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CANARY ISLANDS, GEOLOGY

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The Canary Islands, located between 100 and 500 km from the coast of northwestern Africa (Morocco), consist of seven major volcanic islands forming a rough west-southwest to east-northeast trending archipelago. Together with the Selvagen Islands and a group of seven major seamount complexes (some of which were former Canary Islands) to the northeast, they form the Canary volcanic province. Volcanism in this ~800-km-long and ~400-km-wide volcanic belt (located at 33–27° N and 18–12° W) decreases in age from the northeast (Lars Seamount, 68 million years) to the southwest (Hierro Island, 1 million years) and is interpreted to represent the Canary hotspot track (Fig. 1). The Canary volcanic province is located on Jurassic ocean crust (~150 million years old beneath the western part of the province to ~180 million years old beneath the eastern part of the province), and contains some of the oldest ocean crust preserved in ocean basins.

GEOLOGICAL OVERVIEW OF THE EVOLUTION OF THE ISLANDS

The morphology of the Canary volcanic province show systematic changes from southwest to northeast, reflecting an increase in age (Figs. 1 and 2) and a change in evolutionary stage. As the volcanoes age, they originally go through a constructive phase of evolution in which growth of the edifice through volcanic activity outpaces its
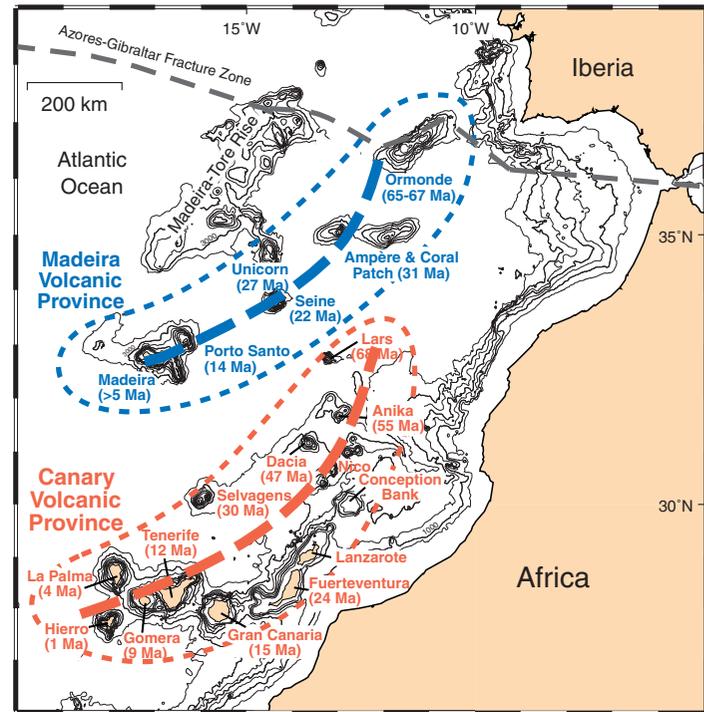
FIGURE 1 Bathymetric map showing the Canary (red) and Madeira (blue) volcanic provinces, including islands and associated seamounts, in the eastern central North Atlantic. Thick dashed lines mark centers of possible hotspot tracks. For clarity, only depth contours above 3500 m are shown. Bathymetric data from Smith and Sandwell (1997); ages and location of the Azores–Gibraltar fracture zone from Geldmacher *et al.* (2005) and Guillou *et al.* (1996).
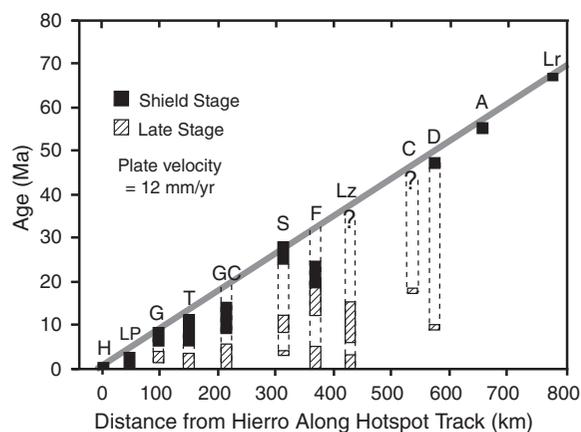
FIGURE 2 Radiometric ages of shield stages and late (rejuvenated or posterosional) stages of magmatic activity on islands and seamounts in the Canary volcanic province versus distance from Hierro. The center of each island is projected onto the proposed curved hotspot track in Fig. 1 along a line perpendicular to the hotspot track. Distances were measured from Hierro along the proposed hotspot track. The regression line calculated for oldest available ages of shield-stage volcanism gives an average rate of plate motion of 12 mm/year. On older islands and seamounts, volcanic units that had low $^{206}Pb/^{204}Pb$ ($\leq$ 19.5) were assigned to the late stage of volcanism, with the exception of the single sample from Lars seamount, which had a slightly lower $^{206}Pb/^{204}Pb$ (19.44). Abbreviations for islands and seamounts: H = Hierro, LP = La Palma, G = Gomera, T = Tenerife, GC = Gran Canaria, S = Selvagen Islands, F = Fuerteventura, Lz = Lanzarote, C = Conception seamount, D = Dacia seamount, A = Anika seamount, and Lr = Lars seamount. References for age data from Guillou *et al.* (1996) and Geldmacher *et al.* (2005).

