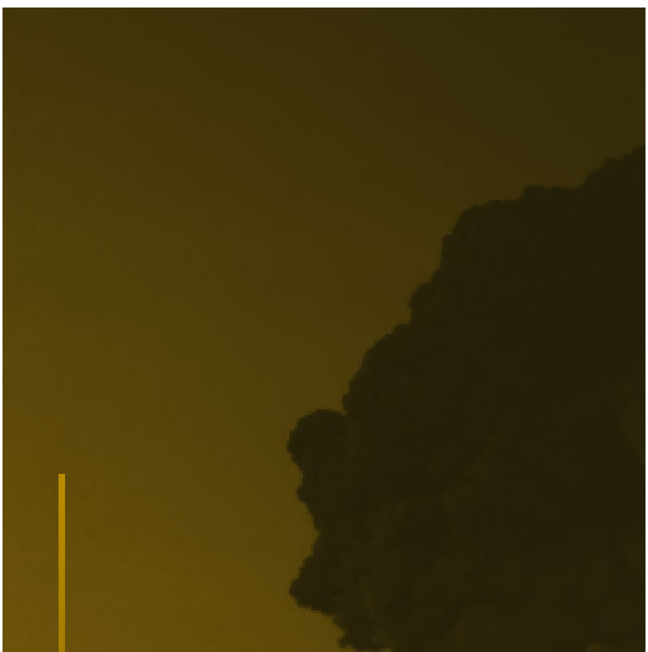

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Teide Volcano

Geology and Eruptions of a Highly Differentiated Oceanic Stratovolcano

123

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Preface

The Canary Islands Archipelago, offshore of the northwestern coast of Africa, originated from ocean-island volcanism over a span of 20 million years. This 600-km-long chain of islands (total population *2 million), with their beautiful volcanic landscapes, beaches, and year-round mild climate, receives more than 12 million visitors each year. The prime tourist destination is Teide Volcano on the Island of Tenerife, the cen terpiece of Teide National Park and the focus of this scientific volume. In 2010, Teide National Park was the most heavily visited national park of any European country and the second most visited worldwide. Teide is a huge volcano that towers 3,718 m (a.s.l.) above the central part of Tenerife, reaching the highest elevation in the Canaries and Spain. Moreover, if its height is measured relative to the seafloor, Teide is the third tallest (*7,718 m) volcanic edifice on Earth after the Hawaiian shield volcanoes Mauna Kea and Mauna Loa. In 2007, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) inscribed Teide National Park as a World Heritage Site, in recognition of its diverse, abundant evidence of the geological processes that underpin the evolution of volcanic islands, complementing other vol canic properties such as Hawaii Volcanoes National Park (USA) and Gala´pagos National Park (Ecuador).

Because of its imposing physical visage, Teide naturally has long attracted scientific attention following the colonization of the Canaries, but especially during the eighteenth and nineteenth centuries when the emerging ‘‘science’’ of geology began to develop. Beginning in the latter part of the twentieth century, many geoscience and related studies— including the systematic geologic mapping and dating of volcano-related deposits—have been conducted at Teide as well as other Canarian vol canoes, resulting in a substantial scientific literature. For example, during the past 6 years, one of the editors (Carracedo) has published and edited three major books (in Spanish) summarizing the volcanic geology and associated hazards of Canarian volcanoes in general, and of Teide in particular. Unfortunately, to date no comparably comprehensive works in English about Canarian volcanism exist. Thus, this volume marks a milestone in remedying this long-standing deficiency. It provides a wide ranging summary of the geologic evolution of Teide—the emblematic volcano of the Canaries. In 14 chapters, this volume addresses a wide diversity of topics and disciplines, including: the prehistoric to present day scientific understanding of Teide, its geodynamic setting within the

context of plate tectonics (i.e., ‘‘hotspot’’ model), development of rift zones and other volcanic structural elements, radiometric and paleo magnetic dating studies, petrologic-geochemical-isotopic evolution of Teide’s magmatic system, island-wide geophysical investigations, erup tive history and styles, and volcanic and other geological hazards.

It is noteworthy that the book's last chapter emphasizes the volcanic hazards of the Teide Volcanic Complex (TVC). While the TVC has erupted five times during recorded history (most recently in 1909), such activity has been relatively weak, causing minimal damage and no fatal ities. However, larger prehistoric eruptions and flank collapses along the volcano's rift zones testify to much more hazardous activity in Teide's recent geologic past. The episode of volcanic unrest at Teide during mid 2004, together with the related, highly controversial specific ''prediction'' of an eruption in October 2004 that did not materialize, has greatly enhanced public awareness of volcanic hazards in Tenerife. The 2004 Teide volcanic ''crisis'' adversely affected Tenerife's tourism economy and disrupted the daily lives of many of its residents. In addition, the sub marine eruption near La Restinga (Island of El Hierro) during 2011– 2012—the first since 1971 in the Canaries—has further increased public anxiety regarding hazards posed by future volcanic eruptions. On the positive side, however, these recent developments also have prompted the expansion of real-time monitoring studies of Canarian volcanoes.

Carracedo and Troll are perfectly suited to coedit this volume, because of their own extensive experience in working at Teide and other Canarian volcanoes. This fact is immediately apparent from a quick glance at the Table of Contents, which shows that they are authors or coauthors of many of the book's chapters. With its comprehensive discussion and broad spectrum of topical coverage—well illustrated by photographs, diagrams, and tables—this volume should prove to be highly useful to nonSpanish speaking practitioners within the global volcanologic com munity, especially those specializing in ocean-island volcanism. Given its scope and breadth, the Carracedo-Troll book is destined to have a long shelf life, serving as a valuable reference work for decades to come. Moreover, this book sets a benchmark for the production of similar summaries of the other historically and potentially active volcanoes of the Canary Islands. The lessons that can be learned from the existing data, and new data to be accrued from future studies, are critical for the preparation of effective emergency-response plans when the next episode of volcanic unrest at Teide, or at some other Canarian volcano, culminates in sig nificant and possibly hazardous eruptive activity.

10 October 2012 Robert I. Tilling Senior Research Volcanologist, Emeritus
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Those researchers who have inspired our thinking on the geology of the Canary Islands, and Teide in particular, shall be acknowledged here also, especially J. M. Fúster, H.-U. Schmincke, J. Martí, R. Cas, C. Stillman, K. Hoernle, T. Hansteen, J. Geldmacher, A. Klügel, A. Gurenko, T. R. Walter, S. Krastel, E. Ibarrola, H. Hausen, P. Rothe, N. D. Watkins, M. Canals, G. Ablay, J. M. Navarro, V. Araña, A. B. Watts, and F. Logopito.

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Abstract
This chapter outlines the progress of geological research into the origin and evolution of the Teide Volcanic Complex within the framework of Tenerife Island, the Canary Islands, and oceanic volcanism in general. Initially considered to relate to either the entrance to 'Hell' or to mythical Atlantis, for von Buch, von Humboldt, Lyell and the other great eighteenth and nineteenth century naturalists Teide eventually helped to shape a new, and at that time revolutionary concept; the origin of volcanic rocks from solidified magma. This school of thought slowly cast aside Neptunism and removed some of the last barriers for the development of modern Geology and Volcanology as the sciences we know today. Despite the volcanic nature of the Canaries having been already recognised by the twentieth century, modern geological understanding of the archipelago progressed most significantly with the advent of plate tectonics. While some authors still maintain a link between the Canaries and the Atlas tectonic regime (see also Chap. 2), geological research truly advanced in the Canaries through comparison with hotspot-derived archipelagos, particularly the Hawaiian Islands. This approach, initiated in the 1970s, provided a breakthrough in the understanding of Canary volcanism, demonstrating Tenerife and Teide to be one of the world's most inter esting, complex and to many, one of the most iconic of oceanic volcanoes.

J. C. Carracedo (&)

1 From Myth to Science: The Contribution of Mount Teide to the Advancement of Volcanology

Juan Carlos Carracedo and Valentin R. Troll

European volcanoes such as Etna and Vesuvius have been constant references in Volcanology

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since Greek and Roman times. Detailed and accurate accounts, most notably the description by Pliny the Younger of the 79 A.D. eruption of Vesuvius that destroyed Pompeii and Hercula neum, laid the foundations of modern Volca nology. Volcanic terminology as common as

1.1 Introduction

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"volcano" and "basalt" were first used in accounts penned by Pliny the Elder, as was "crater" by Aristotle. Etna and Vesuvius became historically relevant because of their frequent catastrophic eruptions that destroyed entire cities, such as Catania, in 1669, or Naples, in 1631, both causing many thousands of victims.

In contrast, the only aspect of interest of Mt. Teide until the eighteenth century was its exaggerated height (Figs. 1.1, 1.2). Teide was considered the highest mountain on Earth until Mont Blanc and the Andean volcanoes were measured and observed to be higher. It is inter esting to note, however, that present-day Vol canology has reinstated Teide amongst the highest volcanic structures on the planet (only surpassed by Mauna Loa and Mauna Kea, on the island of Hawaii). If the base level is taken to be the ocean floor and not sea level, Mt Teide rises above 7,000 m (3,718 m a.s.l.).

While Vesuvius and Etna defined important catastrophic episodes in the history of Italy from Roman times to present, Teide volcano only posed a threat to the smaller population of aboriginal inhabitants on the island of Tenerife (the Guanches). The absence of explosive eruptions and victims since the colonisation of Tenerife at the end of the fifteenth century promoted the image of Teide as the main stable element in the landscape of the entire archipelago and as a prime cultural reference, even locally acquiring a protective role in folklore for example as ‘‘Father Teide’’. The eruptions on Tenerife in historical times have had a limited impact on the population and the economic infrastructure of the island, with the exception of the 1706 eruption which partially destroyed the town of Garachico and filled the harbour with lava (the main commercial port in Tenerife at the time). This eruption, however, was not directly related to Teide, its vent being located 17 km away on the NW rift zone.

The role played by the Canaries and Mt. Teide changed lastingly upon the arrival of well established naturalists such as Leopold von Buch, Charles Lyell, Alexander von Humboldt and Georg Hartung, among many others. During the eighteenth century, geology was at the centre of a long-lasting controversy between those who held the view that all rocks, including what we now see as volcanic rocks, were marine deposits formed by chemical precipitation in the ocean (Neptunists, after the god of the sea in Roman mythology) and those who believed that volcanic rocks resulted from the solidification of molten masses from the Earth’s interior (Plutonists, after Pluto, Greek god of the underworld).

The former school, led by Abraham Gottlieb Werner (1750–1817), a renowned German professor of Geology (Fig. 1.3), and the latter by the Scot James Hutton (1726–1797), established a lively debate with strong religious overtones that lasted almost an entire century. The neptunistic theories rigorously adapted the teachings of the book of Genesis, contrasting the more ‘‘enlightened’’ ideas of the plutonists. The controversy contributed decisively to the development of Geology as a modern science and was based to quite an extent on the observations made in the Canaries by the now famous eighteenth century naturalists.

The relevant role of the Canaries and Mt. Teide in the resolution of crucial problems in Geology and Volcanology arose from the European continent, particularly from Germany, France and Scotland, due to the fact that the volcanic settings in those countries are much more difficult to interpret than Canarian volcanoes. Fervent neptunists and co-workers of the influential Professor Werner, such as von Buch and initially even von Humboldt himself, who had expressed numerous doubts, gradually became ardent defenders of plutonism after travelling to the Canaries, thereby irreversibly opening the door to the advancement of purely scientific Geology that was largely free from religious restrictions. To von Buch we owe the basic concept that minerals in lava are formed by magmatic crystallisation and to von Humboldt that volcanic alignments are due to tectonic activity at depth.

Regrettably, the essential role of the Canaries and Mt. Teide during this important stage in the development of modern Geology and

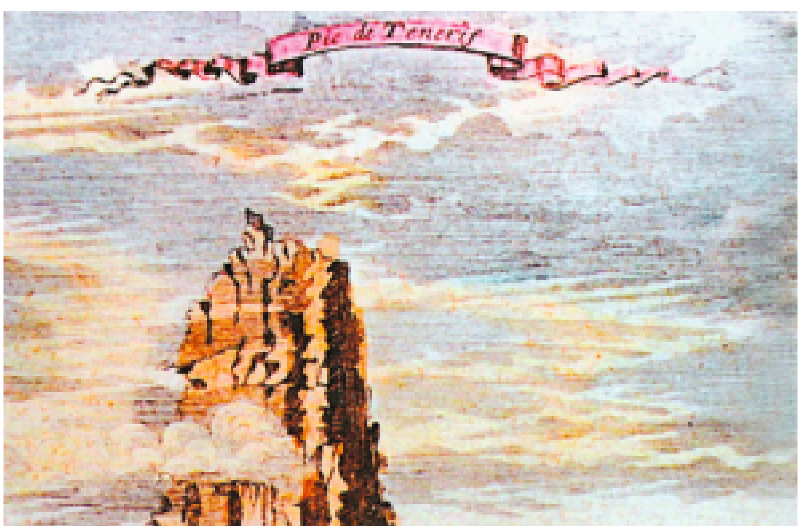


Fig. 1.1 The island of Tenerife and a towering Mount Teide in an engraving by Olfert Dapper in 1686

Volcanology did not continue. There were no research groups or centres in Spain or the Canary Islands at that time devoted to the discipline of Geology. Nonetheless the Canary Islands offered a privileged setting in which to study the Geology of oceanic islands, made possible by exceptional conditions: the absence of significant subsidence, allowing observation of all stages of evolution starting with the oldest formations. This is impossible in most similar archipelagos, where subsidence is a relevant factor causing the insular edifices to be submerged during relatively early stages of their evolution and the scant plant cover and low relative meteorisation rate of rocks and formations, being much lower in the Canaries because of the comparatively low rainfall. These favourable circumstances converted the Canar ies, and Teide and the surrounding area in par ticular, into a world-renowned setting for the study of Volcanology, but this was not under stood until the second half of the twentieth century.

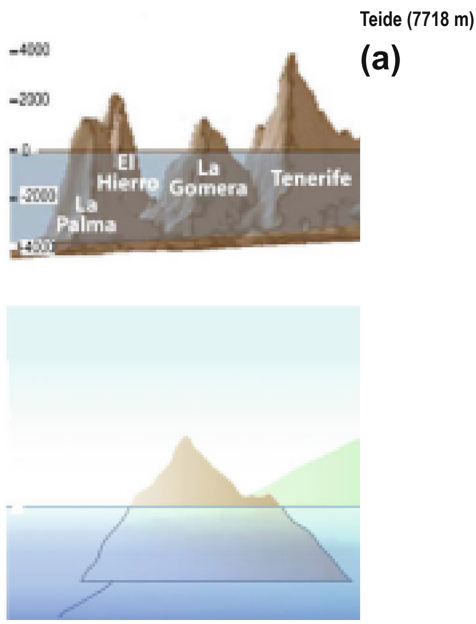


Fig. 1.2 a and b. Teide is by no means earth’s

m

highest mountain, as was generally accepted until Mont Blanc was measured (the first recorded ascent of Mont Blanc, 4,810 m, was in August 1786). However, besides having the highest elevation in the Canaries with only Mauna Kea and Mauna Loa being

0 100 200 300 400 500 600 km **(b)**

8000

and Spain, it is the third highest volcanic feature on earth, higher

6000

TEIDE MAUNA LOA

MAUNA KEA

4000 2000 0

-4000 m

-2000 -4000

Sea level

3718 msnm 4169 msnm 4205 msnm

7718 m 10167 m 10203 m

-5998 m

100 200 300 400 km

Fig. 1.3 Werner described the basalts of Stolpe (the birthplace of Leopold von Buch) as sediments without traces of melting. He interpreted the columnar features as desiccation cracks, like those found in drying mud

study of the Canaries began shortly thereafter, during the 1960s, there is a fundamental differ ence: while in Hawaii the above-mentioned

Establishment of the Hawaiian Volcano Observatory (HVO) by the U.S. Geological Survey at the beginning of the twentieth century is acknowledged as the key element in advanc ing the study of the Hawaiian Islands and leading to the development of modern Volca nology. Although an intense and continuous

Observatory was a centre for the great majority of volcanological studies since 1912, a similar centre was never created in the Canaries, but research was led from Madrid, with the corre sponding loss of efficiency and the dispersion of efforts, hindering the possibility that the Canary Islands could have become a similar world famous setting for the development of Volca nology some 100 years ago.

This is exemplified in the development of volcanological terminology employed in the eighteenth and nineteenth centuries derived from Latin (volcano), Greek (crater, pyroclast, pho nolite, etc.) and, to some degree Canarian Spanish (caldera, malpaís), but American English was the language used, coinciding with the creation of the Hawaiian Volcano Observa tory, since the start of the twentieth century (hotspot, pillow lavas, surge, shield volcano, etc.) and especially Hawaiian terms (e.g., pa¯hoehoe and ‘a‘a¯ lavas) became internationally accepted.

1.2 Teide Volcano in Classical Mythology

There have been some references to Teide, mainly of a mythological nature, in the Classical Era. The best-known and most enduring legend involving the Canaries is the one related to Atlantis, narrated by the Greek philosopher Plato (427–347 BC) in his work Timaeus and Critias. According to this legend, a civilisation, the Atlantean, as advanced and powerful as the Egypt of the Pharaohs, disappeared overnight when the continent sank into the ocean. Only the highest peaks remained above water, to form the archipelagos of Macaronesia: Azores, Madeira, Cape Verde and the Canaries.

It is through Jean Baptiste Bory de Saint Vincent that this legend became scientifically significant in relatively modern times, when he related the Canaries to Atlantis during a visit to the archipelago, described in his work entitled Essais sur les Îles Fortunées et l’Antique Atlantide (Kunzli 1911). Acknowledged as a distinguished naturalist, Bory de Saint Vincent conferred scientific credibility on this legend, which was considered to be one of the possible theories of the origin of the Canaries until the mid-twentieth century. It was only when the Canaries were found to overlie oceanic crust, which moreover is more than 180 million years old, that any scientific basis ascribed to this attractive legend was radically dismantled.

However, reality exceeds even the most imaginative legends. Plato would probably have been stunned by a story involving an entire continent (Africa) moving several thousand kilometres away from America over more than 180 million years to form an ocean (the Atlantic) through which, more than 20 million years ago, the volcanic Canarian Archipelago was formed by a magmatic plume originating from the Earth’s interior at a depth of almost 3,000 km, and producing at its highest point, Teide, stretching vertically over 7,000 m from the ocean floor.

1.3 Mt. Teide in the Pre-Hispanic World

For the Pre-Hispanic population of Tenerife (the Guanches) Teide was the dwelling place of Guayota, an evil mythical creature, god of the deceased and identified with Hell (von Fritsch and Reiss 1868). The Guanches therefore envi sioned Mt. Teide as a demonic spiritual force that brought death and destruction, quite the opposite of the image it adopted later in His panic Canarian folklore. The fear and supersti tion of the Guanches developed as they lived alongside the volcano and may have witnessed at least 6, possibly 8 of its eruptions, mostly around the base of the stratovolcano and on the NW Rift. On the other hand, they learnt how to take advantage of the resources provided by volcanism: the cañadas (flat, pumice-covered paths) for the seasonal migration of their goat herds; the volcanic rocks for building their huts, and the caves and volcanic tubes for occasional shelter. They were adept at mining the glassy volcanic obsidian, with which they skilfully fashioned cutting tools.

Similarly to most nomadic tribes, it is very possible that they used fire to clear the land of brush in order to make new pastures for their livestock, thus providing the source of several references to eruptions on Teide reported in ships' logs. As an example, the pre-historical age (1430 AD) for the volcanic cones nested in the La Orotava Valley comes from a Guanche oral tradition, reported by Humboldt on his journey to Tenerife in 1799. However, charcoal underlying lapilli from this eruption yielded a ^{14}C age of 29.090 ± 190 years BP, and the lavas, a $^{39}Ar/^{40}Ar$ age of 27.000 ± 5.900 ky (Carracedo et al. 2010). The Guanche tradition seems to fit better with the calibrated radiocarbon age of 590 ± 66 years BP, most probably related to a forest fire, obtained from charcoal underlying a pumice deposit mantling the Orotava Valley, probably from the Montaña Blanca eruption (Figs. 1.4, 1.5) (Carracedo et al. 2007).

Only a few Guanche words have survived, mostly in geographical and toponymical terms. The very name of Teide has its origin in the Guanche term Echeide (Hell). It is surprising, however, that this name was given to Teide and not to the island of La Palma, where volcanoes have been much more active during the Guanche period, causing several victims amongst the local population (Rodríguez Ruiz et al. 2002). Perhaps it was the continuous fumarolic activity at Teide's summit (with temporal emission of hot sulphurous gases forming a plume that may occasionally have been quite voluminous) that contributed to Teide being named after Hell, as eruptive activity on Teide's cone itself was limited to a single eruption during the Guanche Pre-Hispanic period (Carracedo et al. 2007).

1.4 References in the Fourteenth and Fifteenth Centuries

The first references to volcanic eruptions in Tenerife are limited to distant sightings by fif teenth century sailors, who used Teide as a natural landmark during their voyages across the

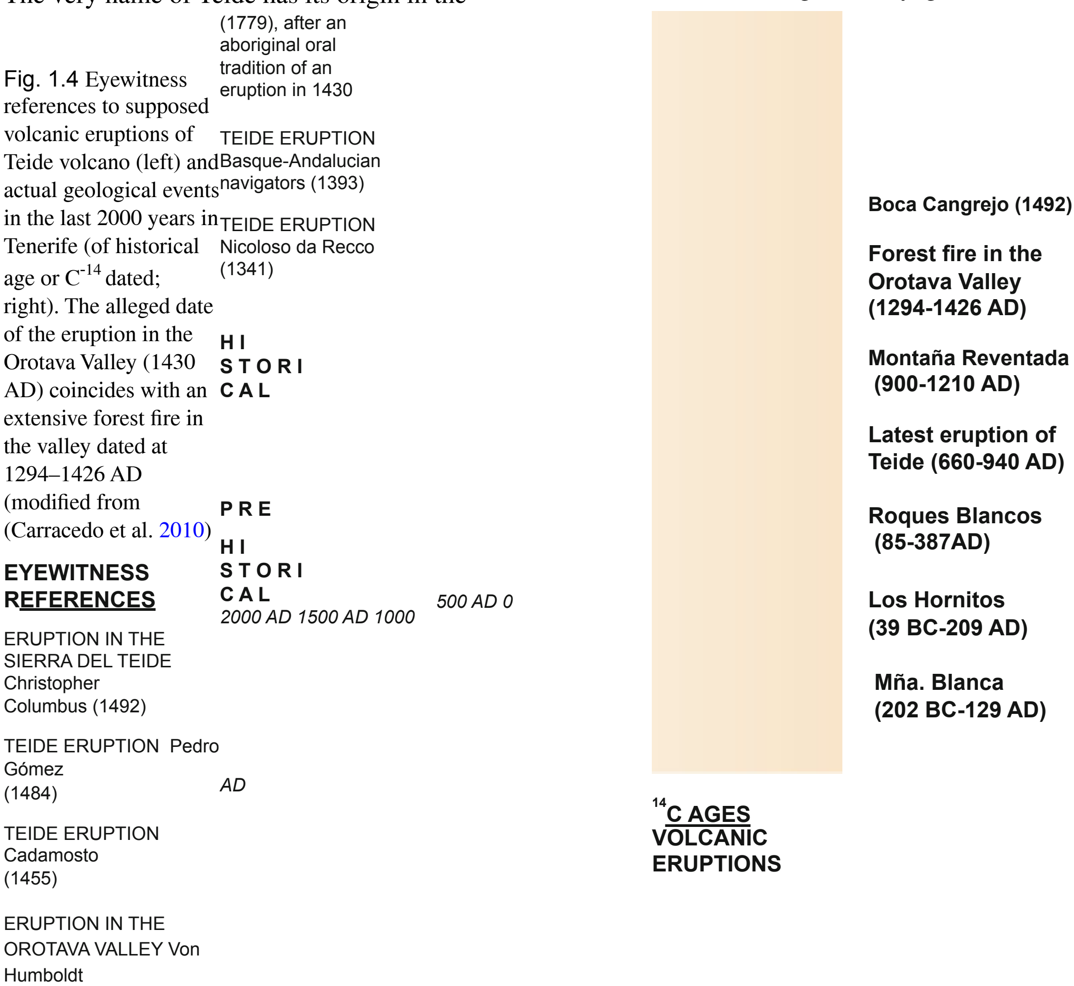


Fig. 1.4 Eyewitness references to supposed volcanic eruptions of Teide volcano (left) and actual geological events in the last 2000 years in Tenerife (of historical age or C^{-14} dated; right). The alleged date of the eruption in the Orotava Valley (1430 AD) coincides with an extensive forest fire in the valley dated at 1294–1426 AD (modified from (Carracedo et al. 2010)

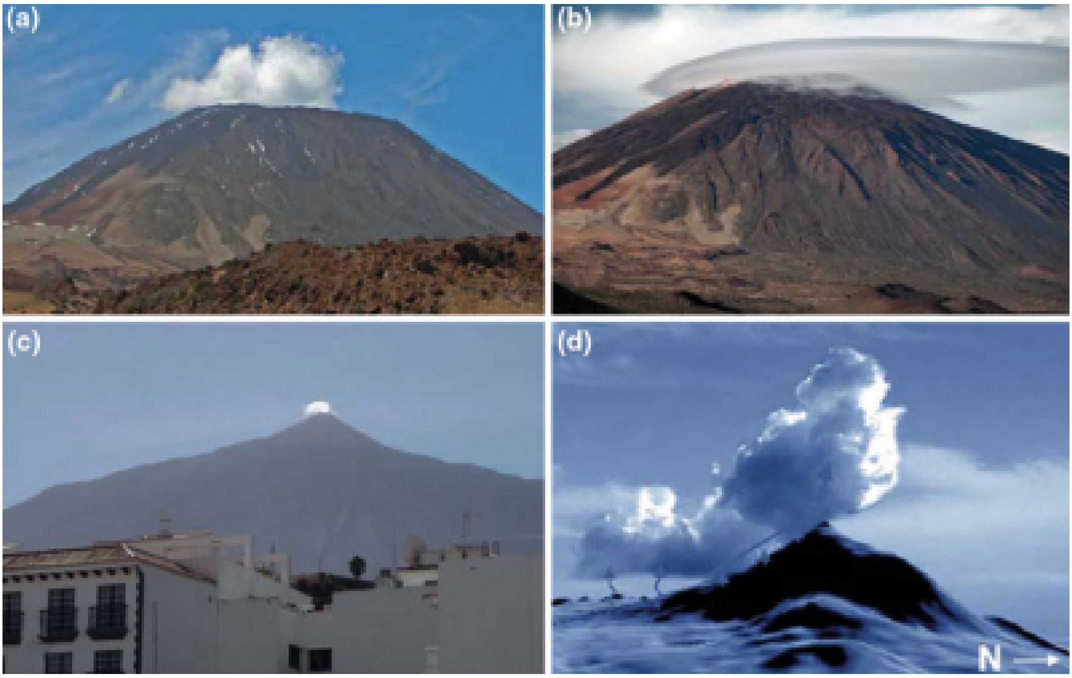


Fig. 1.5 a, b. Frequent spectacular 'plumes' in the summit area of Teide, locally known as 'Teide's headdress'. c. Small plume at the top of Teide in October 2004, initially interpreted as evidence of volcanic reactivation causing considerable alarm, later confirmed as a meteoric cloud (La nube que quiso ser protagonista. EL DÍA. Santa Cruz de Tenerife, 21-10-2004). d. Model of the formation of clouds at the summit of Teide volcano by local orographic convergence (Álvarez and Hernández 2006)

Atlantic because of its great height. Many of those references include descriptions of possible volcanic eruptions.

