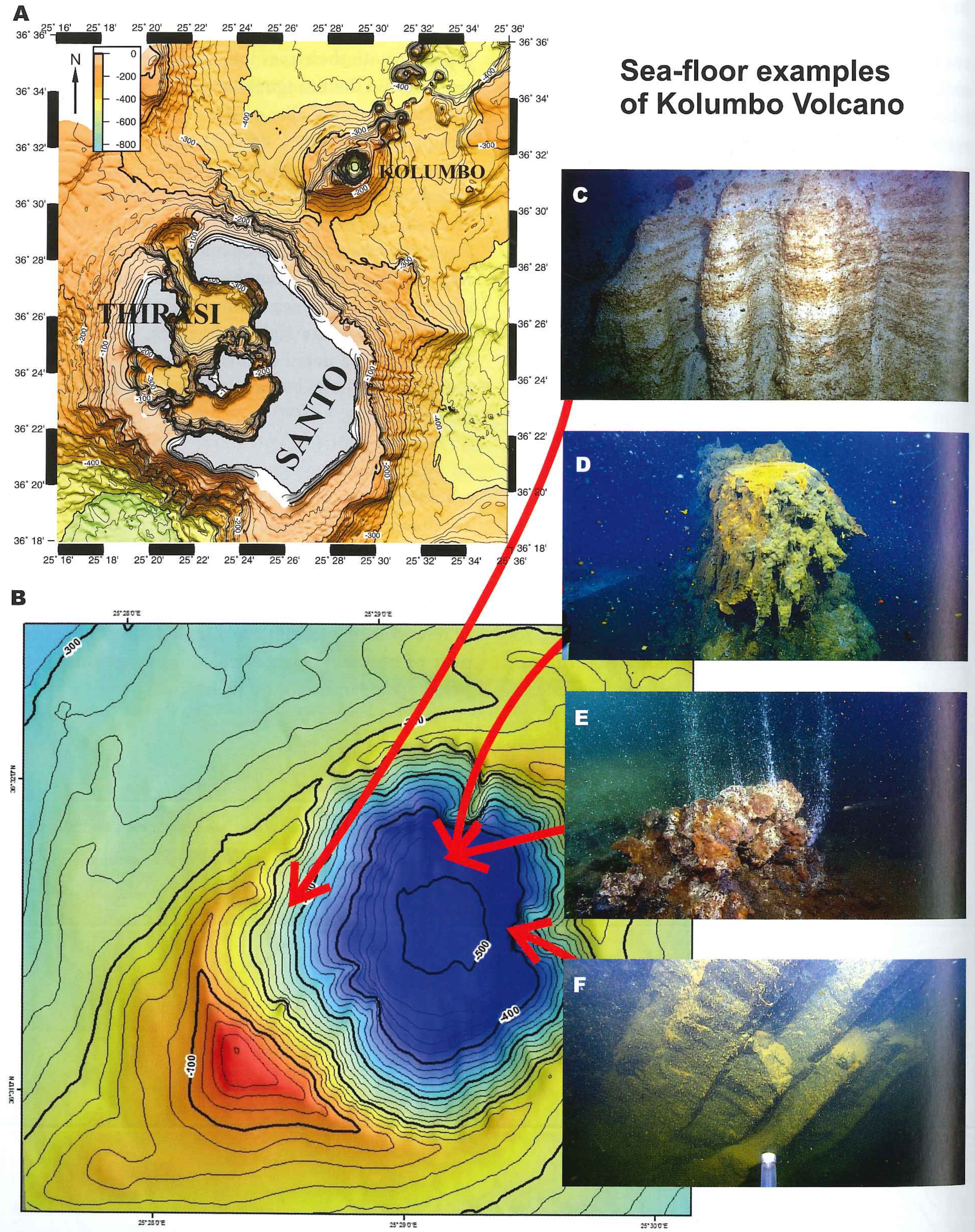


Figure 3.19 The Kolumbo Volcano offshore Santoríni with underwater photos of volcanic features. **A**) Location of Kolumbo NE of Santoríni. **B**) Bathymetry around the Kolumbo crater. **C**) Volcanic tephra layers. **D**) Hydrothermal vent in the northern crater floor of Kolumbo Volcano. **E**) High-temperature hydrothermal vent still discharging gases. **F**) Columnar joints on lava dyke on the western slope (Images courtesy of Paraskevi Nomikou).

Chapter 4

Spain

Introduction

The Canary Islands form Spanish provinces, situated off the Atlantic coast of Africa, between 1200 and 1750km southwest of Cádiz. The archipelago consists of seven main islands. Tenerife, covering 2058km^2, is the largest; El Hierro, only 275km^2 in area, is the smallest; and Fuerteventura lies only 115km from Africa (Fig. 4.1). All the islands belong to the African plate. They fall into two groups. Fuerteventura and Lanzarote form the eastern group and belong to the same volcano-tectonic unit that trends parallel to the African coast. Here the climate is arid, the vegetation is steppe-like, and fissures have dominated the distribution of eruptions to such an extent that neither island has a marked scenic focus. In contrast, the central and western group of islands – El Hierro, La Palma, La Gomera, Tenerife, and Gran Canaria – are more mountainous. Thus, even little El Hierro reaches 1051m and Tenerife rises to a majestic climax of 3715m in the Pico de Teide. They lie in the path of the northeast trade winds, which bring cloud, humidity and a luxuriant vegetation to their northern windward shores, although their leeward southern slopes are often arid. Their lower parts enjoy an equable and mild climate throughout the year, and several have become some of Europe's major tourist attractions. Thus, in any season, the volcanologist is unlikely to be alone on the summit of Teide, and may even encounter tourist-laden camels in Lanzarote. On the other hand, few areas beyond the shadow of Vesuvius have done more for popular appreciation of the impact of volcanism on mankind and the environment.

The Canary Islands contain a great variety of volcanic forms ranging from plateau basalts, which are the remains of large basal shields, to recent cinder cones and rugged lava flows that have often joined into *malpaís*; and their stratovolcanoes have sometimes been decapitated by large calderas. The islands have been considered as the type-locality of the caldera ever since Von Buch published his controversial work on their landforms in 1825. Indeed, the Caldera de las Cañadas in Tenerife is, with Santoríni, among the most spectacular in all Europe. Fortunately, this well-populated archipelago has not undergone a caldera-forming eruption in historical times.

The Canary Islands used to be inhabited by the Guancho peoples, who passed on some references to eruptions before they were exterminated by Spanish settlers. Lanzarote, Fuerteventura, La Gomera and El Hierro were settled from 1402, Gran Canaria from 1483, Tenerife from 1491, and La Palma finally from 1493. Thus, historical times in the archipelago amount to less than 600 years, during which activity has been dominated by basaltic eruptions along fissures, which occurred in Lanzarote, La Palma and Tenerife. In addition, parts of Fuerteventura, Gran Canaria and El Hierro all have cones and flows of such remarkable freshness that they scarcely seem to be more than a thousand years old. Indeed, all the islands except La Gomera have had activity within the past 10,000 years. The recorded eruptions in the Canary Islands have occurred at average intervals of 30–35 years. The latest occurred onshore in La Palma in 1971, offshore El Hierro in 2011–2012, and by far the most prolonged and extensive historical eruption took place in Lanzarote from 1730 to 1736.

The volcanic activity in the archipelago has perhaps historically been the most difficult to explain in all Europe. The islands lie on the passive continental margin of northwestern Africa, on one of the oldest parts of the Atlantic Ocean floor, where the basaltic oceanic crust ranges from 180 to 155 million years old from east to west. A basal complex outcrops on Fuerteventura, La Gomera and La Palma, and probably lies hidden beneath the remaining islands. It contains some sediments, some plutonic intrusions, and some submarine basalts, but chiefly assemblies of dykes. However, most of the Canary Islands are much younger, and many parts of the surface are probably no more than a few thousand years old. The islands were born separately from different sources of magma and did not all develop in the same way. Thus, for instance, the oldest dated volcanic rocks occur in

Figure 4.1 Location satellite maps of the Canary Islands (large map – USGS, zoomed in map – NASA).

Fuerteventura, where they are about 20.6 million years old, but they are no more than 2.0 million years old in La Palma and about 1.12 million years old in El Hierro. The rocks themselves cover a wide range from basalts to rhyolites. Basalts, chiefly emitted from fissures, account for the longest and most prolific eruptive episodes; and the more evolved rocks developed largely beneath the stratovolcanoes, probably in relatively shallow magma reservoirs.

Tectonic movements might have played a role in the growth of the Canary Islands by opening up the oceanward prolongation of the South Atlas Fault of North Africa. Nevertheless, the archipelago probably owes most of its growth to a hotspot, which has given rise to a broad westward development of activity in the islands (see Fig. 4.2). It seems probable that masses from the rising magma have formed individual basal shields, and, at times, domed up their surfaces until major three-arm rift systems have developed, separated by angles of 120°. The fissure systems on these rifts then enabled yet more magma to reach the surface; and they have, for example, become the zones of the most marked concentrations of recent emission centres in the islands. Thus, the rifts have been built up into large, high ridges, which reach spectacular proportions in Tenerife, where they form a Y-shaped pattern centred on Teide. These rift ridges grew up so quickly that they sometimes became unstable. Consequently, in El Hierro, La Palma and Tenerife, parts of these ridges have collapsed into the Atlantic Ocean in major landslides. Most of the eruptions in the Canary Islands during historical times have occurred on the fissures developed along these ridges. During these eruptions, fragments explode and form cones on the upper parts of the fissures, while fluid basalts, and perhaps spatter, emerge lower down. However, they have produced only tiny volumes of broadly alkaline basalts, and formed but small cones and thin lava flows.

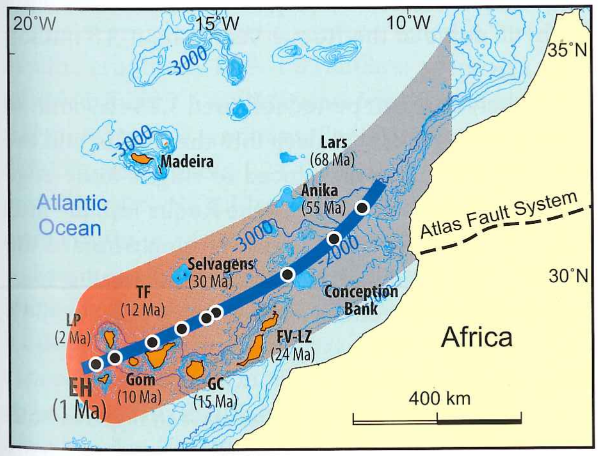


Figure 4.2 Canary Islands hotspot evolution map. The ages imply an east to west age progression in the Canaries, forming a classic hotspot alignment (plume trace) (map courtesy of Val Troll).

Tenerife

Tenerife is the largest of the Canary Islands, covering an area of 2058km^2 and stretching 84km from northeast to southwest and 50km from north to south (Fig. 4.3). Tenerife is the central island, with the greatest volume of erupted materials in the archipelago: more than 15,000km^3, of which some 2000km^3 lie above sea level. It rises from a depth of more than 3000m on the Atlantic Ocean floor, where eruptions began perhaps as much as 11.6 million years ago. The island is Y-shaped, with three main ridges, extending northwestwards, northeastwards and southwards, which have

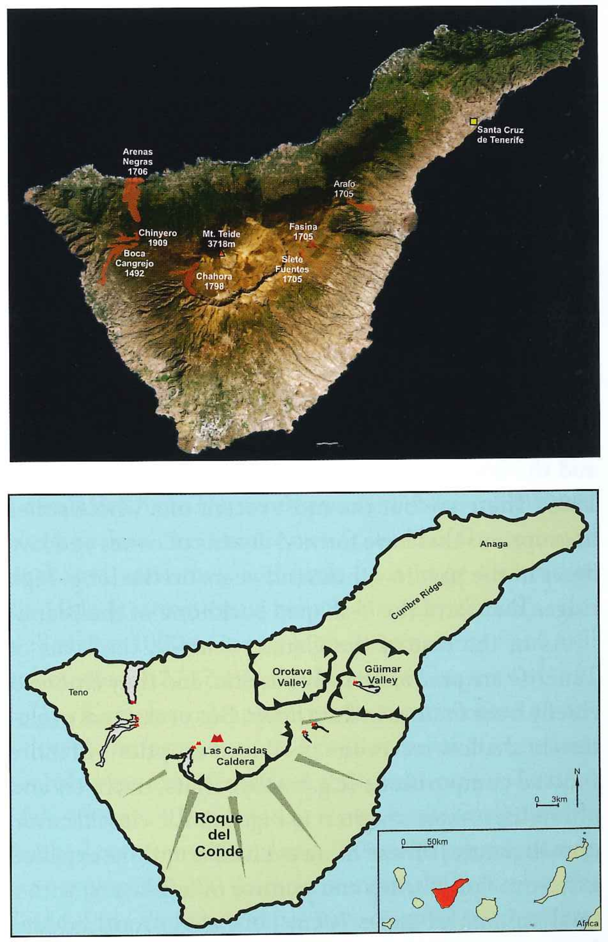


Figure 4.3 Location map, features and outline of recent activity on Tenerife (Satellite Image – USGS).

been formed primarily by basaltic fissure eruptions along rifts. The crowning glory of Tenerife, the Pico de Teide, rises where these ridges intersect and soars from the spectacular Caldera de las Cañadas to a height of 3715m, the highest peak in Spain and in the whole of the Atlantic Ocean, and the highest volcano in Europe outside the Caucasus. It dwarfs its companion, the Pico Viejo, which, at 3134m, is itself almost as high as Etna. But they rise so high because they formed on the floor of the Caldera de las Cañadas, which itself stands 2100m above sea level. Teide has been an unmistakable landmark for six centuries of mariners, ever since the northeast trade winds led the first sailing ships to the Canary Islands. The trade winds also brought their equable climate and orographic rainfall to the northern slopes of Tenerife, which gave rise to rich vegetation and agriculture, in contrast with the aridity of the rain shadow in the south, which is fit only for tourist resorts. Teide itself rises well above the trade winds and enjoys a dry regime of clear skies and westerly breezes.

Teide and Pico Viejo grew up less than 200,000 years ago inside the Caldera de las Cañadas, which has been famous ever since it was described by Humboldt and Von Buch in the early nineteenth century. It formed at the crest of a huge volcanic pile, now called the Cañadas volcano, which had, itself, grown up on top of basal shields built up by basaltic eruptions from the floor of the Atlantic Ocean. Teide is crowned by a small cone, El Pitón, with a white crater emitting fumes. It is unlikely that the Pico de Teide itself has seen any activity since Columbus, en route for the Americas, witnessed an eruption in August 1492. However, several eruptions have occurred in Tenerife since the Spanish settlement, and the latest formed the cinder cone of Chinyero in 1909. These are but the most recent of a whole series of eruptions that have formed dozens of cones and lava flows in the past few thousand years on the long, high ridges that form the Y-shaped backbone of the island.

As in the rest of the Canary Islands, the lavas of Tenerife are predominantly basaltic, and they emerged chiefly from fissures in fluid flows. But occasional evolution in shallow reservoirs produced eruptions of more evolved compositions (e.g. trachybasalts, trachytes and phonolites – see chapter 1, Fig. 1.3 for classification nomenclature). These more evolved eruptions expelled extensive ignimbrites and pumice or ash layers, with a total volume of some 70km^3, but also produced lava flows such as those decorating the southern slopes of Teide, as well as some domes in the Caldera de las Cañadas. Several recent lava flows of both phonolite and basalt in the caldera also have conspicuous blocky obsidian surfaces. Teide itself has a very shallow magma chamber and its eruptions have been basaltic, trachytic and phonolitic.

The basal shields

Eruptions concentrated at first in three separate zones of the ocean floor, where basaltic flows issuing from fissures had built three island shields by about 3.28 million years ago. They now form massifs on the three extremities of Tenerife: the Anaga peninsula in the northeast, the Teno peninsula in the northwest, and the Roque del Conde in the south, near Adeje. The basal complex probably occurs below these basalts, because fragments have been thrown up as xenoliths during historical eruptions.

The Anaga Massif is an accumulation of some 1000m of tabular flows of alkali basalt and basaltic trachyandesite, interspersed by cinder or ash layers and transected by innumerable dykes, and even occasional domes. It was formed 6.5–3.28 million years ago by three similar cycles of activity separated by intervals of repose. The Teno Massif is also composed of tabular basaltic flows, with some explosive breccias, mudflows and cinders in the lower levels and some trachytes in the upper, again transected by innumerable dykes, which can be seen along the Teno (Fig. 4.4). The eruptions began about 6.7 million years ago and ended when the Roque Blanco phonolitic dome erupted about 4.5 million years ago. Near Adeje, in southwestern Tenerife, about 1000m of basalts are exposed in and around the Roque del Conde. The youngest eruptions formed the trachytic dome of the Roque Vento about 3.8 million years ago.

A largely dormant period followed 3.28–1.9 million years ago. Barrancos cut deep into the shields, and the basaltic plateaux were reduced to ridges, knife-edge *cuchillos*, or pinnacles, such as the Roque Imoque near Adeje. At the same time, marine erosion trimmed the faulted seaward flanks of the shields, often revealing spectacular cliff cross-sections of the geology (e.g. Fig. 4.4).

The Cañadas volcano

When activity resumed on Tenerife, it changed in both location and eruptive style. The new concentrated vents built two successive stratovolcanoes where the regional rift fissures of Tenerife intersect. The first stratovolcano, now called Cañadas I, erupted for nearly a million years.

Figure 4.4 Examples of the basal shields; **A**) view along the Teno coastal peninsular looking north with dykes cutting through the volcanics; **B**) students mapping dykes on the Teno Massif; **C**) close-up of dykes cutting through lavas and volcaniclastic rocks at the base of cliffs along Teno peninsular (photo **C** from Shutterstock/ricok).

It grew up from vents on the west of the central area, and its deposits now lie in western Tenerife. Its initial basaltic eruptions, 1.89–1.82 million years ago, were followed about 1.5 million years ago by mixed basaltic and more evolved eruptions. Explosions of pyroclastic density currents about 1.24–1.05 million years ago were probably related to caldera collapse, which brought the main eruptions of Cañadas I to an end.

Eruptions from close-knit vents to the northeast immediately started to build Cañadas II stratovolcano. Its deposits now lie in eastern Tenerife and are well exposed, for instance, in the eastern wall of the Caldera de las Cañadas. They form many layers of ash and lava flows, ranging from basalts to trachytes and phonolites, which are about 650,000 years old. However, effusive phases were interspersed with both explosive episodes and dormant periods, when soils formed. About 600,000 years ago, Cañadas II underwent a phase of collapse, revealed by many layers of fragments exposed in the Cañada de Diego Hernández section of the caldera rim. Nevertheless, the eruptions of Cañadas II continued unabated until they had built up a large and rather unstable stratovolcano, which almost certainly rose well above 3000m, for its highest remaining flank still culminates at 2717m at the Montaña Guajara.

The Cañadas volcanoes together represented a considerable eruptive output. A million years of eruptions probably gave the Cañadas I stratovolcano a volume of 350–400km^3. The Cañadas II stratovolcano probably reached between 150km^3 and 200km^3 in volume during the ensuing 800,000 years. In comparison, however, the Teide–Pico Viejo volcanoes have erupted twice as fast, for together they are already approaching a volume of 150km^3 after less than 170,000 years of activity.

The Caldera de las Cañadas

Arguably the most spectacular feature of the Island of Tenerife is the Caldera de las Cañadas. The formation of the Caldera de las Cañadas was the last and most spectacular event in the evolution of the Cañadas II stratovolcano. This majestic caldera is elliptical, double and asymmetrical, and its main axis trends some 17km from northeast to southwest (see Fig. 4.5). The Caldera de las Cañadas harbours some of the most striking volcanic landforms in Europe, where the crystal-clear atmosphere, the brilliant sunshine and the absence of any continuous vegetation combine to emphasize the varied colours of the rocks, displayed in almost pristine splendour like a painted desert. Here steel-blue, brown, or black and glassy lava flows, and grey or yellow pumice piles and dark red cinder cones decorate the base of the grey Pico de Teide and its black companion, the Pico Viejo, which produced the latest eruption within the caldera in 1798. And, in the south, the rim of the Caldera de las Cañadas protects them all with a cliff that reaches 700m high and curves for more than 20km from El Portillo in the northeast to beyond the Boca de Tauce in the southwest. The Roques de García jut out from this cliff and divide the caldera itself into a larger eastern hollow and a smaller, lower, western hollow. But there is no sign of the northern rim of the caldera, and opinions differ about what might have happened to it. Fine views of the caldera can be found from the caldera rim or during the cable car ascent of Teide and from its summit (see Fig. 4.6).