destruction through mass wasting (e.g., landsliding) and erosion. The constructive phase occurs primarily during the shield-building (or shield) cycle of activity, during which eruptive rates are high, and most of the volcanic edifice is formed. Even though mass wasting is an important process during the shield stage, the volcano continues to increase in size, despite short-term setbacks. The constructive phase of island/volcano evolution can extend into the first late (also commonly referred to as post-erosional or rejuvenated) cycle of volcanism, during which volcanic eruptive rates are drastically lower, but magmas can be more evolved (silicious and thus more viscous), contributing to an increase in volcano height. Late cycles of volcanism are generally separated from the shield stage of volcanism by extended periods of volcanic inactivity or drastically reduced activity. During the destructive phase of evolution, mass wasting and erosion outpace volcanic growth, and the volcanoes (islands) decrease in size until they are eroded to sea level. As the plate moves away from the magma source, it cools and subsides, and the now flat-topped volcanic edifices sink beneath sea level, forming guyots. Despite the differences in age of the volcanoes,

all of the islands have had Holocene acitivity except La Gomera and Fuerteventura. The islands of La Palma, Tenerife, and Lanzarote have had historical volcanic activity, and thus youthful volcanic structures can be found across the entire archipelago, even on the oldest islands.

The two youngest and westernmost islands of Hierro (1500 m above sea level, with oldest dated subaerially erupted rocks at 1.2 million years) and La Palma (2426 m; 1.8 million years old) have been the most active within the Holocene. Both volcanic islands are characterized by mafic alkaline volcanism, high eruptive rates, and volcanism along magmatic rift zones, commonly associated with the shield cycle of volcanism on ocean island volcanoes. Both volcanoes (and associated islands) are expected to continue to grow in size in the future.

The three central islands, intermediate in age, were in their shield stage in the Middle to Late Miocene and have had low levels of late or rejuvenated volcanism in the Pliocene and/or Quaternary. Tenerife in the central western part of the archipelago forms the largest island and is also the third largest and highest (more than 7000 m in elevation above the sea floor and 3718 m in elevation above sea level; 11.9 million years old) volcanic structure on Earth after the Hawaiian volcanoes of Mauna Loa and Mauna Kea. The highest peak of Tenerife is formed by the highly differentiated (phonolitic) Teide volcano, nested in a lateral collapse caldera (formed through mass wasting), indicating that this volcano is at the transition from its constructive to destructive phase. Considering the significantly lower eruption rates of the Canaries as compared to the Hawaiian volcanoes, the similarity in size reflects Tenerife's older age (longer life-span), most likely related to the almost-order-of-magnitude slower motion of the plate beneath the Canary Islands (~12 mm/year) as compared to the motion of the plate beneath the Hawaiian Islands. Therefore, it has taken much longer for Tenerife to move away from its magmatic source than has been the case with the Hawaiian volcanoes. Although crudely round in outline, the central volcanoes of La Gomera (1487 m; 9.4 million years old) and Gran Canaria (1950 m; 14.5 million years old) no longer have conical shapes and are characterized by deeply incised canyons, indicating that these two volcanoes are well into their destructive phase of evolution, with erosion and mass wasting outpacing growth through magmatic activity. Erosion has exposed intrusive complexes and dike swarms on both islands. The compositions of volcanic rocks are highly variable, ranging from mafic (transitional tholeiite to melilite nephelinite) to highly evolved (peralkaline rhyolite to

trachyte to phonolite), reflecting the mature nature of these volcanoes.