An account of a possible eruption of Teide contained in the ship's log kept by Nicoloso da Recco, copied by Boccaccio, was put forward by Santiago (1948) as indicating a Teide eruption: "it must be remembered that, in 1341, the Italians, Castilians and other Spaniards who accompanied Recco observed that smoke issued from the Peak" (Friedlander 1915).

However, the original source, the account by Giovanni Boccaccio ("About Canaria and other islands newly found in the ocean beyond Spain" 1341) clearly describes a well-known meteorological phenomenon, the so-called "Teide's headdress" (Fig. 1.2), a cloud that forms over the summit area due to an adiabatic process similar to the foehn effect: "They found an island at which they did not wish to disembark because a certain wonder occurred there. A mountain is said to exist there, which, according to their calculations, is thirty miles high, or even more… at whose summit there is a mast the size of a ship's, from which hangs a large lateen sail, taut as a shield, that swollen with the wind extends over a large area, only to appear to decrease little by little, as in ships, to rise again at once, always in this same manner."

It is quite surprising that this accurate description of an atmospheric feature—clouds at the summit of Teide volcano that formed by local orographic convergence—has been interpreted as eruptions of Teide even in very recent scientific articles, using this feature to assess the probability of the eruptive hazard of the volcano. It is equally surprising that the development of one of these clouds over Teide on October 20, 2004 was believed to signal the onset of an eruption and caused great alarm among the residents of the island. Scientific and technical personnel continued relating this cloud to an eruptive column, asserting that this phenomenon was related to an increase in seismic activity observed at the time.

Another description of a possible eruption dates from 1393, the original source being the accounts of Andalusian and Basque seamen included in the chronicles of King Henry III, quoted for the first time in 1839 by Webb and Berthelot (Hausen 1955). That account states that "on coming closer to the island they saw flames and smoke issuing from the highlands, whereupon they did not dare to disembark and sailed away from what they then began to call Hell Island". Since the last Teide eruption has been dated at a much earlier date (eighth century), this putative eruption does not fit into the history of the volcano, and probably reflects a meteoric phenomenon.

A further reference to a possible eruption of Teide is that of Ca'da Mosto (Il libro de la prima navegazione per l'Oceano alle terre de Negre de la Basse Etiopia, 1455), citing "Tenerife, the most populated of the islands and one of the highest on Earth…and in clear weather a mountain can be seen from a great distance burning continually in the centre of the island". The radiometric ages obtained do not allow any leeway for a known eruption of Teide in that period (Fig. 1.4), thus these seafarers were most probably describing fumarolic activity at the peak, forest fires or the spectacular meteorological phenomena above Teide.

1.5 References to Teide Volcano at the Dawn of Science: The Renaissance and Baroque Periods (Sixteenth and Seventeenth centuries)

Rather than studying Teide as an active volcano, a task that would be approached centuries later, during the pre-scientific period in which the magical vision of the mountain was maintained, the most important issue was identifying its position and altitude (for navigational purposes).

Teide was surrounded by a mystical aura and believed to be the highest mountain on Earth until the altitude of Mont Blanc was measured. It was said that the sun seemed to be closer when viewed from the peak of Teide and that the heat was irresistible. In fact, Teide is a mountain that is relatively easy to climb (the custom nowadays is for all Canarians to climb the volcano on foot at least once, but there is also access by cable car). Back then, it seemed an extraordinary challenge, however. It is therefore not surprising that the main objective of the early scientists visiting the Canaries was to make the ascent to the Peak of Teide (Fig. 1.6).

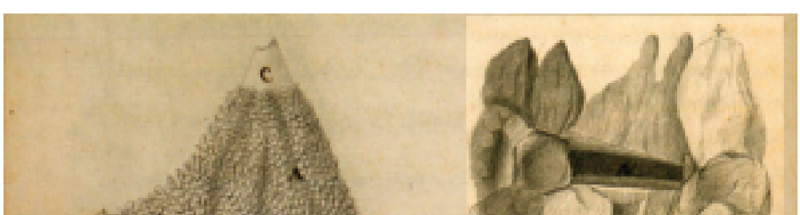
If we examine the altitudes assigned to Teide until the latter part of the seventeenth century (see Fig. 1.1) one notes that they are expressed in miles and even leagues (about 3 miles), while the more suitable method of measuring in toises (190 cm approx.) or fathoms (90 cm approx.) was only introduced in the late seventeenth century.

In 1631, an eruption of Vesuvius that generated "torrens cineris" or torrents of ash—known today as pyroclastic flows—caused more than 4,000 victims. Shortly thereafter, in 1669, Mt. Etna erupted catastrophically, devastating one third of the area of Catania. Those catastrophic events prompted the study of volcanoes. At that time, the newly explored Andean volcanoes were the subject of continual reports, with even greater altitudes and with yet more frequent eruptions.

The scenario was prepared for the crucial visits and observations of the great naturalists of the eighteenth century—von Buch, von Humboldt, Lyell—fully exploiting the possibilities afforded by the industrial and cultural revolution at that time for exploration and scientific progress.

In the mid-seventeenth century, the scientific revolution (Galileo, Descartes, Newton, etc.) established the firm basis of a fundamental tool, the application of scientific method, in contrast with prevailing religious beliefs. Teide would no longer have strong magical connotations and would instead slowly transform to the theme of research it has become today.

Fig. 1.6 Drawing by Louis Feuillée of the "Pic



de Tenerife" (Teide Volcano) and the summit cone (Pain de Sucre or Sugar Loaf, Pan de Azúcar in Spanish) (Feuillée 1724). The path to climb the volcano and a natural reservoir (holding melting ice) are shown as facilities for the ascent

1.6 The Contribution of the Great Eighteenth and Nineteenth Century Naturalists

The main objectives early in this epoch were the ascent of Teide and measuring its altitude. The exact height was crucial for ships to calculate their position by means of simple trigonometric approximations (Figs. 1.7, 1.8, 1.9).

The Royal Academy of Sciences of Paris commissioned the astronomer Louis Feuillée in 1724 to set the precise position of the first meridian (on the island of El Hierro) and the altitude of Teide (see Fig. 1.7). Feuillée's measurement (2193 toises or 4,274 m) was considered incorrect and remained unpublished. In 1776, Jean Charles Borda, sent by the Royal Academy of Sciences of France to Tenerife with the same objective, obtained a value of 1905 toises (3,713 m), very close to the true elevation of 3,718 m (Borda 1776). Even Alexander von Humboldt, who arrived in Tenerife in 1779, was unable to improve Borda's work, which remained the best measurement of Teide's altitude until 1851 (Fig. 1.10).

However, the importance of Humboldt's visit to Tenerife was not only related to the accurate assessment of Teide's altitude, but to his geological and volcanological observations. Despite the fact that von Humboldt was a former student of Abraham Gottlieb Werner, the founder of the school of Neptunism, he completely changed his

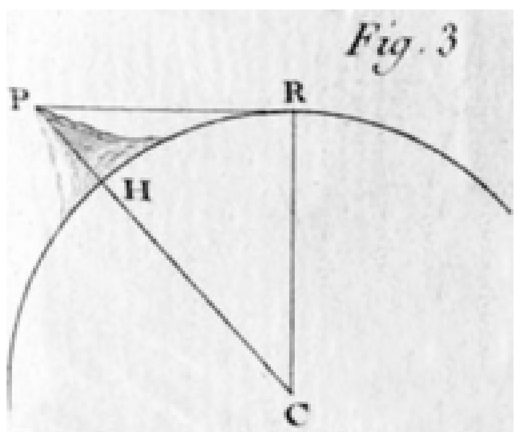


Fig. 1.7 The exact elevation of Teide was important to determine the position of ships by trigonometric calculations (d'Eveux Claret de Fleurieu 1773)

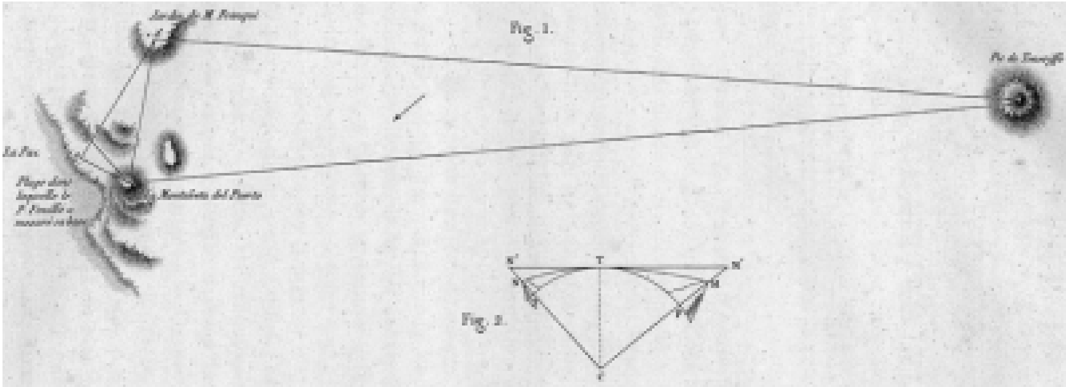


Fig. 1.8 Measurement by triangulation of the altitude of Teide volcano made by Borda in 1776 (Preiswerk 1909)

Fig. 1.9 Painting from the epoch of the measurement of Teide's elevation. Here, a view at the summit of Montaña Taoro (Montañeta del Puerto in the drawing of Fig. 1.8), one of the stations used in the triangulation

Giovanni Bocaccio Alvise Ca'da
Mosto André Thevet
Thomas Herbert
Bernhardus Varenius Edward
Barlow
Allain manesson Mallet
1341 1455 1555 1624 1650 1668
1683
30 miles
60 Italian miles
18 marine leagues 15 miles
4 miles and 5 furlongs 27 miles
15 miles

ideas after travelling to Tenerife and observing the island's volcanism, particularly Teide vol cano and the recent eruptive vents and flows around the stratocone. His former idea that the German basalts were formed through chemical precipitation, crystallisation and deposition in the sea could not resist confrontation with Ten erife and Teide's volcanism, and he eagerly admitted that these rocks were formed by vol canoes. On this journey, he became a qualified and enthusiastic promoter of Plutonism and modern Geology, and of Teide volcano itself,

Robert Challe

Louis Feuillée
Manuel Hernández
John Cross
Thomas Astley
Michel Adanson
Jean Charles Borda
Alexander von Humboldt
Charles Phillipe de
Kerhallet Charles Piazzi
Smyth
Parque Nacional del Teide

1690 1724 1742 1742 1744
1794 1776 1799 1851 1856
1954
2730 toises 2193 toises
2658 toises 2408 toises
2,25 miles
2052 toises 1095 toises
5320 m 4274 m 5180 m
4693 m 4162 m 3999 m
3713 m 3736 m 3715 m
3717 m 3718 m

through his prolific scientific writings and lec tures (Preiswerk 1909).

Fig. 1.10 Recorded elevation of Teide volcano through history

Leopold von Buch, also a former student of Abraham Gottlieb Werner and an ardent nep tunist, visited Tenerife in 1815 following Hum boldt's advice. He also was soon persuaded of the volcanic origin of Teide and the surrounding Las Cañadas Caldera; contradicting Werner, he admitted that volcanism is one of the main processes on Earth. However, after taking this

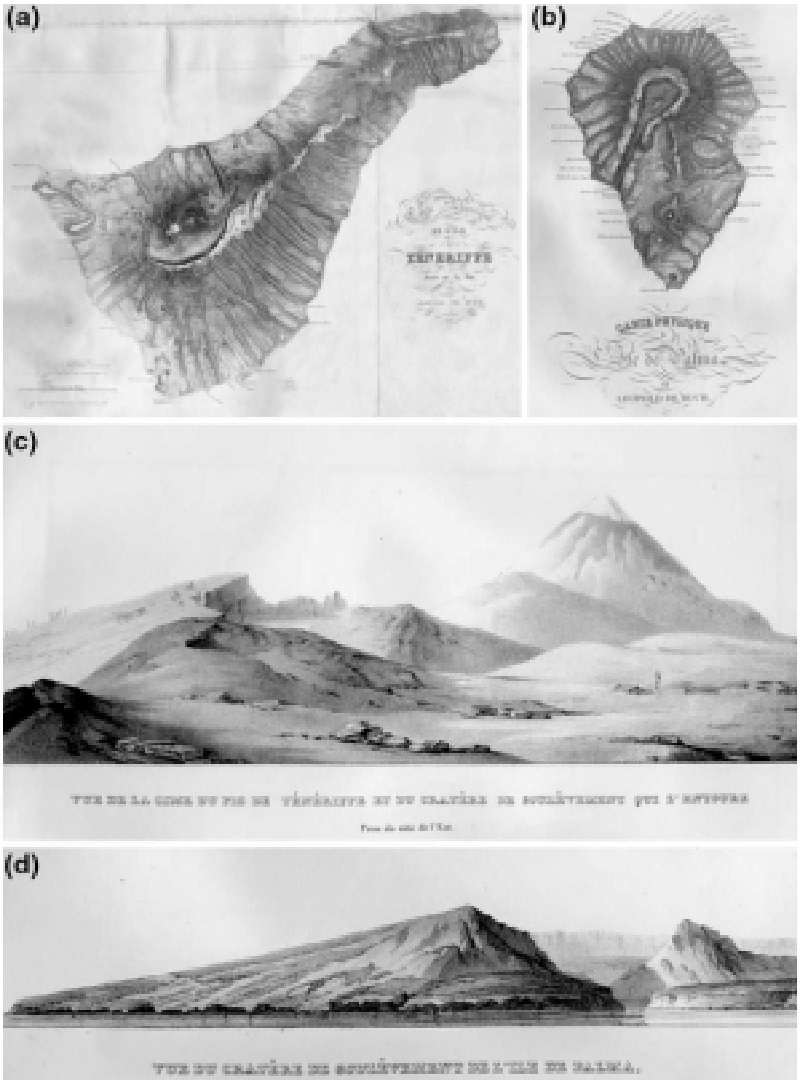


Fig. 1.11 To Leopold von Buch, Tenerife and La Palma were the prototypical examples of uplifted craters (or "craters of elevation", to distinguish them from eruption craters). The islands had been thrust upwards and then collapsed at their centres to form an uplifted crater or "caldera", a term that he took from La Palma. In this theory, that surprisingly had immediate success, the island was not the result of lava accumulation but "emerged ready-made from the interior of the earth". a Map of the island of Tenerife by Leopold von Buch (Jeremine 1930). b Map of the island of La Palma by Leopold von Buch (Jeremine 1930). c The Pic de Tenerife (Mt. Teide) and the encircling "uplifted crater" (the Caldera de Las Cañadas) viewed from the east in a drawing by Leopold von Buch (Jeremine 1930). d View from the west of the "uplifted crater" of La Palma in a drawing by Leopold von Buch (Jeremine 1930)

crucial step forward, von Buch took one step backwards with his theory of Craters of Eleva tion (Erhebungscrater), interpreting the Caldera de Las Cañadas and the Caldera de Taburiente (La Palma) as prototypical examples (Dittler and Kohler 1927) (Fig. 1.11a–d).

The Craters of Elevation theory was defini tively abandoned when Charles Lyell, a student of James Hutton (the founder of Plutonism), arrived in the Canaries in 1853 to prove that the islands were formed by accumulation of suc cessive eruptions, and that their calderas were not caused by uplift, but by collapse and erosion.

These great eighteenth and nineteenth cen tury naturalists provided a crucial scientific basis for the development of modern Geology and Volcanology, and many of their ideas are still accepted today. Humboldt expressed concepts that only recently have been accepted by many geoscientists in the Canary Islands. While many of these present day geoscientists still relate seismicity inside the island's edifices to major oceanic fractures, von Humboldt claimed in 1800 that "large destructive earthquakes have no direct connection with volcanic activities, which are the cause only of small local shocks…", precisely the current distinction between tectonic earthquakes and local seis micity related to volcanism. It was von Hum boldt's idea that "Very high volcanoes have fewer eruptions than those of low altitude, because it is more difficult for lava to ascend them", a clear explanation of the physical filter imposed on summit eruptions (particularly the heavier basanitic and basaltic magmas) in stratocones such as Mount Teide when magmas reach a critical height, favouring the eruption of lighter, phonolitic ones and eventual focus of vents on the volcano's periphery.

A lost opportunity was the frustrated visit of Charles Darwin to Tenerife. Inspired after reading Alexander von Humboldt's account of his ascent of El Teide, Darwin arrived in Tenerife in 1831 as the expedition naturalist aboard the HMS Beagle. However, as Darwin reports "After heaving to during the night we came in sight of Tenerife at daybreak… The peak or sugar loaf has just shown itself above the clouds. It towers in the sky twice as high as I should have dreamed of looking for it. Oh mis ery, misery, we were just preparing to drop our anchor within half a mile of Santa Cruz when a boat came alongside bringing with it our death warrant. The consul declared we must perform a rigorous quarantine of 12 days. Matters were soon decided by the Captain ordering all sail to be set and make a course for the Cape Verde Islands… And we have left perhaps one of the most interesting places in the world, just at the moment when we were near enough for every object to create, without satisfying, our utmost curiosity". The reason to prevent Darwin from going ashore was the cholera outbreak in England in 1831. No doubt Darwin's visit could have made a great difference in the progress of Volcanology!

A significant advancement in the geological knowledge of Tenerife and Teide Volcano came with the work in the second half of the nineteenth century of the German geologists Fritsch, Hartung and Reiss (von Fritsch 1867). The first geological map of Tenerife was compiled by W. Reiss, already depicting the main volcano-stratigraphic units of the island, many aspects of which are still valid today (Fig. 1.12).

The main effort in the last decades of the nineteenth century and the first part of the twentieth was addressed to finding a solution for the origin of the Caldera de Las Cañadas and the Orotava and Güímar Valleys, once von Buch's earlier "Craters of Elevation" theory was abandoned. To Fritsch and Reiss, the two mor phological depressions forming the Las Cañadas Caldera—divided by the Roques de García large spur—are the headwalls of two main drainage

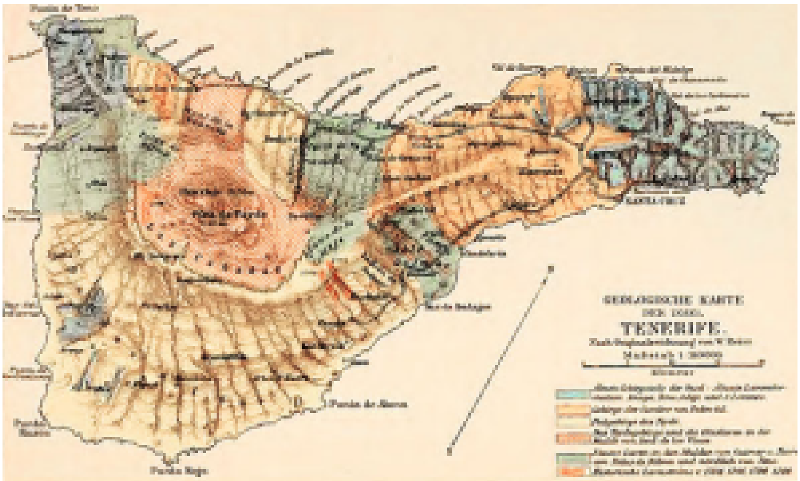


Fig. 1.12 The first geological map of Tenerife (von Fritsch 1867). The main volcano-stratigraphic units of the island are clearly defined: in blue, the oldest lavas (the Miocene Shields); orange, the Cumbre de Pedro Gil (the NE rift zone); yellow, the flanks of Teide (the Las Cañadas volcano); red stripes, Teide lavas filling the Caldera de Las Cañadas and the Icod Valley; green, recent lavas; red, historic eruptions (Meyer 1896)

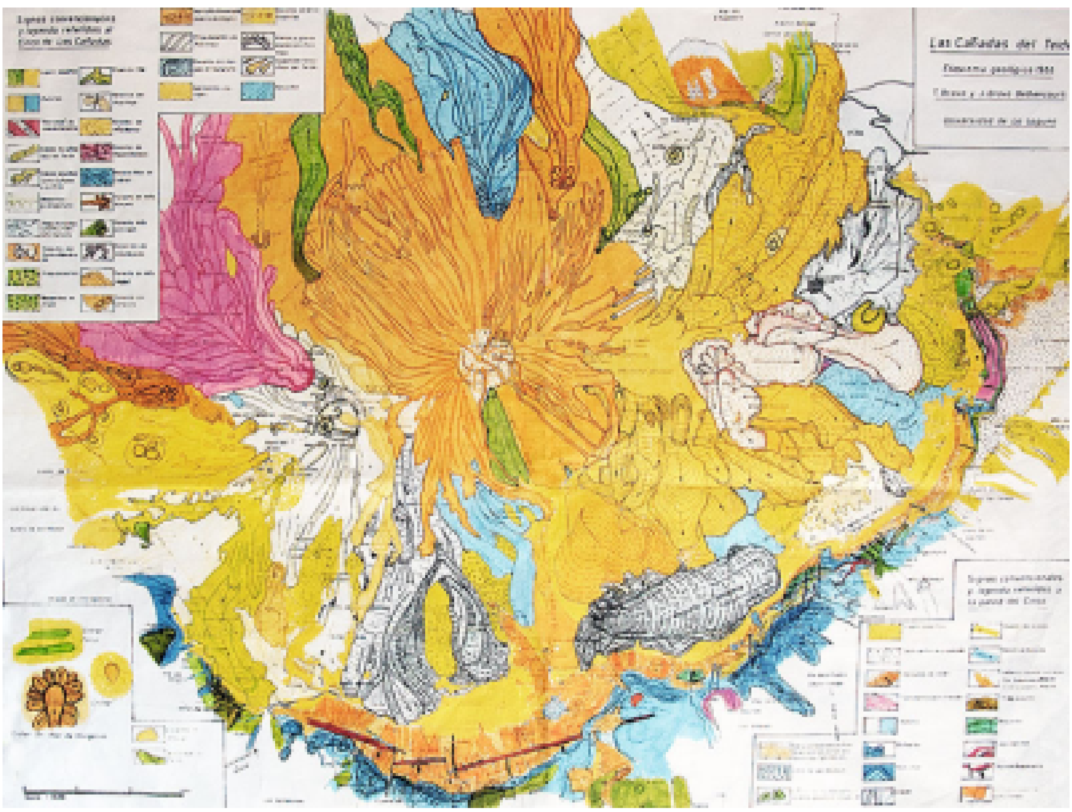


Fig. 1.13 Geological sketch map by Bravo-Bethencourt and Bravo (1989); from (Araña and Coello 1989)

systems, the Las Cañadas Caldera being an erosive feature similar to the Taburiente Caldera in La Palma, as proposed by Lyell in 1835 (von Fritsch and Reiss 1868). In contrast, Gagel (1910) postulated an explosive origin, similar to the Krakatau 1883 eruption, whereas Friedlander suggested a collapse caldera, similar to the Somma-Vesuvius complex (Friedlander 1915). Several models combining erosion, explosion and vertical collapse were proposed in the fol lowing years (Hausen 1955).

The valleys of La Orotava and Güímar were explained by von Fritsch, Hartung and Reiss as ‘‘intercolline Räume’’, valleys formed by lava accumulation at both sides of the depression (von Fritsch 1867).

