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Changes in the geomorphology, vegetation and land use in the historical eruptions of the 20th and 21st centuries on La Palma (Canary Islands, Spain)

Cambios en la geomorfología, vegetación y usos del suelo en las erupciones históricas de los siglos XX y XXI en La Palma (Islas Canarias, España)

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Abstract

This paper analyses the changes in geomorphology, vegetation and land use after three volcanic eruptions (San Juan, 1949; Teneguía, 1971; and Tajogaite, 2021) on La Palma (Canary Islands). It uses aerial photographs, maps and bibliography to analyse new landforms (cones, spatter cones, hornitos, lavas) and evaluate the destruction of vegetation by pyroclastic falls and lava flows. The main method used was photointerpretation, assisted by bibliographical and fieldwork data. In terms of vegetation, the recovery trend is almost immediate after the end of the eruptions, with the appearance of pioneer vegetation communities specific to each bioclimatic belt. Land uses have changed radically, shifting from agricultural, residential, and industrial to purely natural uses, which has favoured the creation of protected areas and intensive cultivation (deltas and midlands). In conclusion, (1) Tajogaite eruption,

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the most recent one, acted as a laboratory to study these processes, (2) through the three eruptions, diverse volcanic structures were created, and (3) some 1,800 ha of surface were affected, mainly impacting Canary Island pine forests. All these events produced profound changes in the affected landscapes.

Keywords: Historical Eruptions; Landscape; Land Uses; La Palma; Volcanoes; Vegetation; Volcanic Geomorphology.

Resumen

Este trabajo analiza los cambios en la geomorfología, la vegetación y los usos del suelo tras tres erupciones volcánicas (San Juan, 1949; Teneguía, 1971; y Tajogaite, 2021) en La Palma (Islas Canarias). Se han utilizado fotografías aéreas, mapas y bibliografía para analizar las nuevas formas de relieve (conos, coneletes escoriáceos, hornitos, lavas) y evaluar la destrucción de la vegetación por caídas de piroclastos y coladas de lava. El método principal utilizado fue la fotointerpretación, con el apoyo de datos bibliográficos y de trabajo de campo. En cuanto a la vegetación, la tendencia a la recuperación es casi inmediata tras el fin de las erupciones, con la aparición de comunidades vegetales pioneras específicas de cada cinturón bioclimático. Los usos del suelo han cambiado radicalmente, pasando de usos agrícolas, residenciales e industriales a usos puramente naturales, lo que ha favorecido la creación de zonas protegidas y cultivos intensivos (deltas y medianías). En conclusión, (1) la erupción del Tajogaite, la más reciente, sirvió de laboratorio para estudiar estos procesos; (2) las tres erupciones crearon diversas estructuras volcánicas; y (3) se afectaron unas 1.800 ha de superficie, principalmente bosques de pino canario. Todos estos eventos han producido profundos cambios en los paisajes afectados.

Palabra clave: Erupciones históricas; Paisaje; Usos del suelo; La Palma; Volcanes; Vegetación; geomorfología volcánica.

1. INTRODUCTION

Volcanism is a natural process acting globally and throughout Earth's history. The largest volcanic events are usually located, in large igneous provinces (Bryan *et al*., 2010), which are scattered all over the world both in continental and oceanic environments (Bryan y Ferrari, 2013).

Volcanic activity is one of the most powerful and transformative forces on Earth having the capability of affecting it globally or locally. Such events can dramatically damage landscapes, and have long-term consequences for ecosystems, human settlements and on the climate. Volcanic ash and gases can enter the atmosphere, influencing temperatures, lowering them, and can remain there from weeks to years (Robock, 2000; Self, 2006).

One of the most evident impacts of volcanic eruptions is the dramatic landscape change. Other consequences include loss of human lives, destruction of housing and disruption of whole communities. Regional economies, tourism, industry and services can also be strongly impacted. Ash fall can cover crops, damaging them and the soil, endangering food security and farmers' livelihoods, and lava flows and lahars can destroy roads, bridges, buildings, electricity networks, and other utilities (Troll *et al*., 2024). Moreover, the effects of the volcanic eruptions on geomorphology can be very significant (Waythomas, 2015).

However, in the long term, volcanic materials can enrich soils with minerals, improving fertility and benefiting future agriculture. In fact, volcanic lands are known for their agricultural productivity. Thus, ecological recovery can be surprisingly fast, with pioneer species colonizing the new surfaces and establishing a new ecological equilibrium in the short term and even promoting biodiversity (Ciriminna *et al.* 2022; Fiantis *et al.* 2019). Indeed, one of the positive impacts of volcanic activity is the creation of new landscapes.

In this context, volcanic islands are interesting environments in which to study volcanic processes and structures. In fact, since its beginning, when an island emerges, it will continue creating landforms, for example, the volcanic archipelagos of Hawaii (USA) and the Canary Islands (Spain). Furthermore, in the Canary Islands, there have been a series of eruptions in historical times (from the 15th century) and several eruptions in the 20th and 21st centuries on La Palma island. The last volcanic eruption was quite recent, the Tajogaite eruption, at the end 2021 (Troll *et al*., 2024).

An illustrative example from the Canary Islands is the case of Timanfaya volcanic field (1730-1736), which destroyed 26 villages and extensive agricultural land (León, 1998; Longpré y Felpeto, 2021) causing cattle to be sent for grazing on the neighbouring island of La Graciosa (Santana-Cordero *et al*., 2016). Lava flows can also create new areas by expanding an island's surface area, as happened in both Hawaii and the Canary Islands (Carracedo *et al*., 1998). Consequently, volcanic eruptions can trigger both the destruction and creation of new habitats, which have major implications for biodiversity and human-environment interaction.

Research in landscape change has focused for the most part on human agency as the root of change while relegating natural events to a less central position. However, a series of conceptual-methodological frameworks have considered natural events as driving forces, behind landscape change (Bürgi *et al*., 2004). Our approach is particularly relevant to volcanic oceanic islands contexts, which are periodically affected by eruptions. Eruptions in these cases are not necessarily the most important factors as their subsequent effects are also key to understanding new landscape dynamics (Quintana Andrés, 2005). Thus, landscape patterns and processes might be affected creating new dynamics, which can be influenced by regional planning posing the question of whether such new landscapes should be converted into protected areas. Changes in land use and land cover can lead to new activities in the area, as in the case of the last eruption in La Palma, in 2021 (Vegas *et al*., 2022; Dóniz-Páez *et al*., 2024a, b).

Volcanic activity has a deep impact ranging from the immediate natural disaster stage to long-term impacts on the climate, economy, public health and infrastructure. These events have shaped human societies throughout history (Quintana Andrés, 2005), such as the eruption of Vesuvius in 79 AD, or of Mount St. Helens (USA, 1980) or that of Pico do Fogo (Cape Verde, 2014-15).

However, in recent decades, geological items with intrinsic values have been viewed as important natural resources to be conserved, protected and subject to special planning as part of so called geoconservation (Henriques *et al*., 2011). These items can have scientific, cultural and ecological value, and methodologies have been designed to characterize and value them (Pereira y Pereira, 2010; Dóniz-Páez *et al.*, 2024a).

In this context, landscapes resulting from volcanic eruptions can constitute unique geological formations and where vegetation and agriculture techniques are singular (e.g. case of Timanfaya, Lanzarote, Canary Islands). These landscapes are valuable for tourism and, in this sense, geotouristic resources constitute the basic elements of geological tourism as a global activity (Ruban, 2015). Thus, singular, and spectacular characteristics of volcanic landscapes can attract many tourists and generate important revenues each year, as seen in the Yellowstone National Park (USA), Mount Fuji (Japan) or the Teide National Park (Canary Islands, Spain). The touristic activity in these places is mainly based on volcanic processes and landscapes, attracting tourists and helping local economies.

This research aims to analyse the impact of volcanic eruptions on the island of La Palma (San Juan 1949, Teneguía 1971 and Tajogaite 2021) in the creation of new landforms, their influence on the landscape as well as the changes in vegetation and land use (Fig. 1).

Figure 1. Construction of the Tajogaite scoria cone and lava flows (photos R. Becerra-Ramírez): a) Formation of the cone in a Strombolian phase and a basal effusive fissure (24 September 2021); b) aa lava flows and channels (21 November 2021, from Montaña de La Laguna).

2. STUDY AREA

La Palma is located in the northwest extreme of the Canary archipelago with an altitude of over 2,400 m above sea level and the furthest island from the African coast (Fig. 2). This makes it a very good recipient of the humid trade winds. It is, therefore, the island with the most water resources in the Canary Islands (Guerra, 2018). The availability of water and the altitudinal range on the island create ideal conditions for the development of the various types of plant landscapes that occur in the Canary Islands, with a very characteristic distribution pattern in altitudinal or zonal bands (bioclimatic belts).

The island has been a World Biosphere Reserve since 2002 (part of the island was declared one in 1983), reflecting its importance for the conservation of global biodiversity. Almost 6,000 species have been catalogued, of which 1,106 are endemic, representing 18% of the island's biodiversity (Martín Esquivel *et al.*, 2005).