On the two easternmost, oldest, and lowest islands of Fuerteventura (807 m; 20.2 million years old) and Lanzarote (670 m; 15.6 million years old), erosion is clearly the main process shaping the morphology of the islands, even though both islands have had rejuvenated volcanism within the last 150,000 years, and Lanzarote even within historical times. Both islands are realtively flat, with little of the original shield volcano morphology being preserved. Instead, they are characterized by isolated older volcanic sequences or erosional remnants and broad valleys. Surprisingly, the largest historical eruption in the Canary Islands and the second largest basaltic fissure eruption ever recorded (after the 1783 Laki eruption on Iceland) was the 1730–1736 Timanfaya eruption on Lanzarote, which produced ~1 km³ of primarily tholeiitic basalts.

AGE OF VOLCANISM

The age of volcanism in the Canary Islands is well known from radiometric age dating. More than 600 K/Ar, Ar/Ar, and ^{14}C ages have been obtained by different groups on igneous samples from the islands. There have been a number of problems, however, primarily in dating older volcanic rocks and the uplifted portions of the seamount formations, some of which are clearly affected by alteration. Samples with excess Ar have produced ages that are too old, artifically increasing the duration of the basaltic shield stage on the islands. Ages obtained by newer techniques, such as Ar/Ar step heating, single crystal laser age dating, and the K/Ar unspiked method, and the employment of stringent age-dating requirements (e.g., sampling from well-controlled stratigraphic sections, and performing replicated analyses and systematic comparison of the palaeomagnetic polarities of the samples with the currently accepted geomagnetic reversal timescales) demonstrate that there is a progression of increasing age of the shield stage of volcanism from west to east in the Canary archipelago and from southwest to northeast in the Canary volcanic province, even though most of the Canary volcanoes have had a very long, complicated history, often including multiple cycles of late-stage volcanism (Figs. 1 and 2).

VOLCANIC HAZARDS

Geological hazards are moderate in the Canary Islands compared, for instance, with the Hawaiian Islands, which have a similar area and population but much more frequent and intense volcanic activity and seismicity. Although high magnitude eruptions (plinian) occurred

in the geological past of the Canarian archipelago, only moderately explosive activity (strombolian to subplinian) took place in the last 200,000 years. Holocene eruptions, predominantly basaltic fissure eruptions, occurred on all the islands except La Gomera and Fuerteventura. Most of these, however, have been located on La Palma, El Hierro, and Tenerife, with only 10–12 events on Gran Canaria during this period and two on Lanzarote (1730–1736 and 1824). The most recent eruption in the Canary Islands was in 1971, from the Teneguia volcano at the southern tip of La Palma. During the Holocene, phonolitic strombolian to subplinian eruptions were associated with lava dome growth in the Teide volcanic complex on Tenerife, and to a lesser extent on the Cumbre Vieja rift on La Palma.

No casualties have been reported in the 16 eruptions recorded after the colonization of the archipelago at the end of the sixteenth century. Reliable prediction of when future eruptions will occur is not feasible because of the low frequency of events and great variability of inter-eruptive periods, from a few years to several hundred years (e.g., on Cumbre Vieja, the most active volcano in the historic epoch, repose periods varied from 26 to 237 years).

GEOCHEMICAL OVERVIEW OF ISLAND EVOLUTION

The geochemistry of the volcanic rocks from the Canary Islands is well understood in the context of volcano evolution. During each growth cycle (shield and late cycles), highly silica undersaturated rocks (nephelinites and basanites) dominate the early stage, more silica-saturated basaltic melts (alkali basalts and transitional thoeleiites) are produced during the peak of the cycle, and both mafic and evolved alkalic volcanic rocks (alkali basalts–basanites–nephelinites to trachytes–phonolites) are erupted during the waning stages. The almost complete lack of tholeiitic rocks and the low eruption rates during shield-cycle volcanism on the Canary volcanoes is likely to reflect a combination of low sublithospheric upwelling (mass flux) rates of the Canary plume and deep depths of melting beneath the thick Jurassic oceanic lithosphere. Although there are no systematic differences in major and trace element composition, systematic variations in isotopic composition do exist, with shield-stage volcanism being generally characterized by higher Pb and Sr and lower Nd and Hf isotopic ratios as compared to late-stage volcanism. These differences are likely to reflect greater amounts of melting of depleted upper or plume type mantle during the late stages of

volcanism, as compared to enriched plume material during the shield stage of volcanism.