1.7 Mount Teide in the Framework of Modern Volcanology: The Twentieth and Twenty-first Centuries

Research on Teide Volcano and the Las Cañadas Caldera during the first half of the twentieth century was mainly focused on petrological studies, prompted by the Chinyero eruption in 1909 (Preiswerk 1909; Kunzli 1911; Dittler and Kohler 1927; Jeremine 1930; Smulikowski 1937).

The Symposium of the International Associ ation of Volcanology and Chemistry of the Earth’s Interior (IAVCEI) hosted in Tenerife in 1968, fostered the geological study of the Canary Islands, particularly Tenerife and Teide Volcano,

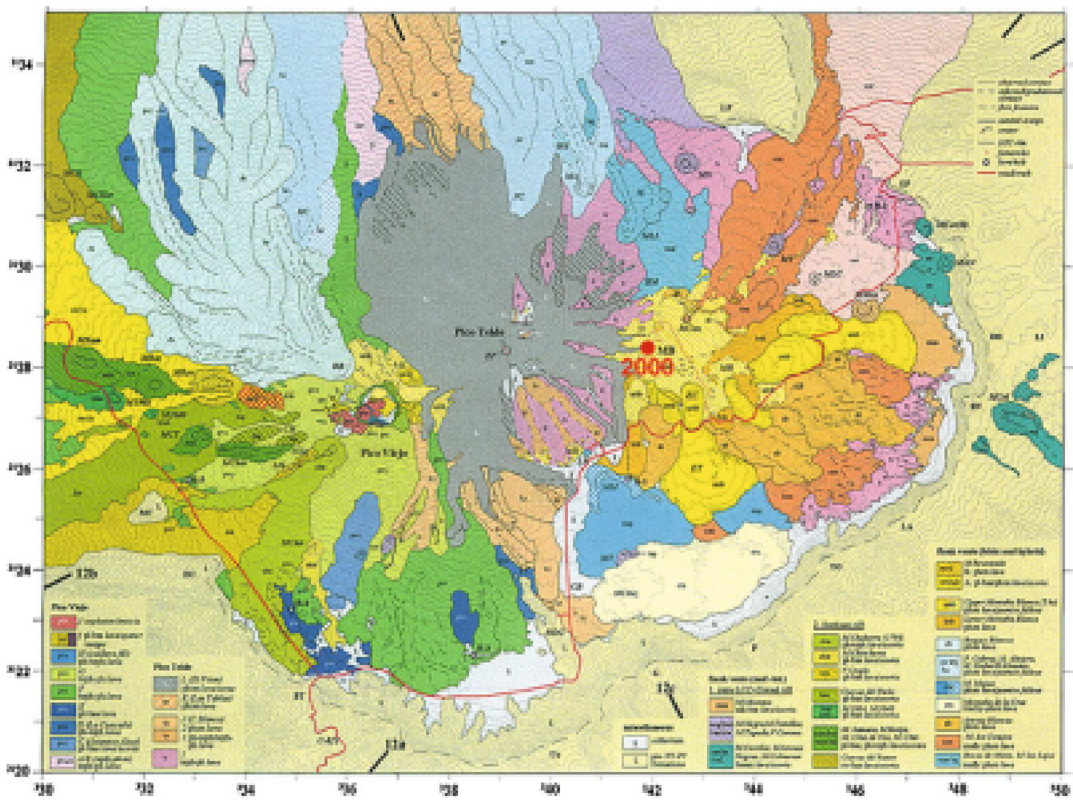
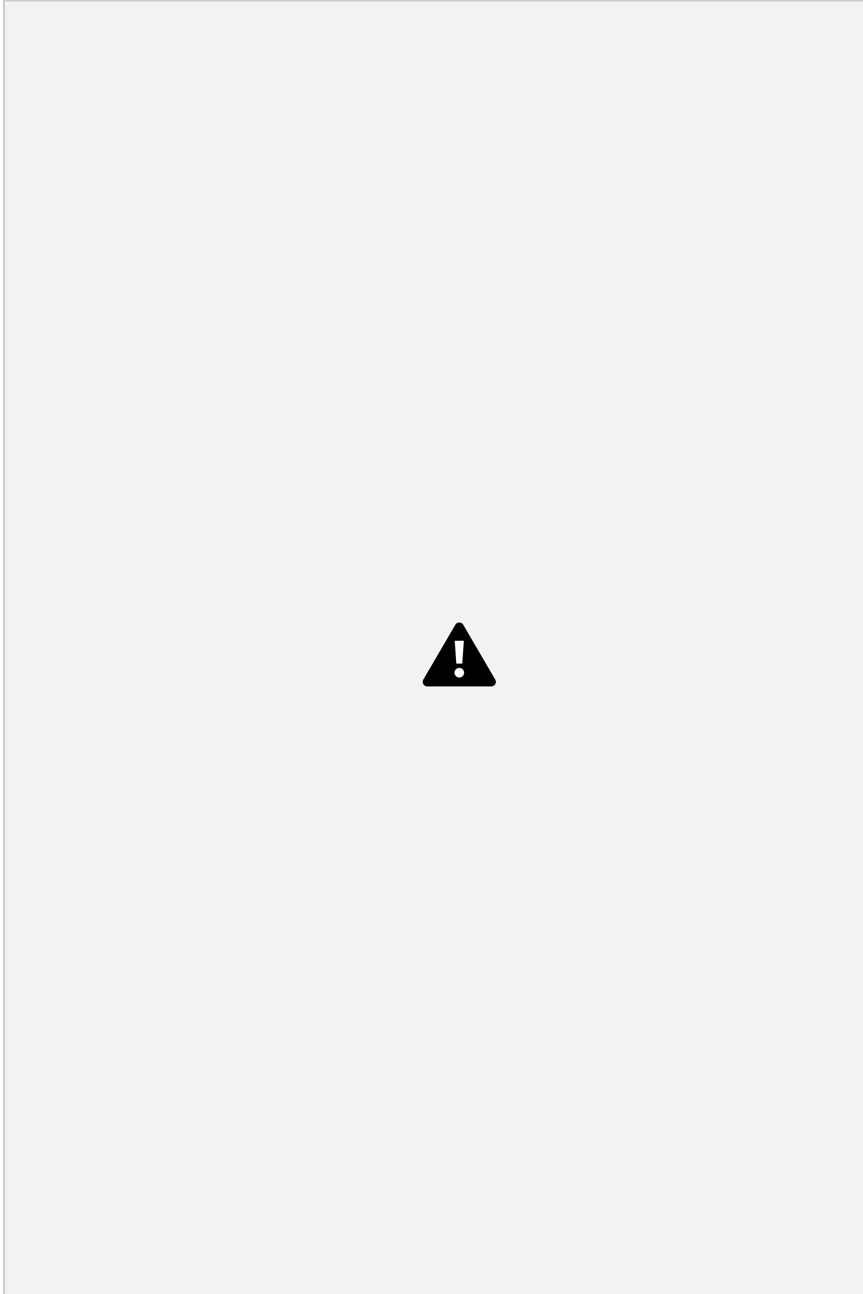
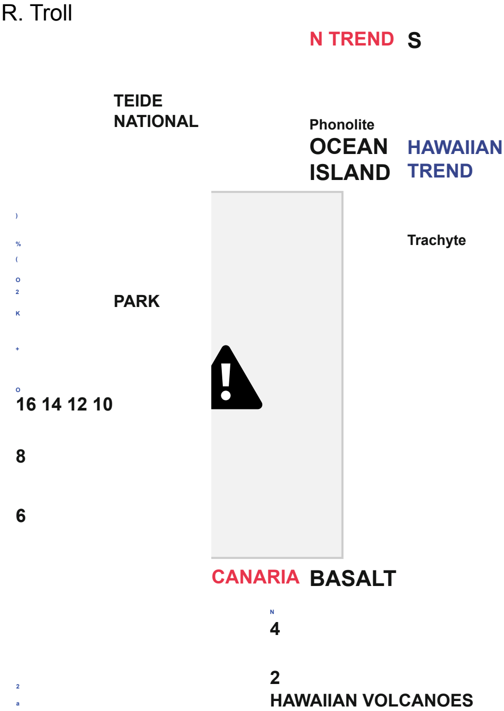


Fig. 1.14 Geological map of the Teide volcanic com plex (Ablay and Martí 2000). This map is restricted to the Teide-Pico Viejo stratocones and vents, and the proximal edges of the NW and NE rift zones. Only one radiometric age is provided, which dates the 2 ky eruption of Montaña Blanca (Ablay and Marti 2000)



eological map of the Teide volcanic complex (Caracedo et al. 2007). This map includes the Teide and Pico Viejo stratocones.


N TREND
S
TEIDE
NATIONAL
PARK
Phonolite
OCEAN
ISLAND
HAWAIIAN
TREND
Trachyte
16 14 12 10
8
6
4
2
CANARIA
BASALT
HAWAIIAN VOLCANOES

ULTRABASIC INTERMEDIATE ACID BASIC

0 40 50 60 70 SiO_2 (%)

Fig. 1.16 Magmatic series of the Teide volcanic com plex and the Mauna Loa and Mauna Kea volcanoes, forming respectively the Teide and Hawaii National Parks. In contrast to the basic magmas of the latter, the eruptions of Teide National Park include more evolved rocks (phonolites, trachytes). Combined, both sites represent the entire series on a large scale, with their corresponding eruptive mechanisms, volcanic features and landforms, justifying both Parks being included in the UNESCO World Heritage list (analytical data from Clague 1987; Rodríguez-Badiola et al. 2006)

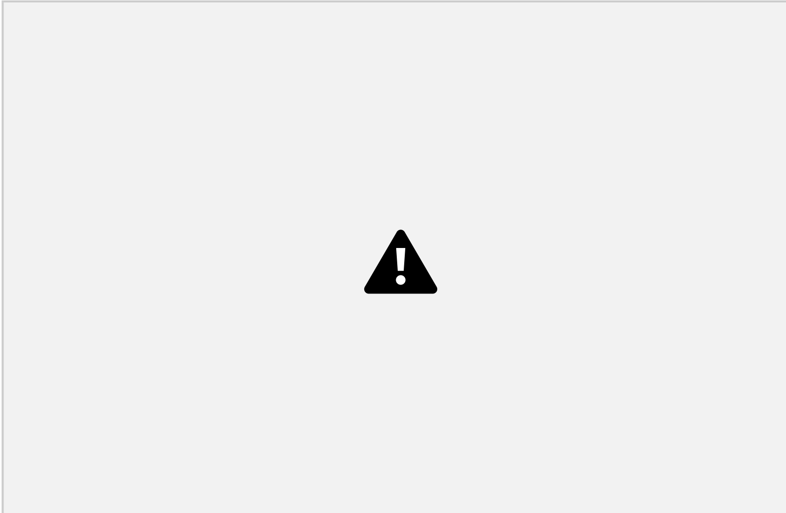
since then a research objective of global interest. Research efforts were directed to the study of the older ([200 ky) pre-caldera Las Cañadas Vol cano (Fúster et al. 1968; Ridley 1970; Araña 1971; Booth 1973; Wolff 1985, 1987; Martí et al. 1994; Bryan et al. 1998, 2000, 2002; Edgar et al. 2002; Huertas et al. 2002; Pittari et al. 2005; Bryan 2006; Edgar et al. 2007) and the genesis of Las Cañadas Caldera (Navarro Latorre and Co ello 1989; Watts and Masson 1995; Martí et al. 1997; Ancochea et al. 1999; Cantagrel et al. 1999; Marti and Gudmundsson 2000).

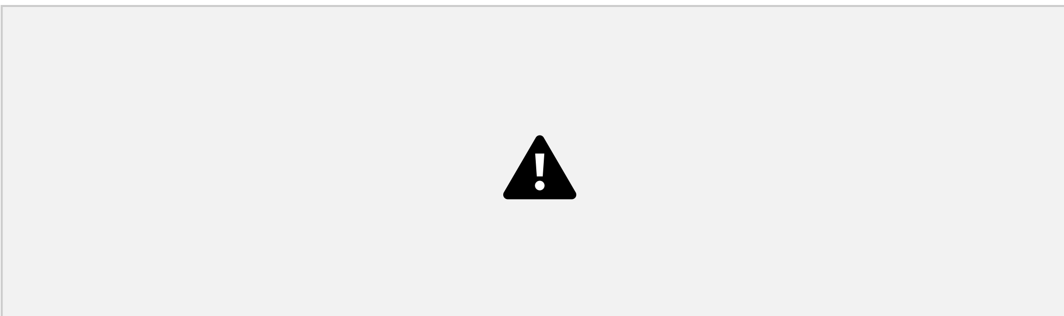
However, since 1968, limited progress was made on the reconstruction of the latest (post caldera) volcanic phase of Tenerife (Fúster et al. 1968). Research was restricted to a revision of the early work and mapping (Navarro Latorre and Coello 1989), although recently petrological and geochemical aspects have improved con siderably (von Fritsch 1867; Ablay et al. 1998; Ablay and Marti 2000; Wiesmaier et al. 2011), as well as the analysis of potential hazards of the volcano (Araña et al. 2000; Márquez et al. 2008; Martí et al. 2008).

Particularly surprising is the almost total lack of geochronological information in many recent papers, since dating was restricted to a single age for the Montaña Blanca lava dome at the base of Teide (Ablay et al. 1995). Several authors (Araña et al. 2000) even stated that dating the Teide volcanic complex was unfeasible, due to the impossibility of applying K/Ar and $^{40}Ar/^{39}Ar$ techniques to this period and the absence of suit able organic material (charcoal) for radiocarbon dating. Eventually this proved possible neverthe less, and a set of 54 new ages provided for the first time precise age constraints of the recent eruptive history of Teide Volcano and its associated vol canism (Carracedo et al. 2003, 2007). These new geochronological data form a framework on which to base the understanding of the structural and volcanic evolution of the Teide volcanic complex, and establish a realistic assessment of eruptive history and potential hazards.

Besides the geological maps of the Teide volcanic complex (Figs. 1.13, 1.14, 1.15) other newly developed resources facilitate the study of this geological area. Very accurate topographic maps (1:5000 and 1:10000) with shaded relief DTMs, 1:1000 and 1:500 orthophotographs and other thematic maps can be downloaded from http://visor.grafcan.es/visorweb/.

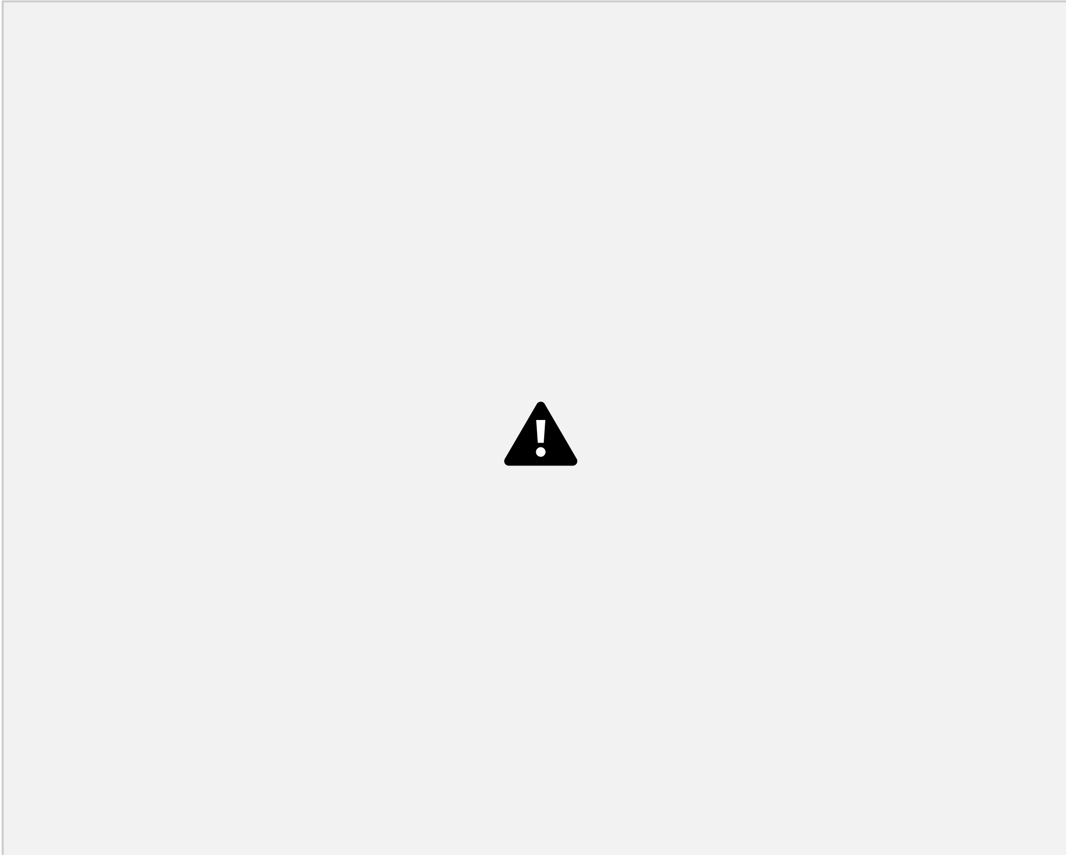
Teide National Park was inscribed on UNESCO's World Heritage List in 2007 (http://whc.unesco.org/en/list/1258) recognised for its natural beauty and its importance in providing





evidence of the geological processes that under pin the evolution of oceanic islands, comple menting those of existing volcanic properties on the World Heritage List, such as the Hawaii Volcanoes National Park (Carracedo 2008).

The contrasting magmatic series of Hawaii and Teide National Parks is probably the basic argument to demonstrate how excep tional Mt. Teide is and how the Teide National Park complements the only listed volcanic National Park in an intraplate island, the Hawaiian Volcanoes National Park (Fig. 1.16). The magmas of Mauna Loa and Kilauea volcanoes located within the Hawaii Volcanoes National Park correspond to the less evolved "basalts" of the magmatic evo lutionary series of intraplate islands. In con trast, the eruptions of Teide National Park span the entire series, including the more evolved rocks (phonolites, trachytes). Com bined, both sites represent the entire series on a large scale, with their corresponding erup tive mechanisms, volcanic features and land forms, justifying both Parks to be registered



in the UNESCO World Heritage List (in 1987 and 2007, respectively).

The Teide area is a major setting for interna tional research with a long history of influence on Geology and geomorphology, which, as we have seen goes back to the works of von Humboldt, von Buch and Lyell, and which made Mount Teide a significant site in the evolution of Volcanology as a science. Access within the Park is restricted these days, with visitors confined to marked paths and roads. Permission is required for collecting rocks and accessing Teide's summit.

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2 Geological and Geodynamic Context of the Teide Volcanic Complex

Juan Carlos Carracedo and Francisco J. Perez-Torrado

Abstract

Long-lived and lively debates commenced in the Canaries several decades ago regarding geological evidence that potentially helps to clarify important features and processes of ocean island volcanism. This included the true nature of the crust underlying the islands, the ultimate cause for the existence of the magmatism in the archipelago, and how large-scale morphological features that shape the islands, such as rift zones and giant landslide scars, have actually formed. The Canaries, once considered to be remnants of an older and larger sunken landmass, are now firmly integrated into the general framework of ocean island volcanism, thus gaining from the abundant geological information published in this field, and in return, providing volcanological data of global significance for ocean islands elsewhere.

2.1 Introduction

As volcanoes develop, they initially go through a constructive phase of evolution in which growth of the edifice through volcanic activity outpaces destruction through mass wasting (Hoernle and Carracedo 2009). During the destructive phase of evolution, mass wasting and erosion exceed volcanic growth and island vol canoes decrease in size until they are eroded to sea level. In this context, Teide Volcano cur rently represents the peak of development of Canarian volcanoes, the western islands not having yet attained this stage, and the eastern ones being already beyond it.

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2.2 The Canary Volcanic Province

Tenerife lies, in time and space, at the centre of the Canary archipelago, the emerged islands forming a 490 km-long chain that increases in age towards the African continent (Fig. 2.1). However, to understand the genesis and evolu tion of this archipelago we have to take into consideration not only the presently emerged islands (Neocanaries) but the older islands, already submerged (Palaeocanaries). As the African plate moves over the magma source, it cools and subsides, and the older volcanoes of the chain sink beneath sea level forming

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Fig. 2.1 Image (NASA) showing the Canary Islands, in the central east Atlantic off the

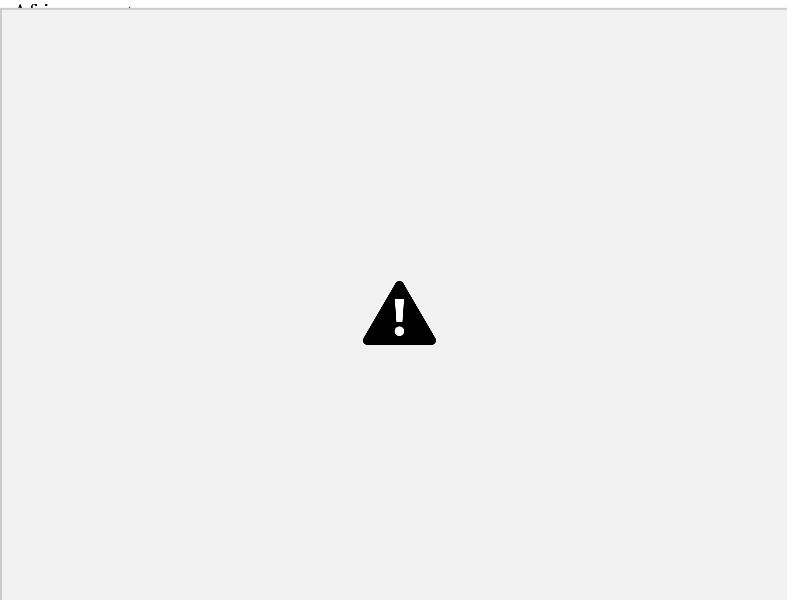

Fig. 2.2 Constant W–E aging of the Canary Islands, consistent with the progressive overlap oceanwards of the islands' aprons (in respective colours), starting at Fuerteventura-Lanzarote. Ages from Guillou et al. (2004). Aprons from Urgeles et al. (1998)

17° 16° 15° 14° 13° W
N
18°
5
4000
Lanzarote
20.2
AGE (MILLION YEARS)
14.6
La Palma
1.1
3000
2 1
9.4 11.9
1.7
3 4
Tenerife
Gran
2000
Fuerteventura
AFRICA
6
100 km
El Hierro
La Gomera
Canaria 1000

seamounts. Therefore, from a geological point of view, it is crucial to take into account the entire chain of islands and seamounts, summarised as the Canary Volcanic Province (CVP).

The west to east aging of the Canaries is very well documented from abundant radiometric age determinations and from marine geophysical data, indicating that the ages of the oldest rocks of the different islands consistently increase from west to east, whereas their aprons consistently overlap in the opposite direction (Fig. 2.2).

Evidence for age progressive volcanism in the submerged, northern part of the CVP (Fig. 2.3) comes from radiometric dating of seamounts (Geldmacher et al. 2001, 2005). As quoted by these authors, additional evidence for age progressive volcanism in the Palaeocanaries is proven by a widespread and time-transgres sive seismic layer, interpreted to reflect volcanic ashes from the Canary hotspot (Holik et al. 1991), present in oceanic sediments marking the Cretaceous/Tertiary boundary near Lars

4 km 0

-4 km

a) Las Hijas Smt. (active?)

a) El Hierro (1.1 M

a) La Palma (1.7 M

a) La Gomera (9.4 M

Tenerife (11.9 M

enerife (active?) (?

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0 100 200 300 400 500 600 700 800 900 1000 km

FUTURE CANARIES? PRESENT CANARIES (0-25 Ma) PALAEOCANARIES (25-68 Ma)

Fig. 2.3 Schematic diagram showing the age progressive chain of islands and seamounts that forms the Canary Volcanic Province (ages from Geldmacher et al. 2001; Guillou et al. 2004)

seamount, but getting younger towards the Canary Islands.

The CVP and the Madeira Volcanic Province (MVP) show some interesting common features. Both volcanic lineations follow parallel curved trends (Geldmacher et al. 2001), suggesting that the islands formed roughly at the same average rate and in the same direction over the last 70 My (Fig. 2.4).

2.3 Genetic Models for the Canaries

Different hypotheses have been published to account for the origin and structural evolution of the Canary Islands. However, two models have been the subject of a lively debate since 1975. Anguita and Hernan (1975) attributed the Canarian magmatism to a propagating fracture from the Atlas mountains, a model based upon structures that cut through the lithosphere to be the cause of, and the control for, the location of the Canary volcanism. Alternatively, Carracedo (1975) postulated an upwelling mantle plume (cf. Morgan 1971), a feature largely independent of the lithosphere.

Although volcanic chains can be formed in relation to transform faults or propagating frac ture zones (e.g., Azores), it is not easy to explain how large volcanic chains such as the Canary Islands can be generated within the context of decompression fracturing (McKenzie and Bickle 1988; White and McKenzie 1989). Furthermore, the lithosphere around the Canaries is among the oldest (Jurassic) and thickest on Earth, and therefore lithospheric faults would be problem atic to account for the large volumes of magma required to develop the Canary and Madeira Volcanic Provinces. Stress-induced magmatism, reactivation of pre-existing fracture zones (Favela and Anderson 2000) or propagating fractures (Anguita and Hernan 1975), may channel the magma inside the lithosphere and control the geographic arrangement of island volcanoes. However, hotspot trails intersecting fracture zones (e.g., Azores) generally do not show a systematic age progression as is evident in the Canary archipelago (Guillou et al. 2004).

