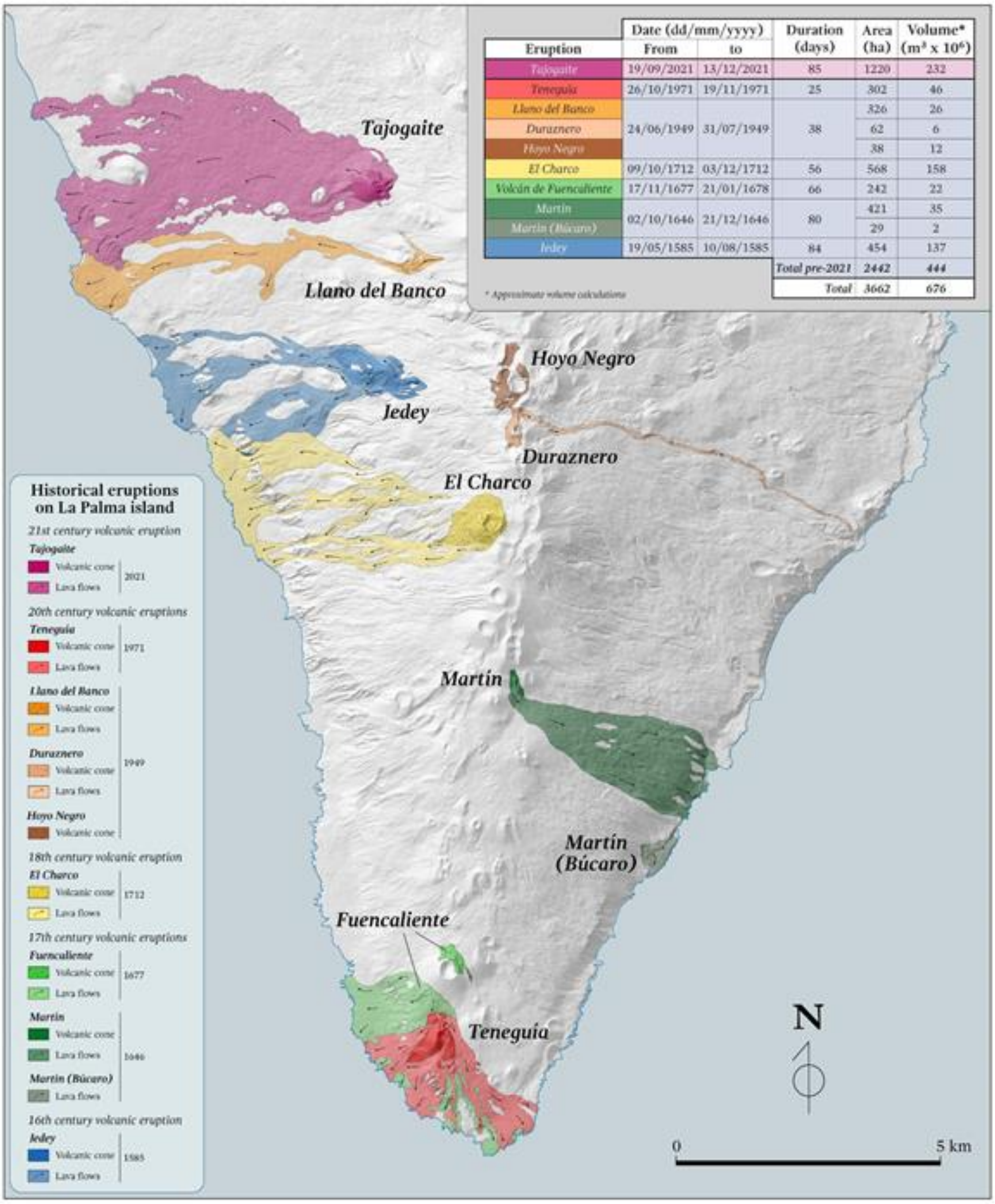
Eruption management and volcano perception; the inevitable clash of society with the volcano

Unlike the 1971 eruption, the 2021 La Palma eruption has provided enormous structural and social challenges for the authorities. On short time scales, there were only limited opportunities to predict the timing and exact routes and extent of lava flows from the CVR and a larger exclusion zone was established to keep people out of harm's way.