GEOLOGY OF THE INDIVIDUAL CANARY ISLANDS

El Hierro

The youngest and smallest of the Canary Islands is formed by three overlapping Quaternary stages of primarily mafic alkaline volcanism from oldest to youngest: Tiñor, El Golfo, and Rift (Fig. 3). A prominent three-branched rift system and related arcuate lateral collapse embayments (landslide scars) between the rifts define the characteristic shape of the island. Four lateral collapses have been recognized on El Hierro. The Tiñor collapse (~0.8-million-year-old) embayment in the northwestern part of the island was rapidly filled by subsequent volcanism, developing a 2000-m-high, 20-km-wide volcano that collapsed (between 130,000 and 20,000 years ago) to form the present El Golfo embayment. The El Julan lateral collapse (occurring more than 158,000 years ago) removed the southwestern flank of the island, whereas the incomplete failure of the southeastern flank (between ~261,000 and 176,000 years ago) generated the San Andrés fault system and the Las Playas slump. The latest eruptive activity of El Hierro, occuring over the last ~145,000 years, forms a conspicuous three-branched rift system, capping most of the island with eruptive vents (at the rift crests) and lava flows (at the flanks), partially filling the respective collapse embayments. The last eruption on the island, from a small vent on the northeastern rift, was dated by ^{14}C at 2500 years ago. An intense seismic crisis, believed to be related to an impending eruption, almost caused the total evacuation of the island in 1793.

La Palma

La Palma, the most active island of the Canaries in the Holocene, is formed by two coalesced volcanoes: the northern circular Taburiente Volcano and the younger north–south elongated Cumbre Vieja volcano to the south (Fig. 3). Two lateral collapses removed much of the southwestern flank of the Taburiente volcano. The uplifted (by about 1000 m) and tilted Pliocene seamount formations are exposed on the floor and walls of the Caldera de Taburiente, formed by the younger gravitational landslide (~0.5 million years ago). The seamount volcanism is composed of basaltic to trachytic pillow lavas and hyaloclastites. Fossils in submarine sequences suggest that the uplifted portion of the seamount stage may be 3–4 million years old, but there is continuing controversy about the validity of these fossil ages.

The oldest subaerial volcanism is separated from the underlying submarine volcanics by an angular unconformity and a 400–600-m-thick sedimentary unit made up of breccias, agglomerates, and sediments. During the Taburiente stage of volcanism, continuous mafic alkaline eruptive activity formed a 3000-m-high shield volcano. Subsequent volcanism migrated southward along the southern Cumbre Nueva rift zone. Continuing southward migration of volcanism ultimately resulted in the extinction of the northern shield ~0.4 million years ago and in the formation in the last 130,000 years of the Cumbre Vieja rift zone, a 20-km-long, 1949-m-high ridge, composed predominantly of mafic alkaline lavas.

Half of the historical (i.e., occurring in the last 500 years) eruptions of the Canary Islands, including the most recent event in 1971, occurred along the Cumbre Vieja rift system (Fig. 3). These eruptions have been characterized by Strombolian activity forming cinder cones and lava flows. The 1971 eruption added several square kilometers of new land to the island, clearly demonstrating that the island is still growing. Phonolites have been extruded in several of the historical eruptions and can form from basanitic parental magmas within 1000–2000 years. The 1585 eruption is famous for the emplacement of giant phonolitic spines (tens of meters high), which, according to an eyewitness account of a monk, rose from the ground like "the devil's horns" at the beginning of the almost exclusively mafic eruption.