Although local seismicity has been detected around the Canaries, no evidence has been found to prove the existence of any major fault con necting the Atlas mountains with the Canaries in any detailed geophysical studies of the area (Martínez and Buitrago 2002) or in the Atlantic around the Canarian archipelago (Watts 1994; Funck et al. 1996; Watts et al. 1997; Urgeles et al. 1998; Krastel et al. 2001; Krastel and Schmincke 2002). Features interpreted to be crustal fractures that predated and facilitated the

Fig. 2.4 Bathymetric map showing the Canary and Madeira Volcanic Provinces, consisting of islands and associated seamounts, in the central east Atlantic. Both

volcanic lineations follow parallel curved trends, suggesting that the islands formed roughly at the same same course over the average rate and followed the last 60 Ma (modified from Geldmacher et al. 2005)

formation of the Canaries, supporting their fracture-related origin (Geyer and Marti 2010), proved to be artifacts associated with ship tracks created during multi-beam data acquisition (Carracedo et al. 2011a).

Conversely, Canary and Madeira Volcanic Provinces age progression and curved synchro nous tracks, clearly different from the E–W orientation of fractures or transform zones in the East Atlantic (Geldmacher et al. 2005), can be better explained in the context of a hotspot model (Carracedo et al. 1998).

Several features of the CVP, however, are not easily explained within the context of the clas sical mantle plume model, particularly the exceptionally long period of volcanic activity of islands in the CVP (e.g., at least 23 My for Fuerteventura). Geldmacher and coworkers

(2005) proposed interaction of a Canary plume with edge-driven convection at the margin of the African craton (Fig. 2.5), consistent with further observations by Gurenko et al. (2006).

2.4 Hot Spot Dynamics and Plant Radiation

Macaronesia is a biogeographical region based on the existence of many common elements of flora and fauna. Recent phylogenetic analyses provided evidence of close similarities between species of the Macaronesian flora and the Iberian and Moroccan populations—particularly laurel forest communities, considered to be relicts of the Paleotropical Tethyan flora, which suggests a common origin.

The wet and warm climate in Southern Europe and North Africa during the Paleogene was conditioned by the influence of the warm east-to-west circum-equatorial global marine current, ensuring high temperatures and monsoon summer rains (Uriarte 2003). These conditions changed dramatically, and the tropi cal flora became extinguished on these conti nents as a result of the climatic deterioration

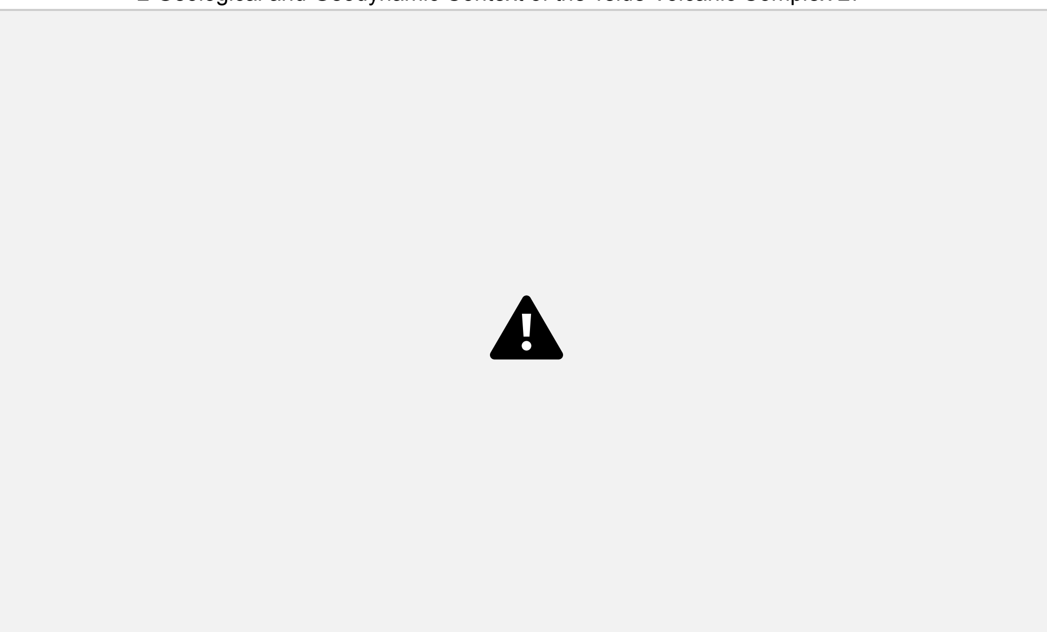


Fig. 2.5 Hotspot or mantle plume model that can adequately explain the linear younging direction along a NE–SW oriented path for the Canary Islands (Carra cedo et al. 1998). The conventional hot spot model cannot readily explain the long history of the Canary

triggered by the arrival of the glaciations at about 3.2 My (Meco et al. 2006) and the onset of the Canarian marine current. The Iberian and Moroccan regions became a late refugium for these populations until the late Pliocene.

However, the presence of palaeo-endemic floral elements in the laurel forests of contem porary Macaronesia is difficult to explain because of the age differences and the excessive distances from paleotropical sources for the ocean-crossing dispersal abilities of species.

A new approach, linking radiation of paleo tropical flora to the Macaronesian archipelagos and the hot spot model has been proposed by (Fernandez-Palacios et al. 2011), suggesting that large and high islands may have been continu ously available in the region for as long as 60 million years (Geldmacher et al. 2005), func tioning both as stepping stones and as reposito ries of paleoendemic forms and crucibles for neoendemic radiations of plant and animal groups. In turn, this model (Fig. 2.6) represents

Islands and the occurrence of historic volcanism in Lanzarote. However, a coherent explanation may be interaction of small-scale upper mantle convection at the edge of the African craton with the Canary mantle plume (modified from Carracedo 1999; Geldmacher et al. 2005)

additional, non-geological evidence that is con sistent with a hot spot origin for the Macarone sian archipelagos.

2.5 Absence of Significant Subsidence as a Crucial Feature in the Canaries

Possibly one of the most relevant differences in the geological evolution of the Hawaiian and the Canarian archipelagos is the absence of high rates of subsidence characteristic of the majority of mantle plume-related islands in the Canaries. While ocean islands generally rapidly subside below sea level to become guyots, the Canaries remain above sea level for very long periods (e.g., Fuerteventura [23 My; Fig. 2.7). Had the Canaries experienced a subsidence history similar to that of the Hawaiian archipelago, only La Palma and El Hierro would still be above sea level.

(a) (b)

Fig. 2.6 Large islands with high altitudes may have been continuously available in the region for as long as 60 million years (Geldmacher et al. 2005), serving both as stepping stones and as repositories of paleoendemic forms and crucibles of neoendemic radiations of plant and

20° W 10° W **70 Ma**

40° N

Atlantic Ocean

Iberia

SMVC

YES

Ampère & Coral Patch (31 Ma)

Ormonde (65-67 Ma)

YES MHS

Ma

40° N

20° W 10° W **55 to 30**

Atlantic

Ormonde
(65-67 Ma)

MHS

YES

Iberia

Lars
NO NO
30° N
Africa
30° N
YES
Anika
Lars
(68 Ma)
Africa
B 200 km CHS
200 km
(55 Ma)
(68 Ma) CHS
(c) (d) 20° W 10° W
20° W 10° W
40° N
20Ma <10Ma
40° N
Iberia
Iberia
NO
Ocean
CSM
Atlantic Ocean
Ormonde (65-67 Ma)
Atlantic
Ormonde
NO
Ampère & Coral
YES
NO
Patch
Ampère & Coral Patch (31 Ma)
YES
Seine (22 Ma)
NO
Seine
(22 Ma) YES
MHS
Lars
(68 Ma) Anika
Madeira
Volcanic
Province
Madeira
MHS
NO
Lars
Anika
Conception
30° N
Africa
YES
Fuerteventura
(55 Ma)
Conception Bank (30 Ma)
30° N Africa
YES
Canary
Volcanic
Bank
(22 Ma) 200 km 200 km
CHS
Province
CHS
Canaries

animal groups. This model may represent additional, non-geological evidence in favour of a hot spot origin for the Macaronesian archipelagos. MHS Madeira hot spot; CHS Canary hot spot; SMVC Sierra Monchique volcanic complex (modified from Fernandez-Palacios et al. 2011)

and the Evolution of the Canaries

Therefore, this particular feature of the Canarian archipelago, possibly related to the characteristics of the oceanic crust in this area of the NE Atlantic (very old and rigid Jurassic crust), accounts for the existence of Tenerife and Teide Volcano (Fig. 2.8), unfeasible in a sce nario of high-rate subsidence as on Hawaii.

2.6 Teide Volcano

The identical source and genetic processes recorded on the islands of the Canarian archi pelago in a hot spot context may account for their similarities. However, significant differ ences between the islands are evident in their volume, elevation, morphology and igneous rock types from W to E, reflecting the increase in age and progression in evolutionary stage.

In contrast with the Hawaiian and most oce anic islands, where subsidence plays a major role, the Canaries show remarkable long-term island stability. Mass wasting and erosion, eventually outpacing volcanic growth, to reduce the size of the islands until they are eroded to sea level, requires periods of time that can exceed 20 My (e.g., Fuerteventura).

The age-dependent ratio of subaerial to sub marine volume in the Canary Islands increases from the youngest western to the oldest eastern islands. However, the increase is not constant but shows a maximum in the central island of Tenerife, reflecting that the western islands have not yet attained the mature stage, while the eastern islands are already in an advanced phase of erosive decay (Fig. 2.9).

Therefore, although Gran Canaria, and prob ably Fuerteventura, also had central differenti ated volcanic complexes (e.g., Roque Nublo Volcano), they have been dismantled by erosion

Fig. 2.7 Schematic diagram illustrating significant differences in the evolution of the Hawaiian and the Canary oceanic archipelagos. The former (left) typify the life history of oceanic island chains derived from very active and fertile mantle plumes on relatively flexible, fast moving plates. These islands grow very fast and subside very rapidly into seamounts (the oldest emerged island of the Hawaiian archipelago formed about 6 My ago). In contrast, the Canaries originate from a less active hot spot that penetrates a slow moving old plate, and are composed of long-lived islands with slow growth rates. The main difference is the lack of significant subsidence in the Canaries, with islands remaining emerged until mass-wasted by erosion (modified from Walker 1990; Carracedo et al. 1998)

(Pérez-Torrado et al. 1995; Stillman 1999; Troll et al. 2002). Likewise, the western islands may develop similar central volcanoes in the geological future, but at this stage of evolution of the Canarian archipelago only Tenerife, representing the present evolutionary peak in the development of the Canaries, appears to meet the conditions for an active felsic central complex such as Teide Volcano.

A simplified synthesis of the evolution of the Canary Islands is shown in Fig. 2.10. About 2 My ago a significant change occurred in the sequential development of the islands. The consistent construct of the Canarian archipelago as a single-line chain split after La Gomera into a dual-line configuration. While the onset of each successive island started once the previous one was in decay, La Palma and El Hierro, still in an early stage of shield growth, are being constructed simultaneously. This duality may account for the remarkably slower progress of island construction in the new dual-line configuration compared to the single-line configuration, with an interval of more than 8 My between the onset of La Gomera and that of La Palma and El Hierro.

and

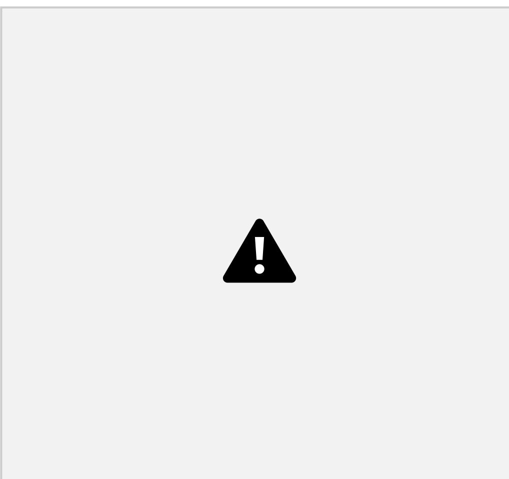


Fig. 2.8 The 3,718 m high Teide Volcano, nested inside the Las Cañadas Caldera, caps the centre of the island of Tenerife, and forms a part of the latest phase of volcanic construction on the island

2.7 Tenerife Before the Construction of the Teide Volcanic Complex

The Geology of Tenerife has been extensively

the island (Roque del Conde massif), and at the NW and NE edges (Teno and Anaga volcanoes). This idea was supported by later observations through water tunnels excavated for groundwater mining (Navarro 1974; Carracedo 1975, 1979).

In a different approach, Ancochea and co-workers (1990) described the island of Tenerife as integrated by three old massifs located at the three corners of the island, representing independent island edifices, each with its own volcanic history (Fig. 2.11a). Most recently, Guillou et al. (2004) proposed, on the basis of observations from galerías and stratigraphic, isotopic, and paleomagnetic data, that a large Miocene shield not only studied (e.g., Hausen 1955; Fúster et al. 1968; Ridley 1970, 1971; Abdel-Monem et al. 1971; Carracedo 1975, 1979; Schmincke 1982; Wolff 1983, 1987; Ancochea et al. 1990, 1999; Watts and Masson 1995; Bryan et al. 1998, 2002; Thirlwall et al. 2000; Wolff et al. 2000; Edgar et al. 2002; Walter and Schmincke 2002; Guillou et al. 2004; Pittari et al. 2005; Walter et al. 2005; Bryan 2006; Pittari et al. 2006; Carracedo et al. 2007, 2011a; Longpré et al. 2009).

Three main shield volcanoes form the oldest part of the island with compositions ranging from undifferentiated to evolved magmas (basanites to phonolites).

2.7.1 Shield Stage

Fúster et al. (1968) described Tenerife as a large shield volcano mantled by subsequent volca nism, with the core outcropping in the south of

forms the central part of Tenerife, but also extends towards the Anaga massif (Fig. 2.11b, c), under lying the NE Rift Zone and the Anaga volcano (Carracedo et al. 2007, 2011b).

In both models, the eruptive history of Ten erife is consistent with the evolutionary pattern of oceanic islands. It is characterised by the growth of three main shield volcanoes and a period of eruptive quiescence followed by post erosive rejuvenation volcanism, mainly at the centre of the island.

The first of these old shield volcanoes devel oped at the central part of Tenerife (the Central Shield, Fig. 2.12a). Erosion and plausibly north bound massive landslides mass wasted the northern, windward flank of the shield, which only outcrops at present in the southwest, leeward flank of the island, and close to the Anaga massif. This geological formation, the oldest outcropping in the island, has been dated by radioisotopic methods (^{40}Ar / ^{39}Ar and K–Ar) between 11.6 and 8.9 million years (Guillou et al. 2004).

About 6 My ago Teno volcano grew attached to the western flank of the Central Shield (Fig. 2.12b), which was probably already in eruptive quiescence at that point. The Teno shield developed in a relatively short period, from ca. 6.11 to about 5.15 My (Guillou et al. 2004; Longpré et al. 2009).

Finally, the shield-building stage of Tenerife was completed with the construction of the

Fig. 2.9 Computer-generated cross section of the Canary Islands, showing age versus height. At present, Tenerife represents the peak of evolutionary development in the Canarian archipelago (Carracedo et al. 1998)

Fig. 2.10 Sequential surfacing of the Canary Islands. An important feature of the Canary Islands is the lack of significant subsidence compared to other hotspot archipelagos, such as the Hawaiian Islands. If the subsidence rate in the Canary Islands were similar to that of the Hawaiian Islands, only La Palma and El Hierro would still exist as islands (modified from Carracedo

1999)

More than 20 million years ago

15 million years ago

From about 2 million years ago

9 million years ago

20-15 million years ago

12 million years ago

Anaga shield on the opposite side of the island, at the end of the northeast prolongation of the Central Shield (Fig. 2.12c). The Anaga volcano development took place in the interval from about 4.89 to 3.95 My (Guillou et al. 2004; Walter et al. 2005).

The main constructive activity in Tenerife ended about 3.5 My ago with the completion of

(b) ANAGA

(a) TENO ANAGA

Pliocene

MIO-PLIOCENE TENERIFE SHIELDS

W TENO

ANAGA E

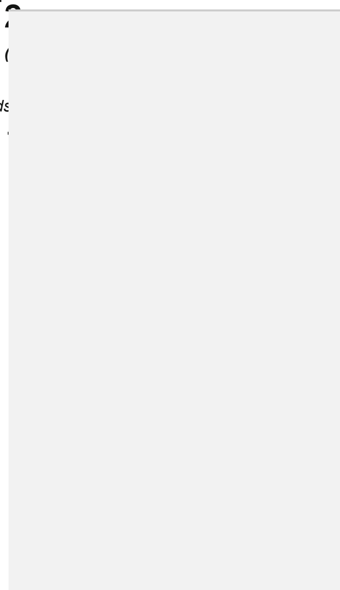
(c) Miocene

Pliocene

Carracedo et al., 2007 CENTRAL SHIELD

Fig. 2.11 a Ancochea and coworkers (Ancochea et al. 1990) described the island of Tenerife as the integration of three old massifs located at the three corners of the island, representing independent edifices, each with its own volcanic history. b An alternative idea proposed by Guillou et al. (2004) of the extension of the Central Miocene shield towards the Anaga massif underlying the NE rift zone and the Anaga volcano. c Cross-section showing the relative spatial arrangement of Tenerife shield volcanoes (Carracedo et al. 2007)

Fig. 2.12 Successive stages and associated main geological features in the development of Tenerife shield volcanoes and the posterosional rejuvenation central composite Las Cañadas Volcano



the three large shield volcanoes that, combined, form the bulk (90 %) of the present volume of the island. The main phase of activity of the Central Shield volcano ceased about 9 million years ago, entering a long (5.5 My) interval of volcanic repose and erosion (erosive gap), coinciding with the main phases of construction of the Teno and Anaga shields.

2.7.2 The Rejuvenation Stage of Tenerife: Las Cañadas Volcano

Renewed volcanic activity at the centre of the island formed Las Cañadas Volcano (Fig. 2.12d), from about 3.5 My ago (Ancochea et al. 1990, 1999; Huertas et al. 2002).

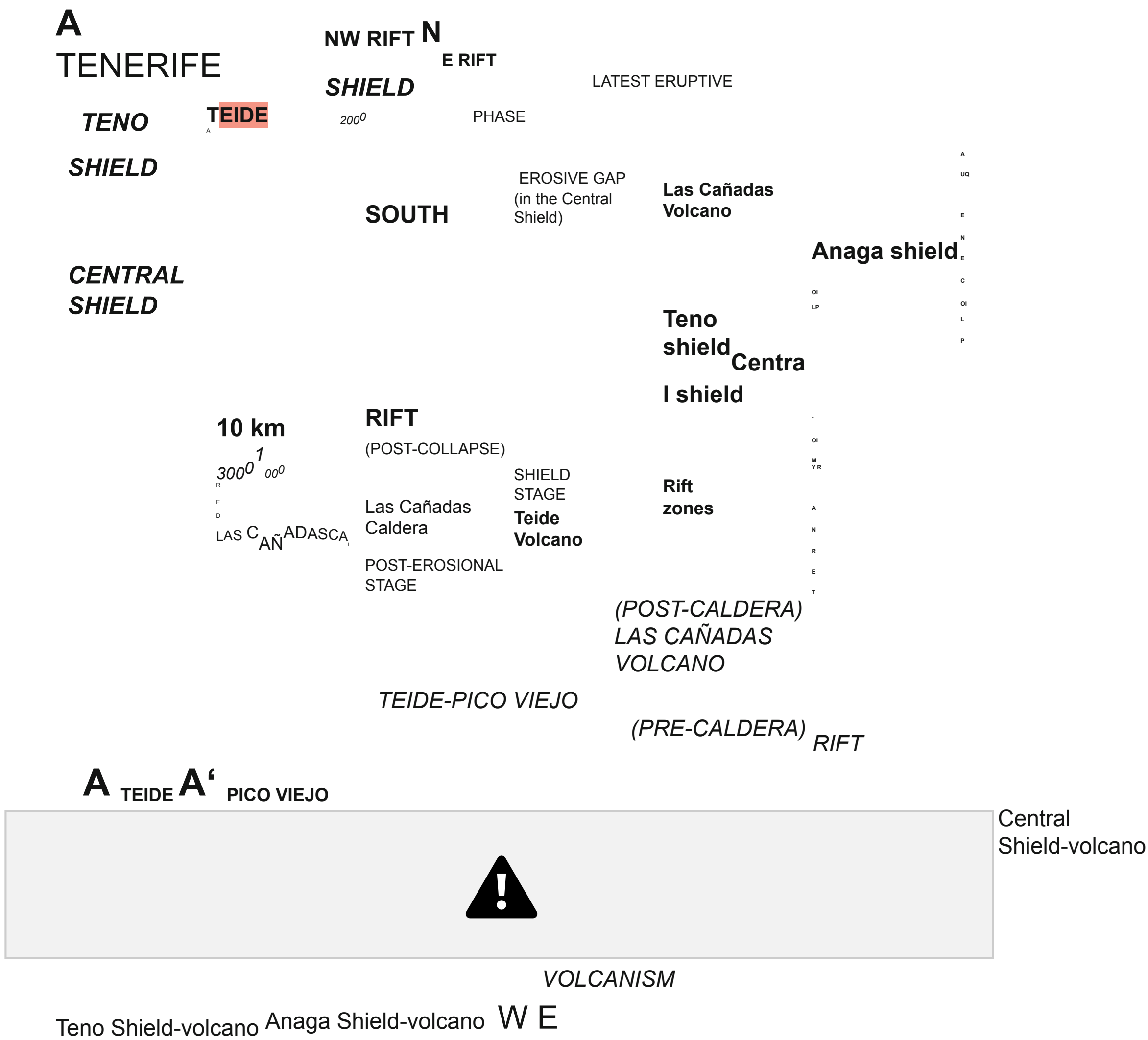


Fig. 2.13 Simplified geological map and cross-section of the post-erosional rejuvenation volcanism of Tenerife, the coeval central felsic Las Cañadas Volcano and the basaltic rift zones

This is the most visible stage of the volcanism of Tenerife, since the main part of the Teide Volcanic Complex (TVC) represents the latest stage of growth of Las Cañadas Volcano (LCV). The coeval activity in the last 3 My of the rift zones (Chaps. 4, 5) and LCV, the latter with abundant central felsic volcanism and the former with predominant fissural basaltic eruptions, cover most of the island's surface, blanketing the outcrops of the shield volcanoes already described (Fig. 2.13).

The LCV has been extensively studied (e.g., Booth 1973; Wolff 1983, 1987; Martí et al. 1990, 1994; Bryan et al. 1998; Ancochea et al. 1999; Cantagrel et al. 1999; Edgar et al. 2002, 2007; Huertas et al. 2002; Brown et al. 2003; Brown and Branney 2004; Pittari et al. 2005, 2006).

According to Ancochea et al. (1999), the LCV developed in three successive phases separated by large scale flank collapses (Fig. 2.14). Phase 1 was predominantly effusive and basaltic, but in phases 2 and 3 eruptions were more differentiated (trachybasalts and phonolites) and more explosive. In these phases, plinian episodes erupted pyroclastic falls and pyroclastic

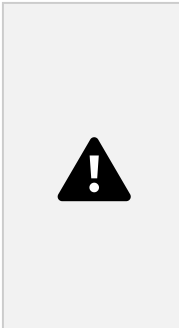


Fig. 2.14 Stratigraphic model for the Cañadas Edifice (modified from Ancochea et al. 1999)

flows, which were predominantly directed by dominant winds to cover the southern flank of the island. Martí et al. (1997) proposed three main basaltic-to-phonolitic cycles of develop ment for the Las Cañadas Volcano, each cycle initiated with mafic or intermediate eruptions that then evolved towards phonolitic products.

This succession of events seems to point to the simultaneous existence and interaction of rift zones and the felsic Las Cañadas Volcano. The former are probably responsible for the basaltic (fissural) eruptions and the successive flank collapses mentioned by these authors. In this context, the development of Las Cañadas Cal dera and the TVC could represent the pinnacle of this latest of cycles.

It is therefore possible that several cycles with similar characteristics occurred before the TVC developed. However, these cycles took place in a posterosional island, where rift zones should be expected to have considerably lower energy than the rifts on ocean-island volcanoes in their mainstage of development (e.g., La Palma, El Hierro, Mauna Loa, and Kilauea). Therefore, the most probable future scenario is that their intensity will likely decline, although this does not imply that the TVC will be the last cycle of its kind to take place on the island of Tenerife.

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3 The Teide Volcanic Complex: Physical Environment and Geomorphology

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Abstract
Teide volcano, nested inside the Las Cañadas Caldera, offers visitors a view on one of the most dramatic landscapes in the world. This is due to a combination of a long volcanic history that ranges from the Quaternary Las Cañadas volcano to the historical Teide lava flows, as well as to the particular climatic and geomorphological setting in which Tenerife lies. In this chapter we review the morphological imprint of the main volcanic and structural features (massive flank failures, Teide stratovolcano and rift zone growth) as well as the Late Pleistocene and Holocene non-volcanic landforms (aeolian and periglacial landforms, debris flows and alluvial fans), which provide a useful record of the morphodynamic history of Tenerife and the variable climate influences to which it is subject.