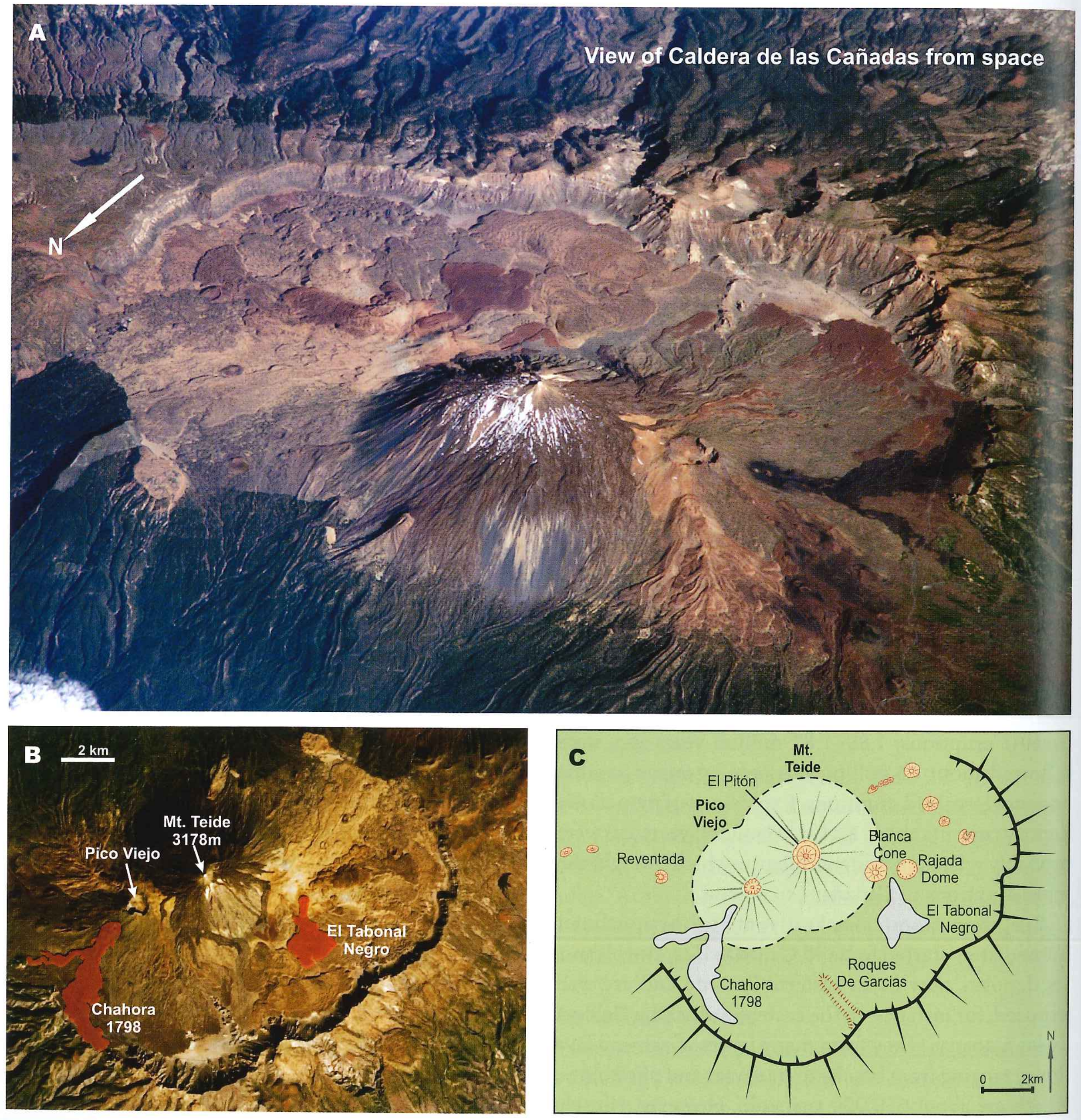


Figure 4.5 The Caldera de las Cañadas: **A**) view looking southeast across the Caldera (NASA); **B** & **C**) satellite map and outline of features and recent activity in the Caldera de las Cañadas (satellite map, USGS).

The Caldera de las Cañadas is a classic among European calderas, and the many opinions about its formation illustrate the changing evaluations of the tectonic, erosional, explosive, collapse and mass-movement processes that have been proposed to explain calderas during the past 200 years. It was first considered a crater of elevation; then an erosional amphitheatre similar to its supposed counterpart, the Caldera de Taburiente in La Palma; and, even later, as the headwaters of two river systems, whose exit northwards had been later covered by Teide and Pico Viejo. Later still, it was thought to have resulted from a massive explosion, like that which was then believed to have destroyed Krakatau in 1883. But it became accepted that it had formed when the summit of the volcano had collapsed after massive eruptions of magma, either in one single or several repeated catastrophes. The intricate network of galleries built to extract underground water show that the northern rim of the caldera is entirely missing. Thus, if collapse formed the northern rim, landslides might have removed it later. In a simpler view, the Caldera de las Cañadas has been seen as entirely the result of a gigantic landslide, whose uppermost arcuate scar forms the majestic southern rim of the caldera. Thus, the upper 100km^3 of the unstable

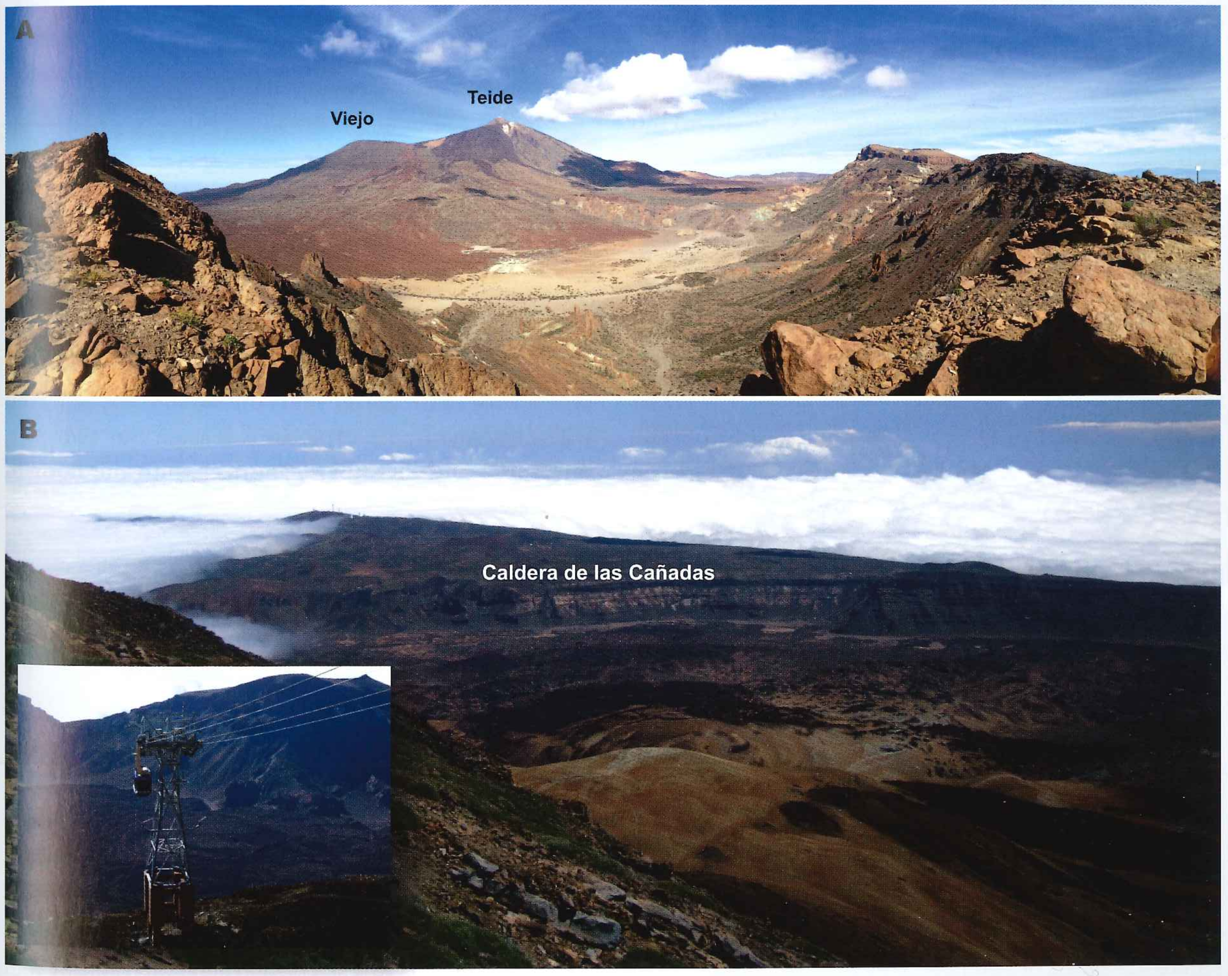


Figure 4.6 Views of the Caldera de las Cañadas. **A**) Panoramic view into caldera with Teide and Pico Viejo in view (photo courtesy of Davie Brown). **B**) View of caldera wall during cable car ascent (inset showing the cable car).

Cañadas II stratovolcano apparently suddenly slipped north-westwards into the Atlantic Ocean, where it seems to be related to vast debris-avalanche deposits on the submarine flank of northern Tenerife. A seaward-sloping layer of chaotic breccia, 100m thick, could represent the sliding plane. Although the landslide was not caused by direct volcanic action, it did, however, unleash pyroclastic density currents. Their deposits still crown the summit of the south-eastern rim of the caldera at the Cañada de Diego Hernández, and have been dated to 130,000–170,000 years ago. They indicate the oldest possible date for the birth of the Caldera de las Cañadas.

The Roques de García, separating the two parts of the caldera, form a ridge that has been dissected into a number of individual pinnacles. The most famous of these is the much photographed Roque Cinchado ('tightened-belt rock'), which is also often referred to as the Arból de Piedra ('tree of stone'). The ridge is about 200m high and 2.5km long, and is composed of an array of brightly coloured, altered volcanic rocks, notably at Los Azulejos. They form an intrusive complex that is apparently older than its surroundings. The Roques de García jut out from a distinct saddle in the southern rim of the caldera and may represent some of the original vents of the Cañadas stratovolcanoes, which have survived in the landscape because they were plugged with agglomerates that offered greater mechanical resistance as the caldera developed.

Soon after the Caldera de las Cañadas formed, the Pico Viejo and the Pico de Teide grew up as a pair of large stratovolcanoes in their own right, along a major fissure trending from northeast to southwest from the Cumbre Ridge to the Santiago area. They erupted from separate vents that issued from a common shallow reservoir, where the three rift-fissure zones of Tenerife intersect. The magma evolved towards a trachytic and phonolitic composition, but explosive eruptions of ash and pumice were punctuated by frequent emissions of viscous lava flows that form the armour-plating on both volcanoes. Pico Viejo and Teide were active during the same period and their products are often interbedded, but they are dissimilar twins, and their different eruptive styles created very different crests. Pico Viejo has a wide crater, whereas the crater of Teide, La Rambleta, has been completely filled by the summit cone of El Pitón. Both volcanoes have remained active during the past millennium.

Pico Viejo

Pico Viejo is broader, lower and more gently sloping than Teide, but still forms a considerable volcano, rising 1034m above the floor of the caldera to a height of 3134m. It erupted many aa lava flows, but many recent flows, like those emitted in 1798, have pahoehoe surfaces. However, some of the youngest phonolitic flows were so viscous that they solidified in thick elongated masses within 300m of their parent vents, even on slopes of 20°.

Pico Viejo is crowned by a circular crater 750m across and 150m deep, which is rimmed by a ragged scarp (see Fig. 4.7). It could have been formed by a large hydrovolcanic explosion, but it seems more likely to be a small caldera formed by recent collapse along ring fractures, because few exploded fragments occur on its flanks. The latest events on the summit occurred when hydrovolcanic explosions blasted out two pits, one 140m and the other 75m deep, into the floor of the crater.

Figure 4.7 Views of the crater at Pico Viejo looking down from Tiede. The island is well signposted about the geology with many information boards, including ones at the top of the volcano (inset photo of Dougal Jerram at one of the information boards about Pico Viejo).

The flanks of Pico Viejo have also witnessed eruptions recently. The oldest occurred on a fissure radiating northwestwards from the stratovolcano and formed the phonolitic dome of the Roques Blancos, which sagged down on its lower, northwestern side and formed a stubby lava flow. The fissure later extended further down slope and expelled a black obsidian flow that eventually reached 3km in length. The second eruption formed Los Gemelos ('the twins') along the saddle linking Pico Viejo to Teide. The twin craters were produced by a brief hydrovolcanic explosion that expelled pumice, ash and breadcrust bombs. Their sharply defined outlines indicate their youth. Most recently, in 1798, the only eruption recorded within the Caldera de las Cañadas took place 1km further down the western flanks of Pico Viejo and formed the Chahorra vents, or the Narices ('nostrils') de Teide (Fig. 4.8).

Figure 4.8 View of the Chahorra or Narices de Teide (nostrils), which erupted in 1798 on the flanks of Pico Viejo. Lavas can be seen in the foreground, and as dark flows down from the side vent on Pico Viejo (photo courtesy of Francis Abbott).

Pico de Teide

The Pico de Teide is a majestic volcano in a splendid setting (see Fig. 4.9). It is a large symmetrical cone, streaked with dark grey lava flows spilling like paint from its summit. Eruptions of trachybasalt and especially of phonolite have built Teide within the past

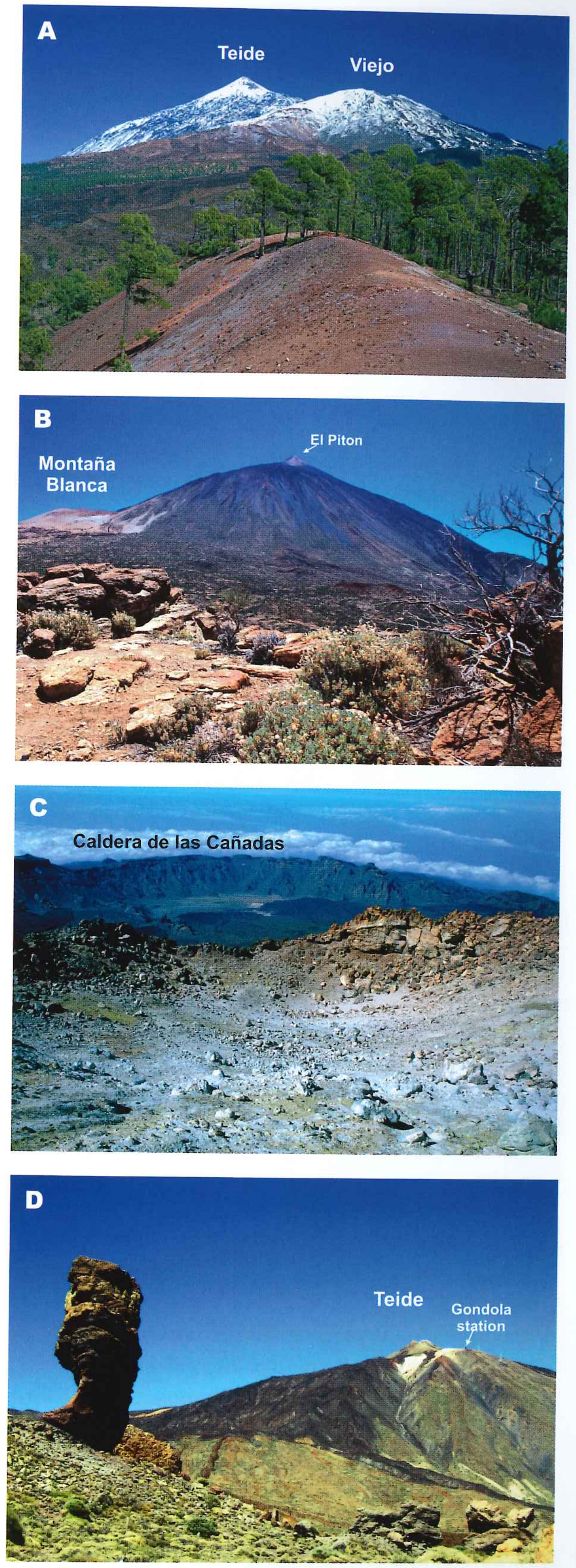


Figure 4.9 Views of Mount Tiede **A**) view of Teide and Pico Viejo with snow covering; **B**) El Pitón on Teide with Montaña Blanca; **C**) Mount Teide summit crater: spectacular views of the Las Cañadas caldera from the summit of Mount Teide stratovolcano at 3718 metres altitude. The small 80-metre wide crater has hundreds of active fumaroles emitting sulphurous water vapour (photos A-C courtesy of Francis Abbott). **D**) Classic photo of Teide with the Roque Cinchado in the foreground.

Meet the Scientist — Valentin Troll

Val is an award-winning volcanologist with a wide range of interests. He is currently the Chair of Petrology at Uppsala University, where he works with a team of exciting scientists doing research on volcanoes around the world. He has been working on the Canaries for many years, and here he provides some insight into his passion for these volcanic islands.

How long have you been working on this volcano/volcanic system?
My first trip to the Canaries was on a research vessel over Christmas 1998 and it rained. I have worked on the volcanic landscapes of the Canary Islands ever since and earned my PhD with a thesis on the *Evolution of large peralkaline silicic magma bodies and associated caldera systems: a case study from Gran Canaria, Canary Islands.* To date, I have published over 50 scientific articles on the Canary Islands in international scientific books and journals and led about one dozen fieldtrips for students and/or scientists from international organizations to the islands. The recent publication of our Springer book on Teide Volcano (Carracedo and Troll, 2013) and the new *Geology of the Canary Islands* (Elsevier) represent the pinnacle of my efforts over the last 15 years.

What has been your most exciting discovery about it?
The increasing knowledge on the interior of the islands. Volcanologists can actually look inside a volcano, by reading the signals the volcano directly or indirectly emits (such as erupted rocks, emitted gasses, deformation pattern and stratigraphy). Volcanoes grow like living beings. There are young volcanoes, like on La Palma, there are mature volcanoes, like Teide on Tenerife, and there are 'emeritus' volcanoes like Gran Canaria. Piecing together the life cycle of a typical island, seeing the links between places and similarities in processes, has likely been the biggest revelation to me so far.

What is the most important thing we still need to find out?
We still need to find out 'exactly what does what inside a volcano?' We really have not been there (apart from Jules Verne) and can only speculate on 'cause and effect' relationships for many aspects. Scaled experiments will be vital in the next decade, as will be comparative studies between eroded plutons and active volcanic systems (e.g. Fuerteventura vs. Teide). This includes the peculiar floating stones erupted during the first week of the 2011 El Hierro events and their significance on a regional scale in the Canaries, an exciting new aspect that is still to be explored.

What inspired you to study volcanoes?
I am inspired by their explosive force and internal dynamics. Explosions occur by rapid, unchecked volume expansion of materials. Dynamite, for example, undergoes a virtually instantaneous volume expansion of factor 60 during an explosion. This phenomenon occurs at volcanoes too, and leaves its mark on the eruptive products. The textures and chemical signals preserved in the rocks can then be interpreted to better understand the inner workings of volcanoes, though, admittedly, much of the 'vocabulary' and 'grammar' of this language still remains to be fully understood.

170,000–130,000 years. Its lower northern flanks are clothed with distinctive reddish-brown or bluish-grey aa and blocky flows of fairly viscous phonolites, which form tongues, about 12m to 15m thick, with lobate ridges, lava moraines and steep rubble-covered margins. On the steepest slopes in the east, lava masses have sometimes detached themselves from the snouts of the flows and have rolled forwards, like snowballs, down slope. Examples of these can be seen as the contrast of black lava block 'eggs' on the light-coloured surface of Montaña Blanca (see Fig. 4.10). In contrast, the flows reaching the floor of the Caldera de las Cañadas sometimes spread out in wide lobes with crescent-shaped pressure ridges that run parallel to their margins. Most of these flows have suffered such limited atmospheric alteration that they cannot be many thousands of years old.

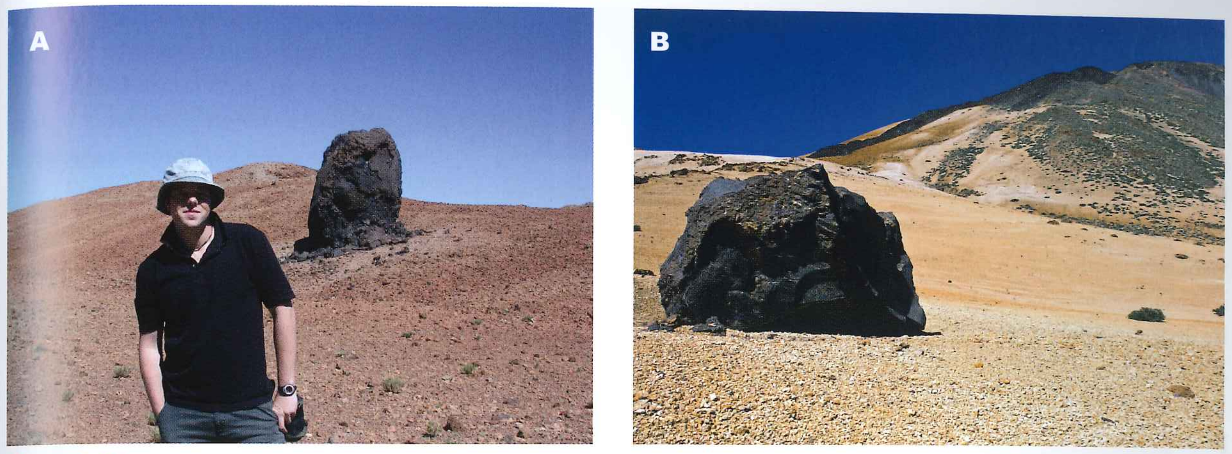


Figure 4.10 **A**) Val Troll on Montaña Blanca, Tenerife, with one of Teide's 'eggs' in the background. These are large fallen blocks from the nose of the last summit eruption at Teide, the lavas Negras (summit of Teide is further to the left); **B**) Close-up view of a fallen block with slopes of Teide in the background (photo **A** courtesy of Val Troll, photo **B** courtesy of Francis Abbott).