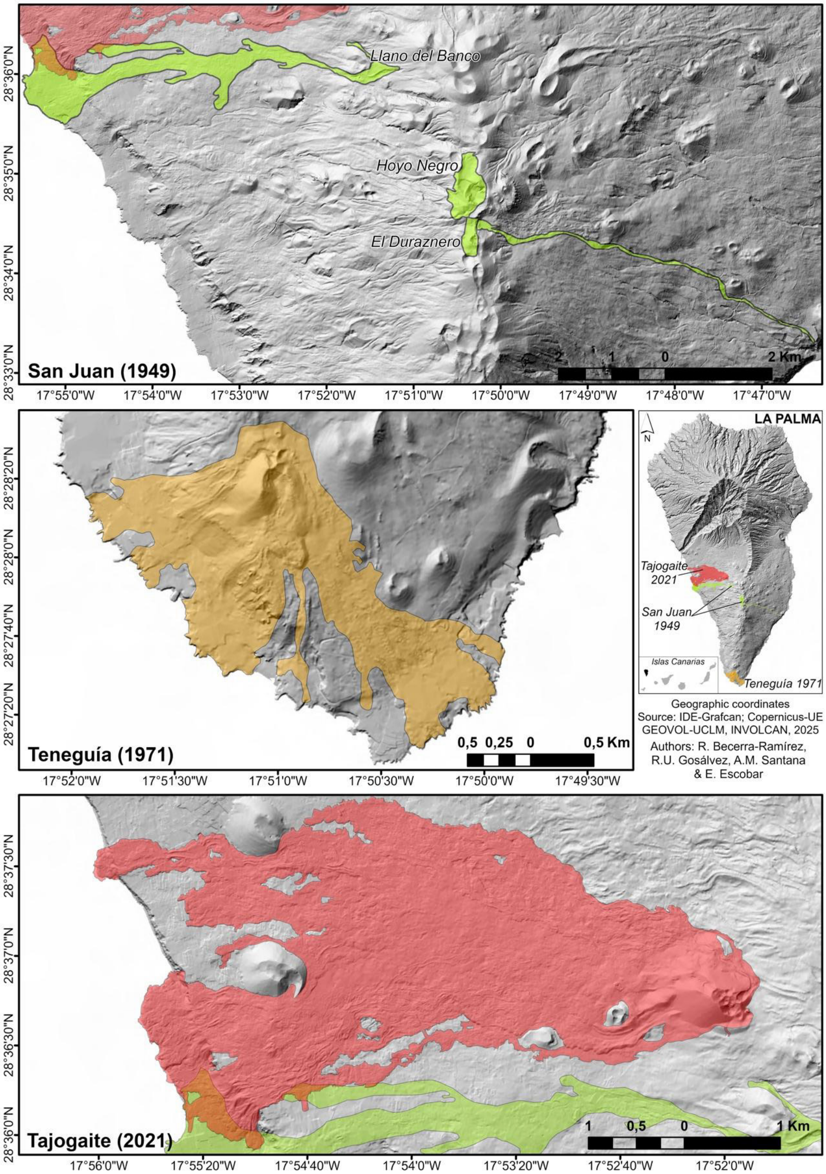

Figure 2: Location of the historical eruptions of 1949, 1971 and 2021 on La Palma island. Self-elaboration.

Volcanic activity has marked the recent evolution of La Palma, as in other volcanic oceanic islands, constituting an important laboratory for geomorphological and biogeographical processes (Romero Ruiz, 1991; Juan *et al*., 2000; Emerson, 2002). All recent eruptions on the island are within the so-called monogenic basaltic volcanism, with mainly Strombolian and effusive styles. They have built complex volcanic edifices with scoria cones with several craters, spatter cones, hornitos, eruptive fissures, and abundant lava flows (Dóniz-Páez *et al*., 2024a).

In the second half of the 20th century, the island experienced two major eruptions (Fig. 2) in the Cumbre Vieja geological domain (Carracedo, 2008). The most recent eruption of Cumbre Vieja, Tajogaite in 2021 (Fig. 1), has been the longest eruption recorded in La Palma and the fourth longest in historical times in the Canary archipelago (Romero Ruiz *et al*., 2023; Dóniz-Páez *et al*., 2024a, b).

Cumbre Vieja is the study area where the historical volcanic activity of La Palma has been concentrated, extending from the area around Pico Birigoyo to the coast of Fuencaliente. In this area, the highest altitudes exceed 1,900 m above sea level at Nambroque (1,924 m), Montaña del Fraile (1,906 m) and La Deseada volcano (1,944 m). This part of the island contains more than 80 recent volcanic cones surrounded by mantles composed of various types of pyroclasts and lava flows. Since the 15th century, up to eight eruptions have been recorded in this part of the island, the oldest being that of Montaña Quemada, dated between 1444-1448 or 1470-1492 (Romero Ruiz, 1991; Romero Ruiz *et al.,* 2024), and the most recent that of Tajogaite in 2021 (Fig. 1).

3. METHODS AND MATERIALS

A morphological characterization of the eruptions has been made following the descriptions of Romero Ruiz (1991) for the San Juan and Teneguía volcanoes. For Tajogaite, it was based on the work carried out by geographers from the Universidad de La Laguna led by Romero Ruiz. The descriptions are in an unpublished document written for the Government of the Canary Islands as part of the *Territorial Framework for the Recovery of Normality after the Eruption («Marco Territorial para la Recuperación de la Normalidad tras la erupción»)* (Romero Ruiz *et al*., 2023). In addition, in July 2022, the geomorphological synthesis units established in the above work were photographed with a *Dji Mavic 2 Pro* drone equipped with a *Hasselblad* optical camera.

The evaluation of the changes in vegetation and land use has been approached through photointerpretation and fieldwork. For the photointerpretation, the GRAFCAN Spatial Data Infrastructure was used. Orthophotographs from the 1951-1957 CECAF were consulted to study the impact of the San Juan eruption (1949). Next, orthophotographs taken in 1964 and 1986 were analysed to identify the impacts of the Teneguía eruption (1971). Finally, orthophotographs taken in 2020 and 2022 were used to assess the impact of the Tajogaite eruption (2021). In the subsequent fieldwork, the areas affected by the eruptions and their surroundings were visited between September 2021 and October 2022.

To analyse the changes in vegetation caused by these eruptions, especially the 2021 eruption, the Canary Islands Vegetation Map (Del Arco *et al*., 2006) was used, including the acquisition of updated vegetation mapping of the island of La Palma in digital format (GRAFCAN, 2021).

For the San Juan eruption, neither orthophotographs nor detailed mapping were available prior to the eruption. In this case, it was decided to compare the immediate surroundings not affected by lava and ash to deduce the vegetation and land uses destroyed. This may entail an error that we believe is acceptable since alternative information is not available for the situation prior to 1949. The work of Ceballos y Ortuño (1951) has been considered as reference material.

4. CHANGES IN THE LANDSCAPE AFTER THE SAN JUAN ERUPTION (1949)

The San Juan eruption began on 24 June, 1949 and continued until August 4 of the same year, giving rise to two volcanic complexes: Duraznero – Hoyo Negro and Llano del Banco (Bonelli Rubio, 1950; Benítez Padilla, 1952; Romero Ruiz, 1991). The first is in the summit area, at approximately 1,800 meters above sea level, while the second opens on the western slope of Cumbre Vieja at approximately 1,250 m a.s.l. All the vents opened within the municipality of El Paso, although lava flows also affected the municipalities of Breña Alta, Breña Baja, Fuencaliente, Llanos de Aridane, Tazacorte, and Villa de Mazo.

On July 8, the eruptive phase of Llano del Banco began 2-3 km northwest of the Duraznero and Hoyo Negro craters, emitting a lava flow that flowed through the Las Cubas ravine until it reached the sea in the Puerto Naos area, creating a lava delta (Bonelli Rubio, 1950; Benítez Padilla, 1952; Romero Ruiz, 1991).

The eruptive activity of Hoyo Negro and Duraznero resumed on July 28 and 30, emitting a lava flow from Duraznero that spilled down the eastern slope of the island, extending along the La Jurada ravine (now La Lava ravine) almost reaching the sea, about 300 m from Punta de la Barqueta (Bonelli Rubio, 1950; Benítez Padilla, 1952; Romero Ruiz, 1991).

An area of 51 ha was affected by the Duraznero – Hoyo Negro eruptive complex, while the Llano del Banco lava flows covered an area of 312 ha. In addition, the lava flows from Duraznero – La Malforada descended the eastern slope, covering an area of 27 ha. In total, the area affected by the 1949 eruption amounted to 390 ha (Table 1).

Table 1. Areas affected by the eruptions of San Juan (1949), Teneguía (1971) and Tajogaite (2021)

Volcano	Year	Area (ha)
Hoyo Negro	1949	36
Duraznero	1949	42
Llano del Banco	1949	312
Teneguía	1971	300
Tajogaite	2021	1,241
Total		**1,931**

Source: Self-Elaboration.

4.1. Changes in geomorphology caused by the San Juan eruption

The morphological development of this eruption involves a complex fracture system with two structural lines in different directions that build two differentiated morphological assemblages (Romero Ruiz, 1991: 1041-1058). One is along the summit line, Duraznero – Hoyo Negro, and the other on the western slope, Llano del Banco.

The morphology of the Duraznero eruptive complex (Fig. 3a) was formed by several funnel-shaped emission centres along a N-S fracture. Strombolian pulses built, a scoria cone inside the old Duraznero (or Montaña del Fraile) crater, which is substantially modified, with a length of just over 200 m. Moreover, an elongated fissure crater arch was formed to the north of the previous one, about 260 m long, which was modified by subsequent effusive activity and covered with spatter (plastrons, shreds and scoria). From this crater, lava flows spilled eastwards, filling La Malforada area until they poured into the La Lava ravine. In total, there are up to nine eruptive vents within this morphological complex, a main scoria cone and the elongated crater arch built mainly by spatter.