3.1 Introduction

The Canary Islands and especially the present day Teide National Park are, if you will, an open-air museum of volcanic geomorphology, one of the reasons why this area was declared a World Heritage Site by UNESCO in 2007. Despite the moderate frequency of volcanic activity, the volcanic landforms are very well preserved and their diversity is extraordinary. This is due to a combination of varied volcanic processes, a mild climate with rare torrential activity (at least dur ing the last 500 years), and a long and complex volcanic history. This diversity of volcanism has given rise to a wide variety of morphologies: (1) macroscale (910–9100 km^3) volcanic mor phologies such as central volcanoes with differ entiated lavas (Teide), and basaltic rift zones, (2) macroscale instability features such as giant

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collapse scars (La Orotava and Güímar, typically 910 km^3), (3) mesoscale volcanic morphologies represented by lava flows and cones (910^6 m^3– 1 km^3), the composition (and viscosity) of which influences the morphology of these eruptive landforms, (4) mesoscale landforms resulting from the morphodynamic and climatic history (e.g., alluvial fans, debris flows, nebkhas), and (5) microscale morphologies (e.g., periglacial features: pipkrakes and sorted stripes). Accurate topographical data and detailed geological map ping (Carracedo et al. 2007, 2011) have allowed the characterisation of the chronology and mor phology of alluvial fans, debris flows, and almost 50 lava flows emplaced over the last 15 ky. This latter information will be useful for further investigations using numerical modelling to understand lava flow propagation as well as hazard assessment (see Chap. 14).

3.2 Geological Outline

Despite the influence of climate and sea level variations, the landforms and long-term mor phological evolution of hotspot islands, such us the Hawaiian, Polynesian, Cape Verde and Canary Islands, are mostly controlled by their volcanic activity and instability. However, as a volcano moves away from above a hotspot, the decline of eruptive rates reduces flank instability and causes lower rates of erosion (Paris 2002). In the Canary Islands, the duration of the hotspot volcanic stage is temporally more extensive than in e.g., Hawaii because of the slow motion of the African plate, thus allowing further volca nic reactivation and landform rejuvenation (Carracedo et al. 1998).

The recent evolution of Tenerife Island has displayed the transition between the hiatus stage (Teno and Anaga shield volcanoes, inactive for 3.9 Ma) and the rejuvenated stage (central Teide and rift zones, still active) of ocean island vol canism. The central part of Tenerife, through which Teide grew, is composed of an eroded shield volcano (Roque del Conde, 11.9–8.9 Ma; Guillou et al. 2004), later covered by several phases of rejuvenation including the Las Cañadas stratovolcano at the island's centre (3–0.13 Ma). Towering above this edifice are Teide (\200 ky) and Pico Viejo (\30 ky) cen tral volcanoes nested inside the Las Cañadas Caldera. Moreover, to the northeast and the northwest are two rift zones, the NERZ and the NWRZ respectively, which converge towards the centre of the island and play a prominent role in its evolution (see Chaps. 4 and 5). Teide National Park, opened in 1954, offers visitors a breathtaking landscape, where landforms reflect the long and unique volcanic history. This however, comes at a price—the view comes hand in hand with the dangers of recurrent flank instability and erosion.

3.3 Massive Flank Failures and Their Morphological Imprint

Flank collapses affecting oceanic shield volca noes are the largest flank failures on Earth, usually involving tens of km^3 of volcanic material. This is the most important process in the destruction of ocean islands and generally occur at the end of the main shield building stage (Carracedo et al. 2011). The lower sub marine flanks of the Canary Islands are covered by 7,500 km^3 of chaotic deposits, mainly pro duced by debris avalanches, as well as by slumps and submarine debris flows (Masson et al. 2002). This volume represents 6 % of the total volume of the archipelago (Paris et al. 2005), and attests to the large role flank failures play in the mor phological evolution of the islands. On the northern flanks of Tenerife in particular, the combined thickness of multiple generations of debris avalanche deposits reaches 700 m with a volume of 500 km^3 (Watts and Masson 1995).

On Tenerife, Teide and Pico Viejo "twin volcanoes" are nested within a large depression open towards the northern shore—the Las Caña das Caldera. The large-scale morphology of the northeastern rift zone also incorporates similar types of depressions or embayments, i.e., the Güímar and Orotava Valleys. It is now com monly accepted that the origin of these

geomorphological imprints is related to flank instability, despite being sometimes associated with other processes as well, e.g., caldera col lapse in the Las Cañadas case (e.g., Giachetti et al. 2011).

3.4 Origin of Las Can˜ adas Caldera

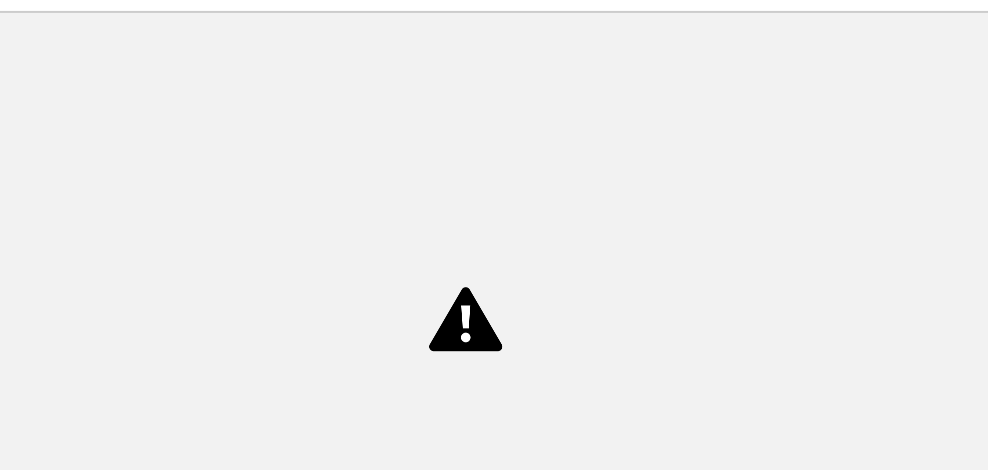
The Las Cañadas Caldera is an asymmetrical, horseshoe-type depression 15 km wide and open to the north, a product of the destruction of Las Cañadas Volcano, a former complex stratovol cano in the centre of Tenerife. The floor of the depression rises to 2,200 m a.s.l. in its eastern part and only 2,000 m in its western part, while the caldera wall rises to an average height of

*600 metres above the caldera floor. Intrusive remnants of the Las Cañadas stratovolcano mark a change in the slope of the caldera floor (Los Roques de García). The highest point of the caldera wall is Montaña de Guajara (2,717 m a.s.l.). However, at the junction with the Orotava Valley the wall is completely dismantled (El Portillo). Indeed, the caldera wall shows topo graphical, lithological and morphological varia tions which reflect the magmatic evolution and spatial migration of the active centre of the Las Cañadas Volcano from west to east (Marti and Gudmundsson 2000). The caldera wall also represents the result of destruction through vol cano instability and long-term erosion, recorded by several generations of colluvium, alluvial fans, and lacustrine and aeolian deposits.

A key hypothesis regarding the origin of Las Cañadas Caldera is a giant landslide on the northern flanks of Las Cañadas Volcano (Car racedo 1994; Watts and Masson 1995; Cantagrel et al. 1999). This is due to the spatial and chronological link between the Icod ‘‘palaeov alley’’, the large embayment in which Teide volcano and the Las Cañadas Caldera are loca ted, and the offshore debris avalanche deposits found to the north of the island (Masson et al. 2002). Offshore geophysical surveys north of Tenerife underline the existence of several enormous landslide deposits (tens to hundreds of cubic kilometres), the youngest located directly offshore from the Icod palaeovalley (Watts and Masson 1995, 2001). Vertical subsidence affecting the central part of Las Cañadas Vol cano has also been a further contributor to the formation of the Las Cañadas Caldera with several medium volume ignimbrite units on the flanks of Las Cañadas Volcano being associated with this process (e.g., Bandas del Sur) (Martí et al. 1994, 1997; Bryan et al. 1998). The ver tical caldera collapse history of the Las Cañadas volcano has likely weakened the edifice and thus prepared the structural framework for the Icod lateral collapse (cf. Troll et al. 2002). Thus the Las Cañadas Caldera walls are interpreted as the eroded remnants of a failure headwall, while the lateral scarps of the embayment are partly exposed near Icod and La Guancha. The timing of the Icod failure can be constrained by the age of the oldest lavas which fill the embayment (198 ky in the Salto del Frontón galería) and the uppermost lavas cut by the headwall: 240 ky in Icod (see Chap. 6), 170 ky in La Fortaleza and 180 ky in Diego Hernández (Ancochea et al. 1990, 1999; Martí et al. 1994). Considering the accuracy of the available dates, the Icod failure may hence have occurred around 200 ky. Erosion by numerous debris flows, rockfalls and rockslides on the steep headwall has subse quently enlarged the depression to the south.

3.5 Reconstructing the Icod Landslide and Teide Growth

The investigation and reconstruction of both the depth of the landslide surface and the thickness of volcanic infill in the Las Cañadas Caldera took advantage of the many ‘‘galerías’’ (a net work of large tunnels excavated to supply the island with water). Thirty-seven of these tunnels penetrate Teide volcano at different depth levels mainly in the northern flank (Márquez et al. 2008). The depth of the base of the breccia deposit related to the Icod landslide and the maximum depth of lava flow infill were used to correlate several geological cross sections, which in turn allowed mapping of the depth of the upper limit of the avalanche deposit. The



Las Cañadas Volcano
(a) (b)

Collapse

Teide and Pico Viejo

(c) (d)

Headward
erosion

Fig. 3.1 Reconstruction of the formation and evolution of the Las Cañadas Caldera: a Las Cañadas Volcano; b collapse of Las Cañadas Volcano; c erosion of collapse scarp; d present-day Teide and Pico Viejo volcanoes

correlation between the off- and onshore breccia distributions shows a U-shaped body covered by several hundred metres of lava flows and extending into the Las Cañadas Caldera and below Teide volcano (Márquez et al. 2008).

New insights into the geomorphological evo lution of Teide strata in the central part of Tenerife have recently been achieved by combining detailed field information with GIS-based modelling. Consequently a topographic reconstruction of the Las Cañadas Volcano, the surface after the giant landslide, and the surface of the erosive retrogra dation of the collapse scarp is now available.

The pre- and post-collapse maps of the Las Cañadas Volcano show the changes on the terrain surface caused by the different processes, including the collapse sensu stricto and those associated with the subsequent (mainly fluvial) erosion. From these topographic surfaces the corresponding Digital Elevation Models (DEMs) can be obtained and from there terrain slopes can be computed (Fig. 3.1). Detailed information about the calibration and validation methodology on the resulting DEMs can be found in Rodri guez-Gonzalez et al. (2010).

A cut and fill analysis process applied to four selected DEMs (the Las Cañadas Volcano, col lapsed surface of Las Cañadas Volcano, erosive retrogradation surface of the collapse scarp and the present-day Teide Volcano) allows compar ison of two raster surfaces of the same area and identifies locations where elevation values differ. These areas are traced to form polygons in an output vector object. The volume of material added or subtracted can then be calculated for each area.

The total original volume of the landslides from the Las Cañadas Volcano to the coastline can be obtained from the difference between the post- and pre-collapse DEMs (173 km^3). This compares favourably with a volume of about 150 km^3 calculated for the deposit by Masson et al. (2002). Likewise, the volume of erosive retrogradation of the collapse scarp is obtained from the difference between the post- and pre erosive border scarp (61 km^3), the morphological evolution of the failure scar depending on the temporal and spatial distribution of the sub sequent volcanism (Paris 2002). The high erosion rates of a scar, that occur directly after a failure,

are associated with debris flows, rockfalls and rockslides from steep slopes. The volumetric comparison between the failure scars and the submarine debris avalanche deposits remains difficult to establish, because of the post-collapse erosion of the scars, hemipelagic sedimentation draping the debris avalanche deposits, and the low accuracy of offshore volume estimates. Using the methodology outlined in Rodriguez-Gonzalez et al. (2010), the volume of eruptive products from Teide Volcano can be determined by cal culating the difference between the present-day DEM and the combined DEMs of the post-col lapse scarp and erosive retrogradation of the border. This calculates to *188 km^3.

3.6 La Orotava and Gu¨´ımar Flank Failures

The large-scale morphology of the northeastern rift zone shows that the Güímar and Orotava Valleys, can also be related to giant landslides. The famous "Valle de La Orotava" is a large amphitheatre-shaped coastal embayment (119 km^2), with two lateral scarps almost perpendic ular to the north coast of Tenerife (Carracedo et al. 2011 and references therein). This geome try suggests an origin related to a landslide. The entire surface of the depression is covered by post-collapse volcanism and sediments, which reach up to 500 m in thickness in some locations. The Los Organos sub-vertical slopes are con sidered to be the eroded remnants of the eastern headwall. The Risco Verde northward-facing wall corresponds to a structural discontinuity between Las Pilas lava flows (1.1–0.7 Ma; Ancochea et al. 1999) and the eastward-dipping Diego Hernández pyroclastic deposits (0.4–0.18 Ma; Mitjavila 1990, Mitjavila and Villa 1993, Ancochea et al. 1995), which are heavily eroded, and cannot be related to the La Orotava collapse. Otherwise, a large and arcuate slope break is observed between the southern Tigaiga-Fortaleza scarps and the western Los Organos scarp. The dip of the lava flows erupted from the Pico del Teide and Cordillera Dorsal eruptive vents varies from 0 to 10 in the caldera to 15–30 at the slope break. The ages of these flows range from 11 to 12 ky (Volcán del Portillo) to 37 ky (Montaña del Cerrillar; Carracedo et al. 2003). Thus, the southern headwall of the La Orotava valley is completely overlain by post landslide lava flows.

The La Orotava flank failure affected the northeastern rift zone and the Las Cañadas edi fice, the two volcanic structures being contem poraneously active for approximately 1 Ma. The large difference between the subaerial volume of the scar (57 km^3: Carracedo et al. 2011) and the submarine volume of debris avalanche deposits (80 km^3; Masson et al. 2002) suggests that the failure reached the highest parts of Las Cañadas III volcano (which was 2,500–2,700 m high, Ancochea et al., 1999). La Orotava landslide occurred between 690 ± 10 and 566 ± 13 ka. The maximum age of the failure can be deduced from the age of the topmost materials which are cut by the headwalls and rims of La Orotava Valley. The 270 ky lava flow dated by Ibarrola et al. (1993) is clearly cut by the western rim of the collapse, but Carracedo et al. (2007) found a 566 ky old lava flow overlapping the eastern rim.

The Güímar Valley corresponds to another flank collapse affecting the northeastern rift zone. With an area of 129 km^2 and a missing volume of 44 km^3, it is comparable in size to the La Orotava Valley (Giachetti et al. 2011). The timing of the Güímar collapse is well constrained by the ages of the youngest lavas topping the walls of the depression (866 ky) and oldest lavas filling the failure scar (831 ky; Carracedo et al. 2011). The morphological evolution and erosion rates of both La Orotava and Güímar failure scars are influenced by the temporal and spatial distribution of the subsequent volcanism filling the embay ments, as previously demonstrated for other fail ures on La Palma and La Gomera (Paris and Carracedo 2001; Paris et al. 2005). Areas preserved by post-collapse volcanism are dissected by deep canyons, and retrograde erosion affects the head walls (e.g., western part of the Güímar Valley).

3.7 Morphology of Teide–Pico Viejo Central Volcano

Teide Volcano (3,718 m a.s.l.) fills the Icod embayment, from the central Las Cañadas Cal dera and beyond to the north coast of the island. After *200 ky of volcanic history, Teide is composed of distinct eruptive vents and mor phological features, such as the two stratovol canoes, many strombolian cones, and also lava domes and associated lava flows. The lava flows are more extensive on the northern flanks of the volcano than on the southern one, due to the geometry of the landslide scar that opens and dips to the north. The length of the flows from the eruptive centres to the north coast is around 12 km, mostly on 5–20 slopes. The transition from the lower flanks to the central volcano itself is marked by a slope break at 1,900 m a.s.l. on the northern flank and at 2,300 m a.s.l. on the southern flank. The central volcano has a cone base 8 km in diameter and displays steep slopes (20–40). A single shaded relief view can be used as a first order summary of the great variety of volcanic landforms of different ages observed on Tenerife (Fig. 3.2).

The 200 m high summit cone (El Pitón) was formed at the end of the last Teide eruption (1,147 ± 140 BP Lavas Negras; Carracedo et al. 2007) and the material composing the cone is often altered by fumarole activity near the sum mit crater. The crater is 100 m wide, less than 30 m deep and partially filled by lava and rock falls. The flanks of the volcano are mostly cov ered by the glassy phonolite of the Lavas Negras flow lobes. The thickest and largest flows are directed towards the southern and the northern flanks, as Pico Viejo has obstructed their path to the west. These materials are well exposed on the southeast and northeast flanks. Erosion has pro duced gullies between the lava flows, generating debris falls and flows to the base of the volcano, the most relevant debris fans being observed at the bottom of Las Calvas ravine (northwest flank: Corredores Munich) and near the cable car station (south flank). The spatial distribution of the lava flows reveals buried morphologies of "Old

Teide", such as (1) a phreatomagmatic vent on the northwest flank at 2,700 m a.s.l., associated with surge deposits found in Las Calvas (see Chap. 12) a 700 m deep depression buried by the terminal cone at 3,500 m a.s.l., open to the east and associated with pyroclastic deposits. Thus, the lavas of "Old Teide" exposed on the east flank could have erupted from this previous depression, which may correspond to a crater or a small graben.

Pico Viejo appears as a secondary volcano on the southwestern flank of Teide, at the junction with the northwest rift zone (NWRZ). Episodi cally active for 27.5 ky (Carracedo et al. 2007), Pico Viejo produces less differentiated lavas than those of Teide and its flanks are less steep (15–35). The main crater (800 m wide and 140 m deep) is truncated to the southwest by a deep phreatic vent (300 m wide and 130 m deep). Surge deposits overlying the remnants of a lava lake can be observed on the southern walls of the main crater.

Finally, the majority of the recent volcanic activity of Teide volcano has been associated with peripheral vents on its lower slopes (e.g., Roques Blancos, Pico Cabras, Montaña Abejera, and Montaña Blanca: see Chap. 6 for ages). The activity of these vents involved at least seven voluminous phonolitic flows on the north flank, three of them reaching the coast (see Chap. 14 on hazards). These lava flows have a blocky texture and are channelled by lateral levees. Their thickness is more than 30 m, but can reach 160 m in Roques Blancos (northwest flank of Pico Viejo). Considering their high volume ([0.5 km^3), these eruptions might last for weeks to months. As a side effect, these massive flows seem to locally have improved the flank stability of Teide Volcano.

The pre-historic and historic lava flows located on the west and southwest flanks of Pico Viejo (e.g., Montaña de Chío, 3932 ± 213 BP; Montaña Reventada, 900 ± 150 BP; Las Na rices, 1798) represent the junction between the Teide central volcano and the northwest rift zone, as demonstrated by the occurrence of intermediate compositions and magma mixing

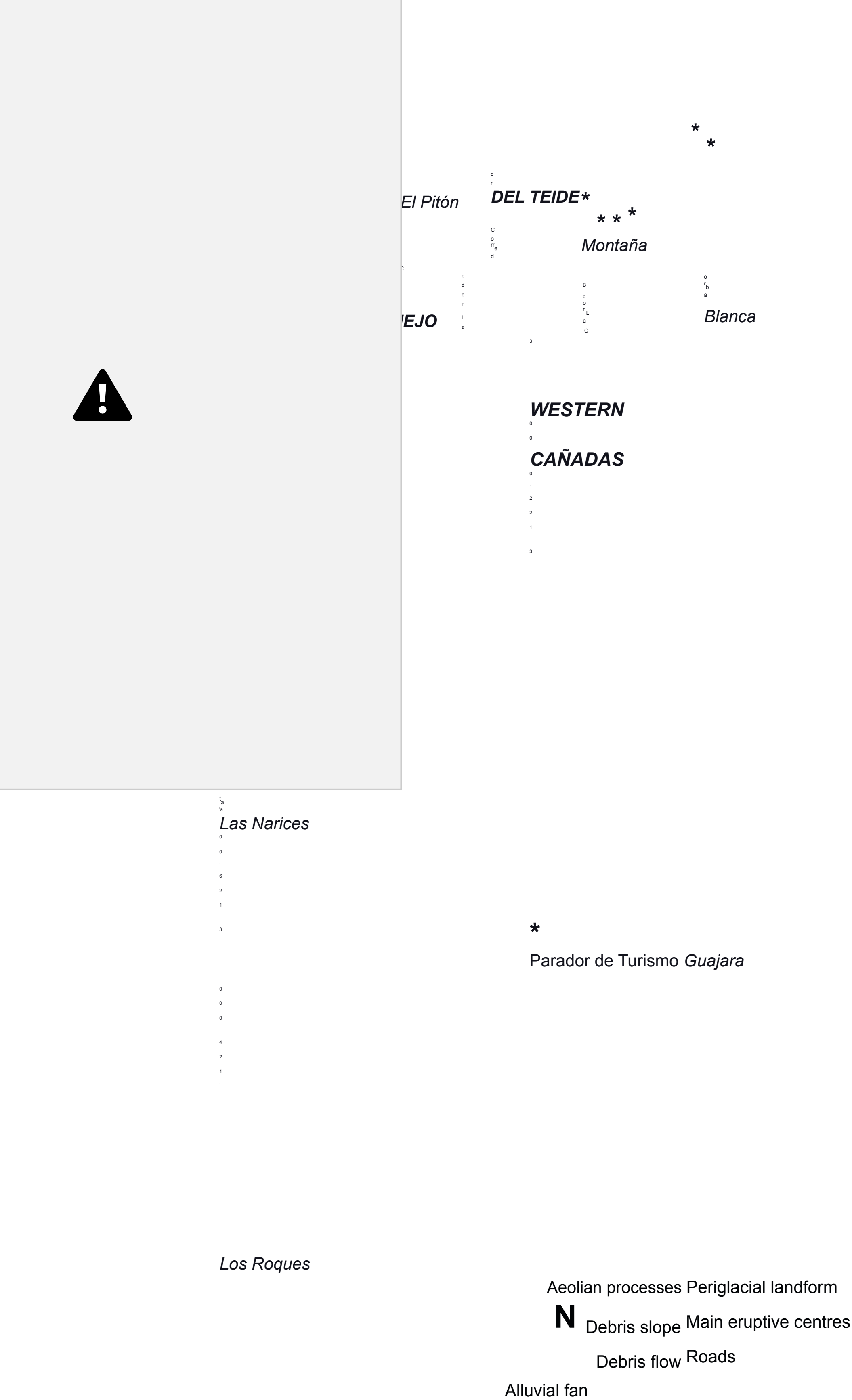


Fig. 3.2 Shaded relief view of Pico del Teide and Pico Viejo volcanoes, showing late Pleistocene and Holocene non

volcanic landforms (UTM coordinates, WGS84 datum)

features between mafic and phonotephrite to phonolite magmas (Wiesmaier et al. 2011; see Chap. 11).