Like Pico Viejo, Teide probably had an open summit crater for a long time, the rim of which can still be discerned as the shoulder at La Rambleta. The cone of El Pitón now fills this crater and crowns Teide like a giant sandcastle. It is itself a small stratovolcano 150m high, which encloses a crater, La Caldereta, which is 70m in diameter and 40m deep. Apart from the contemporary fumaroles that have changed its crater walls to yellow and brilliant white, El Pitón has been as quiet as its parent, Teide, for the past 500 years. The latest magmatic eruption gave off fresh black, glassy, phonolitic aa lavas that spilt from El Pitón and flowed in ridged tongues down the flanks of Teide as far as the Caldera de las Cañadas. This emission was then followed by the throat-clearing explosion that gave El Pitón its present funnel-shaped crater.

Seven satellite vents surround Teide. Five of these vents lie on a circle, 3km from Teide, which probably represents a ring fracture in the Caldera de las Cañadas. The eruptions probably occurred where this ring fracture intersected fissures radiating from Teide.

The Pico Cabras, the Montañas de las Lajes and the Montaña Abejera, in the northeastern sector of Teide, have much in common. Each eruption began with the extrusion of a brown phonolitic dome, which distended and breached on its northward downslope side, and delivered a more fluid phonolitic flow extending towards the northern shore of Tenerife. In contrast, the Montaña Majua and the Montaña Mareta, which erupted on the gentle slopes beyond the southern base of Teide, produced only lobes of unusually fluid black phonolitic lava that are 10m thick and over 2km long and wide. The Montaña Majua lavas eventually accumulated thickly above the vent, but the Montaña Mareta remained as only a low mound. It is very similar to El Tabonal Negro ('the black table'), which issued from a vent low on the southeastern flanks of Teide and emitted thick, blocky black phonolitic flows, decorated by arcuate ridges, that spread over 3km across the caldera floor.

The two remaining flank eruptions of Teide took place about the same time. They formed the Montaña Blanca and the Montaña Rajada, which both had more complicated histories that are reflected in their more varied relief. The first eruptions of Montaña Blanca came from five vents along a fissure radiating from Teide and gave off flows of brown phonolite. They were followed by a subPlinian explosion of frothy phonolites, which was the most violent eruption on Tenerife since the formation of the Caldera de las Cañadas. It formed the Montaña Blanca, a mound about 300m high and 1km across, and composed of loose yellow pumice, with lumps attaining up to 30cm in diameter. The eruption ended with a return to calmer conditions and the emission of small domes and flows. All the flows from the Montaña Blanca are notably rugged, with rough angular blocks on their aa surfaces, and their margins are invariably very steep and rubble-strewn. These eruptions took place about 2000 years ago.

The Montaña Rajada, 1km east of Montaña Blanca, erupted bulky phonolitic lava flows. These travelled 5km, wrapped around the older Montaña Mostaza cinder cone, and formed the remarkable chaos of blocky and shining phonolites of the Valles de las Piedras Arrancadas ('valley of the uprooted stones'). Succeeding emissions were even more viscous and travelled scarcely more than 200m from the vent. The very latest lava emissions from this vent formed the Montaña Rajada itself ('the split mountain'), which is about 250m high and 1km in diameter. It forms a rugged dome of reddish-brown phonolites, whose summit was burst open by an explosion that formed a ragged central hollow into which a similar but smaller dome then intruded. The Montaña Rajada also has a scattering of fine pumice on its surface, which could be derived from the Montaña Blanca nearby. The northwestern flank of the Montaña Rajada also burst open and extruded a very viscous phonolitic flow that congealed before it reached the foot of the 20° slope.

The pyroclastic rocks of Tenerife

Explosive eruptions have littered the volcanic past of the island of Tenerife. Its pyroclastic rocks are worthy of a specific mention, as the island contains some spectacular examples and the deposits from its explosive eruptions have been used to inspire our modern-day understanding of the pyroclastic density currents that result from such volcanic explosions (Fig. 4.11). Numerous widespread, and in some cases large-volume, pyroclastic density currents have swept radially across the island over the last 2Ma. The resultant deposits (ignimbrites) are variously preserved in and around the island, with a good concentration of very good outcrops to be found on the slopes and the coastline around the southern parts of the island, known as the Bandas del Sur ('Band of the Sun'). One ignimbrite of note is the 273,000-year-old Poris Formation, which fills valleys and is exposed along the coast (see Fig. 4.11A). The ignimbrites of Tenerife display many of the classic features associated with deposits formed from pyroclastic density currents, including cross- and massively-bedded deposits, pumice and lithic-rich layers, and accretionary lapilli; and in some cases the material was hot enough when it was emplaced that it started to plastically deform, stick back together and produce welded ignimbrite (Fig. 4.11C, D).

The coastline is also home to many shallow cones and ring-like formations, interpreted to be the result of hydrovolcanic eruptions, termed tuff rings, where water and magma interact explosively in the shallow subsurface. These structures have, in some instances, been dissected by erosion from the sea, and reveal the inside stratigraphy of the tuff rings in extraordinary detail. A classic example of one of these features is the Montaña Pelada tuff ring, near the airport on the southern coast, where complex layers of tuffs are exposed along the beach and slopes, with some showing fantastic impact structures from some of the blocks/bombs associated with their eruption (e.g. Fig. 4.12).

Rift-fissure eruptions

As the Cañadas stratovolcanoes were growing up, Tenerife also resumed, or continued, its old pattern of rift-fissure eruptions that have given the island its characteristic Y-shape, and they have persisted into historical times. The emissions seem to have come from blade-like insertions of magmas that could rise fairly quickly from a deep source, and which formed basaltic cones about 100m high and flows up to 10km long.

Northwest of the Caldera de las Cañadas, for example, a set of rift fissures trending from northwest to southeast gave rise to the Santiago volcanic field of recent cones and basaltic flows. Where these fissures extend into the caldera, they formed the Montaña de Samara, the Volcán Botija, the Montaña de la Cruz de Tea, and the Montaña Reventada ('breached'), which has been dated to AD1000–1300. This set of fissures also produced eruptions in 1706 and 1909. At the northwestern end of these rift fissures, the large Taco cone erupted near the sea at Buenavista. Its unusual size – it is almost 1km across and 200m high – and its large, deep crater, as well as its fine tuff layers, all indicate that it was formed by Surtseyan eruptions in shallow water, during a recent period of higher sea level.

A companion set of fissures erupted aligned cinder cones and fluid basaltic flows that built the backbone of northeastern Tenerife, the Cumbre Ridge. It is 25km long, 18km wide and 1600m high, and probably represents one of the fastest volcanic accumulations experienced on the island. Such rapid construction helped make its flanks unstable and eventually led to the landslides by which the Orotava Valley in the north and the Güímar Valley in the south collapsed between 830,000 and 560,000 years ago (see map in Fig. 4.3).

Both the Orotava and Güímar valleys are 10km wide, with smooth floors sloping gently seawards and bounded by crisply outlined inward-facing straight cliffs extending at right angles to the Cumbre Ridge. They look like two piano keys pressed down on either side of the Ridge. They have been recently interpreted as great landslides displacing more than

Figure 4.11 Pyroclastic rocks of Tenerife. **A)** Students working on exposures of the Poris Formation on the South Coast of Tenerife. **B)** Different layers within ignimbrite deposits made from pyroclastic density currents. **C & D)** Thin welded ignimbrite showing streaked out textures. **E)** Dougal Jerram highlighting a fossil tree mould in an ignimbrite. **F)** Rounded accretionary lapilli showing concentric rings.

$100km^3$ of lavas with a total thickness of 150–600m. They now lie upon a layer of chaotic breccia and sandy clay that was apparently crushed when the volcanic materials slid over them.

One of the most notable fissures recently erupted Montaña Colmenar and the Siete Fuentes cones on the Cumbre Ridge. It extends into the eastern part of the Caldera de las Cañadas, where it has given rise to

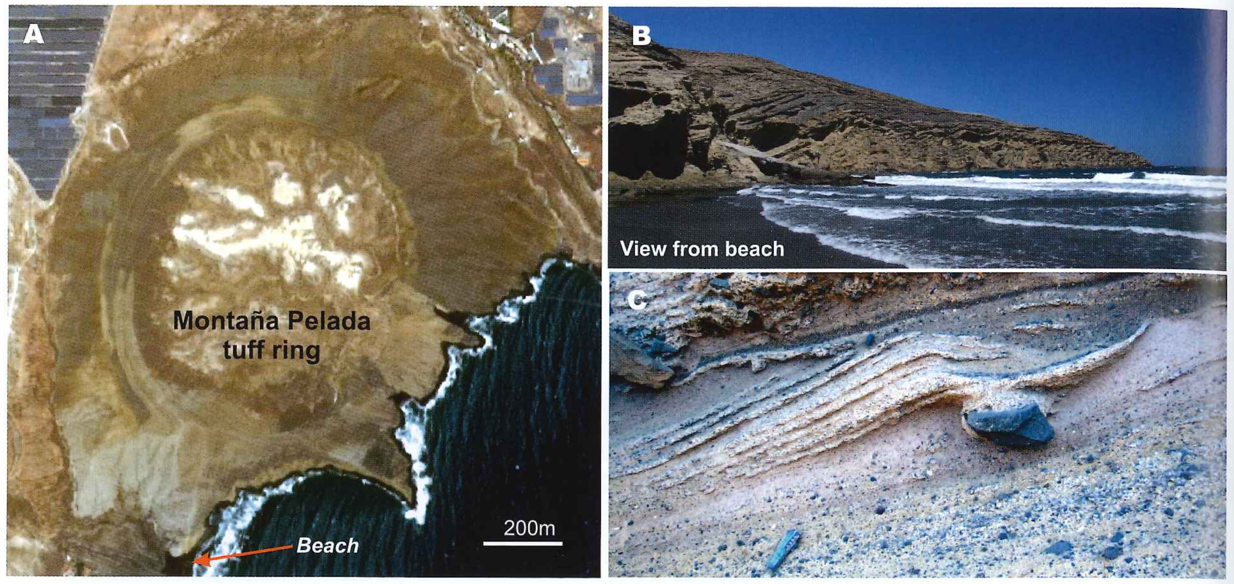


Figure 4.12 The example of the Montaña Pelada tuff ring, southern Tenerife; **A**) aerial view of circular tuff ring; **B**) view of deposits from beach (see location on **A**); **C**) close-up of volcanic bomb and sag on the slopes of the tuff ring (aerial view – NASA World Wind).

The longest lava tube in Europe

Tenerife is home to the largest lava tube in Europe, and offers some fantastic opportunities to explore the underground world of a volcano. Located in the north-east of the island, the Cueva del Viento-Sobrado ('Cave of the Wind') is an underground lava tube complex that extends over 17km in length. The name of the tubes comes from the powerful winds and draughts which rattle through the extensive cave system. Located near the town of Icod de los Vinos, the lava tubes are the result of basalt lava flows sourced from the Pico Vejo area some 27,000 years ago. The tubes display a number of morphological features that help decipher how they formed. Including lava stalagtites, flow patterns and lava ledges mark different levels of lava flows through the tunnels (e.g. Fig. 4.13).

This geological beauty is also of special interest from a biological and anthropological standpoint. The cave is home to a total of 190 known species, most of which are invertebrates. Including some 44 troglobites (animals adapted to underground environments), and specialist mosses, lichens and cyanobacteria. Of these species condemned to live in the darkness, 15 are new to science, such as the eyeless cockroach (*Loboptera subterránea*). Fossils have also been found in the cave system, including the giant rat (*Canariomys bravoi*), and the giant lizard (*Gallotia goliath*). Anthropological findings include artefacts and burial remains of the original 'Guanches' settlers from as far back as 2000 years ago. Today small tourist tours are allowed through parts of the lava tube network, and in 2014 the Cueva del Viento Natural Resource Management Plan was adapted to European legislation for Special Areas of Conservation. Exploration and discovery of the caves on this island and elsewhere on the Canaries is ongoing by scientists and members of the Canary Islands School of Speleology

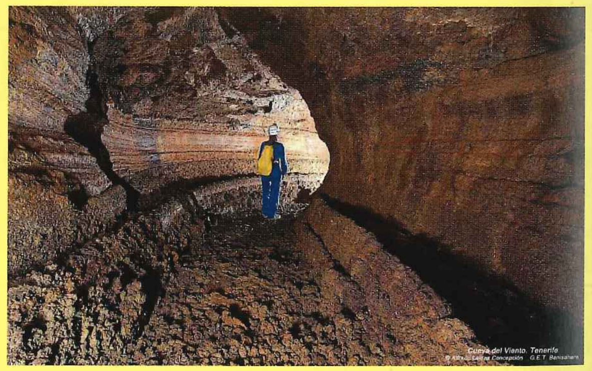


Figure 4.13 View within the Cueva del Viento-Sobrado ('Cave of the Wind'), the longest lava tube in Europe (photo courtesy and © of Alfredo Lainez Conception on behalf of Speleology of Tenerife Benisahare, and La Cueva del Viento, Icod, Tenerife).

the Montañas Negra, Los Tomillos, Los Corrales and the highest, Mostaza, which rises over 100m. Montaña Mostaza was formed before the Montaña Rajada, whose lavas are wrapped around its base.

Historical eruptions on Tenerife

Most of the activity on Tenerife during historical times took place along rift fissures. The early references to eruptions on the island are so vague that it is uncertain when, or even if, they occurred. However, there can be little doubt that, before the Spanish conquest, the local Guanche peoples must have witnessed eruptions on the island, notably on Teide. For the Guanches, Teide was Echeide, the Inferno. As the Italian engineer Torriani wrote in 1592, 'because of the terrible fire, noise and tremors that come from it, they consider it to be the home of demons'.

Andalusian and Basque sailors might have seen an eruption on Teide in 1393 or 1399. Hum-boldt reported that the Guanches had told their Spanish conquerors of an eruption in about 1430, which might have formed the cinder cones of Las Arenas, Los Frailes and Gañañías, in the lower Orotava valley. The Venetian mariner, Cadamasto, approached Tenerife in 1455 and later declared that 'the mountain that rose above the clouds [Teide] … was glowing incessantly.' Alonso de Palencia, chronicler of the conquest of Gran Canaria, wrote that, somewhere between 1478 and 1480, 'fire surged continually from an infernal mouth in the centre of the highest mountain [Teide] … Small chips of stone were carried on the wind to the very edge of the sea'. Christopher Columbus called at the Canary Islands on his first voyage to the Indies. On 24 August 1492, his logbook recorded that, while La Pinta was anchored off La Gomera, 'they saw very large flames coming from the mountain, which filled the crew with wonder. [Columbus] explained the cause of such fire, saying that it was just like Etna.' It is possible that one of these fifteenth-century accounts could refer to the eruption that gave off the fresh-looking lavas that stream down from El Pitón. On the other hand, it is strange that no record survives, of what must have been a spectacular display, from the Spaniards who were established on nearby La Gomera from 1402.

Then, for over a century after the Spanish conquest of Tenerife in 1493, the only signs of volcanic activity were the fumes that issued from the crater of El Pitón. But the first decade of the eighteenth century saw four basaltic eruptions and the destruction of half a town. The crisis began on Christmas Eve in 1704. Twenty-nine earthquakes had been counted before dawn on Christmas Day. During the next few days, more and more earthquakes and rumblings were felt throughout the island. Calm returned on 29 and 30 December. Then, on 31 December 1704, a fissure opened on the Cumbre Ridge and began the little eruption that built the Siete Fuentes cone. A string of vents expelled lava fountains, ash and cinders, which constructed three cones – the largest of which reached only 22m high – and sent an olivine basalt lava flow, 1km long, into the neighbouring valley. Siete Fuentes had probably stopped erupting when the next episode began about 900m to the northeast.

At 08.00 on Monday 5 January 1705, a new set of earthquakes started and, that afternoon, a fissure opened and the Fasnia volcano began to form. Over a length of about 1400m, 30 initial vents formed an array of cones, explosion pits, hornitos, lava fountains and lava flows. The number of active vents fell to eight on 7 January, but they still 'made as much noise as the artillery', and fumes and ash descended on the nearby towns of La Orotava and Güímar. When the eruption ended, on 16 January 1705, the largest cone was 550m long but only 37m high, and half of it had been destroyed as basalts had flowed out into the valley nearby. This aa flow has some fine lava moraines and flow channels. No more lava emerged during the rest of January, but the earthquakes continued, the ground rumbled, the surface cracked and fumes escaped. It is said that one shock threw down 70 houses and killed 16 people in Güímar. If this tale is to be believed, this volcano-seismic event was the most lethal of all the recorded eruptions in the Canary Islands.

The next eruption arose on the same fissure, about 7km northeast of Fasnia volcano. The Volcán de Arafo began to erupt between 16.00 and 17.00 on Monday 2 February 1705, at the very head of the Güímar valley, whose upper walls tower 400m above it. Fountains of lava spurted 30m into the air, and ash and cinders rose much higher. Arafo produced higher columns of fumes, more fragments, more lava, and more noise than its three predecessors – and it lasted at least until 27 February. Thus, Arafo reaches a height of 102m. One of its two main craters is breached by an aa flow that developed distinct flow channels and many accretionary balls, and almost reached the sea, 8km away.

These three eruptions were brief and small-scale, even by the modest standards of their type. All gave out

Figure 4.14 *Eruption 1706* by Ubaldo Bordanova Moreno in 1898 (it is actually a copy/interpretation of an earlier painting by an unidentified artist).

olivine basalts, and covered a total area of only 12km². However, earthquakes continued to shake Tenerife for more than a year afterwards, hinting that another eruption was yet to come. But it came on the northwestern rift fissure and severely damaged Garachico in 1706.

The destruction of Garachico, 1706

The eruption that began at 03.00 on 5 May 1706 was the most destructive that has been clearly recorded on Tenerife. There was only one preliminary earthquake before fluid basalt started gushing from a fissure on the ridge rising behind the flourishing port of Garachico, on the north-western coast (depicted in the painting in Fig. 4.14). Activity tended to migrate from northwest to southeast along this fissure. In the northwest, a spatter rampart, 5m high and about 400m long, formed only along its southern edge, because continuous streams of lava prevented it from developing on the downslope side to the north. On the southeastern part of the fissure, on the other hand, a mixture of explosions and effusions formed a cinder cone 80m high. But there again, persistent lava emissions stopped its northern sector from forming. This cone has been called the Montaña Negra, or the Volcán de las Arenas Negras ('the black sands'), but most often as the Volcán de Garachico, because of the damage that its eruption caused in the little town.

Founded in 1505, Garachico had soon become the main port in northern Tenerife. But, in 1645, floodwaters from a burst dam had badly damaged part of the town, and in 1697, fire had ravaged some of the best buildings along the shore. The new volcano was to bring yet another threat.

At 03.00 in the morning of 5 May 1706, the basalt flowed into the hamlet of Tanque, burned the church and several houses, and destroyed the vineyards nearby. At about 21.00 that same evening, a larger flow swept across the plateau and poured in seven separate cascades down the steep scarp dominating Garachico. It entered the town and filled the harbour to such an extent that little more than a creek remained. At 08.00 on 13 May, an even stronger flow rushed down the scarp, burned watermills and windmills, buried orchards and blocked springs. It reduced the San Francisco monastery and the Santa Clara convent to ashes, overwhelmed the finest quarter of Garachico, set fire to many houses and warehouses along the shore, and then spread in a fuming lobe out to sea. It is said that the basalts glowed for 40 days. But the citizens had time to flee with their goods towards the neighbouring town of Icod, often accompanied by – now equally homeless – members of the religious orders, who sang psalms to maintain morale. Many people in both the town and the surrounding countryside lost their livelihoods, but nobody was killed. The eruption probably ended on 28 May 1706, when the cinder cone had reached a height of 80m and its flows had spread 8km from their vent. During the following decades, Garachico was rebuilt, and more or less the same town plan was retraced over the surface of the new lava flows and lava delta (Fig. 4.15).