The second summit morphological complex is Hoyo Negro (Fig. 3b) at the foot of the ancient Pico de Nambroque (or Mambroque) volcano. It was constructed by much more energetic explosions than those of the Duraznero complex, possibly phreatic or phreatomagmatic phases, as mentioned by Romero Ruiz (1991) and Carracedo (2008), opening a funnel-shaped crater much wider and deeper than the previous ones (~400 m in diameter). This modified the previous relief but did not build a proper cone. The funnel crater does not have a clear rim, but a 'scalloped' rim revealing the previous volcanic deposits and structures.

The third morphological complex (Fig. 3c,d), following Romero Ruiz (1991), is Llano del Banco, on the western slope of Cumbre Vieja some 450 m below the summit where the previous edifices developed. It was the main lava emitter of the 1949 eruption, of a Hawaiian fissure type, with occasional explosive pulses. In its initial phase, it built several hornitos and spatter rampart morphologies, together with a huge lava channel through the Las Cubas ravine, accompanied by several lava tubes, tumuli and lateral spills on the walls formed by the fissure eruption. The lavas show typical aa and pahoehoe surface structures and morphologies, which become much more extensive and varied when they reach Las Manchas area on their way to Las Norias. In this area, a lava tube almost 600 m long was formed, and a second tube with a length of 154 m, which is not connected to the previous one (Cueva de Las Palomas or Todoque tube). These lava flows dropped over the cliff near Puerto Naos, forming a spectacular lava delta (Las Hoyas) and several beaches such as Playa Nueva, which has now disappeared due to the Tajogaite lava delta. The channelling of lavas through the ravines filled them up, changing their previous morphology and runoff, just as the development of the lava delta upon reaching the sea caused changes to the coastline.

Figure 3. Morphologies of the San Juan eruption (1949): (a) Duraznero cone, crater arch and La Malforada lava damming; (b) Hoyo Negro funnel crater with 'scalloped' and lobulated rim, Duraznero in the background; (c) Llano del Banco morphologies covered with Tajogaite lapilli (2021); (d) 1949 lava delta (banana crops), Punta de la Lava (or La Bombilla) lighthouse and Tajogaite lava delta (2021).

An interesting element associated with San Juan eruption is that Bonelli Rubio (1950) pointed out the opening of arcuate faults and scarps in the vicinity of Hoyo Negro along the western ridge flank as a consequence of the eruption, but after the start of the eruptive process, without emitting lava or pyroclastic products. These faults and scarps have served to link the instability of insular volcanic edifices, such as La Palma, as the precursors of landslides that failed to develop (Day *et al.*, 1997; Urgeles *et al.*, 1999).

4.2. Changes in vegetation and land use caused by the eruption

The eruption that gave rise to the Duraznero – Hoyo Negro complex and emitted the lava flow from Barranco de La Jurada impacted all the island's zonal vegetation landscapes (Table 2), but the Canary pine forest bioclimatic zone suffered the greatest surface area loss of 110 ha (Fig. 4). In addition, the pine forests were affected by forest fires caused by the eruptions (Miranda, 2017). This was an open Canary pine forest, the most representative species of which were *Bystropogon origanifolius*, *Chamaecytisus proliferus*, *Cistus symphytifolius*, and *Lotus hillebrandii* (Pérez de Paz *et al*., 1994; del Arco *et al*. 2006). In areas dominated by pyroclast falls (lapilli fields) from prehistoric eruptions, a primocolonizing formation of *Plantago webbii*, accompanied by *Descurainia* gilva, dominates (Santos Guerra, 1983; Del Arco *et al*., 2006; Beltrán y Dóniz, 2009; Beltrán, 2017).

Table 2. Affected areas of each vegetation landscape in the San Juan, Teneguía and Tajogaite eruptions on La Palma Island

Eruption	Vegetation landscape	Affected area (ha)
San Juan (1949)	Canary pine forest	110
	Laurel forest (Monteverde)	10
	Anthropized areas and thermo-sclerophyllous scrubland (broom shrubland, «tabaibales» and *Rumex lunaria* scrub)	156
	Anthropized areas and *Euphorbia* scrub and shrublands («Tabaibal-Cardonal»)	83
	Coastal salt marshes	5
	Pioneer communities vegetation associated with pyroclastic fields	16
Total		**380**
Teneguía (1971)	*Euphorbia* scrub and shrublands (Tabaibal-Cardonal)	67
	Coastal salt marshes	4
	Pioneer rock communities of the badlands (*malpaís*)	200
Total		**271**

Tajogaite (2021)	Canary pine forest	118
	Anthropized areas and thermo-sclerophyllous scrubland (broom shrubland, «tabaibales» and *Rumex lunaria* scrub)	859
	Anthropized areas and *Euphorbia* scrub and shrublands («Tabaibal-Cardonal»)	194
	Coastal salt marshes	22
Total		**1,193**
Eruptions from 1949	Canary pine forest	228
	Laurel forest (Monteverde)	10
	Xerophilous scrubland (Tabaibal-Cardonal)	67
	Anthropized areas and thermo-sclerophyllous scrubland (broom shrubland, «tabaibales» and *Rumex lunaria* scrub)	1,015
	Anthropized areas and *Euphorbia* scrub and shrublands («Tabaibal-Cardonal»)	277
	Coastal halophyte belt	31
	Pioneer rock communities of the badlands (*malpaís*)	200
	Pioneer vegetation communities with pyroclastic fields	16
Total		**1,844**

Source: Self-Elaboration.

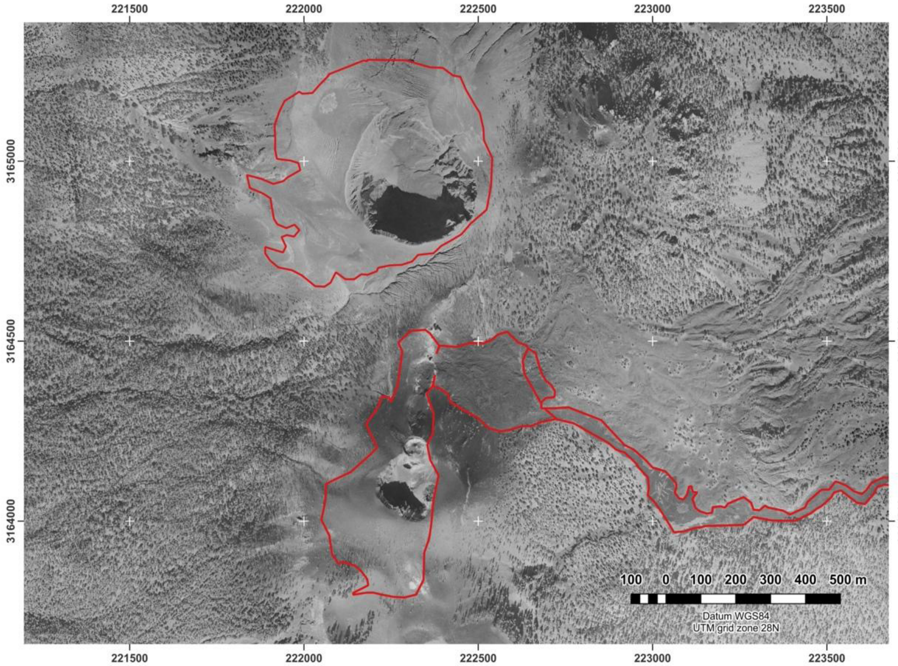

Figure 4. Area of the Canarian pine forest affected by the eruptive vents and pyroclastic deposits from the 1949 eruption at Duraznero and Hoyo Negro. Source: Centro Cartográfico y Fotográfico (CECAF). Years 1951-1955 (IDE Canarias, Grafcan).

La Jurada ravine, through which the Duraznero lava flow was channelled on 30 July 1949, is a deep, linear, fluvio-torrential incision ravine. It runs along the eastern slope of Cumbre Vieja for about 7 km, until it reaches Punta La Barqueta on the coast. The average gradient of this gully is 29%, with maximum depths of more than 20 m and widths that in some places exceed 20 m. The linear, sloping layout means that the ravine crosses different bioclimatic levels and with them the zonal plant landscapes of the Canary pine forest, the «Monteverde», thermo-sclerophyllous scrubland (broom shrubland, «tabaibales» and *Rumex lunaria* scrub). However, orthophotographs available from the 1950s show a very degraded hillside due to the agricultural activities at that time (Fig. 5a), with cultivated terraces up to an altitude of 1,050 m. The crops, pastures and farmsteads of the area are still in use occupying the midlands almost completely, leading to a high degree of degradation of the original vegetation by human action. The best vestiges of the different plant landscapes could be found, at this time, in the La Jurada ravine itself, as is the case today in many of the Cumbre Vieja ravines.

After the Canary pine forests, the area most affected by the eruption in this part of the island is the Laurel forest («Monteverde»), where 10 ha were lost, although at that time it had practically disappeared due to agricultural activity (Fig. 5). The orthophotographs show patches of varying size corresponding to replacement formations with species such as *Morella faya*, *Erica arborea*, *Adenocarpus foliolosus* and *Cistus monspeliensis*. In the contact zone with the thermo-sclerophyllous woodland and its replacement scrub, the «Monteverde» was enriched by the presence of *Rumex lunaria*, *Argyranthemum frutescens*, *Artemisia thuscula* and *Euphorbia lamarckii*, among other species (Ceballos y Ortuño, 1951; Del Arco *et al*., 2006; GRAFCAN, 2021).