3.8 Young Volcanic Landforms of the Rift Zones

Volcanic rift zones display a characteristic morphology defined by the alignment of erup tive centres along a main axis, a lateral distribution of the lava flows from this axis and the absence of a central volcano (see Chaps. 4 and 5). Volcanic rift zones are 10–20 km long and 1,500–2,000 m high (e.g., El Hierro and La Palma islands). The northeast rift zone of Ten erife (Cordillera Dorsal; see also Chap. 5) is built between the Anaga shield volcano (4.9–3.9 Ma; Guillou et al. (2004) and the Las Cañadas Caldera. The available K–Ar ages suggest that the main volume of the NERZ was accumulated in a relatively short time span

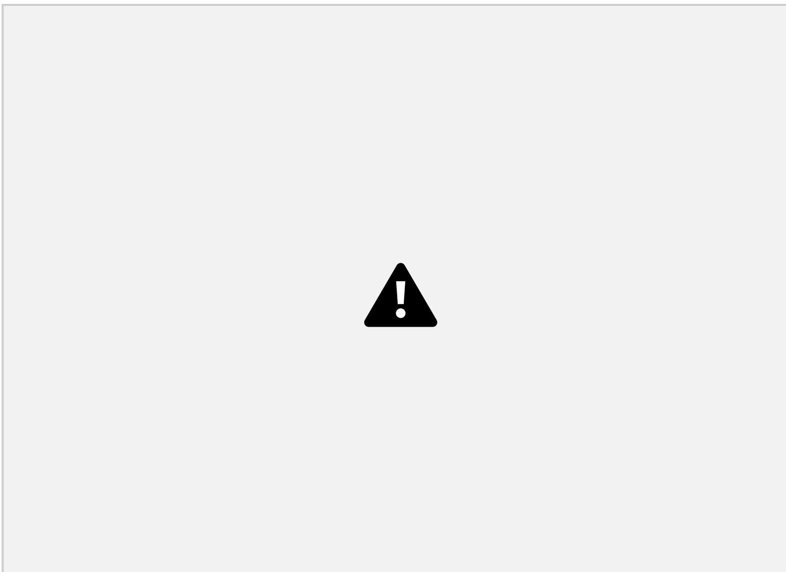


Fig. 3.3 Photographs and 3D images of the different morphologies of volcanic cones along the rift zones of Tenerife. a the cone of Montaña Reventada (900 ± 150 BP) is breached towards the west by lava

(1.1–0.83 Ma; Carracedo et al. 2011). The rift zone volcanics extend up to the eastern part of the Las Cañadas Caldera (e.g., Montaña Most aza, Arenas Negras). Despite the historical eruptions (1704–1705), the NE rift zone appears to be declining in activity, with less than 10 % of its area covered by lava flows erupted during the last 12 ky. The volumes of lava emitted (*150 9 10^6 m^3) during this interval are lower than those of the NW rift zone (*800 9 10^6 m^3) within the same episode, making the NWRZ the most active volcanic structure of the island, with 95 % of its area covered by lava flows emitted during the last 12 ky. In comparison to the Las Cañadas Cal dera the landscapes of rift zones vary little and are mainly composed of strombolian lapilli (picón) and associated ‘a‘a¯ lava flows (malpaís) (‘a‘a¯ flows are defined by an extremely irregular surface, usually covered by decimetric frag ments of broken crust). The diversity of this landscape is therefore controlled by the rela tionship between the age of the lavas and the bioclimatic conditions (vegetation, exposure and altitude).

flows; b Montaña Samara is a strombolian cone with a single central crater; c spatter cones aligned on the south flanks of Teide Volcano, around the cable car station; d fissure cone of the 1798 eruption (Narices del Teide)

3.8.1 Morphology of Volcanic Cones

Volcanic cones are the most common volcanic landforms on Tenerife (Fig. 3.3). They are built up by accumulation of pyroclastic debris around an eruptive vent. The size of the fragments, from ash and lapilli to bombs several metres in diameter, depends upon the VEI of the explo sions (Wood 1980a, b). Gas emissions force the vent open and the ejected pyroclasts follow ballistic trajectories with most falling near the vent to generate a slope with an angle of repose of about 308. The geometry of cones is mostly controlled by the structure of the vent (fissure or central vent) and the pre-existing topography, but also by the wind direction during the erup tion. Cones are rapidly eroded, both by internal processes (hydrothermal activity, instability demonstrated by fissures and slope breaks), further volcanic activity (in the case of poly genic volcanoes) and by external processes (smoothing of the summit ridges, crater filling and accumulation of material downslope). Thus, the morphology of volcanic cones is the result of a combination of volcanic and morphoclimatic

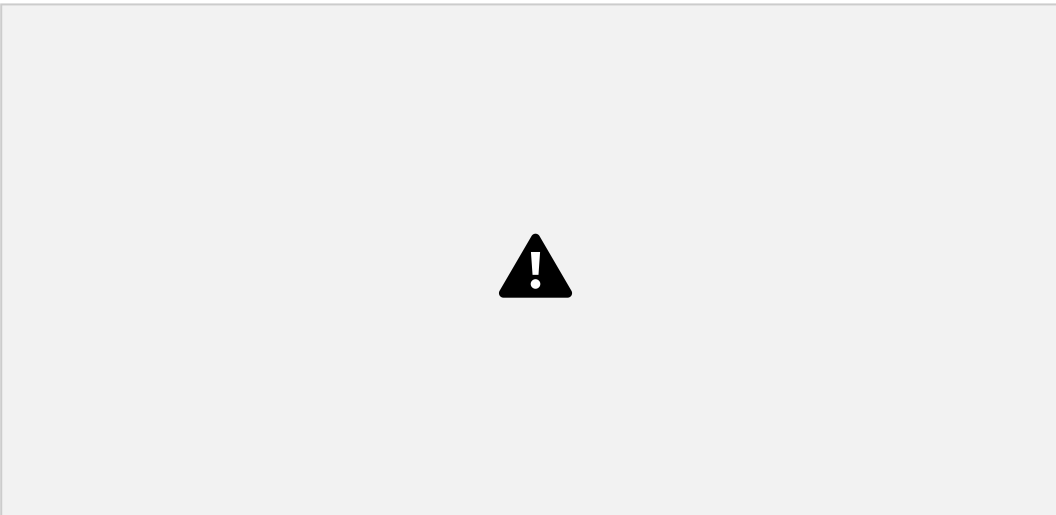


Fig. 3.4 Comparison of vegetation covering two strombolian cones located at different altitudes: left, Montaña del Banco (13 ka, 1,280 m a.s.l.); and right, Montaña Mostaza (15 ka, 2,240 m a.s.l.)

processes. The degradational evolution of these landforms can be broadly correlated with the time they have been exposed to erosion (Wood 1980a, b; Hooper and Sheridan 1998). However, the possibility of accurately dating cones by morphometric analysis is limited (Rodriguez Gonzalez et al. 2012) as cone morphometry in Tenerife is controlled by bioclimatic (Fig. 3.4) as well as lithological parameters (hydrothermal alteration, permeability and induration, etc.).

The recent activity of the rift zones of Tenerife has built dozens of volcanic cones, especially along the northeastern and northwestern rift zones. The northwestern rift zone (NWRZ) dis plays a wide variety of strombolian cone mor phologies (Romero 1992): single cones with a central crater or with nested craters, coalescent cones with multiple ridges, the most common case being a simple cone without associated la vas, and hornitos, which are secondary vents from the surface of lava flows. Further, the interaction between the water table and the magma can lead to phreatic explosions (e.g., upper vent of the 1798 fissure) or phreatomagmatic pulses (e.g., late activity of Montaña Reventada, as evidenced by phreatomagmatic deposits on the rim of the main crater). This can also influence the mor phology of the volcanic edifice by enlarging the diameter and reducing the height of the cone. Lastly, when the gas content of the magma is low, the pyroclastic fragments are larger, more ductile and tend to weld together on landing, thus building a spatter cone, characterized by steep slopes (e.g., Montaña Majúa spatter cones near the cable car: see Fig. 3.3).

3.8.2 Morphology of Lava Flows

Historical and pre-historical lava flows on Tenerife (Fig. 3.5) are mainly ‘a‘ā flows. Their overall topography masks a chaotic morphology of lava channels, levees and tubes, penitents (tilted fragments of lava crust), lava balls and debris at the front of the flows, islets in the middle of main flows and hornitos (see Chap. 12). Pahoehoe lavas are also exposed in the western part of the caldera (pahoehoe lava flows have a smooth surface, are composed of coalescent tubes and tongues and their propagation is controlled by the equilibrium between the cooling crust and the eruptive rate). They were emitted during the 1798 eruption (Las Narices) and also during the early eruptions of Pico Viejo where lavas overflowed the western rim of the caldera, spread over the northwest and southwest flanks

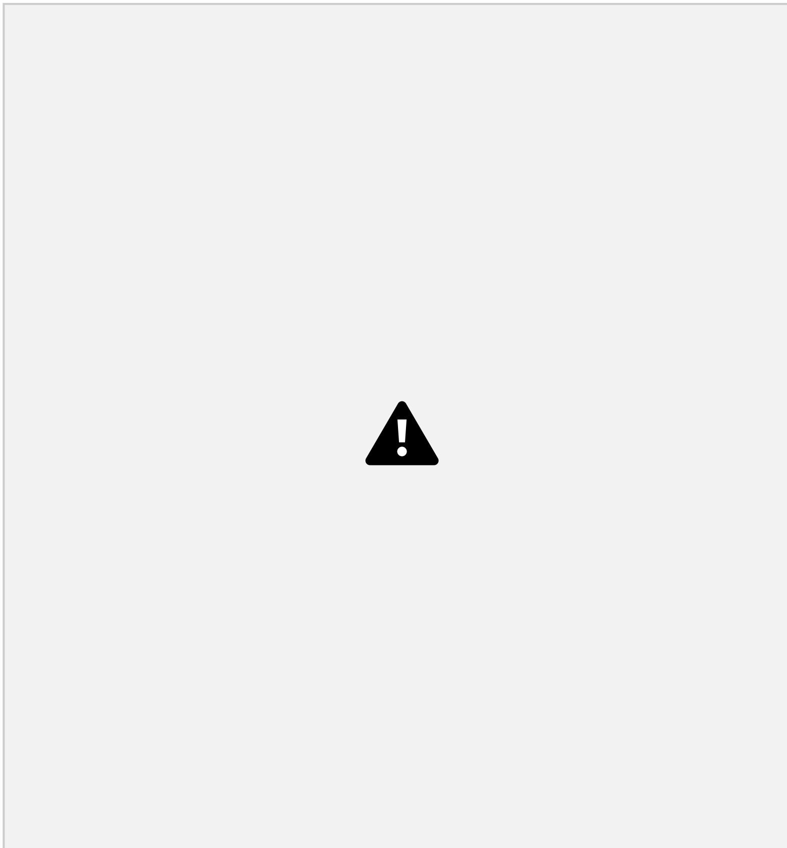


Fig. 3.5 Different morphologies of lava flows along the rift-zones of Tenerife. a ‘A‘ā flow channelled in a barranco (Fasnia, 1705 eruption); b ‘A‘a flow of the 1706 eruption (Garachico-El Tanque); c lava tongue of the Reventada eruption (900 ± 150 BP); d thick phonolitic flows of Roques Blancos (1712 ± 153 BP); e pahoehoe flow of Pico Viejo, covering remnants of Las Cañadas Volcano (Roques de García); f: cross-section showing lava tongues and tubes of a pahoehoe flow from Pico Viejo Volcano (27030 ± 430 BP)

and finally reached the coast near Los Gigantes and Icod.

The surface alteration and colour of the lava flows usually reflect their age, the darker flows being the younger (e.g., Lavas Negras—the black lava flows of 1798 in the Las Cañadas Caldera). Nevertheless, in Tenerife, altitude and exposure to rapid temperature changes and humidity are also predominant factors controlling the weathering or preservation of lavas. For instance, the 1706 lava flow in Garachico, on the wet northern flank of the island, carries much denser vegetation than the 1705 lava flow in Arafo, on the southern flank of the island, which is less exposed to humidity. As a result, the wetter areas are carry more vegetation, weathering weathering is more intense and the lavas are very poorly preserved.

The morphological characteristics of lava flows help to constrain relationships between their runout length, area, surface morphology and erupted volume (Walker 1973; Wadge 1978; Pinkerton and Wilson 1994). Mafic and felsic lava flows are clearly distinguished on the basis of their volume vs. aspect ratio. Aspect ratio is often calculated as the ratio of flow length to flow width, with width being sometimes highly variable along the flow. To counteract the errors induced in the aspect ratio calculation by vari able flow width, we used the area of a circle equal to the flow area as an alternative value.

Variations in the aspect ratio reflect the petrology and viscosity of lava flows. Basaltic flows give lower aspect ratios compared to the more viscous phonolitic lava flows. Both lava types are able to reach the coast, covering a distance of 10–15 km (Figs. 3.6 and 3.7). The phonolitic flows are thick and more voluminous (1.4 km^3 for Roques Blancos and 0.7 km^3 for the last eruption of Teide), whereas the lava

Fig. 3.6 Some morphometric characteristics of Holocene lava flows in Tenerife. Basic and felsic lava flows are clearly distinguished on the basis of their volume vs. aspect ratio. The runout length of flows is not significantly influenced by slope angle, but rather by lava viscosity, eruptive rate and cooling

12
10
8
6
4
2
0
0 1 10 100 1000 10000 **Volume**

(10^6 m^3)

20

Felsic
14
12
10
8
6
4
2
0

20
18
Basic
16
Felsic
14

Basic
18
16

0

flows of the rift zones have volumes rarely exceeding 100 million m^3 (Cueva del Ratón, 75 9 10^6 m^3; Montaña Cascajo, 92 9 10^6 m^3; and Montañas de Chío, 110 9 10^6 m^3). The volume and duration of historic eruptions along the NW rift-zone of Tenerife allows determina tion of their eruption rates. The high eruption rate of the 1706 Garachico eruption (71 m^3/s) is in the range of the 1669, 1980 and 1989 erup tions of Etna, and the 1977–1984 eruptions of Krafla in Iceland (cf. Harris et al. 2000; Crisci et al. 2003). The remaining historic eruptions in Tenerife were less productive (\13 m^3/s), which compares well with examples of the 1983–1987, 1991–1993, 1999 and 2001 eruptions of Etna volcano (Calvari et al. 1994). Considering the range of eruption rates and aspect ratios, the

5 10 15 20 **Runout length (km)**

duration of past eruptions of the NW rift zone may have been typically in the order of a week to one month. However, with individual vol umes greater than 500 9 10^6 m^3, the phonolitic eruptions of Roques Blancos, Pico Cabras, A bejera Alta and the last eruption of Teide (Lavas Negras) may have lasted several months. The total volume of felsic lava produced in the cen tral area of Tenerife during the Holocene exceeds some 4 km^3.

The northern coast near Buenavista del Norte and Icod de los Vinos is interesting from a morphological point of view (see Fig. 3.7). Holocene lava flows of the NW rift zone fossi lised the cliff and built coastal platforms (e.g., Garachico, Liferfe, and Montañas Negras). Considering the ages of these lavas and the

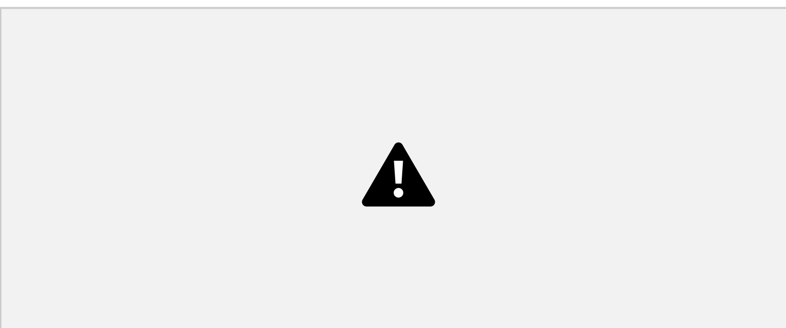


Fig. 3.7 Holocene lavas flowing down from the NW rift-zone, fossilising the cliff and building coastal plat forms on the northern coast of Tenerife. Considering the

coincidence of the platforms with present-day sea level, the island of Tenerife may have been vertically rather stable over at least the last 8 ky. In any case, the surface area of the island increased by these processes and the old cliffs are presently located 2.5 km from the coast at Buenavista del Norte. The lava flows of Pico Viejo were emitted during the last glacial period (27–14 ky), a time characterised by a lower sea level (approximately -110 m). They are now cut by active cliffs and their seaward extension remains to be established.

3.9 Late Pleistocene and Holocene Non-Volcanic Landforms and Climatic Influences

Due to recurrent volcanic activity during the Quaternary, most of the landforms on Tenerife are of volcanic origin, but variably reshaped by erosion. However, Holocene landforms pro duced by periglacial, aeolian and fluvial pro cesses can also be recognized (see Fig. 3.2) and can be used to reconstruct the paleoclimatic history of the high-altitude areas of Tenerife. An aspect of recent interest has been the influence of the growth of Teide volcano and peripheral domes on the microclimate and morphodynamic evolution of Las Cañadas Caldera and its walls.

The Teide edifice is usually above the ‘sea of clouds’ that accumulates on the northern flanks of Tenerife Island and is exposed to trade winds.

ages of these lavas and the coincidence of the platforms with the present-day sea level, the island of Tenerife may have been vertically stable for at least 8 ka

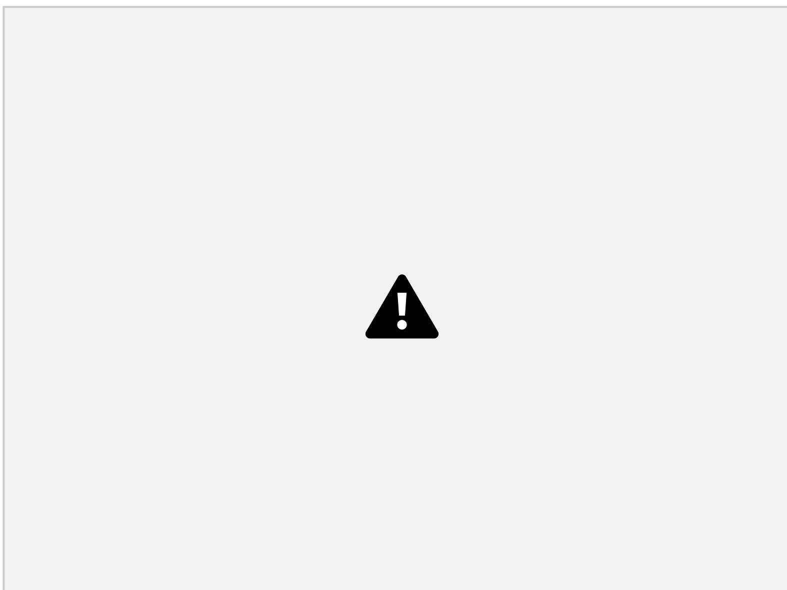
This is a common feature of all Canary Islands and results in a wetter climate on the northern side of the islands and a semiarid to arid climate on the southern flanks. The climate is charac terized by a stable atmosphere and dry air (90 % of the year), bright sunshine (3448.5 h/year) and scarce rainfall (360–501 mm/year, 43.4 days including 12.7 days of snowfall) (Bustos and Delgado 2000). Teide flanks are exposed to significant climatic variations due to slope ori entation and altitudinal changes; the absolute minimum temperature recorded at 2,372 m a.s.l. is -9.1 8C, and -16.8 8C at 3,530 m a.s.l. (Criado 2006). We can assume that above 3,000 m the temperature is below 0 8C for 11 months/year. Thus, the presence of water in rocks and regolith combined with frost activity become important factors in morphogenesis.

Evapotranspiration ranges between 546 and 682 mm/year, causing aridity from July to October. Northwest is the dominant wind direction in the Teide area (50 %), with a mean velocity of 8.1 m/s and a record high of 53.2 m/s. The wind can entrain sand-size and finer particles over the entire area and in some places dust devils are frequent and powerful (Criado et al. 2009; Höllermann 1984) (Fig. 3.8).

3.9.1 Aeolian Landforms

Aeolian landforms are scarce and small in the landscape of Teide National Park. Two types of

Fig. 3.8 Dust devil on Ucanca playa. 7 July 2010 (photo: Nick Brooks)



aeolian landforms can be distinguished. The first derives from the interaction between the aeolian sand fluxes and the shrub vegetation (Spar tocytisus supranubius), forming nebkhas, which are natural accumulations of wind-borne sedi ments within or around the canopies of plants. The second type are ‘climbing-dunes’ which appear when the wind, carrying sediments, comes up against a steep relief. These aeolian landforms are mostly located in the endorheic areas at the base of the Las Cañadas Caldera walls, reworking the distal facies of alluvial fan systems. Occasionally, the surface consists of a pavement of closely packed, interlocking angu lar or rounded rock fragments of pebble and cobble size formed by removal of loose, fine grained particles, a process known as aeolian deflation (Criado et al. 2009).

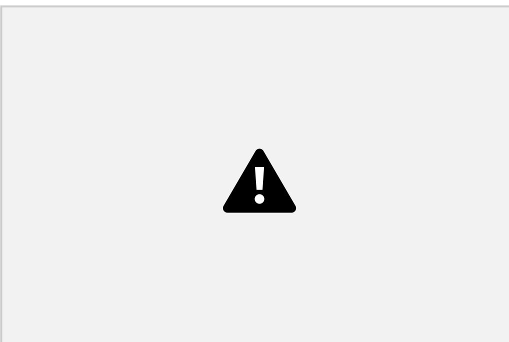
3.9.2 Periglacial Landforms

Periglacial processes from the highest altitude regions of Tenerife have been described since the 1970s (Höllermann 1978; Morales et al. 1977, 1978). Soils and rocks become sufficiently wet to allow water to freeze after heavy rains and snow melt. Frost layers can reach 8–10 cm in thickness

(Höllermann 1978; Martínez de Pisón and Qui rantes 1981) and the soil can be frozen for 3–11 months/year near the summit (Quirantes and Martínez de Pisón 1994; Rodríguez et al. 2010). Frost weathering is very active in the La vas Negras (last eruption products of Teide vol cano), producing debris slopes at the front and flanks of these lava flows, especially on the northern slopes (Corredor de la Isla and Corre

dores Munich). Pipkrakes (needle ices) are very common on flat areas, the active layer being some millimetres to a few centimetres thick. These ice pieces are formed when the liquid water in the soil rises through capillary action to the surface finding air temperatures cold enough to freeze the water. While growing, they push away small soil particles. On sloped surfaces, soil creep may be significantly influenced by needle ice develop ment. Soil movements derived from the frost cycle produce small sorted stripes and polygons. Sorted stripes are frequent in areas occupied by basaltic lapilli (Fig. 3.9), while polygons occur in the Pico Viejo crater, Los Gemelos sector and also in Montaña Rajada crater (Martínez de Pisón and Quirantes 1981; Quirantes and Martínez de Pisón 1994).

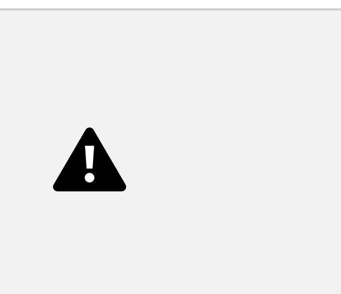
Another periglacial process includes gelifluc tion, a downslope mass movement of soil due to



than 100 m with slopes ranging between 30 and 408. The largest ravines are, from east to west, Corredor Mario (0.34 km^2), Corredor La Corbata (0.74 km^2) and Corredor La Bola (0.50 km^2).

The hydrographical networks of the barrancos are very simple and the head of these barrancos do not display widening. They have developed since at least the Late Pleistocene, as the ravines cut rocky outcrops of Teide older than 32 ky

small polygons. Playa la Grieta,



Pico Viejo volcano

Gelifluction lobes

Fig. 3.10 Pumice deposit shaped in lobes by gelifluc tion, on the northern rim of Pico Viejo crater

the freeze–thaw action upon waterlogged top soils. The most common result are gelifluction lobes, which always appear in pumice ash-fall deposits, are a few metres long and are similar to terraces (Fig. 3.10). The movement of these lobes may reach *50 cm/year (Höllermann 1978).

3.10 Fluvial Landforms

3.10.1 Ravines ("Barrancos")

Ravines (locally known as barrancos) on the flanks of Teide volcano are almost rectilinear and extend in a radial fashion from the summit. Many more barrancos were in existence around Teide until recently, but were buried by the eruption of the Lavas Negras (1.2 ky BP).

The heads of the barrancos are in several cases higher than 1,200 m; their depth normally is less

(Carracedo et al. 2007). Fluvial processes are sporadic within these barrancos but there is evi dence of efficient geomorphological activity during the last millennium. The Barranco de Corredor La Bola is partially filled by the Lavas Negras eruption (Fig. 3.11). The entrance of a branch of the lava flow inside the barranco has modified the geomorphic system, and a new channel, 10 m wide and 5 m deep, was scoured.

3.10.2 Alluvial Fans and Debris Flows

Alluvial fans are depositional landforms occur ring where confined streams emerge from mountain catchments into zones of reduced stream power (Harvey 1997). There are three groups of alluvial fans around Teide and Pico Viejo volcanoes. The first group is located on the lower most southern flank of Teide volcano (Bravo and Bravo-Bethencourt 1989; Martínez de Pisón and Quirantes 1981), the second one on the southern flank of Pico Viejo volcano, and the third on the northern flank of Teide volcano (Corredores Munich). Alluvial fans located on the lowermost slopes of the Las Cañadas Cal dera wall are not included in this chapter.

The first group of alluvial fans is produced by the erosive dismantling of the southern slopes of Teide volcano. The total area of the fan is poorly constrained because it is partly buried by lava flows and domes. Its present-day area is 1.83 km^2, with a maximum length of 3.5 km. In the distal sector (close to the Parador building), the alluvial fan rests upon tephriphonolite flows from Pico Viejo (20.7 ky BP, Carracedo et al. 2007). Evidence of torrential rain activity after the emplacement of Late Pleistocene lavas comes

Lavas Negras (1.2 ka BP)

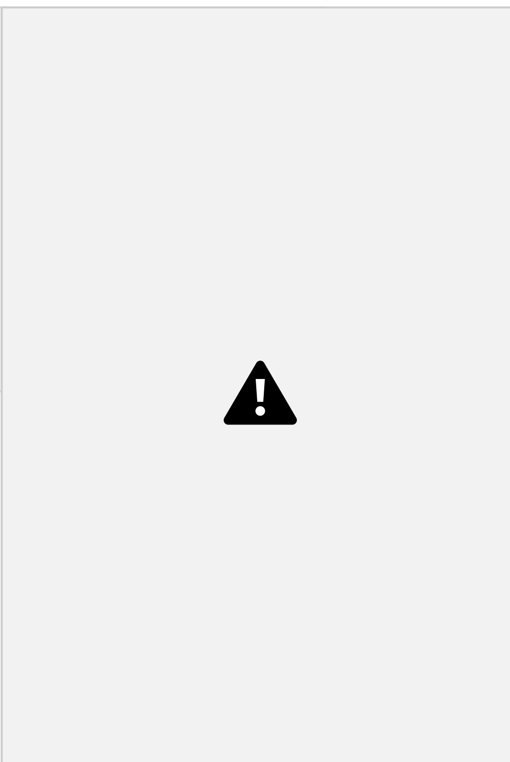


Fig. 3.12 Alluvial fan at the foot of teide resting on a

Fig. 3.11 The Corredor La Bola partially filled by the Lavas Negras eruption

in the form of pockets of rounded pumice gravels belonging to Montaña Majúa (relatively dated 5–4 ky BP, Carracedo 2006). The eastern sector of the alluvial fan covers phonolite flows of the VIII phase of the Montaña Blanca eruption (2 ky BP, Ablay et al. 1995) whereas the former barranco was filled by the Lavas Negras eruption (1.2 ky BP, Carracedo et al.