Figure 4.15 The rebuilt town of Garachico, constructed on the lava flows and lava delta of the 1706 eruption that destroyed the original town (photo Shutterstock/Tatiana Popova).

The only eruption that is certain to have occurred within the Caldera de las Cañadas in historical times took place in the summer of 1798. This time, at least, it happened well away from any settlements – 2300–2800m high on the southwestern flanks of the Pico Viejo. However, it is rather confusingly called the Chahorra, or Narices, de Teide eruption. It took place on a fissure 850m long, and it was unusual for such an eruption to occur on a stratovolcano, because the activity started at the lower end of the fissure and progressed up slope. If it did indeed last for 99 days, as some have supposed, it could have been one of the longest eruptions in the Canary Islands during historical times. Earthquakes had been felt as early as 15 June 1795, but they did not reach their climax until late April 1797. However, the Chahorra magma did not make its appearance until just after 09.00 on 9 June 1798. Fifteen vents opened in the next two days as the fissure spread up the slope, as if Pico Viejo were being unzipped. By 13 June, eruptions had concentrated on three vents: the top vent giving off billowing fumes, the middle vent ejecting lava and fragments in hydrovolcanic and Strombolian activity, and the lowest delivering only lava flows. On 14 June, a large explosion joined the two upper vents together. The new vent gave off a column of snow-white steam before resuming the habits of the old middle vent, with noisy explosions and spurting lavas. It eventually built a cinder cone with two craters. The lower parts of the fissure produced a continuous wall of spatter, but the chief eruptive effort of the lower vent was to disgorge copious lava flows. These have both aa and pahoehoe surfaces that vary in aspect from strikingly rugged to smoothly shining. These basanitic lavas broadened out as they reached the floor of the Caldera de las Cañadas and came to a halt and solidified, with a slabby pahoehoe surface, in a big lobe at the foot of its great boundary scarp, some 8km from their source. On 16 June, one observer saw such a flow reach the floor of the caldera in less than a day. Another observer later declared that the eruption ended in mid-September, but apparently little information about the course of events after June has survived, and it is thus not certain when the activity stopped.

The eruption of Chinyero was the latest to occur in Tenerife (Fig. 4.16). It was typical of the Canaries and lasted for only ten days. It started between 13.00 and 15.00 on 18 November 1909 in the Abeque plateau: not far, in fact, from the Volcán de Garachico. Chinyero caused nothing like the same amount of damage. Although many small earthquakes had been recorded during the previous year, they became more intense and frequent in the autumn of 1909. In the week before the eruption began, they were even accompanied by underground noises, and the ground became warm where the lava was eventually to reach the surface. The

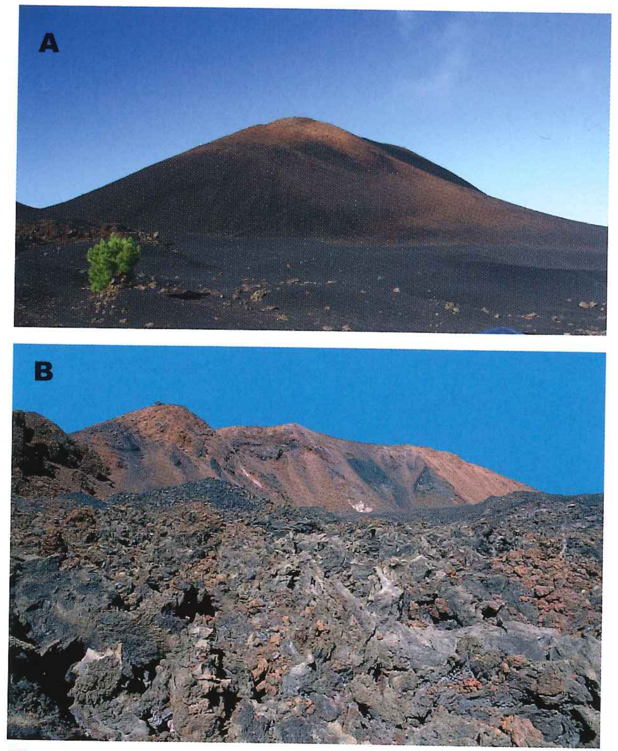


Figure 4.16 Chinyero volcano. **A**) View of the Chinyero volcano with the ash and volcanic bombs that surround it. The common path to the top can be seen winding up its cone. **B**) View back to Chinyero from its rubbly lava flow surface (photo **B** courtesy of Francis Abbott).

eruption started with explosions of ash from three or more vents on a fissure some 650m long that opened on the flanks of an older cinder cone also called Chinyero. Activity migrated towards the northwestern end of the fissure as the new cone grew. Windblown ash fell at least 25km from the vent, at La Orotava, for instance, before the first lava emerged late on 18 November. Next day, four craters were operating, bubbling out frothing lava fountains 50m high and throwing columns of ash 500m into the air, often to the accompaniment of loud explosions. For several days, each crater seemed to take up the main role in turn, but from 25 November activity began to decline, and from noon on 27 November 1909 only fumes issued from the vents. The new cone of Chinyero was of crescent shape and about 50m high, and its olivine basalt flow had wrapped itself halfway around the base of the cinder cone of the Montaña de Bilma, which had, no doubt, grown up in a similar fashion a few centuries or millennia before.

All the historical eruptions of Tenerife covered an area of only about 25.3km², which represents a low rate of production. On average, another eruption on one of the rift fissures may be expected to occur within the next few decades, and add a little more to this modest total.

El Hierro

The site of some of the most recent volcanic action in the Canary Islands is the island of El Hierro. This is the smallest of the Canary Islands, covering an area of 278km², but it is quite mountainous, reaching 1051m at Malpasso (Fig. 4.17). Rising from the ocean floor at a depth of 3000m, El Hierro was the last island to emerge in the archipelago, and two consecutive, mainly basaltic, edifices quickly formed. The recent activity off the coast of El Hierro is testament to the continuing island-building activity at El Hierro (see section below). The oldest dated rocks are about 1.12 million years old and they come from the El Tiñor volcanic complex, which was active for at least about 250,000 years. The second volcanic edifice, El Golfo, grew up on the eroded western flanks of El Tiñor and was active about 545,000–176,000 years ago. It began about 545,000 years ago with dyke-intruded layers of basaltic fragments and ended, about 176,000 years ago, with a predominance of lava flows. Basaltic eruptions from rift fissures then began about 158,000 years ago, virtually as the activity of El Golfo ceased.

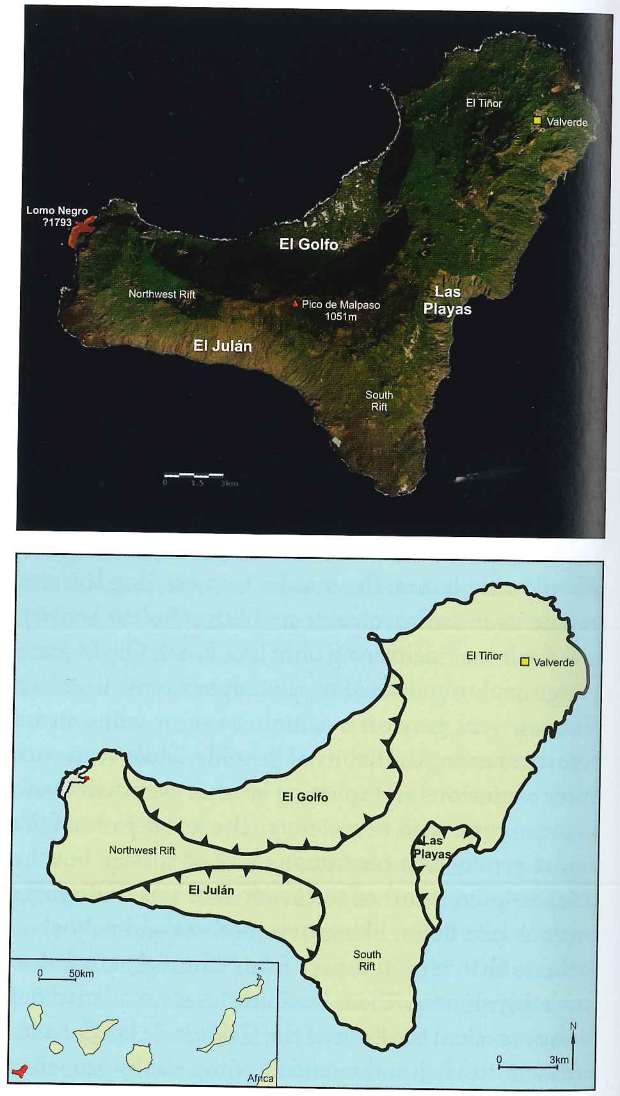


Figure 4.17 Location map, features and outline of recent activity on El Hierro (Satellite Image – USGS).

El Hierro is a trilobate island, and each arm is dominated by a rift zone. These three arms dominate the scenery of the island, and it is here that magma has been inserted, blade-like, into long parallel feeder dykes, which have thus built up the ridges by frequent and largely basaltic eruptions. The island most probably now lies over an active branch of the Canary Island hotspot. El Hierro, indeed, has the greatest concentrations of recent and well-preserved emission vents in the whole archipelago. Many small cones and lava flows, such as Julán and Orchilla volcanoes, are so little weathered that they can scarcely be more than a few thousand years old at the most. For example, near San Andrés on the central plateau the eruptions of the Montaña Chamuscada and the Montaña Entremontañas took place about 2500 years ago, and many vents near the end of the northwesternmost rift of El Hierro seem to have been active even more recently. But, in spite of its youth, El Hierro has had only one possible onland eruption during historical times. The Lomo Negro, at the western end of the island, suffered many earthquakes between 27 March and the end of June 1793, and a small eruption is thought to have taken place at that time.

Coastal embayments are prominent features of El Hierro. The northern coast of the island is scalloped by the impressive embayment of El Golfo, which is 5km across and bounded by cliffs 1100m high. It was apparently caused by an enormous landslide less than 158,000 years ago. Lava eruptions had built up the rift ridge to such a height that its unsupported seaward flank became unstable and slipped into the sea. On the southeastern coast, a similar landslide, 3km across, formed the Las Playas embayment, the bounding cliffs of which rise to 900m. A third landslide forms the Julán embayment on the southwestern coast. It is still uncertain whether these landslides occurred rapidly or over many centuries, as marine erosion progressively undermined the seaward buttress of the accumulated lavas. However, although El Hierro already has a triple rift system like Tenerife, it is apparently still too young to have developed the massive central vent complex of its larger neighbours.

The 2011–2012 submarine eruption at El Hierro

The offshore area west of El Hierro has seen the most recent volcanic activity at the time of writing this book, and warrants its rather elevated position in this chapter for such a small island. The eruption started in October 2011 along the southern submarine rift zone offshore from El Hierro, and was intermittently active until March 2012. The submarine vent that caused the eruptions was situated between 350 and 100 metres below sea level (fluctuating in depth as the eruption episode continued), and was located about 2km offshore. The activity sparked much interest in the press, as it was speculated that a new island or part of El Hierro might rise from the depths as an emergent volcano. This was not realized, but the activity itself produced some rather remarkable materials brought up from the deep.

The eruption was associated with discoloured murky plumes of water (termed 'la mancha'), which stained the sea water around (see Fig. 4.18). Additionally, early in the eruptions material was brought to the surface as frothy and bubbly fragments of lava, which were often still steaming hot when collected (Fig. 4.18C–F). Many of the fragments also contained a very light-coloured material. The latter period of eruptions was characterized by large gas escapes. It was these light-coloured fragments that were to prove most interesting. On closer inspection they were found to contain fragments of the pre-island sedimentary strata, upon which the volcanic island had grown. The rising magma that fed the eruption had plucked off fragments of this material as it rose, and brought them to the surface (e.g. Fig. 4.19). The sediments contained key microfossils (coccolithophores), which can be dated, and the youngest of these turned out to be 2.5 million years old. With sediments from the easternmost islands being around 20 million years old, these newly discovered younger sediments indicate an age progression of old to young from east to west. This age progression of the island to the youngest at El Hierro has been used to help support the idea of a hotspot/plume origin of the volcanic islands of the Canaries (see Fig. 4.2). It is not clear what additional materials El

Figure 4.18 Images of the 2011–2012 submarine eruption off El Hierro (images courtesy of IGN, Instituto Geográfico Nacional).

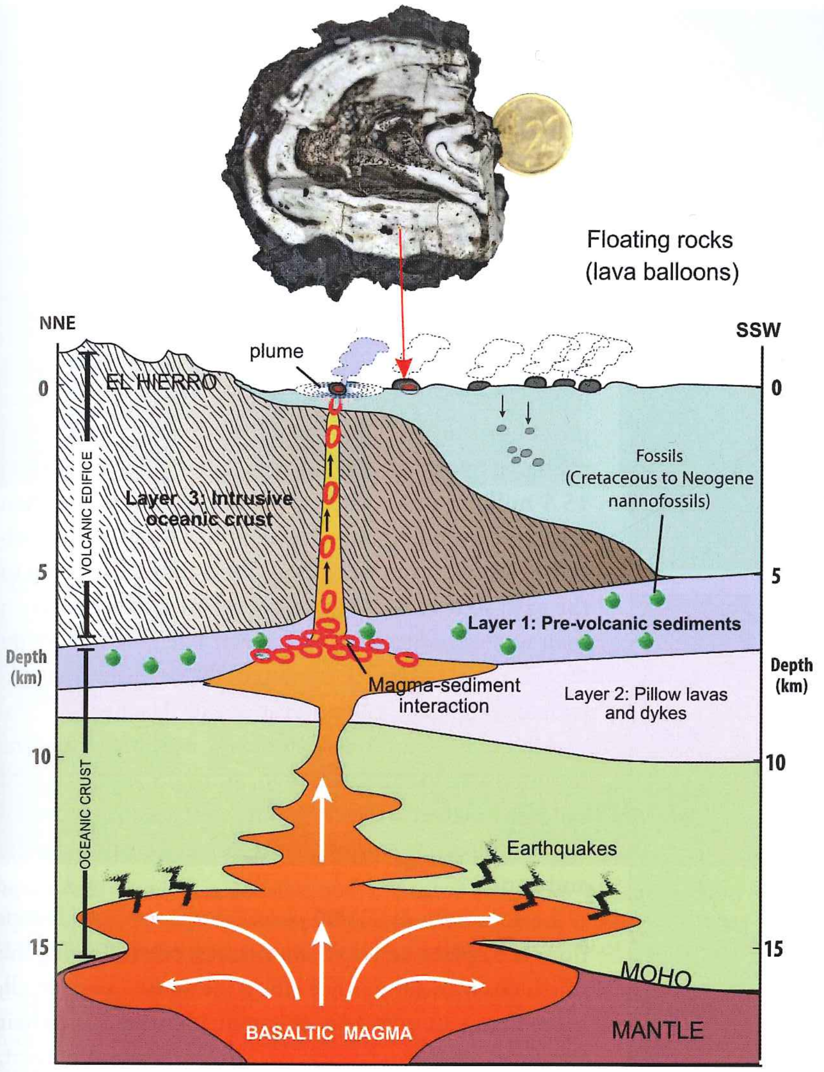


Figure 4.19 Schematic cross-section highlighting the eruptive processes at El Hierro. Magma interacts with the sediment beneath the volcano, bringing sediment inclusions containing microfossils to the surface as floating stones. An example of one of these in section is also highlighted (cross-section courtesy of Val Troll and Frances Deegan; image courtesy of IGN, Instituto Geográfico Nacional)

Hierro will muster from the deep, but it is likely that the island itself will emerge and grow further as the youngest addition to the Canary chain.

Lanzarote

Lanzarote is the northeasternmost of the Canary Islands, covering an area of about 795km². It is 56km long, has a maximum width of 21km and reaches a height of 671m (Fig. 4.20). The higher parts of Lanzarote form the Famara Plateau in the north and the Los Ajaches Plateau in the south, both of which are composed of piles of basaltic lavas and bordered by steep, straight cliffs. Between these plateaux lies the main axis of Lanzarote, an area often below 300m, where lava flows form aprons around cinder cones that have erupted along fissures. The products of the older eruptions are covered with pale ochre caliche, but, in the northwest, black or reddish basalts form a grim wilderness of cones and flows that erupted between 1730 and 1736, and briefly again in 1824.

The volcanic forms of Lanzarote are all the more striking because the rainfall averages less than 200mm per year and the natural vegetation is often limited to xerophytic plants ranging from *Sempervivum* to prickly pear. There are thus no permanent streams on Lanzarote and, although many older cones are ribbed by gullying, there are very few *barrancos*. However, much of the centre of Lanzarote is blanketed with layers of black ash and lapilli, or picón, in which the farmers have planted vines or vegetables (Fig. 4.21).

Practically all the volcanic activity on Lanzarote sprang from fissures that generally follow the overall trend of the island. Eruptions from similar fissures also, no doubt, built up the whole mass of Lanzarote from

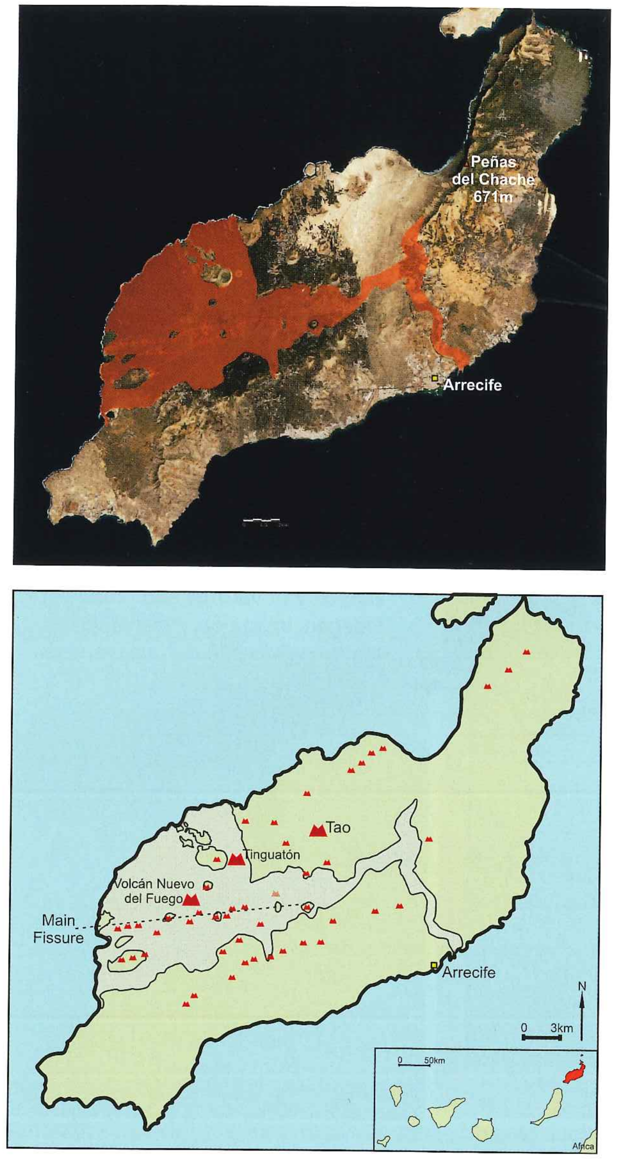


Figure 4.20 Location map, features and outline of recent activity on Lanzarote (Satellite Image – USGS).

Figure 4.21 Vines protected by semi-circular dry stone walls in the La Geria region of Lanzarote (photo by Yummifruitbat – Wikimedia Commons).

a depth of at least 2700m on the floor of the Atlantic Ocean. The first eruptions above sea level in Lanzarote have been dated to about 15.5 million years ago, but three quarters of the surface area of the island erupted from more or less parallel fissures probably less than 500,000 years ago – including one quarter that erupted between 1730 and 1736. Almost all of the lavas found on Lanzarote are basalts of one description or another.

The oldest basalts form the Famara and Los Ajaches plateaux, which are similar in age, origin and nature, and are covered in caliche. Their olivine basalts are at least 670m thick and they came from fissures that first produced thin fluid flows, then cinder cones, and then yet more thin flows. The emissions took place between 15.5 million and 5 million years ago, but were often separated by long intervals when thick fossil soils developed. The plateaux were then tilted about 15° down to the east, so that fault scarps or marine cliffs formed on their western edges. The cliffs reach a height of 500m on the west coast of Famara, but have been widely masked by later eruptions on the west of Los Ajaches.

After over 3 million years of rest, basaltic emissions resumed 1–2 million years ago. Some 25 vents, aligned on east-northeast to west-southwest fissures, formed aa lava flows and cones that now have eroded craters and flanks.