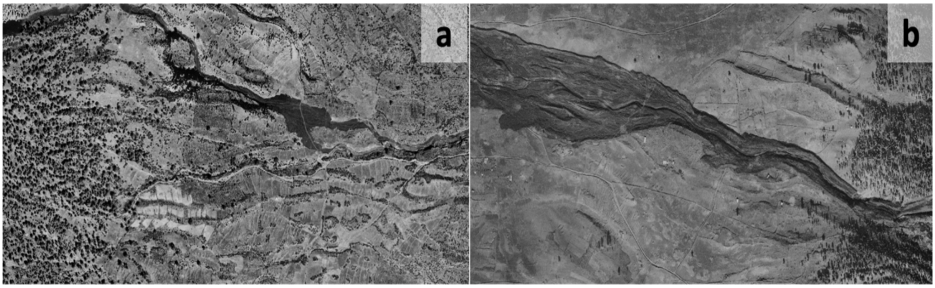

Figure 5. Slopes of Cumbre Vieja, orthophotographs from 1951-1957 (IDE GRAFCAN, 2024): a) Eastern slope highly degraded by agricultural activities and terraces up to 1,000 m a.s.l. in the La Jurada ravine, clogged by the lavas of La Malforada and El Duraznero; b) western slope highly degraded in the surroundings of the Las Cubas ravine, clogged by the lavas of Llano del Banco.

In the area of thermo-sclerophyllous woodland and scrub, an area of about 6 ha was affected, although in reality almost all of it was agricultural plots, with scattered specimens, or in small patches, of *Retama rhodorhizoides*, *Euphorbia lamarckii subsp. wildpretti* and *Euphorbia regis-jubae*, *Euphorbia canariensis*, *Rumex lunaria*, *Artemisia thuscula*, *Echium brevirame* and *Periploca laevigata*. Finally, less than half a hectare of xerophytic scrub, mainly tabaibal formations were affected.

The area impacted by the eruption around Llano del Banco, on the western slope of Cumbre Vieja, has similar characteristics in terms of vegetation layout and human occupation to those on the eastern slope. The outlet opened at an altitude of 1,250 m a.s.l., in an area dominated by Canary pine forest.

Orthophotographs from 1951-57 reveal large-scale deforestation affecting the midlands (thermo-sclerophyllous woodland and sweet tabaibal) in favour of crops and pastures for livestock, as well as numerous hamlets and villages (Las Manchas, Las Norias and San Nicolás) (Fig. 5b). In this case, the lava expelled by the volcano was channelled into the Las Cubas ravine, a fluvio-torrential incision, although shallower than the La Jurada ravine, and it destroyed all the original vegetation there.

Consequently, in Llano del Banco, scrubland has replaced the thermo-sclerophyllous woodland and crops that was most damaged by the eruption (Fig. 3c and Table 2), with lava flows occupying more than 150 ha in this area. There are a few patches and isolated specimens of *Retama rhodorhizoides*, *Euphorbia regis-*

jubae, *Rumex lunaria*, *Artemisia thuscula* and *Lavandula canariensis*, as well as other species, among the numerous agricultural plots that occupied this vegetation landscape at that time.

Canary pine forests covering 30 ha, and *Euphorbia* scrub and shrublands («Tabaibal-Cardonal») and crops spread over 77 ha are the other two potential plant formations most affected by the lava as it descended towards the sea (Table 2). The eruption also destroyed 5 ha of Coastal halophyte belt, which disappeared under the lava.

5. CHANGES IN THE LANDSCAPE AFTER THE TENEGUÍA ERUPTION (1971)

The eruption began on 26 October and ended on 18 November 1971. It was located at the southern tip of the island, in the municipality of Fuencaliente de La Palma, at an altitude of 350 m above sea level (Romero Ruiz, 1991; Araña, 1999). The lava flows did not affect populated areas and when they reached the sea they created a lava delta with a surface area of 29 ha, forming a beach known as Echentive or Playa Nueva. The Teneguía eruption spewed some 40 million m^3 of lava and covered an area of 271 ha (Carracedo, 2008; Table 1).

5.1. Changes in geomorphology caused by the Teneguía eruption

Martínez de Pisón y Higes Rolando (1972) refer to the «remarkable speed of the creative and modifying action of volcanic activity» since the paroxysm of Teneguía in 1971, which they describe as brief, of low violence, precise location, average volume of products emitted, and a moderate edifice size and lava flows, less harmful than spectacular in its formation.

Romero Ruiz (1991:802-825) points out the simplicity of the morphology resulting from this eruption, which she attributes to its homogeneity and its adaptation to simple fracturing, conditioned by the final eruptive pulses of the eruption. Romero Ruiz speaks of the marked initial fissure character of the eruption, which resulted in its concentration at a main point and the development of the volcanic edifice around this point (great contribution of effusive and explosive materials). The later vents, close to the main one, acted as 'adventitious conduits', that is, secondary volcanic foci that 'remodelled' the morphology of the main edifice.

The main edifice (Fig. 6a), according to Romero Ruiz (1991), developed a morphology of a horse-shoe scoria cone open towards the sea (southern area), some 89 m high and clearly dissymmetrical due to the greater development of the eastern flank. Several vents can be distinguished on this cone: Teneguía I, open to the north, where the first lava flows spilled out, turning to the east and then to the south on their way to the sea. There was also Strombolian behaviour by Teneguía IV and V, to the north and northeast, and later lava flows, which built small spatter cones initially and, later, ended up joining the main part on its northern flank. Teneguía IV is a double crater, a main one open to the north and a secondary one in the form of a funnel. Teneguía V corresponds to an effusive outcrop open to the west.

The main crater (Fig. 6b), Teneguía I, appears clogged with welded slag in its interior and on its rim, as well as internal debris typical of post-eruptive and erosive processes. There are important retraction cracks that appear on its rims (as terraces) and on the flanks of the main cone. Something similar occurs in crater IV.

Romero Ruiz (1991) also mentions other minor morphologies associated with the main edifice due to a change in eruptive style during the eruption. There is an individualised circular spatter cone to the north, about 12 m high, known as Teneguía III. In addition, a cumuliform effusive accumulation corresponds to a concentration of lavas from a centre to the south of the main morphological complex, in a flat topography and covered with pyroclasts from crater I. Finally, there is a scoriaceous mountain to the north resulting the accumulation of aerial projection materials of Teneguía IV in this sector, which has been separated from the morphological complex.

As for lava flows, we can distinguish various structures and morphologies typical of the aa and pahoehoe lava flows, channelled towards the cliffs through lava channels and superimposed (Fig. 6c), partly on the 1677-78 lavas, developing a new lava delta as they reached the sea, extending the coastline. Multiple lava flows can be seen overlapping each other and forming well-defined arcs, lava channels and levees, both in the flatter areas and in the sudden changes in slope formed by the previous cliff down which the lavas flowed. At the base of the cliff, accretion balls detached from the lava flows accumulated in the area of Echentive beach.

Non-volcanic geoforms related to subsequent erosion processes are also identified throughout the Teneguía area, such as wind erosion in the lapilli fields, or the formation of beaches due to the effect of waves. All these phenomena caused morphological and topographical changes along the coastline, expanding the perimeter of the island; 'fossilising' cliffs that had been active until then, which were then covered by lava flows and debris, forming active slopes; and the development of small beaches, among which Echentive stands out.

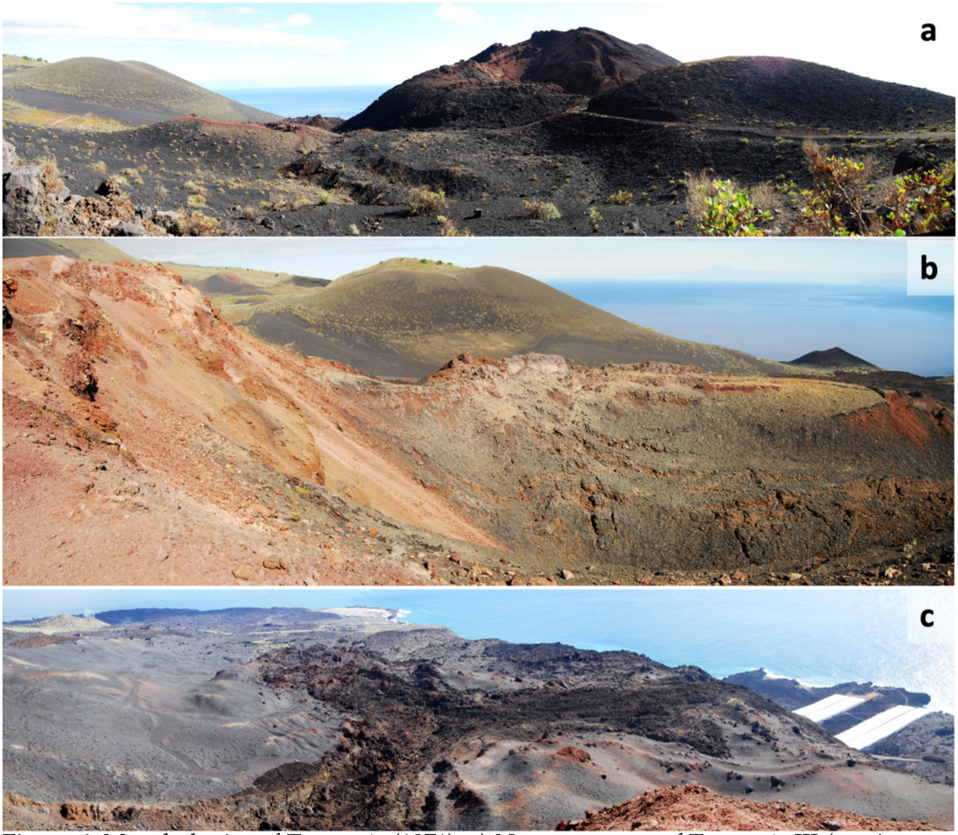

Figure 6. Morphologies of Teneguía (1971): a) N sector, vents of Teneguía III (scoriaceous conelete), Teneguía IV and the main cone, Teneguía I; b) crater of Teneguía I covered with scorias, intracrater debris and retraction cracks; c) S sector and palaeo-cliff through which the lavas overflowed into a lava channel.