2007) (Fig. 3.12).

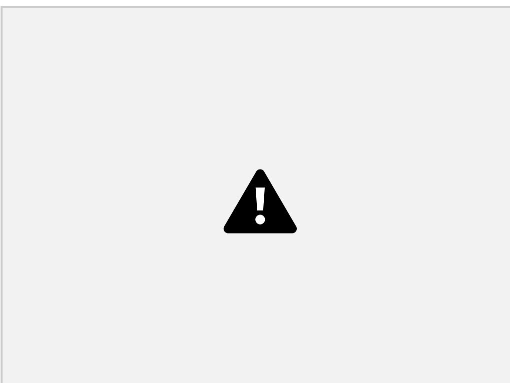
At the apex of the Cañada Blanca alluvial fan there are sectors occupied by debris flow deposits, including boulders up to 18 metric tons. Associ ated with these boulders are Guanche dwellings and abundant pottery remains, providing evi dence of debris flows before the sixteenth century AD. In addition, in a trench next to road TF-21, the debris flow deposits are overlying the Lavas Negras eruption (Fig. 3.13). Field surveys of the levées of more recent debris flows, resting on debris older than the Lavas Negras eruption, did not reveal any pottery or tools from the Guanche culture. This suggests that these debris flow

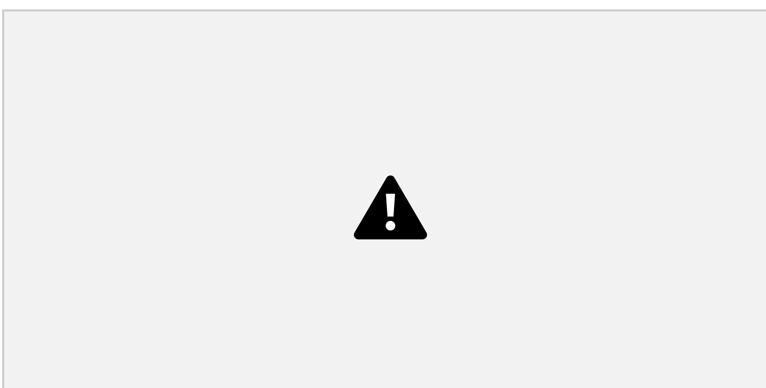
trachyte lava flow from phase VIII Montaña Blanca (*2 ka BP, Ablay et al. 1995); the associated channel was filled by the Lavas Negras flow (1.2 ka BP)

Fig. 3.13 Debris flow facies on Cañada Blanca alluvial fan. The cross-section is located on the TF-21 road. Blocks with alunite (white arrow) come from fumarolic areas of the Teide summit

deposits were generated during the last 500 years, by extreme events of heavy rains (Fig. 3.14). The most important storm in historical times in the Canary Islands was the 1826 hurricane (Bethen court-Gonzalez and Dorta-Antequera 2010), which may have been the very occasion on which this fan formed.

Today torrential activity occurs in channels with a restricted annual period of activity, due to limited supplies of melt water and heavy rains. Stump trees (Pinus radiata) partially covered by recent sediments are solid evidence for sporadic torrential activity. Nevertheless, on September





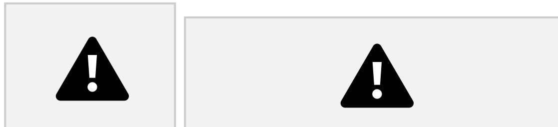


Fig. 3.14 Geomorphological map of debris flow emplaced at the junction of Corredor La Bola and La Corbata ravines and detailed cross section along A-A' (UTM coordinates, WGS84 datum)

22, 2010 an unusual summer storm that produced heavy rains ([90 mm/day) and powerful erosion of fine hydrothermally-altered material (by fu maroles) occurred at the head of the Corredor La Bola. The resulting debris flow transported sedi ment 2.5 km downstream and stopped only a few metres from the TF-21 road (Table 3.1).

The second group of alluvial fans is located at the mouth of barrancos on the southern flanks of Pico Viejo volcano. They are less important in terms of volume. Present-day activity is limited to small amounts of sediment reworking inside these channels. In this area, archaeological remains from the Guanche culture are frequent but never buried by recent deposits.

The alluvial fans associated with the Corre dores Munich are very young (\last millennium). In the lower part of the debris cones there is a system of debris flows with sharp levées. The lowest ones have been colonized by a natural pine forest over the last century. The highest debris flow shows evidence of recent sediment transport, especially blocks and gravels produced by frost weathering on Late Pleistocene phreatomagmatic breccia (Calvas del Teide) and Lavas Negras flow. The influence of the Little Ice Age on the activity of these channels and related debris flows is questionable (Martin Moreno 2011), and fur ther investigations are needed to corroborate and affirm any correlation (Table 3.2).

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alluvial fans and debris flows from the southern side of Teide Volcano based on their relationshi _*D caved w

Table 3.1 Chronology of different

Lithology/facies	Geomorphology	Age 14C 1995; Carracedo et al. 2007)

Location

Alluvial

Volcanic event

22 September event

Very narrow debris flow

Debris flow

Corredor La Bloa ravine

Present

2010

2,500 m long

Alluvial sediment

Very narrow and shallow

Present activity day

On the channels

Present

alluvial channels scarred

(gravel and sand)

mpsday

of Corredor La

Debris flow

Debris flow with very

Nineteenth activity

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Bola and La Corbatara ravines

well preserved levées

century AD

Alluvial

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Inactive alluvial fan (channel

Alluvial fan

Dense stone pavement,

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Den

Alluvial fan

Mainly inactive, weak activity

C-able

the existence

sparse boulders

in the lowest part of small

railway DA

ravines beside Maja alluvial

a ñ da a

In the former confluence of

Debris flow,

Dense stone pavement,

Older than alluvial fan

fan station

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spreading and broad Montaña – Dome volcanic event in the Phonolite Dome lavas-short eastern flank of Teide volcano

surfaces covered by Blanca

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Table 3.2 Chronology of debris flows from the northern side of Teide Volcano based on their relationship with volcanic landforms (Carracedo et al. 2007), archaeological

Archaeological remains from the Guanche culture and their resultant effects cal forestry Ty

phology Age 14C Archaeological remains from the Guanche culture and their resultant effects on history

rem ians Volcanic Alluvial event Location Lithology/ Geomor

fa ics

No evidence event

ty Present-day Corredores Munich Debris flow Very well-developed debris flow system Present

(to day 1.2–0 BP No evidence activi

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Lavas from the top of the Teide Phonolite

Lavas

AD Lavas

forest cover)

Little Ice Age

Corredores

Munich

Debris

The volume of the alluvial fans on La Corbata debris flow and the large sizes of clasts (up to boulders), which were produced before 1.2 ky BP, can be explained as the result of extreme events of heavy rains, such as the hurricane of 1826 (Table 3.2).

Acknowledgments Authors acknowledge the Teide National Park for access to the areas investigated.

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4 Structural and Geological Elements of Teide Volcanic Complex: Rift Zones and Gravitational Collapses

Juan Carlos Carracedo and Valentin R. Troll

Abstract

Initially recognised in the Hawaiian Islands, volcanic rift zones and associated giant landslides have been extensively studied in the Canaries, where several of their more significant structural and genetic elements have been established. Almost 3,000 km of water tunnels (galerías) that exist in the western Canaries provide a unique possibility to access the deep structure of the island edifices. Recent work shows that rift zones to control the construction of the islands, possibly from the initial stages of island development, form the main relief features (shape and topography), and concentrate eruptive activity, making them crucial elements in defining the distribution of volcanic hazards on ocean islands.

4.1 Introduction

Rift zones constitute the most pronounced and persistent structures in the development of oceanic volcanic islands because they: (1) control the construction of the insular edifices, possibly from the initial stages; (2) form the main relief features (shape and topography); (3) concentrate eruptive activity; (4) frequently play a key role in the generation of flank collapses and the catastrophic disruption of well-established volcano plumbing systems; (5) are crucial structures in the distri

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bution of volcanic hazards; and (6) condition the storage of natural resources, such as groundwater (Navarro and Farrujia 1989).

Although rifts were initially recognized on the Hawaiian Islands (Fiske and Jackson 1972; Swanson et al. 1976; Walker 1986, 1987, 1992; Dieterich 1988), a good part of the progress made in understanding their genesis and struc ture has been achieved through their study in the Canary Islands (Carracedo 1975, 1979, 1994, 1996, 1999; Carracedo et al. 1992, 1998, 2001, 2007, 2011; Guillou et al. 1996; Walter and Schmincke 2002; Delcamp et al. 2010).

Compared with those of the Hawaiian Islands, the rifts of the Canaries are considerably longer lasting, exert greater overall control on the construction of the islands, and present more pronounced elements of relief. The lower mag matic activity of the mantle plume or hotspot

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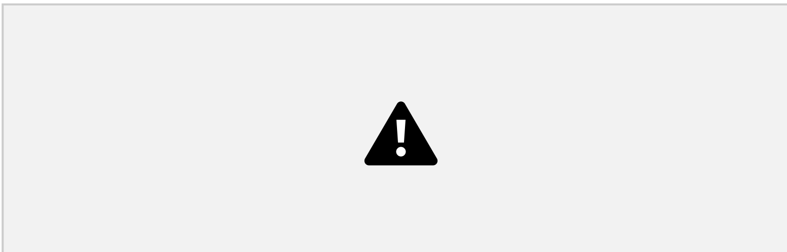


Fig. 4.1 Panoramic view from the top of Pico Viejo Volcano onto the North West Rift Zone of Tenerife, an excellent example of the evolution of a recent volcanic rift. The Teno Miocene Shield outcrops in the far distance (about 20 km)

that has generated the Canaries produces much lower eruptive rates (Geldmacher et al. 2001). This favours higher-aspect-ratio rift zones by accumulation of relatively short flows, promot ing the growth of prominent ridges in the relief of these islands (Fig. 4.1). The very low drift velocity of the African plate and the apparent lack of significant subsidence of the Canaries allow for long periods of subaerial activity of the islands (at least 22 My), with corresponding long-lasting rifts that frequently display recur rent activity (Carracedo et al. 1998, 2011).

4.2 Oceanic Rift Zones. What are They and What Do They Represent?

Elongate zones where eruptive vents concentrate to form ridges are common and very pronounced features of oceanic volcanoes. Where erosion has incised sufficiently deeply into these features, their internal structure appears as a dense swarm of dykes broadly parallel to the axis of the ridge, forming ''coherent intrusion complexes'' (Walker 1992) or ''rift zones'' (Fiske and Jackson 1972; Carracedo 1975, 1994; Swanson et al. 1976; Wyss 1980; Stillman 1987). This swarm of dykes generally shows a gaussian distribution, with the intrusion density falling rapidly to near zero at the margins of the complexes. A similar pattern is apparent in the distribution of eruptive vents in the ridges (Fig. 4.2).

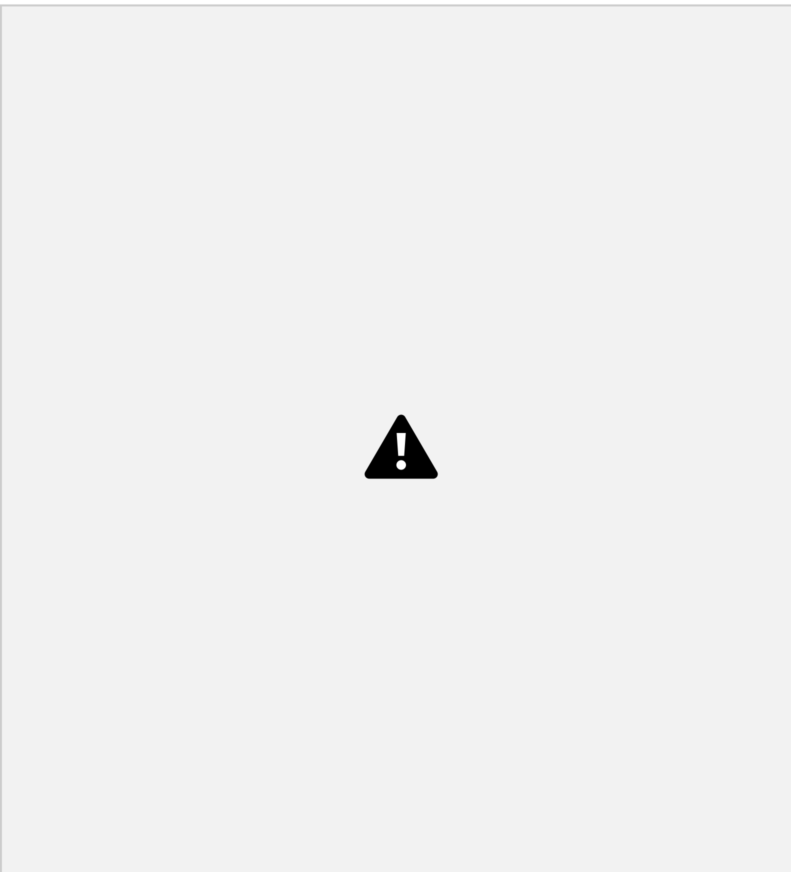
A high concentration of dykes in the rift zones was first deduced by MacFarlane and Ridley (1968) from conspicuous gravity ridges in the Bouguer anomaly map of Tenerife (Fig. 4.3). According to these authors, the growth of the island was largely controlled (both subaerial and submarine parts) by dyke injection along three major rift zones, with angles of about 120 between them. This idea was also applied by Macdonald (1972) to explain the ground plan, shape and internal structure of the Hawaiian shields.

Detailed studies of these features have been carried out on the Hawaiian volcanoes since the 1960s (Macdonald 1965; Fiske and Jackson

1972; Macdonald 1972; Swanson et al. 1976; Walker 1986, 1987, 1992; Dieterich 1988). Eventually, Walker (1992) defined rift zones as the surficial expression of vents and eruptive sites fed by dyke complexes at depth, pointing out that these structures may be an invariable characteristic of ocean volcanoes.

A significant advancement in the understand ing of oceanic rifts has been attained in the Canary Islands, particularly on El Hierro, La Palma and Tenerife from the 1990s onward (Carracedo 1994, 1996, 1999; Guillou et al. 1996; Carracedo et al. 1999, 2007, 2011; Gee et al. 2001; Walter and Schmincke 2002; Walter and Troll 2003; Walter et al. 2005; Delcamp et al. 2010). This work took advantage of the numerous water tunnels in Tenerife and La Palma used for groundwater mining (locally called "galerías", 2 9 2 m and several kilometres long, with a combined length for both islands exceeding 3,000 km). These galerías facilitate access to the deep structure of the rift zones, providing a unique opportunity for direct observations and sampling (see Fig. 4.3 in Carracedo 1994).

Fig. 4.2 Concentration of Quaternary eruptive



LA PALMA (CUMBRE VIEJA)

HAWAII (MAUNA KEA)

prolongation

Eruptive vents/km^2 1-4 4-8 >8

5 km 5 km Submarine

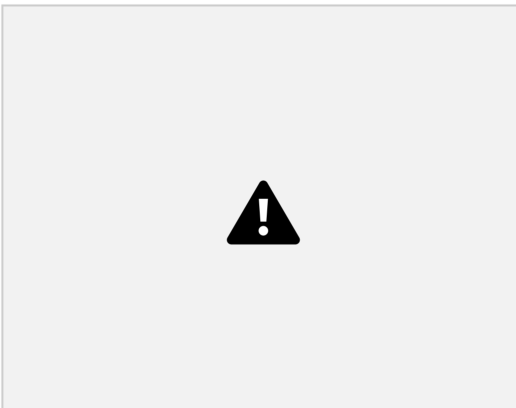


Fig. 4.3 Bouguer anomaly map of Tenerife showing a three-pointed star shape (from MacFarlane and Ridley 1968)

The Taburiente shield and Cumbre Vieja Volcano, both on the island of La Palma, are end-members in the evolutionary stages of rift zones. There, an old and extinct (Plio-Pleistocene) deeply eroded dyke complex (Taburiente), and a recent (\125 ky), active rift zone (Cumbre Vieja) make up the key architectural elements of the island. The latter allows observation of the surface distribution of eruptive vents in these situations, and their main eruptive facies (1 in Fig. 4.4). This comprises a volcanoclastic facies (Fig. 4.4) at the central axis of the rift, and a lava facies (lf) at the flanks of the structure. Deeper in the rift zone, there appears to be a dense group of dykes, oriented approximately along the rift axis (2 in Fig. 4.4). These dykes are the conduits feeding the eruptive vents of the rift, although part of them probably never reaches the surface (Gudmundsson et al. 1999). The internal organisation of the dyke complex can be observed at the floor of the Caldera de Taburiente, where a lateral collapse exposed the core of the shield (3 in Fig. 4.4). The root of the dyke complex is

TABURIENTE VOLCANO

Submarine

Dyke complex

Mafic plutonics

3

Subaerial shield

2

shield

1

vf

Cumbre Vieja Rift Zone

Lava

Fig. 4.4 Anatomy of oceanic rift zones: Cumbre Vieja, La Palma. The successive layers show the internal structure of rift zones, from the eruptive vents at the surface of the ridge, to the dyke swarm and the tight cluster of cumulate and plutonic rocks in the deeper part of the structure

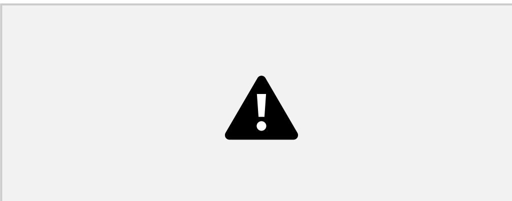


Fig. 4.5 In triaxial rift zones, two of the three arms are usually more active, the third acting as a buttress. Repetitive injections into the active rifts force the enclosed block between these rift arms outwards oppos ing the buttress and, eventually cause collapse

formed by a plexus of mafic plutonics and cumulates related to the magma chambers and pockets that supply the overlying rift eruptions.

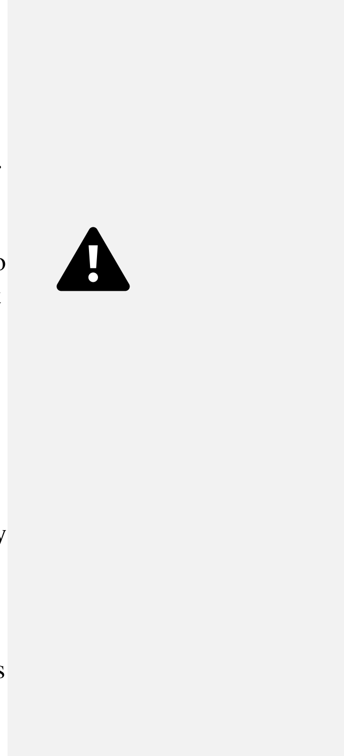
Repetitive injection of blade-like dykes pro gressively increases the anisotropy of the com plex, forcing new dykes to wedge their path parallel to the intrusions (like a knife between the pages of a book, Fig. 4.5). If this process is sustained and if injections are sufficiently fre quent, parts of the rift zones may remain hot (thermal memory) to preferentially guide the path of successive intrusions (e.g., Vogt and Smoot 1984). However, intrusion can only progress in a dyke complex if the structure can accommodate fresh injections. Since repetitive intrusion would progressively increase com pressive stresses, new injections can only occur if either flank of the rift zone is free to move apart (see Fig. 4.5). Therefore, extensional for ces add up in growing rift zones and eventually reach a critical rupture threshold that can trigger massive landslides.

4.3 Development of Rift Zones

Rifts in ocean-island settings can represent the surface expression of initial plume-related frac turing, in response to vertical upward loading (MacFarlane and Ridley 1968; Wyss 1980; Lu ongo et al. 1991; Carracedo 1994, 1996) and/or extensional fissures due to volcano instability and spread, which develop once a volcano has grown to a certain height and instability (Walter and Troll 2003; Walter et al. 2005; Delcamp et al. 2010, 2012).

Despite advances in the understanding of volcano deformation, it remains unclear how particular rift zones develop. Fractures and rift

zones in Tenerife have repeatedly developed in triaxial patterns. These triple-armed rifts are thought to result from magmatic doming, and thus slight upward bending of the crust (Carra cedo 1994), or gravitational spreading effects (Walter 2003; Walter and Troll 2003; Walter et al. 2005). Several such “triaxial rift zones” exist on the island (as also on El Hierro), some of which were active simultaneously. Endogenously driven mechanisms are



thought to play a major role in establishing axial volcano architectures. Plumes typically cause uplift that ruptures the rigid oceanic plate along three rifts meeting at triple junctions. Commonly, two of these rifts become a plate boundary (either a ridge or a ridge/transform) while the third does not spread and becomes a failed arm. A similar mechanism was postulated by D'Albore and Luongo (2009) and Luongo et al. (1991) for the tectonic structures of the Neapolitan area, with the Phlegraean Fields occupying the centre of a triple junction generated by a rising crustal tumescence (a plume). The regular triple-armed junctions and triaxial rift zones on volcanoes would then result from the least-effort fracturing of the brittle crust at 120 angles (Luongo et al. 1991; Carracedo 1994, 1996). This least-effort model (Fig. 4.6) is considered to explain (a) the aligned concentration of eruptive sites on the Canaries (Tenerife, El Hierro and La Palma), (b) the longevity and direction of rift zones, and (c) the genesis of volcano sector collapses located in-between 2–120 rift arms (Carracedo 1994, 1996). In this model, the rift zones are thought to have initiated early in the history of the islands and form their deep inner structure.

However, important objections to this model have been raised. If triaxial rift zones developed simultaneously on particular islands (e.g., Tenerife, Hawaii) the location of the centres of those rift systems should be sufficiently distant from each other considering the highly viscous relaxation behaviour of the upper mantle and flexure wavelengths of the crust (Watts and Masson 2001). If Tenerife shield volcanoes (Teno, Anaga and Central shields) are thought to be triaxial structures, they are probably located too close to one another to meet those conditions (Walter and Troll 2003).

An alternative process is that flank deforma tion is caused by rifting, once a volcano becomes sufficiently unstable for dyke intrusions to force the flanks of the volcano to spread and creep seaward (McGuire et al. 1990; Elsworth and Voight 1995; Iverson 1995; Elsworth and Voight 1996; Delcamp et al. 2010). Therefore, the question arises whether rifting is a conse quence of flank deformation, or rifting causes a flank to deform. Both models (a and b in Fig. 4.7) have a completely different initiation, but the final results are similar. Therefore, multiple rift systems may develop differently. Triple-armed rift zones can result from the least effort fracturing of the brittle crust (see a in Fig. 4.7), at the initial stages of development of a particular island (e.g., the Central Shield of

Fig. 4.6 Model proposed by Carracedo (1994, 1996) linking volcanic rift zones and landsliding in the Canary Islands. Three-armed rifts, spaced at *120 , seem to be the naturally preferred configuration, as in the case of El Hierro and Tenerife. This architecture is thought to be a response to least-effort fracturing. The resulting three sided base pyramidal edifice geometry may be further enhanced by landsliding between the rift arms, propa gating perpendicular to the rift direction

Fig. 4.7 Whether rifting is a consequence of deforma tion from plume-derived updoming and fracturing (a), or rifting (forceful intrusion) causes a flank to deform by creeping and spreading (b), the final result of both processes is convergent. There are pros and cons for both models and no definitive evidence favours either of them.

Tenerife) where plume-related or oceanic frac tures may provide important magma pathways (e.g., Carracedo 1994; Geyer and Martí 2010; Carracedo et al. 2011). Alternatively, ridge-like volcanoes have been shown to develop a third arm once the edifice has matured and developed instabilities. Then, a more passive rift arm may open opposite the collapse scar due to exten sional stresses (e.g., Walter and Troll 2003; Walter et al. 2005).