Less than about 10,000 years ago, more basaltic eruptions took place on two main fissures, one following the north coast and the other along the south coast. In all, more than a hundred vents can be identified and their lava flows are the most extensive in Lanzarote at present. These eruptions began with an explosive phase, forming cinder cones and ash layers, but later gave off abundant lava flows, which have now weathered enough to be extensively cultivated. The northern fissures include the Sóo volcanoes, near the north coast, which show a sequence of Surtseyan eruptions from aligned vents that were so close together that each cone was partly destroyed when its successor erupted. At the same time, several fissures inland produced, for example, the Pico del Cuchillo and the Caldera Blanca. The latter is not a true caldera but one of the largest cones on the island, rising 175m, whose vast lava-breached crater is 150m deep and 1200m across. Although it erupted inland, it has the typical dimensions of a Surtseyan cone and owes its name to the pale caliche covering its surface. The beautiful shallow ribbing on its outer flanks displays the typical dissection of the cones of this period (see Fig. 4.22)

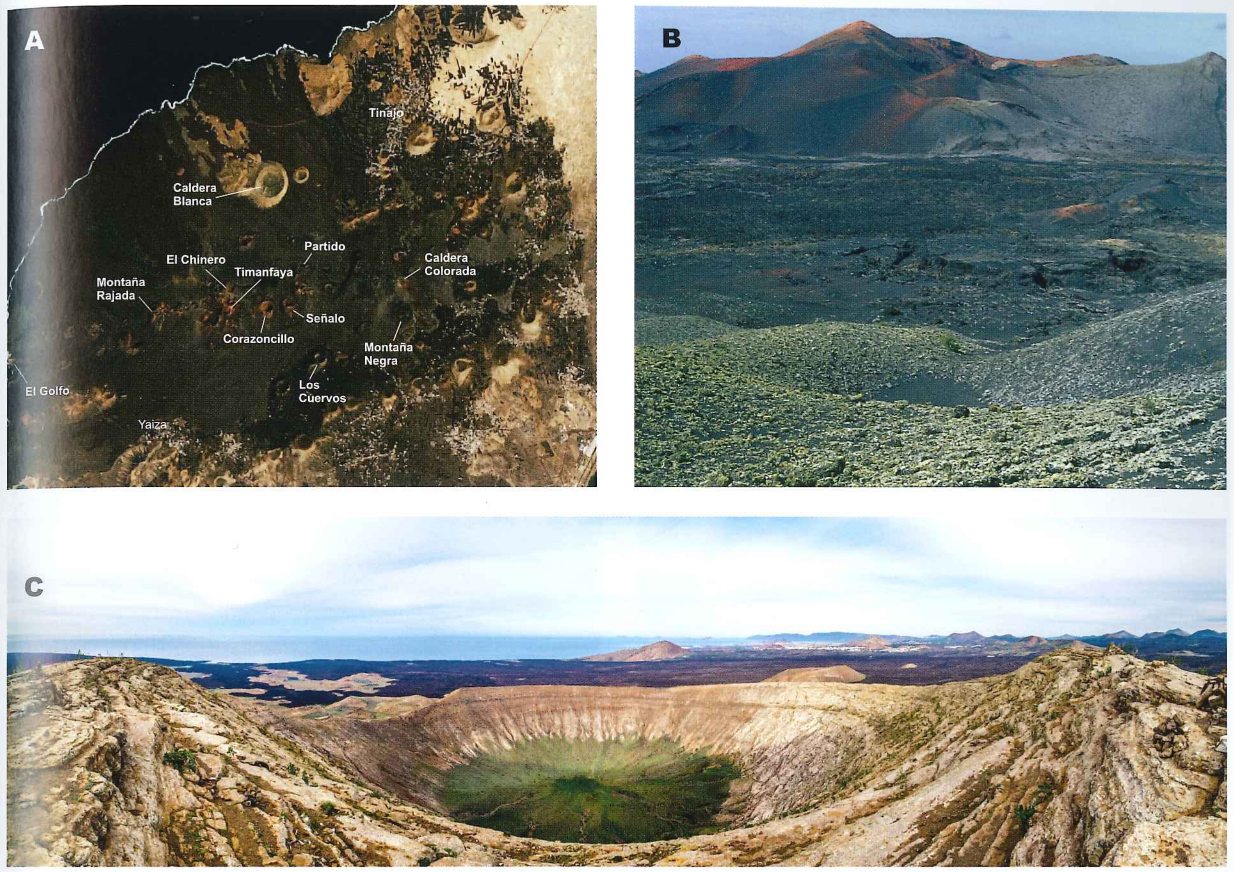


Figure 4.22 The young volcanic area of central Lanzarote. **A**) Satellite view with some of the volcanic cones and features labelled. **B**) Timanfaya volcano is the largest of a number of volcanic cones to be found in the National Park of the same name (photo courtesy of Francis Abbott). **C**) Panoramic view of Caldera Blanca (Shutterstock/FlorianKunde).

The southern bunch of closely parallel fissures produced essentially similar forms. Its cones include Tahiche, Zonzomas and the Montaña Blanca, and two notable cones in the southwest: the Montaña Roja (red) and the Atalaya de Femés ('lookout'). Both erupted on the same fissure. Montaña Roja is the older of the pair and it dominates the Rubicón plain in the far west of Lanzarote. As its name indicates, it forms a reddish cinder cone, 130m high, which is thickly mantled with caliche and many thin, reddish basaltic flows covering about 7km^2 on the western Rubicón plain. At 608m, the Atalaya de Femés lives up to its name as one of the highest points in Lanzarote, and it forms a cone 100m high. It grew up in three stages: the smaller northern crater probably formed before the larger southern crater, and a minor cone then erupted on the rim between them. Its blocky lava flow reaches the sea and covers about 20km^2 of the eastern Rubicón plain. This flow is quite young because it covers a recent beach now raised about 5m above the present shore.

At about the same time, the seaward ends of these fissures gave rise to notable Surtseyan cones. At El Golfo, in the far west, the sea has gouged out the deep crater to form the gulf that gave the volcano its name, and exposed innumerable multi-coloured layers of tuffs in the cliffs enclosing the green lagoon (Fig. 4.23). Originally, El

Figure 4.23 The crater and green lagoon of El Golfo, Lanzarote (photo by Gernot Keller– Wikimedia commons).

Golfo may have resembled the five large cones composing the islet of Graciosa that lie at the opposite end of this northern group of fissures. Each cone is almost 1km across, with a typical deep Surtseyan crater that has been protected from marine erosion because the eruptions took place some 5m or so above sea level.

The latest eruptions before the settlement occurred after the latest raised beaches had formed. They include the six cones aligned on a single fissure that crosses the Famara Plateau from northeast to southwest. They probably date from just before the Spanish settlement, because their forms are remarkably fresh, just as *quemado* (burnt) describes their appearance. Their cones include Quemado de Orzola, the Montaña de los Helechos, La Quemada, and especially the Montaña Corona. These vents have erupted a *malpaís* of olivine basalts that extends mainly eastwards to the coast and covers about 50km². The main contributor was the Montaña Corona, which was probably the youngest cone in the series, 609m high and with a crater 418m deep, which was breached on the downslope side by a lava flow that built a broad bulge out into the ocean. This flow contains some well-developed lava tunnels, here called *jameos* (The word used to refer to the large openings in the tube due to collapse). One of these exceeds 6km in length, is 35m high in places and wide enough to have been converted into a concert venue and nightclub. It is also host to the Cueva de los Verdes, a spectacular section of the lava tube system and one of the island's great volcanological tourist attractions (see Fig. 4.24).

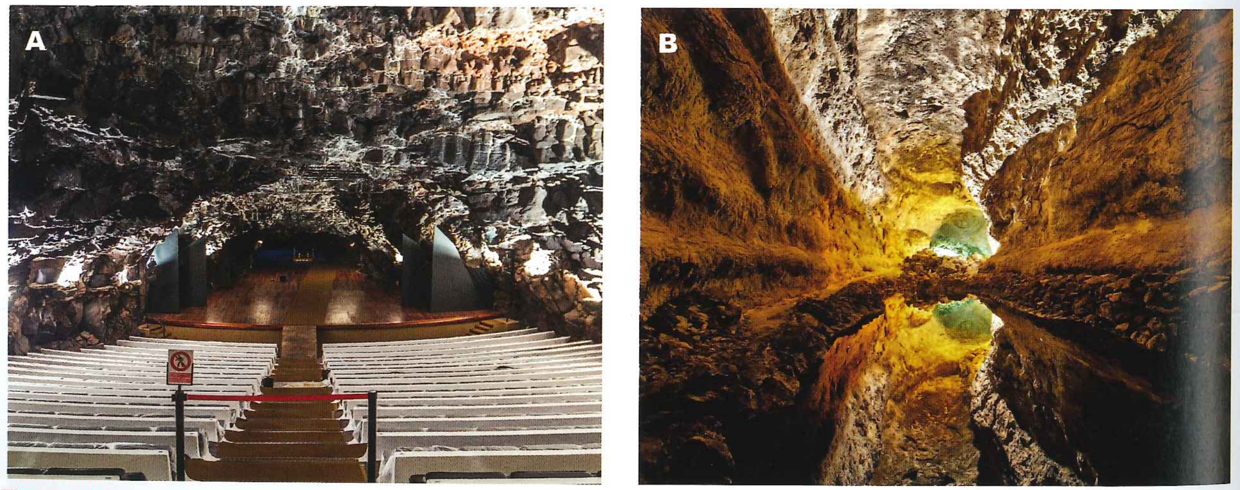


Figure 4.24 Cueva de los Verdes. **A**) Concert theatre and night club venue in the lava tunnel (Shutterstock/Jorg Hackemann). **B**) Stunning reflection along section of the lava tube in the Cueva de los Verdes (photo by Luc Viatour – Wikimedia Commons – see also www.Lucnix.be)

The eruptions in 1730–36

The historical eruptions of Lanzarote took place from 1730 to 1736, after at least three centuries of calm. Between 1 September 1730 and 16 April 1736, the island was the scene of one of the longest eruptions in Europe during historical times. One quarter of Lanzarote was given an entirely new landscape of cones and lava flows, and farms and villages in the west and centre were buried completely. Access to part of this area is restricted to protect the landscape as an educational and ecological volcanic reserve in the Timanfaya National Park. But the volcanic forms are equally fine in the rest of the area, where access to this spectacular tourist attraction is free.

During the five and a half years, the focus of activity switched from place to place, and eruptions may not, in fact, have been incessant. However, the magma probably came from the same deep source, and the olivine basalts with a tholeiitic tendency erupted from fissures forming a belt, about 18km long and some 4km broad, running east-northeast to west-southwest. The eruptions produced an extensive *malpaís* decorated with a variety of cones, often with evocative names, such as Calderas Quemadas (burnt), Montaña Rajada (split), Pico Partido (cloven). The cloven profile of Pico Partido, for example, makes it the most distinctive volcano on the island, and its jagged black outline, rising 230m above the *malpaís*, dominates the skyline of central Lanzarote. It is made all the more distinctive by a lava flow, outlined by pale-green lichen, which has spilt like paint down its black lapilli-strewn northern flanks. Pico Partido was, in fact, formed from a cluster of vents (see Fig. 4.25) – Mt. Colorada ((red)-coloured), Mt. Roja del Fuego (fire-red), Caldera Fuencaliente (hot spring) and Volcán Negro (black). They make the starkest and most brutal landscape in the Canary Islands, where scarcely a bush has yet taken root after more than two centuries.

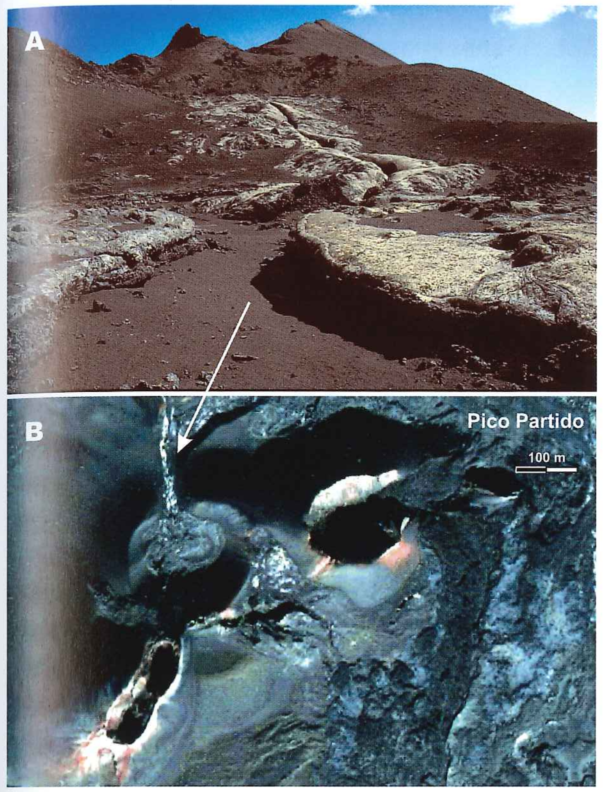


Figure 4.25 Pico Partido. **A**) Its craters form a distinctive cloven summit. An incompletely covered lava tunnel exists from the now solidified lava lake just below the summit. **B**) Pico Partido was formed from a cluster of vents that can be seen from an aerial view (image – NASA World Wind).

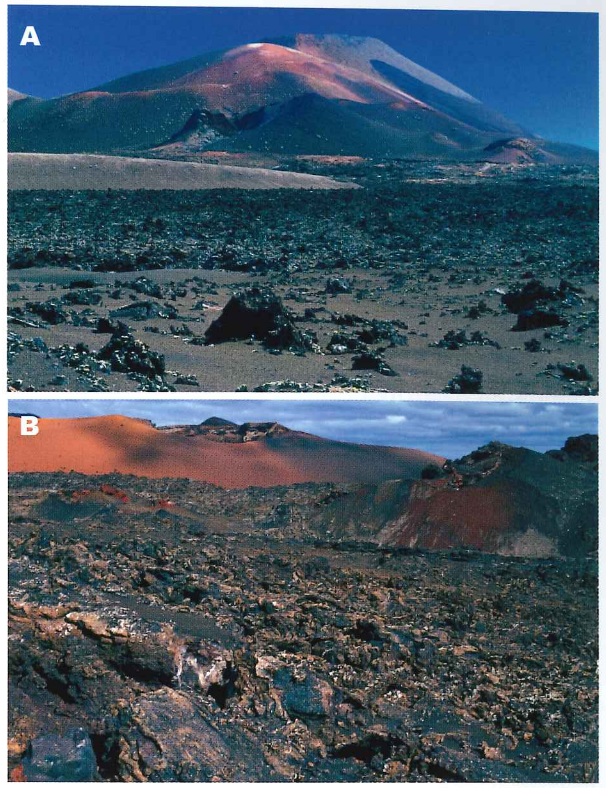


Figure 4.26 Volcanoes and vents from the eruptions in 1730–36. **A**) Montaña del Señalo, Lanzarote, Canary islands. **B**) Caldera del Corazoncillo, Lanzarote, Canary islands. The Caldera del Corazoncillo is located close to the Timanfaya volcano and is one of a number of cones to have been formed during the 1730 to 1736 eruptions (photos courtesy of Francis Abbott).

During the first 16 months of the eruption, Father Andrés-Lorenzo Curbelo, parish priest of the village of Yaiza, kept a diary of events. The original is lost, but the German scientist Leopold von Buch published a summary, albeit spiced with his own interpretations of events. Other accounts have emerged recently in the Spanish National Archives at Simancas, which describe some of the first efforts ever made to manage a volcanic crisis.

It is uncertain whether any earthquakes preceded the eruption on 1 September 1730. It began modestly with the formation of the Los Cuervos cone over the next 18 days. Calm then returned until 10 October, when the Santa Catalina and Pico Partido cones and flows began to erupt on top of the villages of Santa Catalina and Mazo respectively. The eruption could now be seen from Gran Canaria. An ad hoc committee was set up in Lanzarote to deal with the crisis, but it could do little to alleviate the ensuing distress. Santa Catalina and Pico Partido stopped erupting on 30 October, but Pico Partido resumed with even greater violence on 10 November, and probably continued for the rest of the winter. By 20 March 1731, a new series of vents had begun more than three months of eruptions that built the Montañas del Señalo (Fig. 4.26A). In June, the focus of activity suddenly switched to the sea off the west coast, where Surtseyan eruptions occurred for a time before the fissures extended onto the land nearby. For the rest of the year, successive vents exploded the cones of El Quemado, in June, Montaña Rajada, in July, and the four Montañas Quemadas from October 1731 to January 1732.

The construction of Timanfaya, a little to the east, seems to have occupied most of 1732 and probably the following year, for this is one of the largest in the area. Eruptions may have been less vigorous in 1734 and 1735, but in 1736 they found a new site in the east, in March, when the Las Nueces cone was formed; and they reached their last abode in early April when the Colorada cone erupted. The whole episode finished on 16 April 1736.

These eruptions gave rise to some impressive and varied landforms. Timanfaya is a complex accumulation of reddish-brown lapilli and cinders forming a sharp crescent-shaped ridge, 190m high, surrounding a crater about 80m deep. The chief lava emissions came from small vents on its western flanks and made a major contribution to an extensive *malpaís*, decorated with a sinuous lava tunnel that has partly collapsed. East of Timanfaya, Corazoncillo is one of the most striking cones, attracting attention as much by its colour as by its form (Fig. 4.26B). The squat cone, 65m high, forms a circular rim 500m across, enclosing a deep funnel-shaped crater. Its steep and perfectly smooth slopes are clothed entirely in small pink tuffs. Corazoncillo is reminiscent of features formed from a Surtseyan eruption, although it is some distance from any visible water bodies. In direct contrast, there is no evidence of the slightest influence of water about 500m to the west, where the same fissure erupted three spatter cones, several hornitos, and – most notably of all – the copious basaltic flows that threatened Yaiza. These could have been the eruptions on 28 December 1731 that caused most of the people of Yaiza to abandon their homes. However, a few people must have stayed behind, because the whole township registered 93 births and 71 deaths between 1732 and 1736. Numbers reached their lowest in 1733, when only 9 births and 6 deaths were recorded, but there was a return to normal by 1737. It may be inferred from these statistics that the volcanic activity waned after 1733, which could, therefore, have encouraged the refugees to return home. In fact, Yaiza was spared and remained on the edge of the new *malpaís*.

When the eruptions ended, 11 villages had been overwhelmed and 400 houses destroyed. The fields made fertile by careful husbandry had been blanketed with rough lava, livestock had been killed, and over 30 cones formed a threatening assembly 18km long. But although many people had to abandon their goods and their homes, not a single human life had been lost.

Although lavas undoubtedly entered the sea, and some eruptions occurred within it, most of the vents were on land. Thus, probably only a small proportion of the 200km^2 that was resurfaced by the eruptions represented additions to the area of the island. The area of Timanfaya now forms the impressive national park between the municipalities of Tinajo and Yaiza (Fig. 4.27).

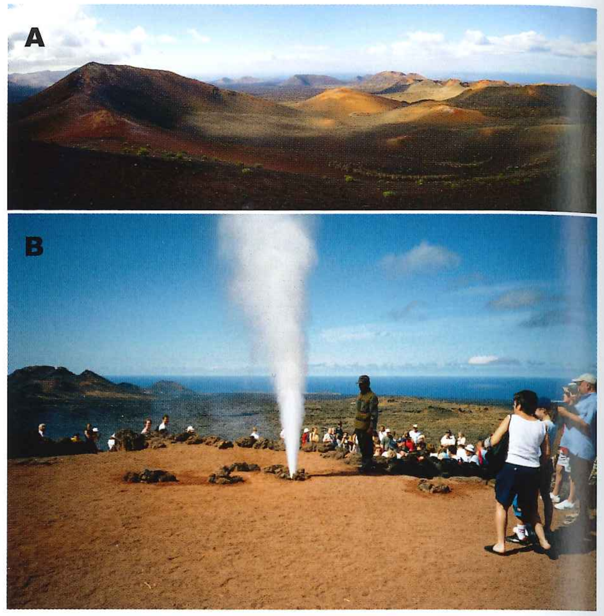


Figure 4.27 Timanfaya National Park. **A)** View of the park with its barren volcanic landscape (photo by Gernot Keller –Creative Commons, Wikimedia). **B)** Man-induced geyser eruption for tourists at the Islote de Hilario in the national park (photo by Andreas Tusche – Creative Commons, Wikimedia).