On the scale of centuries and decades, it can be that lava flow eruptions will affect the Cumbre Vieja Ridge as outlined by e.g. Marti and coworkers in 2022. The area affected in 2021 was close to the 1480s Quemada eruption and also to some of the flows of the 1949 San Juan eruption, and not too distant from the lavas of the 1712 and 1585 eruptions (**Figs. 1, 5 & 6**). It could therefore be argued that potentially damaging eruptions in that area were predictable. However, the eruption of 1971 took place at the southern tip of the CVR and in an area that was sparsely populated, as did eruptions in 1677 and 1646. The 1949 eruption affected the same area as the 2021 disaster, but happened at a time when population densities were generally much lower (**Fig. 7**), so human memory had limited comparison of a disastrous eruption on the island. Human emotional memory will rapidly decline if not repeatedly activated, as described by neuroscientists such as LaBar and Cabeza in their work from 2006, and usually does not extend across generations (i.e. some 30 years). Thus, events some 30 or more years prior are often not considered by many within the assessment of direct threats. Disastrous eruptions in the Canary Islands with enormous loss of infrastructure were the 1706 Garachico eruption on Tenerife and the 1730-36 Timanfaya eruption on Lanzarote as described in detail by Carracedo et al., 1992 and 2007. Both sites are now tourist attractions and bus tours show the Garachico harbour that was flooded with lava, as well as the Timanfaya National Park that welcomes over 1.5 million visitors per year. Volcanism is therefore also prevalent on the other islands. In this context, the return of volcanism to the northeast of the CVR was geologically inevitable on a decadal to centennial time scale when using the historical eruptions mentioned above and geoscientists were clearly aware of it. However, population growth, a growing tourism sector on the island and the link of tourism to volcanoes on La Palma (e.g. the Ruta de los Volcanes, the Fuencaliente volcano visitor centre, the 1949 lava tunnel visitor centre) are all examples where volcanism has helped the islands economy, thus potentially blurring the picture as to its harmful aspects amongst wide echelons of the local population.

Existing and persistent volcanic risk and eruption hazards

Land is altered for generations in volcanic eruptions. Areas that were recently made up of settlements are now lava fields, known in the Canary Islands as "malpaís" (badlands), as they cannot be used for agriculture or for direct settlements as they are rocky, jagged and often treacherous due to possible hidden lava tunnels, former gas vugs and other inconsistencies in the lava rock. In respect to future settlements and population increase on the CVR, the question of acceptable risk needs to be assessed. A high level of long-term risk of lava inundation from eruptions will persist, but the willingness of people to move to areas along the CVR over the last decades will likely continue. This includes a growing number of expatriates seeking to find a retirement home or a better life away from the metropolitan areas of mainland Europe. Using simple statistics, the likelihood of another eruption on the CVR is about 50% for the next 50 years, i.e. there is a 50:50 chance of another eruption in the next 5 decades. Moreover, the distribution of historical eruptions does not follow a clear age progression, which is typical for fissure fed systems, implying that a future eruption can occur anywhere along the CVR (**see Fig 8**). Indeed, using historical eruption locations, it appears that there is no place on the Cumbre Vieja ridge that is truly free of the risk of being affected by future volcanic events, as recently pointed out by Martí and coworkers in 2022. These long-term eruption intervals are difficult to factor into short term (annual to decadal) land use plans as such infrequent events are commonly discarded in short term plans that are often driven by political programs of elected governments and are usually focussed on legislative intervals rather than volcanic eruption intervals.



Eruption	Date (dd/mm/yyyy) From	to	Duration (days)	Area (ha)	Volume* ($m^3 \times 10^6$)
Tajogaite	19/09/2021	13/12/2021	85	1220	232
Teneguía	26/10/1971	19/11/1971	25	302	46
Llano del Banco	24/06/1949	31/07/1949	38	326	26
Duraznero				62	6
Hoyo Negro				38	12
El Charco	09/10/1712	03/12/1712	56	568	158
Volcán de Fuencaliente	17/11/1677	21/01/1678	66	242	22
Martín	02/10/1646	21/12/1646	80	421	35
Martín (Búcaro)				29	2
Jedey	19/05/1585	10/08/1585	84	454	137
			Total pre-2021	2442	444
			Total	3662	676

Figure 8. Summary map of historical eruptions on the Cumbre Vieja Ridge of South La Palma with detailed flow indicators for the lava flows and fields and eruption durations (after Perez-Torrado et al., 2023). Distribution of historical eruption sites along the ridge is not systematic with age, a feature that is typical for fissure fed magmatic systems where age progression is usually absent as magma may ascend along any segment of a rift of fracture system (compare Carracedo and Troll 2021). This implies that future eruptions may occur anywhere along the Cumbre Vieja.