5.2. Changes in vegetation and land use caused by the eruption

The entire area affected by the eruption is located on the bioclimatic belts, which is mainly occupied by thermo-sclerophyllous woodland and *Euphorbia* scrub and shrublands and by Coastal halophyte belt along the coastline. It should be noted that this is an area that was already affected by the eruption of the San Antonio volcano in 1677-78[1] which covered 450 ha, creating a coastal platform of 160 ha (Carracedo, 2008). Vegetation prior to the Teneguía eruption was limited to

1 Some authors refer to this as the Fuencaliente eruption– and do not consider the San Antonio volcano to be historical, attributing it an age of more than 3,000 years (Carracedo *et al.*, 1996; Carracedo, 2008). However, we have chosen to use the source provided by Romero Ruiz (1991: 94, 998), which she calls the San Antonio or Fuencaliente eruption, to name this volcanic edifice, without entering into a discussion of its chronology.

pioneer rock communities associated with historical lava flows (*malpaís*) (DGOT, 2007; GRAFCAN, 2021).

The 1964 orthophotography reveals areas devoid of vegetation, a few small agricultural plots and areas covered by very open and fragmented patches of *Euphorbia* scrub and shrublands, including species like *Euphorbia balsamifera*, *Euphorbia lamarckii subsp. wildpretti*, *Euphorbia regis-jubae*, *Echium brevirame*, *Kleinia neriifolia*, *Artemisia thuscula, Bosea yerbamora*, *Descurainia millefolia*, *Lavatera acerifolia*, *Salvia canariensis*, *Retama rhodorhizoides*, *Rumex lunaria* and *Rubia fruticosa*. On fields of lapilli and volcanic sands, there is a white salt marsh or *iramal*, whose most frequent taxa are *Schizogyne sericea* and *Euphorbia lamarckii subsp. wildpretti*, as well as *Echium brevirame* and *Kleinia neriifolia* (Ceballos y Ortuño, 1951; Del Arco *et al*., 2006; DGOT, 2007; GRAFCAN, 2021). The humidity retention capacity of lapilli has enabled small-scale vine cultivation within the area affected by the eruption. On the coast, where lava deltas were formed, the population chose to plough and fill the land with soil in order to carry out intensive banana cultivation, in most cases in greenhouses to obtain greater profitability.

A floristic inventory currently available for this area (DGOT, 2007) lists a total of 15 non-vascular plants and 130 vascular plants, of which 51 are endemic species of the Canary Islands, 14 of them exclusive to the island of La Palma. The combination of all these species allows us to identify four main plant formations in the area affected by the eruption (DGOT, 2007):

i. Rupicolous communities: this is the most widespread in the area, characterised by the presence of *Ceropegia hians*, *Aeonium david-bramwelli* and *Todaroa aurea ssp. suaveolens*, among other taxa. High lichen cover on the surface of the lava flows are dominated by species such as *Xanthoria spp*., *Lecanora sulfurella*, *Parmelia pseudotinctorum* or *Ramalina spp*.

ii. Thermo-sclerophyllous scrub: these are pioneering formations that have colonised the lapilli fields surrounding the Teneguía volcano (Fig. 6). *Echium brevirame* and *Micromeria herpyllomorpha*, accompanied by *Rumex lunaria* and white broom *Retama rhodorhizoides*.

iii. Xerophilous scrub and shrublands: this pioneering vegetation has established itself in the lower areas of the lava flows and, on the breakwaters, and slopes of the old coastal cliff, in some cases with the influence of sea spray. *Schizogyne sericea* dominates here, together with other species characteristic of the coastal halophyte belt, such as *Astydamia latifolia*. In the higher parts, the white salt marsh is combined with various species of tabaiba (*Euphorbia lamarckii*, *Euphorbia regis-jubae* and *Euphorbia balsamifera*) and with *Rumex lunaria*, *Echium brevirame* and *Micromeria herpyllomorpha*. In the northeastern zone, it is accompanied by *Retama rhodorhizoides* and *Euphorbia lamarckii*.

iv. Scrubland associated with the coastal halophyte belt: this is located on the coastal cliffs directly exposed to sea spray, it is characterised by the presence of perennial halophyte and rupicolous communities. These are scrublands of low or medium cover, consisting almost exclusively of *Frankenia ericifolia*, *Limonium pectinatum* and *Reichardia ligulata*.

We should highlight the presence of two large kipukas, in the lava flow that went southeast, towards La Caleta Alta and Punta Malpaís. They are easy to recognize by photointerpretation because they have older vegetation growing on them, surrounded by the new lava flows (Fig. 7). One is located further south, in the area known as Los Graneles, and other further north, in the area known as Los Jablitos. In its interior, very open patches of white salt bushes with *Euphorbia regis-jubae* are preserved. From a biogeographical perspective, «kipukas» can become important refuges for plant and animal species, help protect native species from invasive species, and can act as a starting point for subsequent recolonization of nearby new lava flows (Peterson *et al.*, 2021).

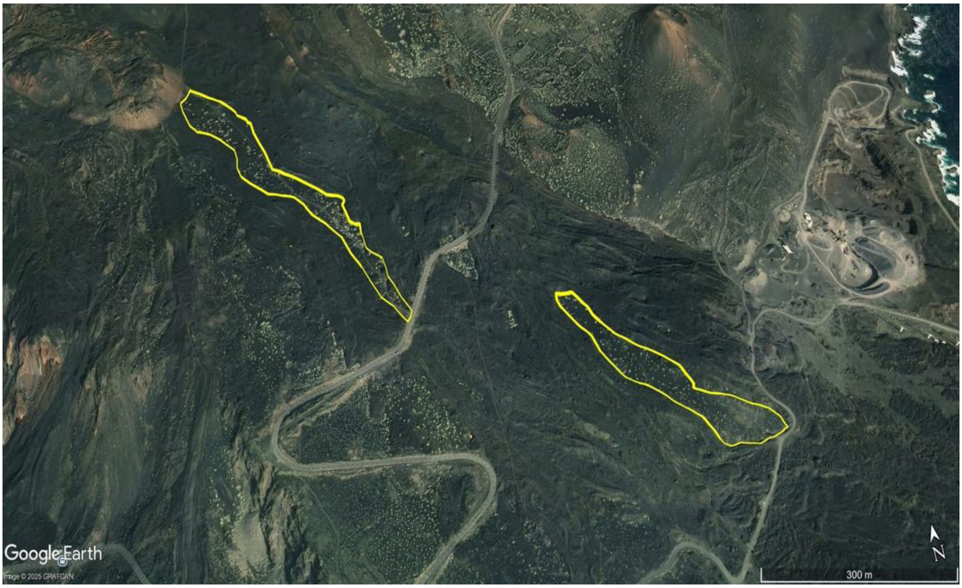

Figure 7. Kipuka in Los Graneles site in the Teneguía lavas (1971). Orthophoto taken on 01/01/2008. Source: GRAFCAN-Google Earth Pro, 2024.

6. CHANGES IN THE LANDSCAPE AFTER THE TAJOGAITE ERUPTION (2021)

The eruption began on 19 September 2021 in the area known as the Hoya de Tajogaite, at 1,040 m above sea level, and lasted 86 days (until 13 December). It affected a significant part of the Aridane Valley. During this period, a complex volcanic edifice was formed with a volume of 36.5 million m^3 and a height of ~250 m (Civico *et al.*, 2022; Romero Ruiz *et al.*, 2024). In addition, 177 million m^3 of lava were emitted covering an area of 1,241 ha and 45 million m^3 of pyroclasts that affected almost the entire island at some point during the eruption (Civico *et al.*, 2022; Copernicus, 2021; Romero *et al.*, 2022). The volcano also released 1 million tons of SO_2 into the atmosphere (Weiser *et al.*, 2022). Despite the large size of these figures, the eruption only seriously affected approximately 4% of the island (Nogales *et al.*, 2022), but in a densely populated area where agricultural activity (mainly banana cultivation) and tourism (Puerto Naos resort) were very important for the island's economy.

6.1. Changes in geomorphology caused by the Tajogaite eruption

The Tajogaite volcano created, among other geoforms, a scoria cone with multiple craters, about ~250 m high and 800 m in diameter, which covered an area of about 12.25 km^2 with lava (Romero *et al.*, 2022; Ferrer *et al.*, 2023; Romero Ruiz *et al.*, 2024).

The main morphologies developed during the eruption are associated with airborne materials (scoria cones, hornitos and lapilli fields) and extensive lava fields (with typical structures and morphologies of pahoehoe, aa - in blocks and balls). They include sliding and erratic blocks, volcanic channels and lava tubes (levees, overflows, dykes and accretion balls, redistribution of lavas...), *jameos* (collapse of the roof of a tube – it is a local Canarian toponym), lava cascades and deltas, lava slopes, tumuli, shatter rings, scutulums, etc.). There are also several effusive fissures, fields of pyroclasts all around the eruption area and post eruptive sedimentary forms (Romero Ruiz *et al.*, 2023: 5-10; 2024). Erosion and accumulation have formed small gullies (debris-flows), cliffs, taluses, dunes and beaches (Ferrer *et al.*, 2023; Romero Ruiz *et al.*, 2023; Dóniz-Páez *et al.*, 2024a). Therefore, as in the case of previous eruptions, the construction of the cone and the channelling of the lavas through the ravines they fill have completely altered the previous morphology, causing the runoff to develop a new drainage network. The development of the two lava deltas has caused significant changes to the island's coastline and has led to the creation of new beaches thanks to the erosive action of the sea.