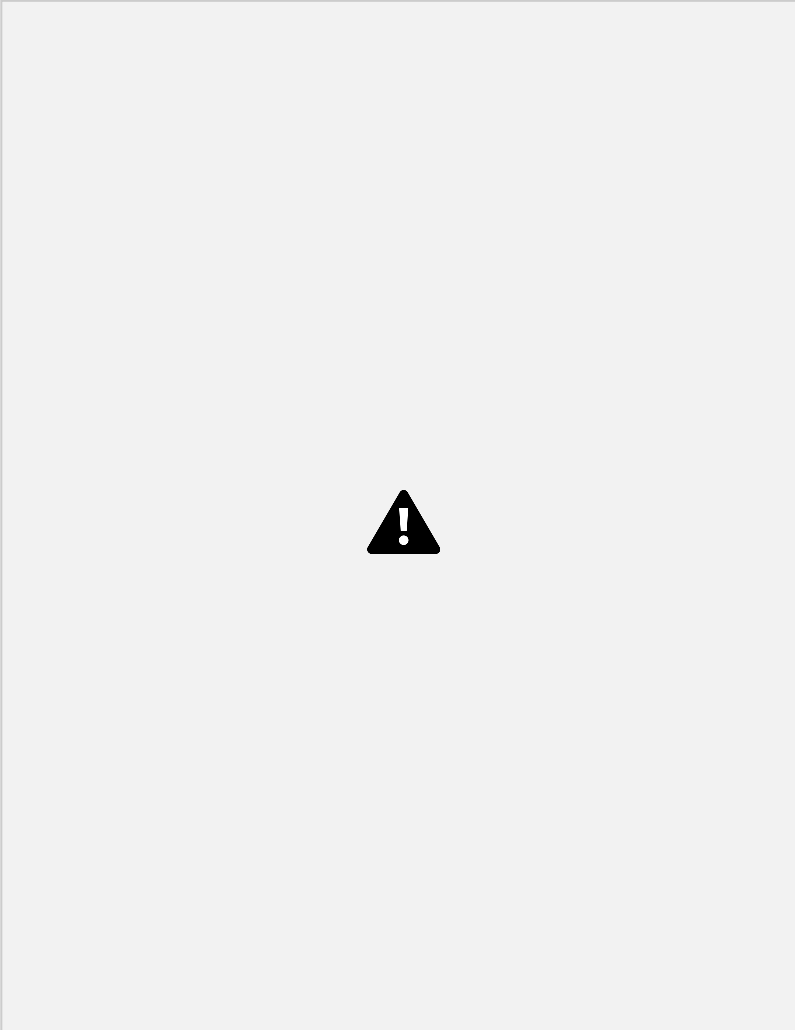
In fact, both types of rift zones may be present in the Canaries, with type A predominant in the early stages of construction of the island volcanoes and type B becom ing more prevalent in the latter stages of rift develop ment. N number of dykes; L distance across the rift

Observations on Tenerife and El Hierro shields as well as in analogue gelatine experi ments have shown that slight eccentricity of the creeping sector focuses dyke intrusion along two curved axes tangential to the stable/unstable

Fig. 4.8 a Eruptive vents and dyke outcrops of the Taburiente shield volcano (*0.77–0.4 Ma), La Palma, with rift zones forming a radial structure. The incipient three-armed rift organisation (solid lines) was apparently left incomplete by the
extinction of Taburiente Volcano at an early stage of development (from Carracedo et al. 2001). b Stages of structural evolution of La Palma from an initial radial structure. The position and direction of the creeping flank favoured extension in an east–west direction on the southern flank, and thus the formation of a north– south rift zone. Once formed, the main south rift stabilized by the
alternation of constructive and destructive processes such as volcanism,

interface. In contrast, strong eccentricity results in only one main tangential rift, while other rifts remain poorly developed (Walter and Troll 2003; Walter et al. 2005). With initiation of a creeping sector, an initially radial or ridge-like geometry is likely to reconfigure and produce rift-zones that will lead to additional rift arms. The most com mon arrangement resulting from such geometry would be another (third) arm to form the frequent triple-armed systems. Intrusion into the margin between stable and unstable sectors may thus favour the triple-armed configuration.

This architectural evolution may be illus trated in the development of the Taburiente shield in the early subaerial construction of La Palma, where rift zones seem to have progressed from an initial disperse radial distribution of eruptive vents (Fig. 4.8). Southward migration



RIFT ZONE

PUNTALLANA

RIFT ZONE

~120°

Collapsed area

CUMBRE NUEVA
RIFT ZONE
Cinder (Vents)

Dykes

landsliding and erosion
STABLE CONDITION
UNSTABLE CONDITION
SOUTH RIFT
INTENSIFICATION

(a)

N

PUNTAGORDA

(modified from Walter and Troll 2003)

(b)

rift ~ 1 Ma ~ 750 ka 550 ka-present

Radial Tangential rifting One main

Radial structure

EWRZ

Caldera
Taburiente Volcano (extinct)

Unstable sector
NWRZ
(active)

Taburiente

(active)

SRZ
(Cumbre Nueva)

Taburiente Volcano

Cumbre Vieja Volcano

of volcanism left the shield extinct and probably interrupted the organisation of rift zones (Car racedo et al. 2001). Conversely, regular long lived triaxial rift zones develop where magma plumbing remains stationary, e.g., the Central Miocene Shield and the Plio-Pleistocene Las Cañadas Volcano, in Tenerife (Fig. 4.9).

Analogue gelatine and sand-box experiments confirm the generation of a triangular system of conjugate graben axes in settings reproducing the steady conditions of El Hierro (Fig. 4.10), where magma plumbing apparently has remained stationary, suggesting that these triaxial rift zones may be a late reconfiguration as a progressive response to volcano deforma tion (Walter and Troll 2003; Münn et al. 2006). However, observations in galerías in the central part of Tenerife show that the dyke complex of the Miocene Central Volcano follows broadly the very same orientation as the rift zones that developed during the formation of Las Cañadas Volcano and those of the present day rift zones (Carracedo 1975, 1979).

At present there is no definitive evidence in favour of either of these models—endogenously driven mechanisms or rifting by spreading and creeping of volcano flanks. Both mechanisms, although very different at the start give similar results. A plausible assumption is that large, deep triple-armed rift zones develop at the early stages of island construction by plume related updoming and fracturing, with later modifica tions due to volcano edifice stability issues, whereas smaller rift systems (not necessarily multiple) might form entirely from gravitational spreading and associated structural re-arrange ments at unstable volcanoes.

4.4 Rift Zones of the Teide Volcanic Complex

The Teide Volcanic Complex provides one of the best possible scenarios to study the charac teristics and evolution of rift zones in ocean volcanoes. The North East Rift Zone (NERZ) presents a superb opportunity to study the entire cycle of activity of an oceanic rift zone. This rift,

Fig. 4.9 Classical triple armed rift zones are usually not well developed when moving magmatic sources are involved (e.g., a La Palma). A stationary magma supply, however, gives rise to concentrically overlapping volcanoes and well-developed triple armed rift zones (e.g., b Central shield in Tenerife) (modified from Carracedo et al. 2001)

exposed (Delcamp et al. 2010; Carracedo et al. 2011). On the other hand, the North West Rift Zone (NWRZ) represents an outstanding exam ple of the latest stages of rift development, demonstrating interesting patterns of spatial and temporal distribution of eruptive vents and associated geochemical and petrological varia tions (Ablay and Martí 2000; Carracedo et al. 2007), including rare examples of complex magma mixing (Wiesmaier et al. 2011).

4.4.1 The NE Rift Zone

This rift zone extends for about 35 km, from the foot of Teide to the Anaga massif. The deep core of the rift is an extension of the Central Miocene shield towards the Anaga massif (Guillou et al. 2004; Carracedo et al. 2011), outcropping at the NE end of the rift and underlying the Pliocene inactive for hundreds of thousands of years along most of its length, has been deeply mass wasted by erosion and massive landsliding, allowing an in-depth study of its internal struc ture, including the complex network of dykes

Anaga Volcano (Fig. 4.11). The present config uration of the NERZ is characteristic of rift structures, with a cluster of eruptive vents form ing the crest of the ridge and lava flows at the flanks (Fig. 4.12). Vents are tightly packed at the

The rift apparently had three successive cycles of activity—in the Miocene, the Pliocene and the Pleistocene (Fig. 4.13). The last one (comprising the last million years) is the best documented and is the only one that is related to the TVC, at least in its final stages. This latest cycle of activity of the NERZ has been coeval with the development of Las Cañadas Volcano, but both volcanoes were clearly interacting, as suggested by sequences of basaltic lapilli from

ing with beds of phonolitic

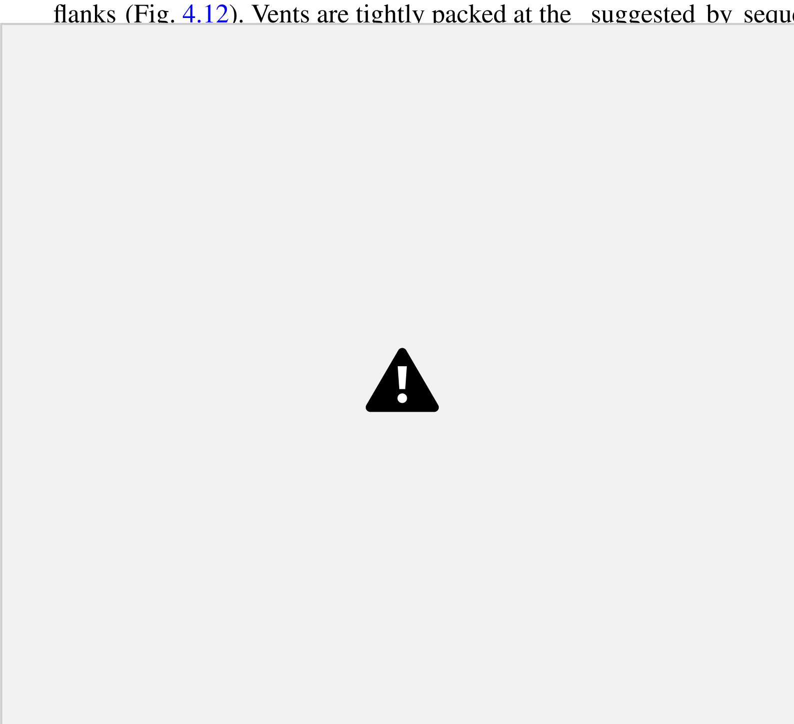
Cañadas Volcano. It appears

e dates, in fact, imply that the

unger than the central edifice,

ment of shields to form rift

ig. 4.10 somewhat unlikely.



(d)

Fig. 4.10 a, b Scaled analogue experiment with gelatine models. a Gelatine cone before injection of a liquid (the magma) into the interface creeping/non-creeping sector and a slight southwestward eccentricity of the lubricated base. b After injection, 80 % of the experiments produced a triple-arm intrusion arrangement (Walter and Troll, 2003). c, d analogue experiment with sand

Three reasonably well-dated and documented successive giant landslides in the latest active cycle of the NERZ provide relevant information to understand the genesis and characteristics of mass-wasting processes in oceanic volcanoes, and help to clarify the succession of events giving rise to the formation of the Las Cañadas Icod-La Guancha collapse depression and the subsequent nested Teide Volcano.

4.4.2 Evolution of the NE Rift Zone

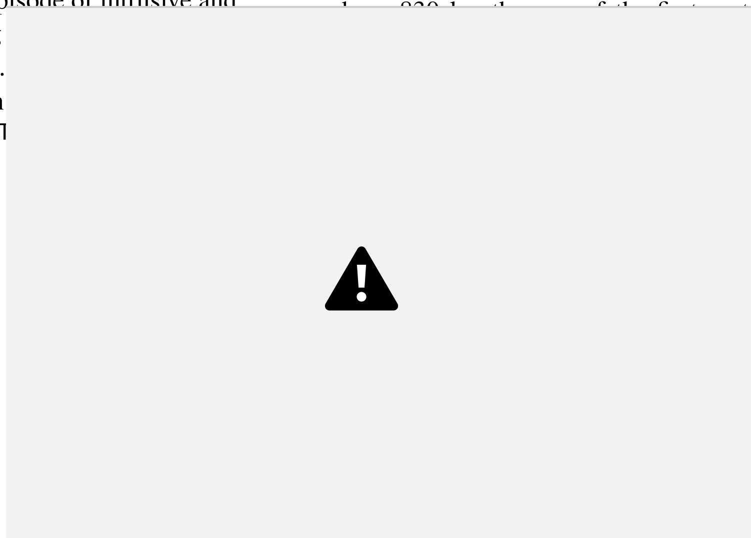
The initial, pre-collapse stages of the latest cycle of activity of the NERZ developed a volcanic ridge that may have reached an altitude of about 2,000 m a.s.l. (Fig. 4.14a). The critical phase of construction was between ca. 1,100 and 860 ky, when the growth rate may have reached 3.5 m/

cones simulating the overlapping "Tiñor cone" and the "Southern Ridge" (El Hierro) emplaced simultaneously. After 7.1 h, the "El Golfo cone" was added overlapping the 'Tiñor cone' and the ridge. In d, the two cones and the ridge have spread for 34 h showing a triangular system of conjugate graben axes (Munn et al. 2006)

ky, indicating an intense episode of intrusive and eruptive activity leading instability of the volcano. dykes changing direction

increasing instability at this stage (see e.g., Walter and Troll 2003; Delcamp et al. 2010) from 20 to 40 , the main orientation of intru sions in the NERZ, to 0 –10 at the final stages.

The main constraint for the time of occur rence of the first lateral collapse (Micheque), with an estimated volume assessed from digital elevation model analysis of *60 km^3, is pri marily based on the ages obtained in the Los Dornajos galería (see upper section in Fig. 4.13), which suggests that this collapse must have



ENLARGED

Miocene volcanics

TENERIFE

N

Cañadas towards the Miocene-Pliocene Anaga massif.

The landslide scars of La Orotava and Güímar are clearly visible, unlike the Micheque landslide, which is com pletely covered by post-collapse volcanism (image Google Earth)

Fig. 4.11 Google Earth image of the NE Rift Zone of Tenerife viewed from the Anaga massif (oblique view of Tenerife from the NE). The rift had already extended in the Miocene from the central edifice of what is now Las

Fig. 4.12 Simplified geological map of the NE Rift Zone of Tenerife showing the distribution of eruptive vents and lava flows. Ages (in ky) from Carracedo et al. (2011)

Ages (in ky)

Vents ^{14}C Post-collapse

Lavas

NERZ activity K/Ar

La Orotava landslide

A

Nested volcanism

Dyke

VALLE DE LA OROTAVA

Micheque and Güímar landslides

Pre-collapse

NERZ activity

50^0

>33

566 800

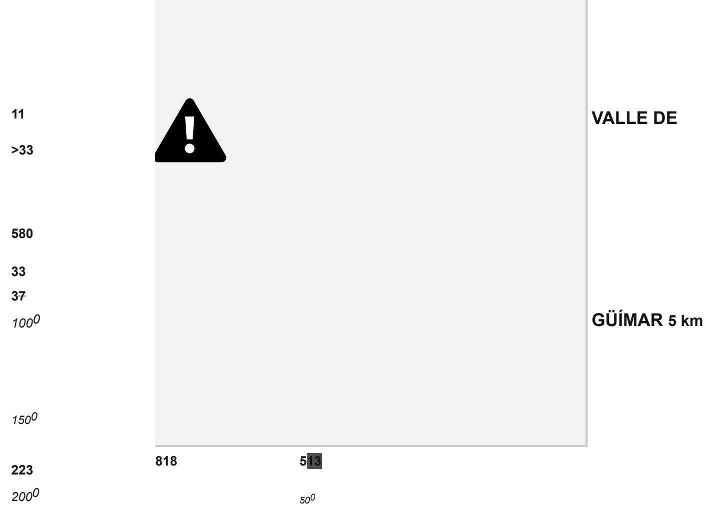
29

100^0

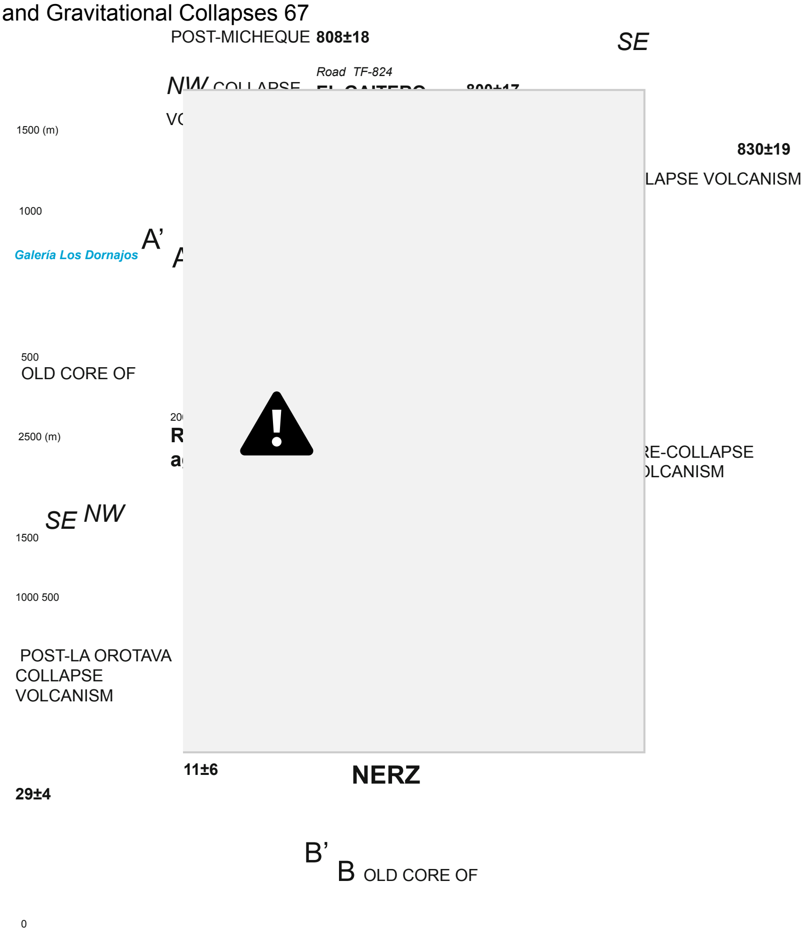
798

798

929



probably extending towards the present-day valley of La Orotava (Fig. 4.14b). Subsequent volcanism filled large parts of the collapse basin, extending beyond the coastline, concealing the scar and the avalanche breccia to be only found in galerías in the northern flank of the rift zone. A second landslide (the Güímar lateral col lapse, estimated volume: 47 km^3), at the east



Debris avalanche THE NE RIFT 10 km

Fig. 4.13 Geological cross-sections of Tenerife (NERZ) perpendicular to the rift axis (compare with Fig. 4.12 for section lines). Two of the lateral collapses (Micheque and La Orotava) are crossed by the sections, showing that the rift zone has been operating for at least for 2.7 Ma. Ages in ky (from Carracedo et al. 2011)

flank of the NERZ, formed a pronounced (10 9 10 km) depression (Fig. 4.14b). The tim ing of this collapse is constrained by the age of 860 ± 18 ky obtained from lava flows topping the southern collapse scar (Pared de Güímar), and that of the first volcanism nested inside the landslide embayment, dated at 831 ± 18 ky.

The eruptive rate and volume of the Güímar in-fill formations seem much lower than those of the Micheque event. This suggests that, although roughly contemporaneous, the Micheque col lapse may have been the first of the two to occur, coinciding with a phase of intense volcanic and intrusive activity. This may point to a funda mental difference in the mechanism that caused the two flank failures: distensive stresses asso ciated with intense eruptive and intrusive activ ity in the Micheque collapse, and gravitational instability increased by the response to the ear lier collapse in the case of the Güímar landslide. This would explain the observation that, by far, the greater part of volcanism continued to be concentrated in the interior of the first, the Mi cheque collapse, even after the Güímar landslide took place. This caused the total infilling of the Micheque depression and the evolution of sig nificant volumes of magma (0.5–1.0 km^3) towards highly differentiated compositions in this sector (Fig. 4.14c, d).

A third collapse at the northern flank of the NERZ (Orotava lateral collapse, estimated vol ume: 57 km^3) formed the Orotava Valley (Fig. 4.14d). The relatively accurate dating of the previous collapses has not been achieved in this last case. Its age is constrained by a mini mum age of 566 ± 13 ky from lavas of felsic compositions of the Micheque nested volcanism cascading over the eastern scar of the Orotava Valley (Carracedo et al. 2011), and the age of 690 ± 10 ky, obtained by Abdel-Monem et al. (1971) from the lower part of the collapsed sequence at the southern (Tigaiga) scar (Fig. 4.14d). It seems therefore that the Orotava collapse occurred between 690 ± 10 and

THE NE RIFT 840 ky AGO Present outcrops of the

4200±60 8050±140

ANAGA VOLCANO prior to the Micheque and Güímar lateral collapses

(PLIOCENE) THE NE RIFT 830 ky AGO

Micheque

Miocene NE Rift (8-7 Ma)

Inferred extension of the1st (Miocene) and 2nd (Pliocene) phases

2710±58 929±20

of activity of the NE Rift basin.

Inferred extension of the 3rd phase of activity of the NE Rift (Pleistocene), 7203±155

N

Initial volcanism nested in the Micheque collapse

3rd phase of activity of the NE Rift (Pleistocene), prior to the Micheque and Güímar lateral VOLCANISM MICHEQUE

NESTED lateral collapse

830±19

200⁰

N

E RIFT NE RIFT

963±21 1008±22

Present outcrops of the

100⁰ collapses

AGES Abdel-Monem et al., 1972 Ancochea et al., 1990 Ibarrola et al., 1993

200⁰ 100⁰

RADIOISOTOPIC

Carracedo et al., 2011 Guillou et al., 2004

831±18

860±18 Carracedo et al., 2007

Güímar lateral collapse

Initial volcanism nested in the

(a) (b)

10 km

Güímar collapse basin.

BASALTIC FISSURE

THE NE RIFT FROM 780 ky TO PRESENT DAY

THE NE RIFTIN THE PERIOD 815 ky–780 ky (M-B boundary)

Thirlwall et al., 2000 (Ar/Ar)

Pyroclasts

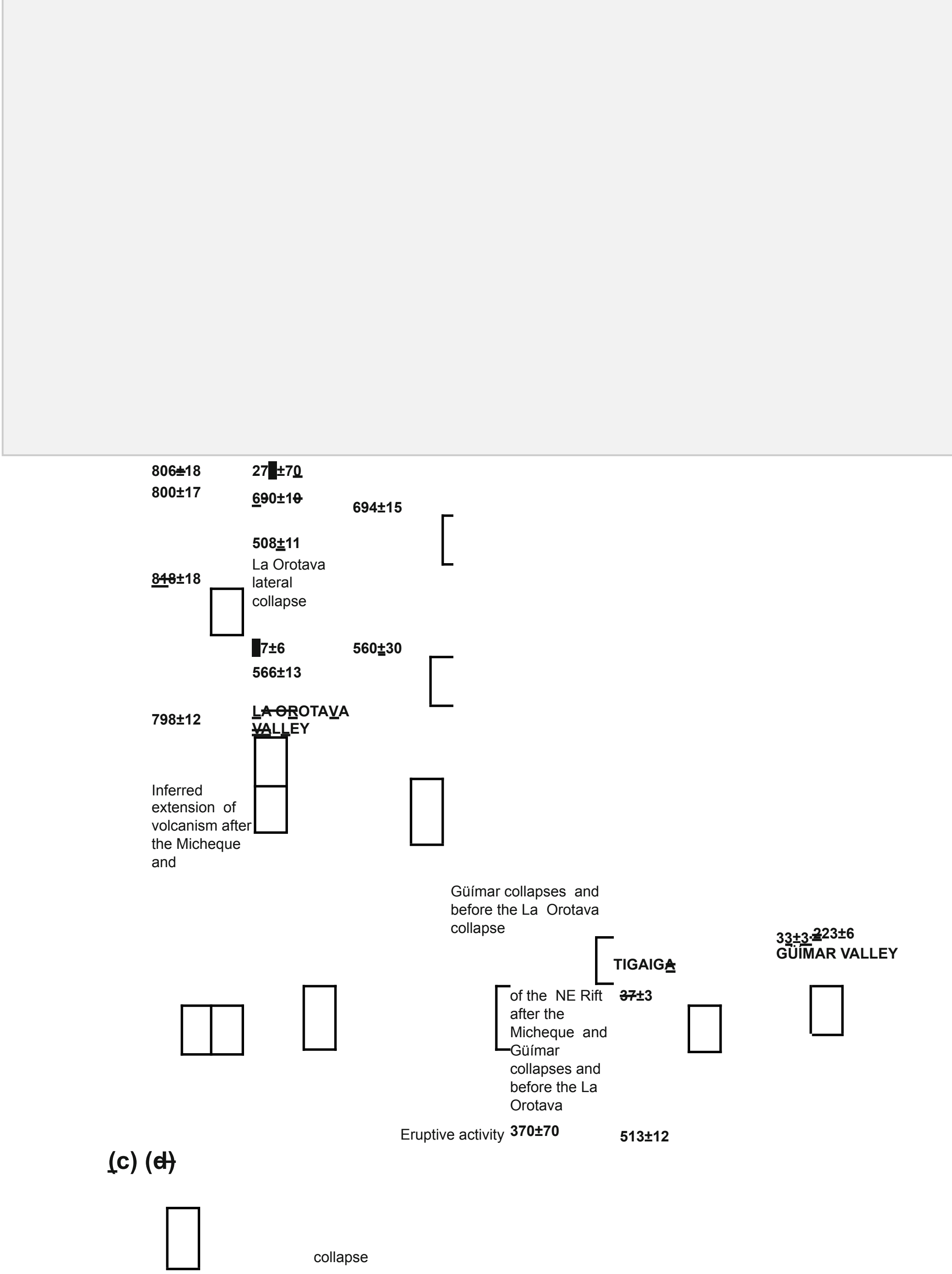


Fig. 4.14 Successive stages of development of the NE Rift Zone of Tenerife (modified from Carracedo et al. 2011; Abdel-Monem et al. 1972; Ibarrola et al. 1993; Thirlwall et al. 2000)

566 ± 13 ky, which places it significantly after the Micheque and Güímar landslides.

4.4.3 Decline and Dispersed Activity of the NERZ

Following the three collapses, the rift entered into a stage of stabilisation and progressively decreasing eruptive activity. Simultaneously, the dispersion of the eruptive centres, previously grouped preferentially at the crest of the rift, increased, particularly at the distal NE end (see Fig. 4.14d). These eruptions, all of normal polarity, have given ages of 513 ± 12 ky (Car racedo et al. 2007), 540 ± 40 ky (Abdel-Mo nem et al. 1971) and 560 ± 30 ky (Ancochea et al. 1990). NERZ eruptive activity, although