The eruptions of 1824

The calm that returned to Lanzarote in April 1736 has been broken only by three eruptions of olivine basalt from the same fissure in 1824. These eruptions were brief, mild and covered only 3 km^2. They were described by Father Baltasar Perdomo, the parish priest of San Bartolomé. Although earthquakes had been felt in Lanzarote as early as 1822, stronger shocks occurred in the centre of the island during July 1824. Earthquakes were so strong in the early hours of both 29 and 30 July that people fled from their homes. Near Tao, the ground vibrated and rumbled 'as if it was boiling' and fumes escaped from newly formed cracks. The eruption started from a fissure near Tao at 07.00 on 31 July 1824, on land belonging to the priest, Luis Duarte. Hence the cone is often known as the Volcán del Clerigo Duarte, although its more official name is the Volcán de Tao. It spent most of its life giving off nothing but fumes. The actual basaltic eruption proved to be one of the shortest

The early months of the eruption seen from Yaiza

'On the first of September 1730 between nine and ten in the evening, the earth suddenly opened up near the village of Timanfaya, two leagues [in fact, 8km] from Yaiza. During the first night an enormous mountain [Los Cuervos] rose up from the bosom of the Earth and it gave out flames from its summit for 19 days. A few days later, a fissure opened up … and a lava flow quickly reached the villages of Timanfaya, Rodeo and part of Mancha Blanca. This first eruption took place east of the Montaña del Fuego, half way between that mountain and Sobaco. The lava flowed northwards over the villages, at first as fast as running water, then it slowed down until it was flowing no faster than honey. A large rock arose from the bosom of the Earth on 7 September with a noise like thunder, and it diverted the lava flow from the north towards the northwest. In a trice, the great volume of lava destroyed the villages of Maretas and Santa Catalina lying in the valley. On 11 September, the eruption started again with renewed violence. The lavas began to flow again, setting Mazo on fire and then overwhelmed it before continuing on its way to the sea. There, large quantities of dead fish soon floated to the surface of the sea or came to die on the shore. The lavas kept flowing for six days altogether, forming huge cataracts and making a terrifying din. Then everything calmed down for a while, as if the eruption had stopped altogether. But on 18 [in fact, 10] October, three new openings formed just above Santa Catalina, which was still burning, and gave off great quantities of sand and cinders that spread all around, as well as thick masses of smoke that belched forth from these orifices [Santa Catalina and Pico Partido] and covered the whole island. More than once, the people of Yaiza and neighbouring villages were obliged to flee for a while from the ash and cinders and the drops of water that rained down, and the thunder and explosions that the eruptions provoked, as well as the darkness produced by the volumes of ash and smoke that enveloped the island. On 28 October, the livestock all over the area nearby suddenly dropped dead, suffocated by an emission of noxious volcanic gases that had condensed and rained down in fine droplets over the whole district. Calm returned on 30 October.

Ash and smoke started to be seen again on 1 November 1730 and they erupted continually until 10 November, when a new lava flow appeared, but it covered only those areas that had already been buried by previous flows. On 27 November, another lava flow [from Pico Partido] rushed down to the coast at an incredible speed. It formed a small islet that was soon surrounded by masses of dead fish. On 16 December, the lavas changed direction and reached Chupadero, which was soon transformed into what was no more than an enormous fire. These lavas then ravaged the fertile croplands of the Vega de Ugo [1 km east of Yaiza]. On 17 January 1731, new eruptions [from Pico Partido] completely altered the features formed before. Incandescent flows and thick smoke were often traversed by bright blue or red flashes of lightning, followed by thunder as if it were a storm. On 10 January 1731, we saw an immense mountain rise up, which then foundered with a fearsome racket into its own crater the self-same day, covering the island in ash and stones. Burning lava flows descended like streams across the malpaís as far as the sea. This eruption ended on 27 January. On 3 February, a new cone grew up [Montaña Rodeo] and burned the village of Rodeo. The lavas from this cone … reached the sea. On 7 March, still further cones were formed, and their lavas completely destroyed the village of Tíngafa. New cones with craters arose on 20 March [Montañas del Señalo] and continued to erupt until 31 March. On 6 April, they started up again with even greater violence and ejected a glowing current that extended obliquely across a previously formed lava field near Yaiza. On 13 April, two [of the Montañas del Señalo] collapsed with a terrible noise. On 1 May, the eruption seemed to have ceased, but on 2 May a quarter of a league further away, a new hill arose and a lava flow threatened Yaiza. This activity ended on 6 May and, for the rest of the month, this immense eruption seemed to have stopped completely. But, on 4 June, three openings occurred at the same time, accompanied by violent earthquakes and flames that poured forth with a terrifying noise, and once again plunged the inhabitants of the island into great consternation. The orifices soon joined up into a single cone of great height, from which exited a lava flow that rushed down as far as the sea. On 18 June, a new cone was built up between those that already masked the ruins of the villages of Mazo, Santa Catalina and Timanfaya. A crater opened up on the flanks of this new cone, which started to flash and expel ash. The cone that had formed over the village of Mazo then gave off a white gas, the like of which nobody had ever seen before. More lava flows also reached the sea. Then, about the end of June 1731, the whole west coast was covered by enormous quantities of dead fish of all kinds, including some that had never been seen before. These eruptions took place under the sea. A great mass of smoke and flames, which could be seen from Yaiza, burst out with violent detonations from many places in the sea off the whole west coast. In October and December, further eruptions [of the Montañas Quemadas] renewed the anguish of the people. On Christmas Day 1731 the whole island was affected by the most violent of all the earthquakes felt during the previous two [sic] years of disasters. On 28 December, a new cone [in the Montañas Quemadas] was formed and a lava flow was expelled from it southwards towards Jaretas. That village was burned and the Chapel of San Juan Bautista near Yaiza was destroyed.'

Many of the panic-stricken villagers of Yaiza then decided to take refuge in Gran Canaria. (excerpt from Andrés-Lorenzo Curbelo, in von Buch 1825).

ever recorded in the Canary Islands, for it had only one day of glory. Ash, spatter and several lava flows issued from as many as 25 vents that formed three small cones, one reaching 38m high. Lines of craters developed on their summits, which followed the northeast–southwest trend of the fissure. But, from 04.00 on 1 August, activity was reduced to emissions of fumes, with rare explosions of ash.

At length, on 21 August, new cracks opened in the ground after an earthquake and precipitated the most notable event of the eruption at 07.00 on the following morning. Brackish water suddenly spurted from the ground and great columns of steam and fumes soared into the air, accompanied, from time to time, by fine ash. Such hydrothermal activity had never been seen before in the Canary Islands. The Alcalde Mayor had some of the water collected and sent to Santa Cruz de Tenerife, where analysis revealed that it contained various soda salts and sulphuric acid. This hydrothermal activity lasted until 25 August, when it stopped as suddenly as it had started. Thereafter, Clerigo Duarte's volcano returned to its fumarolic somnolence until the eruption ceased altogether on 29 September.

By then the next eruption was already under way and, in contrast, was almost entirely magmatic. It began on the western end of the fissure, 13km from its predecessor, and formed the Volcán Nuevo del Fuego. Lava in both fountains and flows immediately emerged from the fissure, but ash explosions soon followed. The sky glowed like the Aurora Borealis as the eruption entered its climax between 2 and 4 October. The ash and the sulphurous fumes made breathing difficult, even 20km away in Arrecife. The cone attained a height of 60m, with two craters breached on their northern sides by lava flows. The basalts arrived on the north coast, 6km away, at 09.00 on 3 October, after having travelled at a speed of about 65m an hour. But they did little damage because they flowed mainly across the *malpaís* that had formed in 1730–36. Activity came to an end with a bang. In the early hours of 5 October, there was a loud explosion and Volcán Nuevo del Fuego gave off nothing but fumes thereafter. The baton was soon taken up by the final eruption of 1824. It formed the Volcán de Tinguatón, about 4km along the fissure from its predecessor. It started at about 06.15 on the morning of 16 October with explosions, which created a terrifying din and seemed to light up the whole island. An hour later, three lava flows emerged. This mixed explosive and effusive activity lasted until noon on 17 October, when the flows were hardly more than 1km long, and the cone of cinders and spatter, elongated along the fissure, was scarcely 30m high. No further magmatic materials erupted.

However, then began perhaps the oddest episode of any eruption in the Canaries since the Spanish settlement. That afternoon, vigorous explosions sent black columns of gas, steam, and old volcanic fragments soaring skywards. Then, at 16.30, hot water suddenly gushed from the crater in powerful jets reaching 16m high. With them came billowing columns of steam, fumes and old ash – sometimes white, sometimes dark brown, and sometimes like cypress fronds. The eruption seemed to combine the hydrothermal and Surtseyan styles, although the source of the water is not clear in such an arid area, which is both 200m above and 8km from the sea. The water developed enough erosive power to break through the walls of the crater and then deposit a delta of fragments on the flows to the north. This extraordinary eruption ceased on Sunday 24 October 1824. Now the Volcán de Tinguatón stands like a squat ruined castle in the midst of the flows of central Lanzarote. Six deep and narrow pits on the floor of the crater mark the vents that disgorged the water: the Cuevas del Diablo or the Simas del Diablo.

The respite for Lanzarote can only be temporary. Molten magma, with a temperature probably between 900°C and 1100°C, still lies only about 4km below the surface. A maximum temperature of 600°C has been measured at a depth of only 13m, and over 100°C has been recorded beneath several craters and fissures. Steam emissions, and temperatures high enough to kindle straw bundles and even to cook food, continue at the Islote de Hilario in the national park, and an artificially-induced geyser is erupted for tourist parties (Fig. 4.27B).

Fuerteventura

Fuerteventura is the second largest of the Canary Islands, 100km long, less than 30km wide, and 1725km^2 in area (Fig. 4.28). It is separated from Lanzarote only by the La Bocaina channel, which is less than 40m deep. Lying less than 115km from Africa, Fuerteventura is arid, and its climate bears more of the stamp of the Sahara than of the northeast trade winds. Thus, many areas have developed a caliche that has given an unusual buff colour to the lavas, although many older volcanic formations have been laid bare in the *barrancos* cut by ephemeral streams. The relief of Fuerteventura falls naturally into three longitudinal zones. In the west, the rolling hills of the Betancuria massif form the area where the old basement complexes are best exposed. They are transected by one of the most remarkable dyke swarms in the world, which trends from north-northeast to south-southwest. Fissures running in the same direction erupted thin, but widespreading flows, often exceeding 700m in total thickness, which eventually buried most of their associated cinder cones. They now form an eroded tableland of horizontal basalts in the east, which rises to 807m at the Pico de la Zorza, the highest point of the island. The possibly downfaulted central depression between them is more than 25km long and between 5km and 10km broad.

Fuerteventura rises in a long hump from a depth of about 3000m on the Atlantic Ocean floor, where the oceanic crust is some 180 million years old. But the rocks of Fuerteventura are altogether much younger. The eroded remnants of three ancient volcanic edifices – the northern, central and southern volcanic complexes – erupted between 22.5 and 13.2 million years ago. They now form much of the plateaux, mesas and *cuchillos* of the east and southeast, and in the Jandía Peninsula in the south, and they have developed a thick and widespread caliche.

After a long period of calm, eruptions resumed about 2 million years ago and gave rise to basalts that were concentrated chiefly in the northern and central parts of Fuerteventura. As time went on, the emissions became

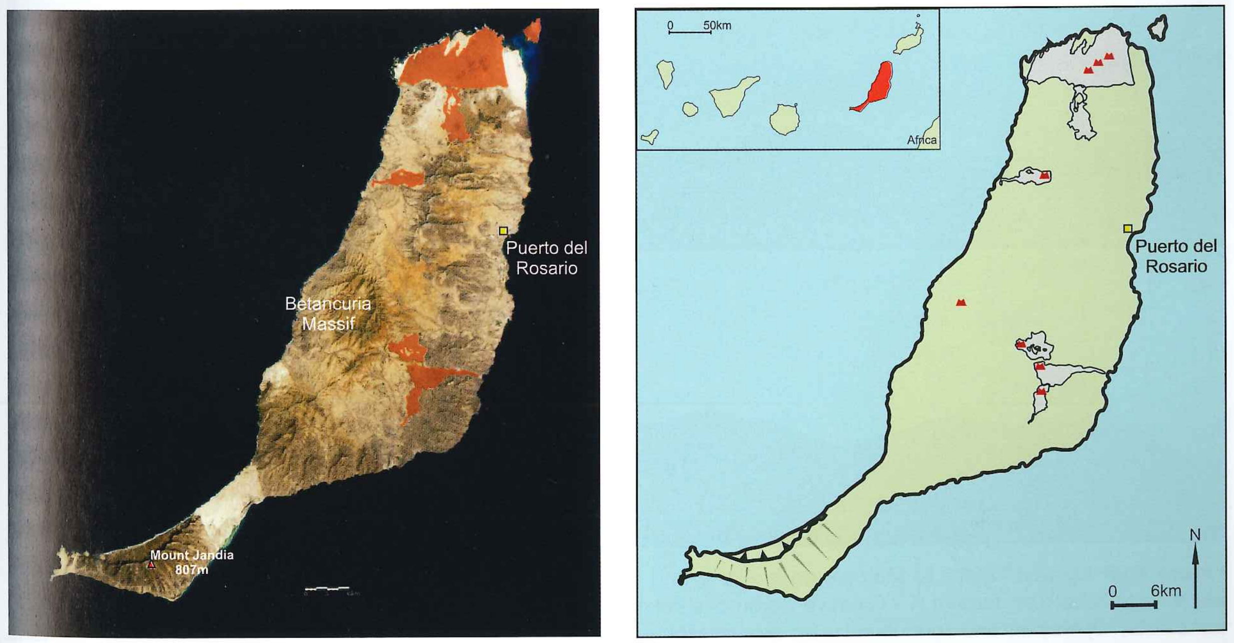


Figure 4.28 Location map, features and outline of recent activity on Fuerteventura (Satellite Image – USGS).

smaller and less frequent and less voluminous. Eruptions along fissures produced a wealth of cinder cones and lava flows, which have been dated chiefly according to the thickness of the caliche, the depth of gullying upon the cones, and in relation to raised beaches around the island. The lavas show some variations from alkali olivine basalts towards those approaching the nature of trachybasalts, although the newer basalts show tholeiitic rather than alkaline affinities.

The olivine basalts were the most extensive of these emissions. At first, they formed shield volcanoes, such as La Ventosilla, but more explosive fissure eruptions later formed large caliche-covered cinder cones and widespread aa flows, such as Piedra Sal, Temejereque, Montaña San Andreas and La Caldereta near Tetir. The more recent eruptions of olivine basalts have given rise to many cinder cones, spatter cones and rugged *malpaís* (Fig. 4.29), which are so well preserved that they cannot have long preceded the Spanish settlement of Fuerteventura in 1402. Devoid of caliche, vegetation or gullying, they have retained their original form and colours so that they stand out readily in the landscape. They form, for instance, the Pajara cones, the Malpaís de la Arena, the Malpaís Chico, in the centre, and the Malpaís Grande, in the south of the island. The Volcano Arena, which rises to 420m with its surrounding *malpaís*, provides an impressive example between the villages of La Oliva, Lajares and Villaverde (Fig. 4.29A).

But their greatest volcanic contribution to Fuerteventura occurred when the northern promontory of the island was formed. Here, fissures trending from east-northeast to west-southwest gave rise to a dozen cinder cones and thin fluid flows, which pushed seawards and reduced the width of the La Bocaina straits between Fuerteventura and Lanzarote. At this time, alternating eruptions of cinders and tuffs formed the Isla de Lobos in the straits themselves. The southwesternmost of the volcanoes is Montaña Colorada with the impressive Calderon Hondo (Fig. 4.29C, D). Eruptions along the same fissure gave rise to the cinder cones of Rebenoda, Encantada, Las Calderas and Bayuyo (see Fig. 4.29B), which dominate the landscape of the northern promontory. Contemporaneous emissions of voluminous lava flows breached each cone down to its base. In all, the most recent episode of volcanic activity on Fuerteventura probably added some 50km^2 to the island. Although no eruptions have been witnessed in Fuerteventura in historical times, activity may be expected to resume, most probably in the north, perhaps within the next few millennia.

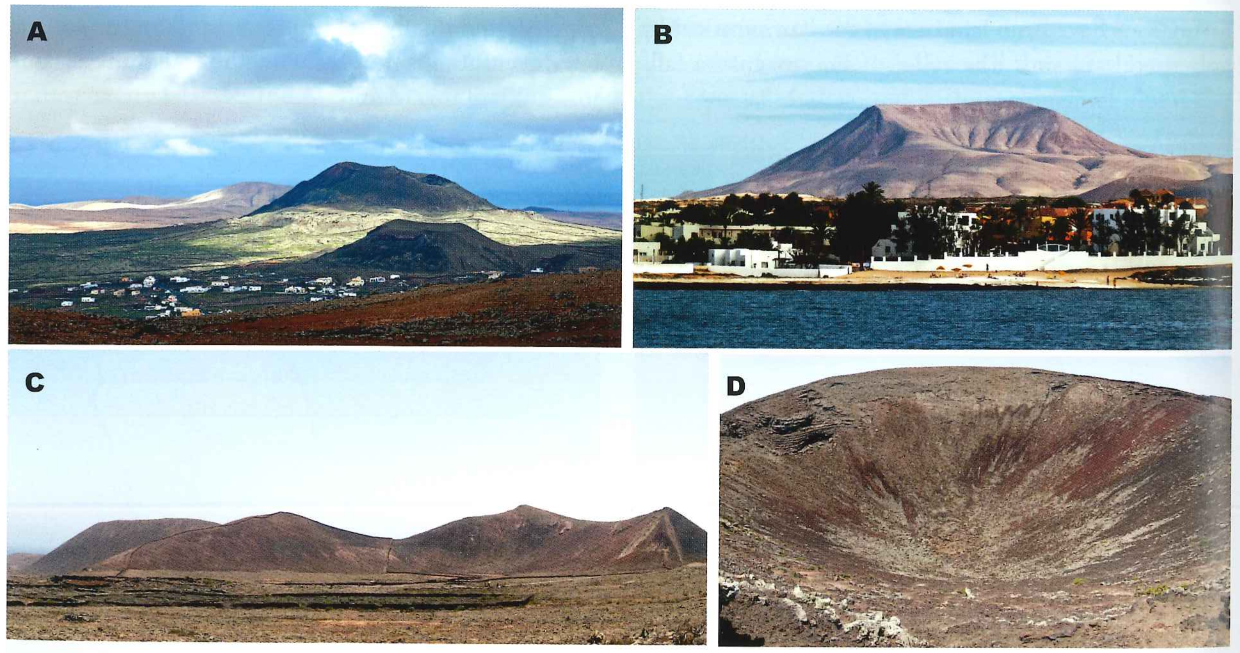


Figure 4.29 Location map. **A)** Malpaís de la Arena and Montana de la Arena (Volcano Arena), as seen from Montana Escanfraga (photo by Tamara K – Creative Commons Wikimedia). **B)** Corralejo with cone of Bayuyo (seen from the ferry to Lanzarote). **C)** *Malpaís* and agricultural walls around Montana Colorada near Lajares. **D)** Calderon Hondo volcano, Montana Colorada near Lajares (photos **B**, **C** & **D** by Norbert Nagel – Creative Commons, Wikimedia).

La Palma

La Palma is mountainous, rising to 2426m at the Roque de las Muchados and covering 728km^2. It rose above sea level during the past two million years from a base on the ocean floor about 3000m deep. La Palma is pear-shaped in outline, 47km long. It is broadest, at 28km across, in the north, where a high and complex shield has accumulated (Fig. 4.30). Occupying the heart of this shield is the most famous landform on the island, the Caldera de Taburiente, which is 7km wide, 15km long and nearly 2000m deep, and surrounded by the highest peaks in the island. In the south, it is joined to a shallower companion, the Cumbre Nueva caldera. La Palma has a volcanic sting in its tail: the modern eruptions have been concentrated on the series of parallel fissures stretching southwards along the Cumbre Vieja ridge.

In the north, the Taburiente stratovolcano grew up above a basal complex of altered basic and ultrabasic rocks about 2.0 million years ago. It is composed mainly of thick accumulations of basaltic flows interspersed with cinders and transected by innumerable basaltic dykes, whose upper layers have been dated to between 853,000 and 566,000 years old. A rift developed southwards from the Taburiente volcano and quickly grew into the steep, unstable Cumbre Nueva ridge, which may have reached a height of 2500m. About 180– 200km^3 of this area then collapsed about 560,000 years ago, and another volcano, Bejenado, erupted within the collapsed area during the following 60,000 years. There seems then to have been a quiescent period of some 370,000 years, during which the Caldera de Taburiente developed. A straight, fault-guided stream, the Barranco de las Angustias, formed on the southwestern flanks of the Taburiente volcano in a particularly favoured position between the faulted edge of the Cumbre Nueva collapse structure and the new Bejanedo volcano. Vigorous headward erosion thus cut the vast hollow of the Caldera de Taburiente deep into the heart of the volcano. Consequently, fluvial erosion continued what gravitational collapse had started.