Romero Ruiz *et al*. (2023: 11-14) identify three main geomorphological units of the Tajogaite eruption:

i. The main cone and associated fissures of a three-fracture system (Fig. 8a). A multiple scoria cone was built along 650 m following the NW-SE main fissure at 850-1,000 m altitude. This fissure was active during the whole eruptive process and the main eruption craters opened along it. The other eruptive fissures developed along a parallel fracture 800 m long, in which several effusive vents, rooted and unrooted hornitos, scutulum structures and abundant lava flows, mainly pahoehoe, opened. Also in this unit, there are blocks that detached from the main cone during the 25 September landslide. The whole unit is covered by extensive fields of pyroclasts ejected by the volcano (Fig. 8b).

ii. The southern fissure system. There are up to 6, with 68 effusive emission points and very short path lengths (between 29 and 136 m) located at altitudes of between 430 and 685 m a.s.l., with high geodiversity (simple and complex morphologies, collapses, spatter walls, hornitos, tubes, channels, inflation structures and outflow flows) (Fig. 8c,d).

iii. An extensive lava field. Aa lavas (typical, ball-shaped, or block-shaped), composite pahoehoe lavas (occupying the central sector of the lava field), and lava deltas can be distinguished (Fig. 8e,f). This is a highly complex lava field, with patches of lava disconnected from their source because of the superposition of different subsequent lava flows with different morphological structures. Also notable is the multitude of lava outlets, especially in the aa lava flows and, in their channels, and levees. The lava deltas formed during the eruption spread over 5 ha in the area of Punta del Perdido in the north and 75 ha in Las Hoyas (or La Bombilla lighthouse) in the south (Ferrer *et al.*, 2023), that is, lava deltas have caused important changes in the coastline. Romero Ruiz's team differentiates between the simple delta of the north, the result of a single feeder flow, and the complex delta in the south fed by a multitude of lava flows of different morphologies until the end of the eruption, and which was superimposed on the lava delta of the 1949 eruption. In both deltas, new beaches and cliffs of different heights have formed, depending on the thickness of the lavas that form them (Fig. 8f).

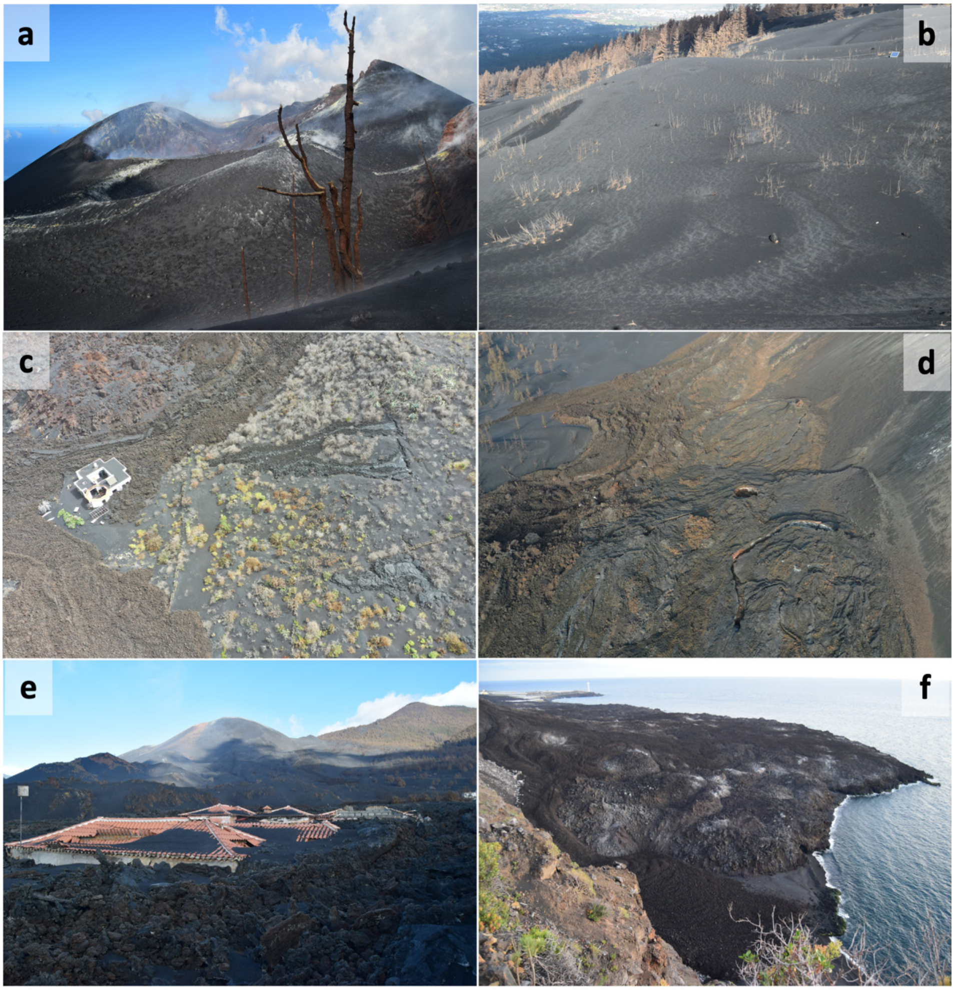

Figure 8: Tajogaite morphologies (2021): a) Main cone and craters; b) lapilli field and eolian processes (dunes); c) eruptive fissures and lava flows near Las Manchas cemetery; d) hornitos and lava flows in the fissure at the base of the cone; e) cone and pahoehoe lava flows that affected Las Manchas; f) Southern lava delta (Las Hoyas – La Bombilla), slope and coastal platform with lavas of different morphology, cliffs, new beaches and taluses.

Summarising the data obtained from several studies (Romero *et al*., 2022; Ferrer *et al*., 2023; Romero Ruiz *et al*., 2024), after the eruption ended, significant changes were observed in both the topography and morphology of the affected area. The most significant of these changes is the formation of the Tajogaite cone, which completely altered the area where the first eruptive vents opened and where most of the paroxysm was concentrated. In the area there were previously ravines, ancient cones and craters, which were buried by the materials from

2021. The lava has also been one of the elements that has caused the greatest morphological and topographical change in the area, and of course the damage caused to the population, with accumulations ranging from a few meters to more than 70 m and lava channels between a few meters and more than 80 m wide and depths between 2 and 11 m. In addition, the lava deltas (with average thicknesses ranging from 8 to 18 m in the northern delta and from 20 to 50 m in the southern delta) fossilised the cliff and increased the surface area of the island (~1 km^2), creating new beaches and taluses. On the other hand, it is worth noting the lapilli fields that have covered an extensive surface in the cone area with an average thickness of ~3 m, on the western slope of Cumbre Vieja and the summit, and which are developing eolian processes as a result of wind action, and small debris flows due to the action of runoff.

6.2. Changes in vegetation and land use caused by the eruption

The area affected by lava flows from the Tajogaite eruption was 1,241 ha, including 48 ha of lava deltas reclaimed from the sea (Table 1). There was also 118 ha of Canary pine forests affected as well as 859 ha of thermo-sclerophyllous scrubland heavily modified by human action (residential, industrial, commercial, agricultural and road use), 194 ha of xerophilous *Euphorbia* scrub and shrublands and 22 ha of formations linked to the coastal halophyte belt (Table 2). The entire area affected by the eruption was dominated by human activity (urban, rural, industrial and agricultural areas) such that the natural vegetation, mainly located in midlands area, was limited to abandoned crops or old volcanic flows (Fig. 9).

Figure 9. Midlands area in Las Manchas during the first week of the Tajogaite eruption (25 September 2021). The strong human intervention of the territory can be observed with a plot of land that alternates land uses, with a predominance of abandoned agricultural areas.

The abandonment of crops favoured the appearance of a degraded thicket composed of *Rumex lunaria*, *Carlina falcata*, *Euphorbia lamarckii subsp. wildpretti*, *Bituminaria bituminosa*, *Kleinia neriifolia*, *Sonchus hierrensis*, *Phagnalum umbelliforme*, *Aeonium davidbramwellii* and *Aeonium balsamiferum*, among other taxa.

The opening of eruptive vents took place in an area of Canary pine forest with mountain firs and rocky vegetation. The most common species present in the area are *Pinus canariensis*, *Lotus campylocladus*, *Bystropogon origanifolius*, *Cistus symphytifolius*, *Adenocarpus foliolosus*, and *Chamaecytisus proliferus*. In addition, there were plots with crops of *Prunus dulcis*, *Castanea sativa*, *Ficus carica*, *Opuntia maxima*, and *Vitis vinifera* vineyards (Medina *et al*., 2021). The Canary pine forest has been greatly affected by the eruption since the volcano originated there, producing a direct impact due to heat and the emission of lava and pyroclasts, and an indirect impact due to high gas emissions. The prevailing NE winds carried gases (SO_2 and CO_2) and pyroclasts towards the southwest, impacting mainly on the Canary pine forest (Fig. 10a).

The intense pyroclastic fall also affected the Canary pine forest and thermo-sclerophyllous scrub areas closest to the crater. The pine understory species, primarily *Cistus symphytifolius* and *Chamaecytisus proliferus subsp. palmensis*, endemic to the Canary pine forest habitat, were severely affected by the ash. Finally, lava flows covered much of the vegetation landscapes and land uses in the midlands and on the coast (Fig. 10b).