La Gomera

La Gomera, presently undergoing a volcanic hiatus, is a heavily eroded, circular (22 km in diameter) volcano (Fig. 4). During the Late Miocene, the mafic alkaline shield volcano (~9–8 million years old) experienced a northward lateral collapse. Continued volcanic activity filled the collapse embayment and spread over the entire island, forming a central volcano with differentiated rocks at its terminus. The remains of a central caldera in this volcano crop out north of Vallehermoso, comprising trachytic and phonolitic lavas and intrusives with the latter forming radial dike swarms and cone sheets. A local unconformity separates the late-cycle Pliocene (occurring primarily 5–4 million years ago) mafic alkaline eruptions from the Miocene shield. Numerous phonolitic domes, some of the most conspicuous and spectacular volcanic features of the island, intrude both the Miocene and Pliocene mafic sequences. Volcanic activity was sparse during the last 4 million years and ended completely on the island
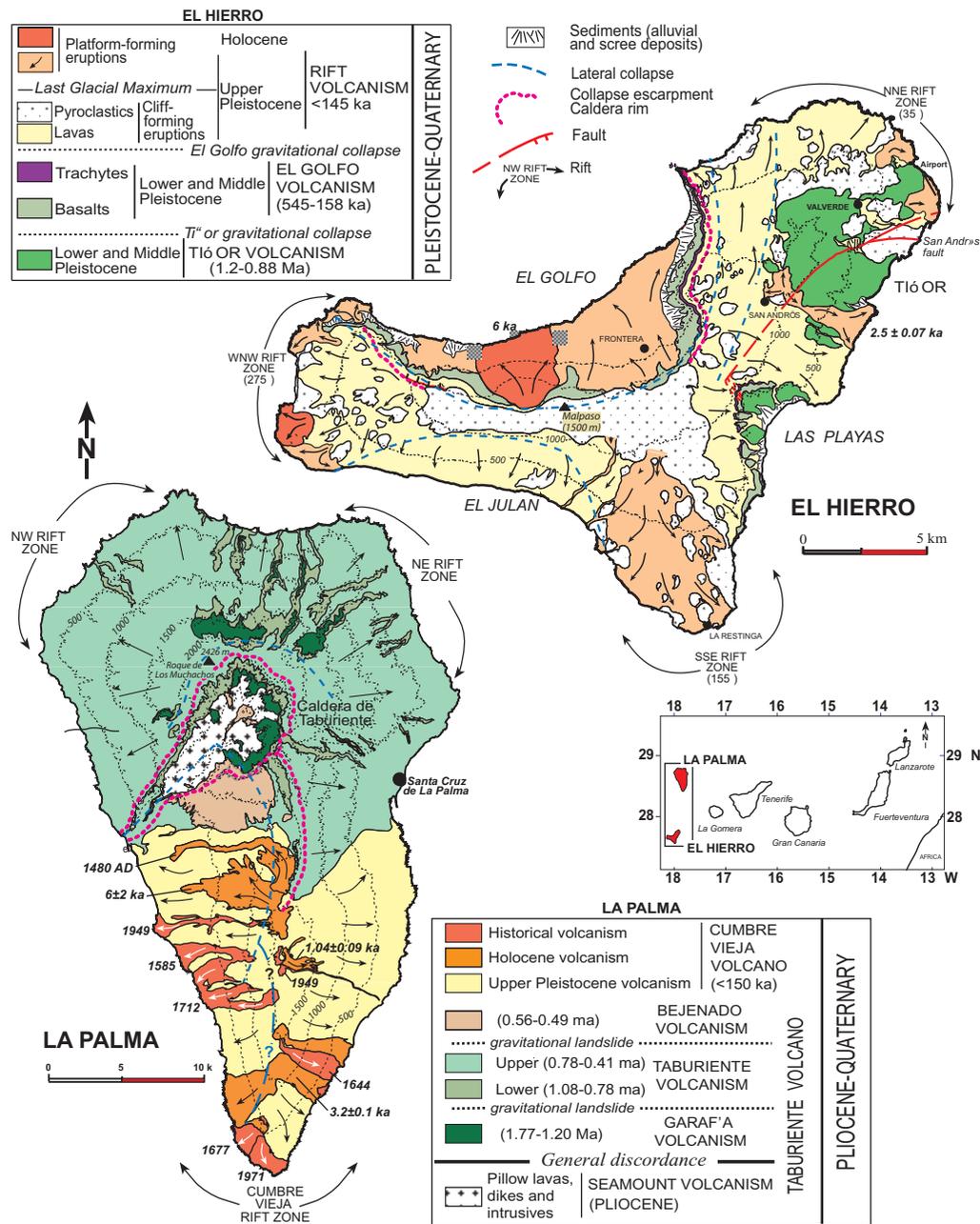
FIGURE 3 Simplified geological map of the western Canaries: El Hierro and La Palma. Modified from Carracedo *et al.* (2002).

1.9 million years ago, the age of the younger intra-canyon lavas located south of the capital San Sebastián.