From about 125,000 years ago, the eruptive emphasis on La Palma pushed further southwards and began to develop the present rift-fissure activity that

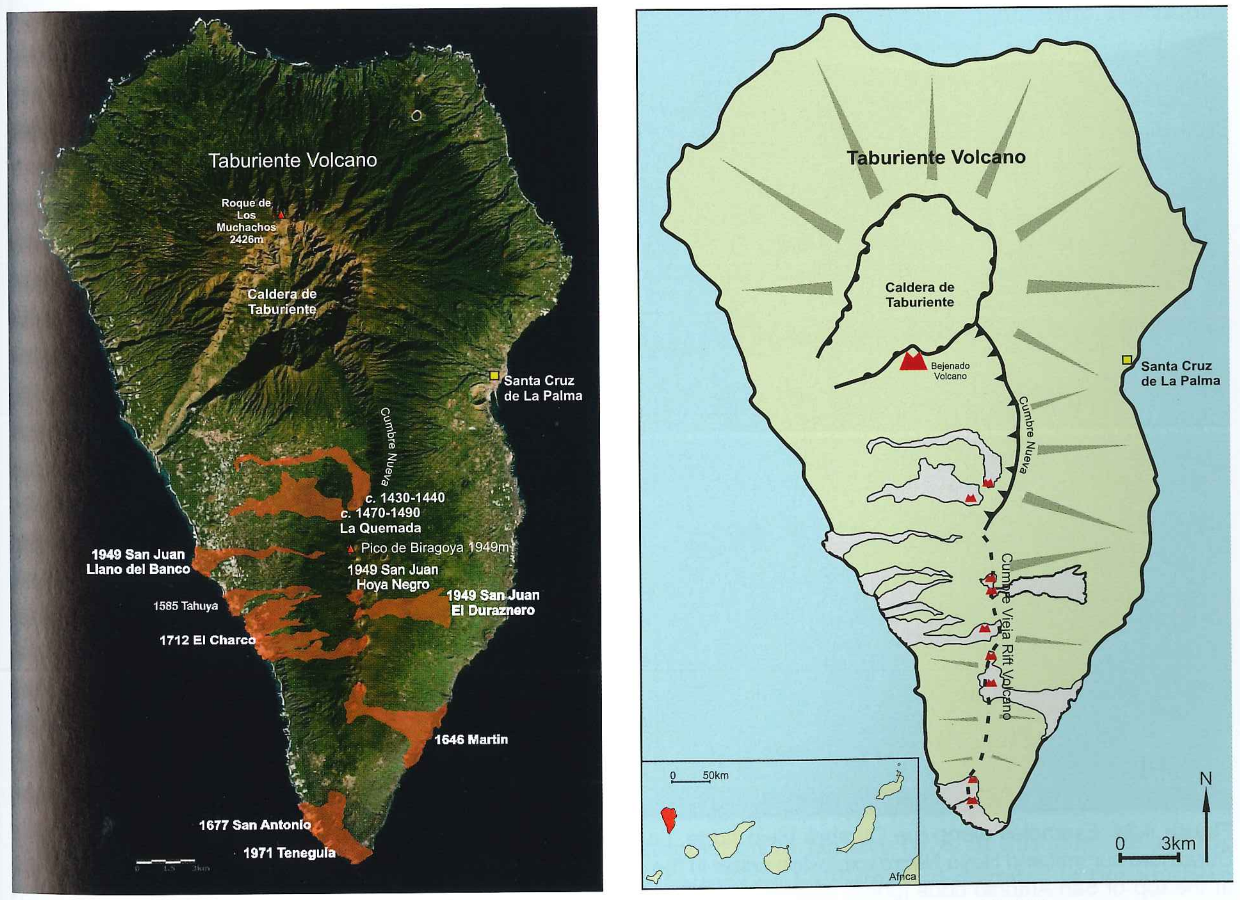


Figure 4.30 Location map, features and outline of recent activity on La Palma (Satellite Image – USGS).

Figure 4.31 Examples along the Cumbre Viejo ridge, La Palma. **A**) The crest of the Cumbre Viejo Volcano with the El Duraznero summit and Hoyo Negro explosion crater in the centre (photo courtesy of Juan Carlos Carracedo). **B**) Panorama at the top of San Antonio cone (photo courtesy of Helen Robinson). **C**) El Duraznero volcano. **D**) Detail within The Hoyo Negro (Black Hole) (photos **C** & **D** courtesy of Francis Abbott).

is still forming the Cumbre Vieja volcano. However, the eruptions were much reduced between 80,000 and 20,000 years ago, during which time marine erosion pared the flanks of the ridge and formed imposing cliffs around the island. Then, some 20,000 years ago, activity increased both on the north–south rift and also on a northeastward trending rift. For the next 13,000 years, this renewed activity lengthened and widened La Palma as lava flows cascaded down the old cliffs and formed lava deltas at their bases. But 7000 years ago, activity became almost exclusively concentrated on the north–south rift. These eruptions added the latest touches to the Cumbre Vieja. It was on this volcano, too, that all the historic eruptions of La Palma have occurred (Fig. 4.31 and maps in Fig. 4.30).

Historical eruptions on La Palma

All the historical eruptions on La Palma were explosions of ash and cinders and emissions of fluid, basaltic lavas. There was an eruption on the northern axis of the Cumbre Vieja ridge just before the island was settled in 1493, but its exact date, location, and even its name, have been subject to some discussion. It seems to have occurred either between 1430 and 1440 or about 1470–90. It probably formed the Montaña Quemada, a cinder cone rising 118m high, with a breach on its northern side from which issued a lava flow about 6km long.

An eye-witness, Father Alonso de Espinosa, and an Italian engineer, Leonardo Torriani, recounted the events of the next eruption in 1585. It was one of the most complex eruptions in the Canary Islands since the Spanish settlement. From late on Sunday 19 May, earthquakes of increasing vigour and frequency were felt, especially at Los Lanos, on the northern side of the Cumbre Vieja ridge. The ground began to swell up and became riddled with fissures. The magma duly reached the surface on the night of 26/27 May. Within the next two days, explosions produced masses of ash, cinders and high columns of fumes, quickly formed the Tahuya (or Teguso) cinder cone, and emitted a lava flow that eventually reached the west coast. There, said Father Espinosa, 'the lava extended half a league into the sea, warmed the waters, boiled the fish therein, and melted the tar of the boats.' The activity weakened considerably during the ensuing month. Then came the most extraordinary event of the eruption. The fissures began to exude huge masses of old phonolite from the substratum, which now form the Companions of Jedey, named from the hamlet nearby. At the same time, about 1km north of the main cone, more than half a dozen vents started exploding, which may have continued until 10 August 1585.

In the autumn of 1646, a much smaller eruption formed the Volcán Martín at Tigalate, on the southeastern flanks of the Cumbre Vieja ridge. On 30 September, earthquakes rumbled all over La Palma and the islands nearby. The eruption started on 1 October, and ash and cinders built a prominent cone during the next three days. The explosions could be heard in Tenerife, and, at night, the volcano 'glowed like a candle'. Renewed earthquakes on 4 October preceded the opening of new vents along a fissure that spurted out ash and lava flows for the next six weeks. On 15 November, yet another fissure opened close to the coast, and the flows reached the shore in a band 4km wide. One day, the people processed to the eruption with a miraculous image of the Virgin. The following dawn, the volcano was covered in snow. On 21 December 1646, a few days later, activity ceased.

Activity resumed in 1677 in the far south of the Cumbre Vieja, between the coastal spa of Fuente Santa and the town of Fuencaliente, 5km inland. It was long believed to have formed the large, often hydrovolcanic, San Antonio cone (Fig. 4.31B), which in fact is probably over 10,000 years old. The scope of the events in 1677 was much more limited: a small vent opened on the northern rim of San Antonio, and four rows of little vents erupted on its steep southwestern flanks. On 13 November, there was 'a pestilential odour of sulphur in the air' and earthquakes split open fissures 'that were difficult to jump across'. The magma burst from the fissures at sunset on 17 November. The vent on San Antonio volcano exploded ash that formed a small cone, 30m high, perched on its crest, but accompanying earthquakes shook most of it into the larger crater – and, no doubt, also destroyed the church tower in Fuencaliente. In December, the small cone gave off carbon dioxide, which sank into the valley near Fuencaliente and killed many head of cattle, rabbits and birds, and a peasant. In January 1678, 27 goats succumbed to the invisible gas. While the upper vent was exploding fragments, the lower vents were emitting spatter and fluid basaltic lavas. These flows buried the spa of Fuente Santa on 26 November 1677. Indeed, basalts had covered much of the southernmost toe of La Palma when the eruption stopped on 21 January 1678. At this date, the historic eruptions on La Palma had migrated to the southern end of the island in a little over two centuries.

The following eruption paid no heed to this trend, and broke out at El Charco in 1712. It was only 2.5km from the Volcán Martín, but it occurred this time on the north-western flanks of the Cumbre Vieja ridge. Earthquakes began to offer their usual warnings on 4 October, and ash explosions duly started on Sunday 9 October from a fissure 2.5km long. They soon built up a cinder cone that perched rather uneasily on the steep flanks of the ridge: its downslope side now rises 361m, but the upslope side reaches no more than 25m high. It is crowned by three craters, one of which is 135m deep. After the cone formed, activity concentrated on the lower parts of the fissure, where fluid lava gushed out and reached the coast in a broad apron about 5km wide, before the eruption stopped on 3 December 1712.

After this minor flurry of activity, which had seen four eruptions in 128 years, La Palma rested. Nearly 237 years later, the fissures sprang back to life on the Feast of St John the Baptist, 24 June 1949. This is why this episode of widespread activity is named after San Juan. The main focus of explosive operations lay near the crest of the Cumbre Vieja ridge, between the older volcanoes of Nambroque and El Duraznero. Notable underground rumblings and earthquakes started on 21 June. At 08.30 on 24 June, a hydrovolcanic explosion burst out north of El Duraznero. Soon ash was raining down all over southwestern La Palma, and similar pulsating emissions went on until 7 July. At 04.30 on 8 July, a more vigorous hydrovolcanic eruption heralded the opening of another fissure, about 3km away, across the Llano del Banco. At once it became the new focus of activity and brought with it a new eruptive style: emissions of fluid basalts. They cascaded down the coastal cliffs, reached the sea, 7km away, in a wide delta by 10 July, and continued to gush out until 26 July.

Meanwhile, the El Duraznero fissure (Fig. 4.31C) had two last flings. On 12 July, hydrovolcanic explosions began blasting out the Hoyo Negro (Fig. 4.31D), which, by the time they had finished on 30 July, had created a 'Black Hole' 192m deep, which was surrounded by a small tuff ring. At noon on 30 July, the El Duraznero fissure started spewing out fluid lavas. This phase lasted for eleven hours and eventually formed a flow 8km long. The San Juan eruption had an unusual epilogue for a Canarian eruption. The first autumn rains on 28 November 1949 produced several volcanic mudflows, or lahars, that destroyed several bridges and a stretch of the coastal road. Luckily, they hit only a thinly populated area, and no lives were lost. The San Juan eruption also produced unusually strong seismic activity, and the fissures developed during this eruption may mark the inception of another great landslide like those of the Caldera del Taburiente and the Cumbre Nueva caldera just to the north. The latest eruption in La Palma was in 1971 at Teneguía at the southern end of the Cumbre Viejo volcano (Fig. 4.32). In all, La Palma is presently one the most active of the Canary Islands, and its historical eruptions have covered a total area of 37km^2.

The eruption of Teneguía in 1971: the case of the migrating breach

The latest on-land eruption to be recorded in La Palma – and in all the Canary Islands – built the Teneguía cone and surrounding flows between 26 October and 18 November 1971 (Fig. 4.33). It occurred close to where the eruptions had taken place near the San Antonio cone almost 300 years before. Earthquakes warning of the impending eruption began on 15 October 1971. They made up in frequency what they lacked in power, for over a thousand were recorded between 21 and 24 October. Then two days of relative calm ensued. But at 15.00 on 26 October, a fissure opened and lava fountains spurted from many vents along it. Basaltic flows soon emerged and reached the sea near Fuencaliente lighthouse the following dawn. On 27 and 28 October, explosions formed two successive cinder cones. The second cone to form was, in fact, known as Teneguía I because it soon became the main focus of activity. During the next two days, a lava flow breached the cone on the sector facing up slope to the north. The flow could not easily defy gravity for long, and, in the early hours of 31 October, the position of the breach began to migrate clockwise. The slope of the land tended to shift the flow sideways towards the east, and thus undermined the eastern arm of the cone. At the same time, ash and cinders could then pile up over the original exit and thus extend the western arm round over the original northern breach. This migration went on until 3 November, when the flow had shifted the breach to the south-southeast, where the land sloped most steeply away from the cone and offered the easiest exit for the lavas. Thereafter, of course, the breach stayed in this optimum position.

Meanwhile, at 12.39 on 31 October, an explosion 200m north of the main cone formed Teneguía III. This remained active for only two days and formed a little pit circled by a tuff ring. It was to revive briefly once more, on 5 November. However, the effusions of the main cone continued at an increasing pace, when sustained lava fountaining continued for eight days. On 8 November an explosion blasted out another pit, called Teneguía IV, on the northern flanks of the main cone. Two days later, a similar explosion alongside it created yet another pit, Teneguía V, whereupon the activity of the main cone began to wane. On 18 November, lava started to issue from the pit of Teneguía V. Like the effusions from El Duraznero in 1949, these flows heralded the end. At midday on 18 November, the whole eruption came to a halt, and the cone has produced nothing but fumaroles ever since. The horseshoe cone was 89m high and the lava flows had reached the sea in four broad and rugged tongues that covered 4km^2.

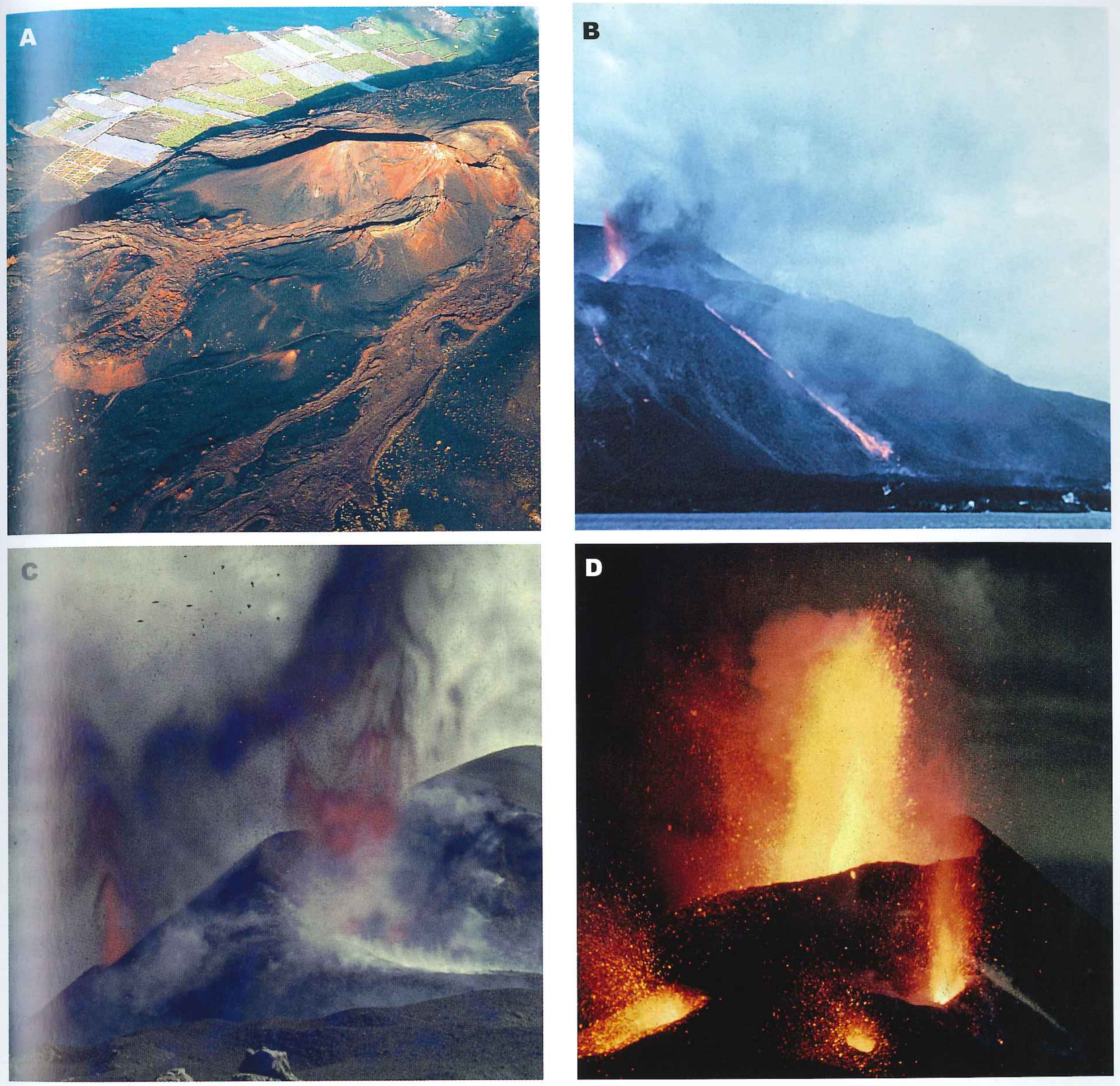
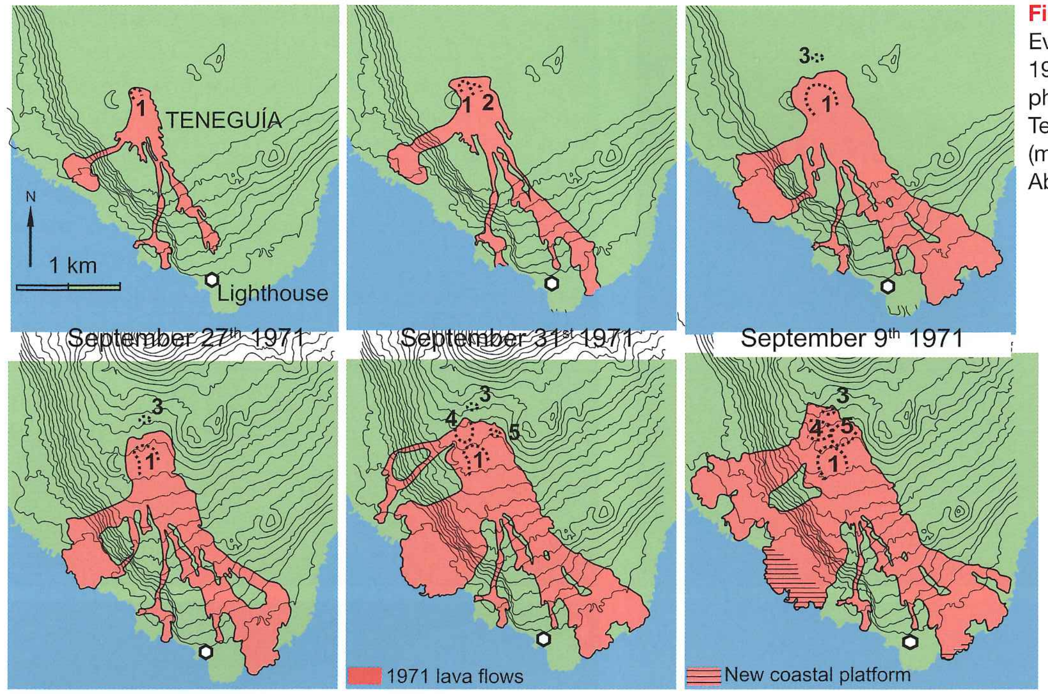


Figure 4.32 The Teneguía eruption of 1971. **A**) Teneguía from the air showing the eruption centres and flows. **B**) Lava entering the sea and extending the coastline. Inset stamp from special edition 'Sciences of the Earth and the Universe' stamp depicting the 1971 eruption of the Teneguía Volcano as well as a seismograph issued in 2006. **C** & **D**) Explosive eruptions at the Teneguía vents (photos courtesy of Juan Carlos Carracedo; stamp image sourced from UPU – Universal Postal Union).

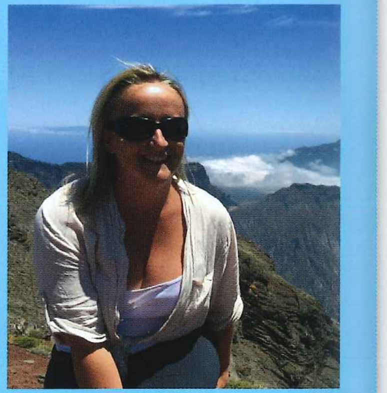


September 27th 1971 September 31st 1971 September 9th 1971

November 3rd 1971 November 16th 1971 November 19th 1971

Figure 4.33 Evolution of the 1971 eruption phases from Teneguía volcano (map courtesy of Abigail Barker).

Meet the Scientist –Helen Robinson



At the time of writing Helen is finishing her PhD at the University of Glasgow. She has undergone a number of monitoring and geothermal projects in the Canaries, Africa and is branching out further looking at the geothermal potential of volcanoes. She sheds some light on the work on La Palma and on how gas monitoring can help volcanoes help us.

How did you first start getting into research on volcanoes?
When I was young my parents loved all the 'natural world' type of documentaries; it was a Sunday evening ritual. I became mesmerized by the things I saw on the TV. Then when I was about seven years old I saw a documentary on Mount St. Helens and that was it! I was hooked. My mum would probably agree that I had a slightly morbid obsession with natural disasters from then on in.