Figure 10. Vegetation affected by the Tajogaite eruption (2021): a) Canarian pine forest badly affected by chlorosis due to high SO_2 emissions south of the volcano; b) SW area of the volcano badly affected by ash and lapilli fall that destroyed areas of Canary pine forest and thermo-sclerophyllous scrubland, both buried under tons of falling pyroclasts.

During the eruption, three large ashfall events occurred, covering the land with fine ash more than 2 m thick (Nogales *et al*., 2023) at a short distance from the crater and gradually decreasing away from the volcano. In the areas closest to the volcano's crater, vegetation did not survive due to the heat emitted by the eruption and the accumulation of pyroclasts and lava. In more distant areas, the accumulation of ash caused branches and trees to break due to excessive weight. In intermediate areas, species with secondary woodiness were able to survive (Nogales *et al*., 2022). In areas further from the volcano, vegetation barely suffered any consequences, beyond a temporary accumulation of ash on leaves and branches that disappeared due to the action of wind and rain.

As mentioned above, the vegetation in midland areas was scrubland replacing the original thermo-sclerophyllous woodland, and mainly limited to abandoned crops or unproductive ancient volcanic flows (Medina *et al*., 2021). This scrubland, which was severely affected by lava flows and ashfall, featured notable species such as *Asparagus umbellatus*, *Schizogyne sericea*, *Lavandula canariensis*, *Salvia canariensis*, *Argyranthemum haouarytheum*, and *Teucrium heterophyllum*.

The *Euphorbia* scrub and shrublands, closest to the coast (Del Arco *et al*., 2010), had been severely depleted by the development of banana cultivation, becoming isolated on coastal crags and cliffs, as well as on abandoned agricultural plots. The most relevant species in this area were *Echium brevirame*, *Euphorbia balsamifera*, *Euphorbia canariensis* o *Aeonium nobile*. The arrival of lava flows to the cliffs caused the disappearance of the only population of cardoon in the area (Medina *et al*., 2021).

According to the «Comisión mixta para la reconstrucción, recuperación y apoyo a la isla de La Palma» (2022), during the 85 days that the eruption lasted, pyroclasts and, above all, lava covered more than 1,200 ha of land, burying 73.8 kilometres of roads and affecting 2,988 buildings. The consequences were particularly severe for the primary sector, with 370 ha of crops destroyed, the final section of the north-south canals through which water is distributed for irrigation rendered unusable, and a ban on fishing in the Tazacorte area, where the main port is located. Likewise, the tourism sector, which was beginning to recover after the COVID-19 pandemic, once again suffered a decline in the number of visitors and overnight stays, with the cancellation of more than 500 flights.

7. DISCUSSION: EVALUATION OF THE OBSERVED CHANGES

7.1. Assessment of the changes after the eruption of San Juan (1949)

The eruption of San Juan in 1949 affected the summit area and, through two fluvio-torrential incision ravines, La Jurada and Las Cubas, the two slopes of Cumbre Vieja, covering 380 ha (Table 1). The eruption built three morphological complexes at different altitudes, with material emitted on both sides of Cumbre Vieja, demonstrating enormous dynamic and geomorphological complexity. On one hand, it built the scoria cone, fissure spatter rampart and hornitos in the Duraznero area, with lava flows that filled previous topographies and were channelled through the La Jurada ravine on the eastern slope. On the other hand, the phreatic and phreatomagmatic crater of Hoyo Negro and the set of arcuate faults in its surroundings. And finally, the Llano del Banco eruptive fissure, the most notable result of which was the lava that spilled down the Las Cubas ravine on the western slope to the sea to build the spectacular Las Norias lava delta, that meant the island grew by 80 ha. In addition to the lapilli fields, lava channels, and detailed morphologies observed on the lavas, along with the fossilisation of the cliff and the creation of new slopes and beaches.

The lavas and pyroclasts from the 1949 eruption had an impact on all the bioclimatic belts and associated vegetation landscapes on Cumbre Vieja, from the Canary pine forest to the scrubland of the coastal halophyte belt (Table 2). The vegetation landscape most affected by this eruption was the thermo-sclerophyllous scrublands. There are formations that replaced the woodland of the same name, which were already highly degraded at that time due to agricultural activity and human occupation, as they are in the midlands, which is a favourable area for population settlement. The Canary pine forests were the second most directly damaged by the eruption (Table 2).

The paradox is that the modification of these vegetation landscapes has led to the appearance of new ones, rocky landscapes currently occupied by pioneer vegetation communities, especially on lava flows, in which the protagonists are the lichen *Stereocaulon vesuvianum* and ferns of the genus *Cheilanthes* or *Kleinia neriifolia*. These rocky landscapes have been recognised as habitats of Community Interest in the framework of the European Habitats Directive of 1992, including lava fields within rocky habitats and caves (Habitat 8320). These are substrates derived from recent volcanic activity (lava, ash and lapilli fields, lava tunnels and fumaroles) before any appreciable development of soil and vegetation has taken place (Beltrán y Dóniz-Páez, 2009).

From the point of view of geoconservation and protection, the morphologies of the San Juan eruption (1949) are located entirely within the Cumbre Vieja Natural Park (Ley 12/1987 de Declaración de Espacios Naturales de Canarias). The entire natural park was also classified as a Special Area of Conservation – SAC within the framework of the EU Natura 2000 network (habitats *Endemic macaronesian heaths*, *Thermo-Mediterranean and pre-desert scrub*, *Fields of lava and natural excavations*, *Canarian endemic pine forests*, *Endemic oro-Mediterranean heaths with gorse* and *Macaronesian laurel forests*). Part of the lavas of Llano del Banco are outside the protected area of the natural park, but a section of Cueva de las Palomas was declared a Natural Monument for the volcanic tube of Todoque (Ley 12/1994 de Espacios Naturales de Canarias, previously a natural site of national interest) and SAC (habitat fields of lava and natural excavations), and has a visitors' centre and is a point of interest for geotourism on the island. In addition, the whole eruption site is included in the Inventory of Sites of Geological Interest – IELIG, of the IGME (IGME, n.d.) with codes IC6004 (*Hydromagmatism associated with the 1949 eruption of San Juan*) and IC6007 (*Fractures from the 1949 eruption*).

7.2. Assessment of the changes observed after the Teneguía eruption (1971)

During the Teneguía eruption, significant morphological changes occurred in the southern sector of the Cumbre Vieja ridge, particularly due to the construction of the complex edifice and associated spatter cones, in addition to the intense lava flows that ran downhill towards the sea, overlapping the 18th-century flows and extending the coastline with the lava platform, along with other processes not strictly volcanic mentioned above (new cliffs and slopes, fossilisation of ancient cliffs and beaches).

This eruption took place exclusively within the bioclimatic belts of *Euphorbia* scrub and shrublands («Tabaibal-Cardonal») and the coastal halophyte belt. Some of the lava flows and lapilli fields were superimposed on the lavas of the San Antonio eruption (1677-78). In net terms, the impact on the vegetation landscape was slight and, in any case, what occurred was a rejuvenation of the evolutionary processes of vegetation colonization of the 17th century lavas. This is an area that has suffered two major eruptions in the last 300 years, an area that is constantly changing and evolving, volcanic activity permitting, towards a vegetation landscape made up of typical tabaibal-cardonal formations. Today, what can be observed are large expanses of lava without vegetation. The vegetation that is present are low-growing, stunted formations with a low spatial cover (Figs. 6 and 7).

The Teneguía volcano and its lava flows are also subject to geoconservation and protection actions. Initially, the volcano was included in the Cumbre Vieja Natural Park (Ley 12/1987), but it was reclassified and became a Natural Monument (Ley 12/1994 de Espacios Naturales de Canarias). This also includes the San Antonio eruption (1677-78) and the visitors' centre. The northeastern sector of the natural monument is included in the Tamanca SAC, which includes four habitats (*Thermo-Mediterranean and pre-desert scrub, Fields of lava and natural excavations, Canarian endemic pine forests* and *Endemic forests with Juniperus spp*.) Finally, the whole of the eruption is included in the IELIG IC6003 (*Volcanic deposits from the 1971 eruption of Teneguía*).

7.3. Assessment of the changes observed after the Tajogaite eruption (2021)

7.3.1. New geomorphological elements of interest and their protection

Vegas *et al*. (2022) highlight the volcanic morphologies from the Tajogaite eruption as being of great scientific value, unique on the island and even in the whole Canary archipelago. This led to the inclusion of the entire area affected by the eruption in the IELIG with the code IC6031 (*Volcano, lava flows and pyroclasts from the 2021 eruption of La Palma*) (IGME, n.d.).

From a geomorphological point of view, territorial zoning has been established at four levels according to the number, diversity, rarity and representativeness of geomorphological and volcanological elements and their landscape characteristics: Very high, high, medium and low (Romero Ruiz *et al*., 2023). These levels include exceptional, singular, exclusive or highly representative areas of the 2021 eruption, such as pahoehoe, aa and block lava fields, lava tubes, eruptive fissures, filling of ravines, lava deltas and isolated lava spaces between lava flows that have no spatial continuity with the main flows, and which Romero Ruiz *et al*. (2024) include as areas of high geomorphological and landscape value.

Given the high geodiversity and geographical interest of the Tajogaite eruption, the works of Dóniz-Páez *et al*. (2024a, b) also select several geomorphosites with great geotourism interest in the area affected by the eruption. These are representative of the natural and cultural heritage associated with the previous landscape affected by the eruption and the landscape generated during the eruption, and which can be used as a geotourism resource. The Tajogaite eruption, despite the enormous damage it caused, became, from the outset, an attraction for scientists, visitors and tourists, and today, the landscape generated by the Tajogaite volcano and its territorial effects continue to attract thousands of people to the island (Dóniz-Páez *et al*. 2024a).