Moreover, rapid population growth from 73,749 in 1970 to 83,458 in 2020 (**Figs 7**, ISTAC, 2022) is likely to continue. This is due to the growing tourism sectors, a rising trend for retirement residents from Europe (ca. 21% of the population on La Palma is over 65 at present), and expanding agriculture on the island. These developments will ensure that the number of vulnerable populations, which was never as high as in 2021, will continue to rise as a function of the very high population density on several parts of the CVR. The government of La Palma is now opening new roads to permit traffic along the major North-South traffic route on the West of the Island, including access to isolated properties within the lava field. This will allow an increasing number of residents to return to their properties and likely encourages continued development of settlements, population increase and illegal urbanisation, a problem that has caused many properties to be insufficiently insured (as mentioned above, only ca 50% of affected properties were fully insured), leading to enormous loss of property values for many residents during the 2021 crisis. Another aspect is that a number of residents have apparent difficulties struggling to prove ownership of land and houses for governmental support and/or insurance reimbursement purposes as they left behind legal documents in their houses in the rush to evacuate (as code orange was not called). In future, double 'bookkeeping' of documentation by authorities, insurance companies, and private land or property owners will be vital and should be insisted upon when closing insurance contracts in future. As current plans are tending towards a renewed settlement cycle, which will not reduce but rather perpetuate or increase risk for local residents in the region (compare for instance to Houghton and coworker's 2021 discussion of recent developments on Hawaii), the only alternate long-term option that can reduce the risk for populations is to ensure that land use is connected to full insurance cover against volcanic destruction in the CVR region, and that refusal to insure properties will disqualify owners from emergency support by governmental support systems. Such a strategy may not be popular in the current social and economic climate on the island and during a general recession across Europe in the months and years after the 2021 eruption disaster, but appears to be the only long-term solution to prevent loss of livelihoods for many in case of renewed volcanic activity on the island (**Fig. 8**). Remarkably, many local people report that while insurance pay-outs were released relatively swiftly, governmental finance support is proving slow and is associated with high levels of bureaucracy, implying that governmental emergency help is much less desirable than insurance cover to help affected families and businesses in times of crisis. The decisions made now will shape the long-term financial safety of future generations in the region and any permanent risk reduction requires, in addition to a long-term evacuation plan, a financial protection program for residents to ensure that livelihoods are not at risk or can be fully recovered. This includes both family homes and businesses such as farms and vineyards in the region and these plans need to be updated and maintained even if no eruption will occur for several decades. Otherwise, the next financial and social disaster is almost guaranteed, especially when planners and populations turn their back on the 2021 eruption and soon forget the lessons learned from this disastrous event.

The 2021 eruption and the current post-eruption volcanic quiescence on La Palma now provide the incentive and the crucial opportunity to increase public awareness and hazard preparedness, improve communication in crisis situations, and so improve societal resilience in light of natural hazards. It is imperative that the current post-eruptive time window is used by authorities, civil protection organisations, and the inhabitants of the Canary Islands to further develop and refine the emergency procedures in place and prepare for, and mitigate against, future human losses, damage to infrastructure and housing, and take measures to prevent associated economic hardships on La Palma and the other islands in the archipelago in case of future volcanic eruptions.

Author contribution statement

The study was conceptualised by VRT, MA, and JCC. HG, FPT, VS, FMD, CB, FW, HA, GG, JMDD, ARG, EG, and KD have contributed to the development of the presented concepts and discussion of the implications. CB, FW, FPT, AGR, VRT, and HG have contributed to the production of the figures. All authors have contributed to editing the final manuscript.

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