I then did some coursework on renewable energy; I chose geothermal as my subject, and found it really fascinating. Everything I have done since has snowballed from there.

When did you first visit the Canaries and which islands have you seen?
I only first visited the Canary Islands for the first time last year (2015). Mt. Teide has been on my 'must climb' list for a few years!

You took part in a programme of gas measurements on La Palma: what was it about?
This was working in collaboration with the Instituto Volcanológico de Canarias (INVOLCAN) and GeoTenerife. Every year small teams from INVOLCAN head out to locations across the Canary Islands and Cape Verde to monitor the volcanic activity. This involved collecting soil gas samples, spring samples and *in situ* CO_2 efflux data. The soil gases are used to analyse annual changes in the quantitative volumes of CO_2 and helium in soils on the flanks of the volcanoes; some of the samples were also used to evaluate $^{13}C/^{12}C$ ratios.

The spring samples are used for ratio analysis of $^{3}He/^{4}He$ and the CO_2 efflux measures how much is escaping into the atmosphere. After water vapour, CO_2 is the most abundant gas dissolved in magma and the main species released along tectonic structures. As the gas ascends it is modified by a range of processes; we can use the efflux data to monitor how much arrives at the surface. We use the $^{13}C/^{12}C$ ratios to determine how much of this gas has a magmatic source and how much has a crustal source. The helium ratios are also used for a similar analysis. Changes in this annually collected data can assist in identifying changes in the volcanoes that may lead to an eruption. This, coupled with a range of other data collected, can help develop education programmes for locals, tourists and governments, as well as highlight the need for evacuations in extreme circumstances and protection of key infrastructures.

Which other volcanoes are you working on and why?
At the moment I am working on a few volcanoes. My main area of study is Menengai Volcano and summit caldera in the Gregory Rift, East African Rift Valley, Kenya. My work here is largely associated with the geothermal power generation in the country. It is estimated that only ~30% of Kenyans have access to the national grid. The country relies on hydro-schemes for their electricity generation, yet it is a country under great water stress. This often leads to an inability to meet base load demands, the result of which is energy rationing, high prices, and an unreliable power source.

The geothermal project at Menengai (one of many planned across Kenya) is believed to have the potential to provide Kenya with ~17% of its electricity needs. The area is already well developed for power generation, so I have been developing comparatively cheap surface exploration methods and comparing the results from these to the data already collected, allowing me to support the methods and conclusions from this work.

I have also started doing some hazard monitoring of the volcano, as it has the potential to be dangerous in the future. The data collected from the hazard monitoring will hopefully provide support for a more long-time monitoring programme.

I am also working on Fantale Volcano in the Main Ethiopian Rift Valley, Ethiopia and the Butajiri-Silti Volcanic Field, also in Ethiopia. These two localities have been identified for geothermal surface exploration. I will be using techniques tried and tested at Menengai.

I have also started phase 1 studies of the geology and potential for geothermal resources in the Comoros Islands and Mauritius in the southern Indian Ocean.

What do you think can link monitoring gases on volcanoes with energy?
For the development of rational engineering designs and cost-effective drilling programmes in geothermal projects, it is of vital importance to target the fault and fracture networks in the sub-surface that are actively used as fluid and gas conduits. Collecting data relating to soil gas volumes and compositions will enable those developing the project to identify, from surface data, where the sub-surface structures are that need to be targeted. The soil gas and efflux methods are low-cost and quick to complete, resulting in a more efficient surface exploration survey and reducing the cost of 'trial and error' drilling that is often used in East Africa.

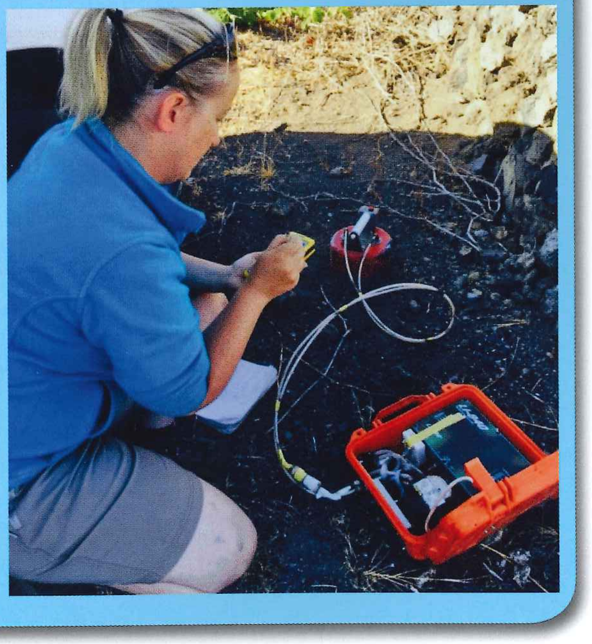


Figure 4.34 Helen Robinson soil gas sampling on La Palma.

Gran Canaria

Gran Canaria forms the emerged centre of an eroded shield, 45km across, which covers an area of 1532km^2. It rises from a depth of 3000m on the ocean floor to a height of 1949m above sea level at the Pozo de las Nieves (Fig. 4.35). This compact and symmetrical mass is deeply scarred by radiating *barrancos* and trimmed by marine cliffs where thick piles of lava are often exposed in sections approaching 100m high. Generally speaking, the older volcanic rocks are exposed in the southwestern part of the island, whereas the younger formations occur in the northeast, most notably in the peninsula of recent cones composing La Isleta north of the capital, Las Palmas.

The basal complex of Gran Canaria was masked when intense emissions occurred during a very short interval about 14.5–13.9 million years ago, at an average rate of about 5km^3 per thousand years. They formed a basal shield of long, thin flows, ranging from alkaline basalts to basaltic trachyandesites, that now constitutes more than 90 per cent of Gran Canaria.

There was a short burst of violent eruptions of trachytes, trachyphonolites and peralkaline rhyolites about 13.5 million years ago. They form lava flows, tuffs and ignimbrites and ash that were expelled when the hub of the old shield collapsed to form a caldera 15km across and 1000m deep. Similar eruptions continued much more feebly until about 10.5 million years ago. Gran Canaria then experienced a long period of volcanic calm and much erosion.

The third major eruptive phase took place between 5 million and 3 million years ago with the formation of the Roque Nublo stratovolcano, which covers much of the centre and northeast of the island. At first, basanites, tephrites and phonolites erupted in thin lava flows, but, as the volcano grew to about 3000m, widespread pyroclastic density currents and a few phonolitic domes erupted from vents concentrated around Tejeda in the centre of Gran Canaria. The stratovolcano then collapsed to form the Roque Nublo caldera, and an avalanche over 3km^3 in volume swept southwards for 28km down its flanks. Roque Nublo itself forms a prominent pinnacle 60m high, an attractive tourist site on the island (Fig. 4.36).

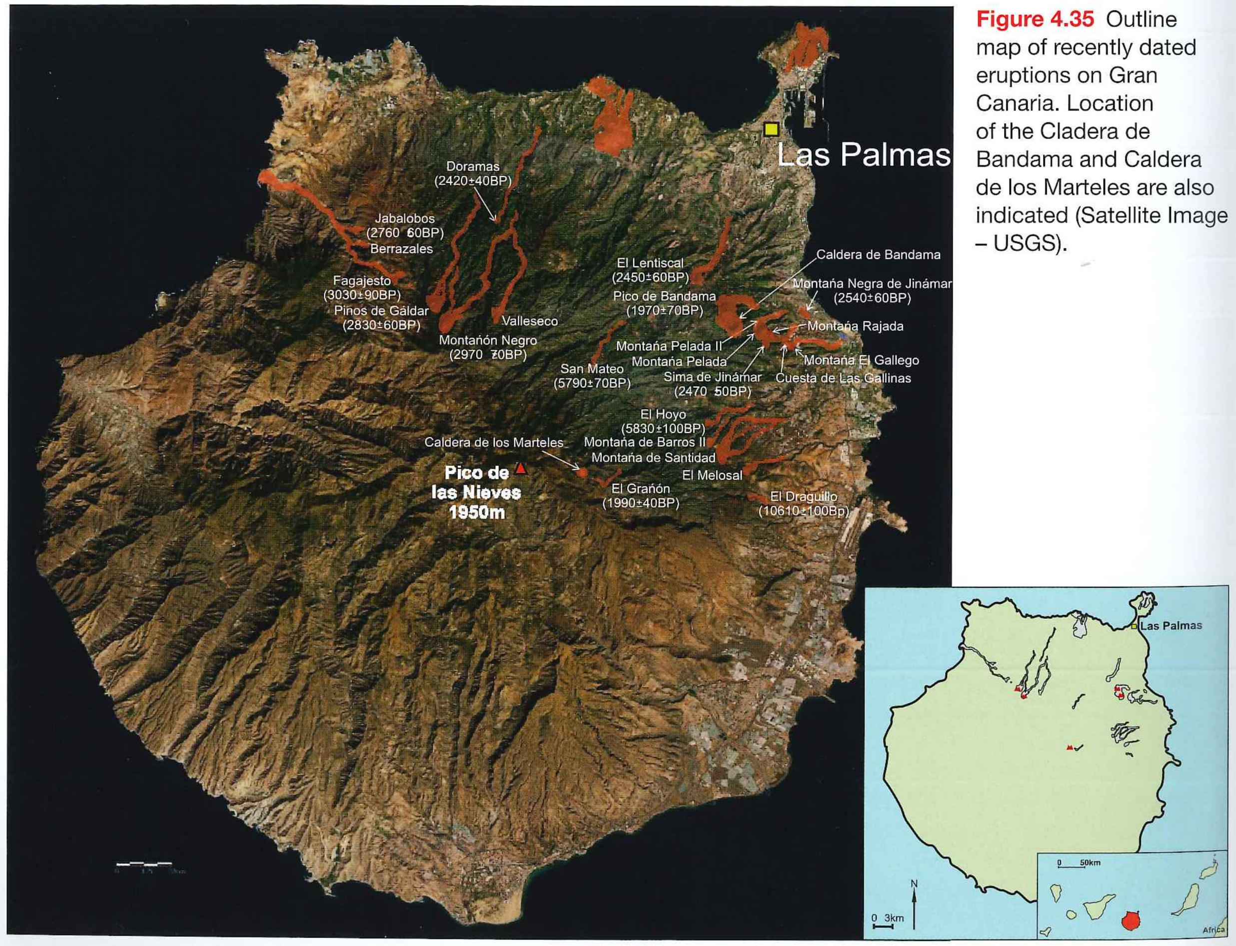


Figure 4.35 Outline map of recently dated eruptions on Gran Canaria. Location of the Cladera de Bandama and Caldera de los Marteles are also indicated (Satellite Image – USGS).

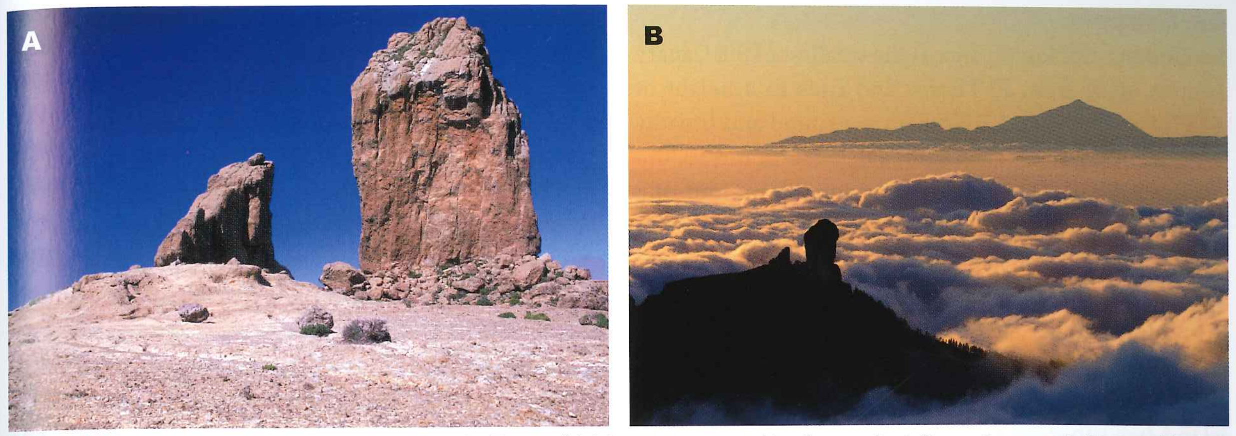


Figure 4.36 **A)** Roque Nublo, Gran Canaria. The Roque Nublo, once revered by the ancient Guanche population and today visited by thousands of tourists each year, is the emblematic symbol of Gran Canaria. **B)** Roque Nublo, Gran Canaria in the forground with Mt. Teide and the outline of Tenerife in the background (photos courtesy of Francis Abbott).

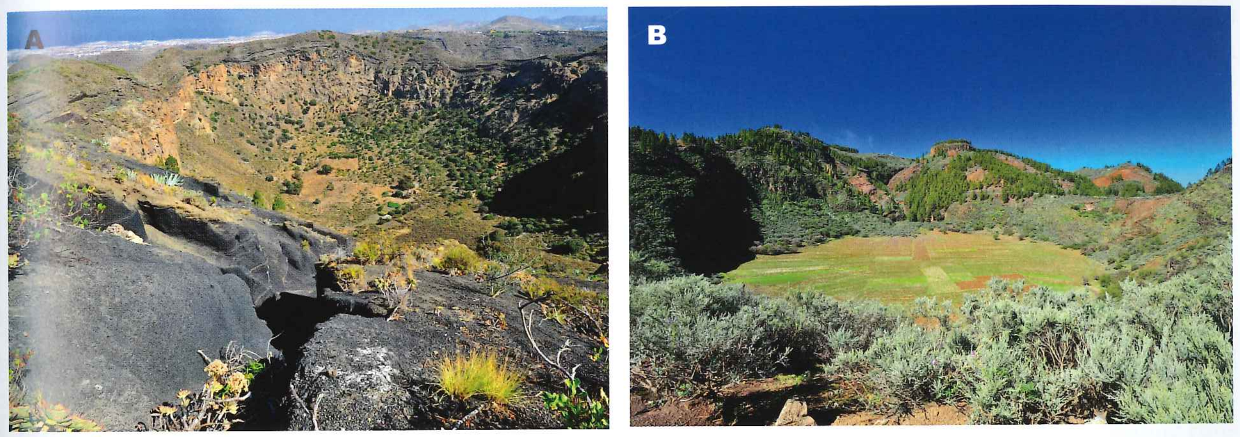


Figure 4.37 **A)** Caldera de Bandama, Gran Canaria. The Caldera de Bandama is one of a number of small calderas to be found on Gran Canaria. This caldera of 1km in diameter and 200 metres depth has been dated at 20**BC**. Originally a double cinder cone, the caldera was formed later. **B)** Caldera de los Marteles, Gran Canaria. Situated close to the summits of Gran Canaria (Pico de Las Nieves) and at the head of the Guayadeque canyon, the Marteles caldera was formed some 100,000 years ago by a phreatomagmatic explosion (photos courtesy of Francis Abbott).

The latest phase of activity on Gran Canaria was different. Eruptions occurred from vents, often aligned on fissures, which were overwhelmingly concentrated in the northeastern half of the island. The eruptions took place in brief spurts of activity from 2.85 million to 1.5 million years ago, and they generally became less voluminous and more scattered as time went on. They mark much the smallest major volcanic episode on the island, and produced fresh-looking cinder cones and lava flows. The older eruptions covered much the widest area and came from scattered vents. For example, cinder cones such as the Osorio volcano have lost their original sharp outlines, and erosion has exposed the columnar cores of their thick flows. Later eruptions, such as those forming the Pico Gáldar, were concentrated in the northeast of Gran Canaria, and the most recent have preserved most of their original freshness. Their basanitic cinder cones and rugged aa flows, for example, constitute much of the La Isleta peninsula near Las Palmas, the Montaña de Arucas and Las Montañetas. Hydrovolcanic eruptions also formed the well-preserved maars and tuff rings of the 'Calderas' of Bandama, Las Piños de Gáldar and Los Marteles (see Fig. 4.37). No eruptions have been recorded on Gran Canaria during historical times, but the fine state of preservation of many of its most recent features indicates that they cannot have erupted long before the Spanish Conquest of the island in 1483.

La Gomera

La Gomera, 380km^2 in area, is the smallest of the Canary Islands apart from El Hierro and rises to a height of 1487m at Garonjay. La Gomera is a round and broadly symmetrical island rising from a depth of some 3000m on the Atlantic Ocean floor. It forms the summit of a vast shield volcano that has been constructed in eruptive bursts separated by long periods of erosion over several million years. La Gomera has witnessed no historical eruptions, and perhaps none for 4 million years.

In proportion to its size, La Gomera has the largest exposed surface area of the basal complex, because the island has subsequently undergone marked uplift. As elsewhere, it is composed of peridotites, gabbros and dolerites, and it is riddled with many dykes that make up two-thirds of its total volume. The basal complex underwent a long period of erosion lasting over a million years before activity resumed with eruptions of lavas some 12.5 million years ago. These flows now cover much of the island, and were erupted in two main bursts: about 11 million years ago and between 8 million and 6 million years ago. After another long dormant episode, the fluid Younger Basalts covered 200km^2 between 4.6 million and 4.0 million years ago. During the subsequent dormant period, La Gomera has undergone considerable erosion, so that clearly displayed volcanic features are rare, with the notable exception of cliffs revealing fine basaltic colonnades.

Chapter 5

Portugal

Introduction

A mixture of green, fertile, and sometimes misty islands rising from the Atlantic Ocean floor, the Azores are an autonomous region of Portugal situated in the Atlantic Ocean 1500km west of Lisbon and about 880km northwest of Madeira. The archipelago of nine islands is scattered over 600km and falls into three groups: Flores and Corvo in the west, Santa Maria and São Miguel in the east, and a central cluster of five islands – Terceira, Graciosa, São Jorge, Pico and Faial (Fig. 5.1). Seven of the islands rise from the Azores Platform on the eastern flanks of the Mid-Atlantic Ridge. Only Flores and Corvo rise on its western flanks. All the islands are active except Santa Maria, which is the furthest from the Ridge. All except São Jorge have stratovolcanoes, and all except one have been decapitated by calderas. The Pico do Pico, soaring to 2351m above sea level, is the only stratovolcano that still retains the pristine glory that makes it the incomparable landmark of the Azores.

Although the Azores are almost entirely volcanic, they are far from stark and bare: laurels, hydrangeas and azaleas dominate a floral extravaganza that is rarely seen in temperate climates. The Azores were uninhabited when the Portuguese explorers were led to them by the goshawks, the Açores, which were flying about the islands. Settlement began first on Santa Maria and São Miguel in 1439 and then on Terceira in 1450, on Pico and Faial in 1466, on Graciosa and São Jorge in 1480, and on Flores and Corvo at the start of the next century. A map from 1584 higlights the extent to which the islands were known even at this early stage (Fig. 5.2). Historical records of eruptions therefore extend back to between 500 and 600 years, with over 30 eruptions that have taken place during this period, either on the islands or offshore. However, the Azores are not growing rapidly: Iceland has a much higher output of lava per visible eruption; eruptions occur four times more often in Iceland; and eruptions of similar composition have built the Canary Islands five to ten times faster. But, of course, Iceland is 40 times larger than the Azores islands, and many submarine eruptions must have passed unnoticed on the Azores Platform.

The Azores and their submarine plinth grew up on the Mid-Atlantic Ridge near the triple junction of the North American, Eurasian and African plates. Their activity is probably related to a weak hotspot, and perhaps also to a secondary band of seafloor spreading. The Mid-Atlantic Ridge, forming the boundary between the North American and Eurasian plates, passes through the Azores. The western islands of Flores and Corvo belong to the North American plate, but the location of the boundary between the Eurasian and African plates is not at all clear (see Fig. 5.1). The East Azores fracture zone runs from the Mid-Atlantic Ridge along the southern edge of the Azores Platform. Thus, if the fracture zone forms the main plate boundary, then the central and eastern Azores must belong to the Eurasian plate. However, an axis of secondary seafloor spreading runs through the central Azores along the Terceira Rift, which probably passes through Graciosa, Terceira and São Miguel. In either case, parts of the central and eastern Azores could therefore belong to the African plate or to an Azores microplate. The volcanic activity in the Azores was most probably also intensified by one large, or several small, hotspot plumes. Whatever the reasons behind the growth of the central and eastern Azores, all display a common and impressive predominance of stratovolcanoes, rifts, faults, fissures and volcanic alignments, running parallel to the spreading axis, that have been the elements in the development of their scenery.

The stratovolcanoes in the Azores are mostly gently sloping cones, usually more than 10km in diameter and rising about 1000m above sea level. They are crowned by beautiful deep calderas, which so impressed the early settlers that they also rather confusingly gave the name Caldeira (cauldron) to the whole mountain. These calderas are the hallmarks of the Azores.

The eruptions that have taken place along fissures running from northwest to southeast are the second