The Decreto-Ley 9/2023 of 18 December (BOE no. 59 of 7 March 2024: 2711-27138) sets out the territorial and urban planning measures for the economic and social recovery of La Palma after this volcanic eruption, based on the reports drawn up and compiled in the *Territorial Framework for the Recovery of Normality after the Eruption* (https://lapalma.planderecuperaciondecanarias.es/prclp/). One of its objectives is to establish the measures to allow the construction, reconstruction or rehabilitation of the buildings that existed before the volcanic eruption in the spaces now occupied by the lava flows, establishing the precise conditions to do so safely.

Many of the geoforms generated in the eruption are unique in the Canary context and are disappearing under the action of excavators (Fig. 11a), considerably modifying the most recent volcanic landscape in Spain. The opening of roads and access roads to some houses (Fig. 11b) were carried out in haste, ignoring geological and geomorphological reports, modifying and destroying forever part of the rich volcanological heritage built by the eruption.

Figure 11: Excavators removing volcanic material for the opening of roads and paths.

7.3.2. Impact of the eruption on vegetation and land use

This eruption affected the coastal halophyte belt, *Euphorbia* scrub and shrublands («Tabaibal-cardonal»), the thermo-sclerophyllous woodland and its replacement scrubland and the Canary pine forest, basically, all the vegetation landscapes on the western slope of Cumbre Vieja. The impact caused by Tajogaite was catastrophic for the first 400 m around the crater, causing the disappearance of practically all the vegetation in the area (Fig. 12a).

However, the effect of the eruption on the vegetation landscape gradually decreases with increasing distance from the volcano, due to the decrease in the thickness of ash, the gases emitted and the direct effects of the lavas. The recovery of biodiversity has followed a similar pattern, increasing with the distance from the cone and its craters and lava flows (Nogales *et al*., 2022).

The Canary pine forest has been the most affected vegetation in the cone area as it was the dominant vegetation formation here (Figs. 10a, 12a; Table 2). Pyroclastic fall and sulphurous gases were the main elements affecting the pine forest over a large area. Also, *Euphorbia* scrub and shrublands and the thermo-sclerophyllous scrubland in the midlands lost a large part of their surface area due to the progressive advance of the lava towards the sea.

The Tajogaite lava flows also left bare land, and a so-called «kipuka», as happened in Teneguía, the largest being that of Cabrejas (Fig. 12b), with a surface area of about 8 ha. In this case, this small outcrop of land was almost entirely devoted to crops and dwellings, and there are also some plots of land with xerophytic scrub.

Figure 12. Impact of the Tajogaite eruption on vegetation and land use: a) The vegetation landscape closest to the emission vents destroyed, replaced by a new habitat type: lava fields and lapilli (Habitat 8320); b) «kipuka» of Cabreja, several land uses (crops, houses, and «tabaibal-cardonal»).

7.3.3. Impacts on community habitats and protected areas of the Tajogaite eruption

The Tajogaite eruption has had a minimal impact on Community Habitats and Natura 2000 network sites protected by the European Union through the Habitats Directive and on the Red Canaria de Espacios Naturales Protegidos («Canary Islands Network of Protected Natural Areas»). This is due to the high degree of environmental deterioration that already existed in the area affected by the volcano and its lava flows due to the humans pressure exerted on the Aridane valley for centuries.

In the case of European Habitats, three have suffered losses due to the eruption. Habitat 1250, *Cliffs with endemic vegetation of the Macaronesian coasts*, of which 2 ha have been lost. Also, Habitat 5330, *Thermo-Mediterranean and pre-stepic scrubland*, located at the base of the cones of the Aridane volcanoes (Montaña Todoque and Montaña de La Laguna), with 10 ha affected. Furthermore, there is the Habitat 9550, *Canarian endemic pine forests*, with a loss of 35 ha, located in the eruptive fissure and its immediate surroundings in Tajogaite. In total, just under 50 ha of habitats protected by the European Union have been lost, a minor area compared to the total number of these habitats on the island of La Palma. Paradoxically, the eruption has led to the creation of 1,241 ha of new areas which should be categorised and included in Habitat 8320 *Lava fields and other natural excavations* (Fig. 13b).

Two Natura 2000 network sites have been affected by the eruption: the Cumbre Vieja SAC, with 35.13 ha, in the vicinity of the eruptive vents, and the Franja Marina de Fuencaliente SAC, with just under 50 ha, in this case due to the lava deltas which reclaimed land from the sea.

Finally, the protected areas included in the Red Canaria de Espacios Naturales Protegidos that have been affected by the Tajogaite volcano were the Volcanes de Aridane Natural Monument, which lost 10 ha (Fig. 13) and the Cumbre Vieja Natural Park, with 35 ha affected.

Figure 13. Montaña Todoque acted as a parapet that slowed down and accumulated the lava flows on its way to the sea, even invading the interior of the crater.

8. CONCLUSIONS

Recent historical eruptions, especially the Tajogaite eruption of 2021, are an exceptional scientific laboratory to study how volcanoes affect island landscapes (both natural –morphology and topography, vegetation cover– and urban/anthropic). It is also important to investigate their recovery over time, with and without human intervention.

A comparative analysis of the historical eruptions of San Juan (1949), Teneguía (1971) and Tajogaite (2021) on La Palma island shows that volcanism is a determining factor in the geomorphological, ecological and socio-economic configuration of island territories (Romero Ruiz *et al*., 2023; Dóniz-Páez *et al*., 2024a). Each eruptive event generated a distinctive set of volcanic structures (scoria cones, hornitos, *jameos*, lava tubes and deltas on the coast) that profoundly transformed the relief and land use. In total, the three eruptions affected approximately 1,850 ha, with significant impacts on the midlands, the Canarian pine forests and the coastal ecosystems (Bonelli Rubio, 1950; Carracedo, 2008).

From a geomorphological point of view, the eruptive processes of Cumbre Vieja demonstrate the capacity of monogenic volcanic systems to modify the landscape in very short periods of time. The eruptions of 1949 and 1971 produced lava deltas that expanded the island's surface area, while Tajogaite, in 2021, created a 250 m high cone and two large lava deltas that increased the island's surface area by approximately 1 km² (Civico *et al*., 2022; Ferrer *et al*., 2023). These new landforms not only alter local drainage and topography, but also generate habitats of high ecological and scientific value, currently considered geosites of international importance (Vegas *et al*., 2022).

In biogeographical terms, the three eruptions show remarkable ecological resilience. After volcanic activity ceased, pioneer communities—lichens, ferns, and endemic species adapted to recent substrates, such as *Stereocaulon vesuvianum* and *Kleinia neriifolia* – quickly colonised the new terrain (Del Arco *et al*., 2006; Beltrán & Dóniz-Páez, 2009). These initial plant succession processes promote the restoration of vegetation cover and biodiversity, confirming that volcanic ecosystems function as natural laboratories for regeneration. For example, in the Teneguía and Tajogaite eruptions, the lava flows surrounded topographically elevated areas, called «kipukas», that can act as important biodiversity refuges and serve as starting points for the recolonization of new lavas. However, the impact degree varies according to altitude and the level of previous anthropisation: pine forests were the most affected in 1949 and 2021, while in 1971 the impact was concentrated on xerophytic and halophytic scrubland.

In terms of land use, there is a general trend towards abandoning agricultural, residential and industrial areas in favour of natural or conservation uses (Romero Ruiz *et al*., 2024). The new volcanic areas have encouraged the creation of both protected areas and areas of geotourism interest. The case of Tajogaite also stands out for having functioned as a natural laboratory where scientific research, territorial planning and environmental education converge (Dóniz-Páez *et al*., 2024b). Actions are currently being taken to dismantle the lava flows (including the lava deltas) in an attempt to rebuild residential and industrial areas destroyed in 2021 and recover land for banana cultivation. These actions are causing this new geoheritage of extremely high international scientific interest to disappear.

From this point of view, we must highlight that these are areas with high geodiversity, both in terms of the major landforms created by eruptions (scoria cones, craters, spatter cones, lava flows and deltas) as well as in the smaller morphologies that can be observed when visiting these areas (hornitos, detailed lava forms, erratic blocks, channels and *jameos*, lava tubes, dunes on lapilli fields, etc.). Such is the interest they arouse that their geoconservation has been paramount in their assessment, which has led to their declaration as natural protected areas or sites of geological interest. This extremely important geoheritage of the Canary Islands, and specifically of La Palma, should be used for the development of sustainable economic activities such as geotourism (volcano tourism). There are currently several proposals made by Hernández *et al*. (2024, 2025) who have selected 52 sites of geotouristic interest (including these three historical eruptions) and a georoute that runs along the Cumbre Vieja ridge, taking advantage of the Ruta de los Volcanes (official GR131 hiking trail) that crosses the morphologies and landscapes of the San Juan and Teneguía historical eruptions. These proposals seek to promote volcanic tourism and diversify the tourist leisure offer on the island, taking advantage of the natural resources offered by the historical volcanoes.

In summary, recent eruptions on La Palma have had a significant impact on the landscape of the southern part of the island. They have transformed its geomorphology creating new volcanic formations, altering the distribution and composition of vegetation and generating new opportunities for recolonization and conservation of endemic species, and severely impacting human activities on the island. Therefore, these historical eruptions show the duality of volcanism: its immediate destructive potential and its role in generating new landscapes and opportunities for sustainable endogenous development. Integrated risk management, conservation of geoheritage and promotion of geotourism emerge as key strategies for harmonising the relationship between society and an environment in constant transformation.

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