Tenerife

The triangular-shaped island of Tenerife is the largest and highest in the Canarian archipelago and has a complex volcanic history (Fig. 4). The oldest visible volcanic rocks on Tenerife correspond to three deeply eroded mafic alkaline massifs: the Central, Anaga, and Teno shield volcanoes. The Central shield, the first to develop, is at present covered by later volcanism, with the exception of some outcrops in the southern flank of the island (the Roque del Conde massif). The shield stage of the island was completed with the growth of two new volcanoes, the

FIGURE 4 Simplified geological map of the central Canaries: La Gomera, Tenerife, and Gran Canaria. Modified from Carracedo *et al.* (2002).

Teno volcano, overlying the western flank of the Central volcano, and the Anaga volcano, which developed at the northeastern part of the island.

Late-cyle volcanism took place after 4–5 million years of eruptive quiescence and discordantly overlies the Central volcano. In this rejuvenated cycle, a 40-km-wide, 3000-m-high, progressively differentiated central volcano (Las Cañadas volcano) developed with contemporaneous basaltic eruptions along a three-arm rift system on the flanks of the Central volcano. Major explosive eruptions from the central volcano formed trachytic ignimbrites, pyroclastic flows, and ash-fall deposits mantling the southern flank of the island (the Bandas del Sur formation).

About 200,000 years ago, the summit of the Cañadas central volcano collapsed, forming the Caldera de Las Cañadas and the La Guancha–Icod depressions. Activity on the northeastern and northwestern rift zones may have played an important role in activating this gravitational landsliding. This catastrophic event marked the onset of the latest eruptive phase in Tenerife, characterized by continued mafic alkaline activity on the rifts and by the subsequent growth of the phonolitic Teide central volcano, nested within the collapse embayment. Parts of the northeastern rift zone also collapsed to form the La Orotava and Güímar valleys.

Relatively abundant eruptive activity occurred in this latest volcanic phase of Tenerife. At least 42 events took place during the Holocene, the greater part (60%) as mafic alkaline fissure eruptions on the northwestern and northeastern rift zones and 40% as phonolitic eruptions inside the Caldera de Las Cañadas and on the Teide–Pico Viejo volcanoes, particularly as lava domes and coulees. The latest eruption of the Teide volcano (Lavas Negras eruption) is generally believed to be the eruption seen by Christopher Columbus in 1492 on his way to discovering America. The radiocarbon age of 1150 ± 140 years BP, however, indicates that this could not have been the eruption observed by Columbus. The 1492 sighting of Columbus probably corresponds to Montaña Boca Cangrejo, a vent located in the northwestern rift zone with a radiocarbon age of 400 ± 110 years BP. The four most recent eruptions took place in 1705, 1706, 1798, and 1909.

Gran Canaria

The subaerial evolution of Gran Canaria can be divided into three cycles of volcanic activity: a Miocene shield cycle (~14.5–8.8 million years ago) and two late cycles in the Pliocene (~5.6–1.7 million years ago) and Quaternary (less than 1.3 million years ago). The oldest subaerial rocks on Gran Canaria (older than 14.5–14.0 million years), outcropping primarily in the southwest of the island, are alklali basaltic lava flows belonging to the shield stage of volcanism (Fig. 4). The Miocene basalts are overlain by up to more than 1000 m of evolved ignimbrites, lavas, and fallout tephras, respresenting the largely explosive outflow facies of the large elliptical, northwest–southeast trending, 20 by 17–km, 1000-m-deep Caldera de Tejeda. The Tejeda caldera may be unique in the Canary Islands in that it formed by collapse of the summit of the basaltic shield volcano above a large shallow magma chamber (at a 4–5-km depth). The onset of the collapse occurred upon the eruption of the widespread (covering an area of more than 400 km^2), voluminous (~45 km^3) P1 ignimbrite 14 million years ago, zoned from rhyolite to trachyte to basalt (from bottom to top). The outflow facies of the caldera become more silica-undersaturated in their upper sections (changing from predominantly peralkaline rhyolites to phonolites), with most activity having ended by ~9 million years ago. Alkali syenite intrusives and a spectacular trachytic–phonolitic cone sheet swarm of dikes, which erosion has exposed in the central part of the island, provide the last evidence of Miocene magmatic activity lasting to ~7 million years ago.

Late or posterosional volcanism started around 5.6 million years ago with the eruption of low volumes of nephelinite to basanite lavas and pyroclastic rocks from monogenetic centers. The Roque Nublo stratovolcano (~4.2–3.5 million years old) began with thick sequences of mafic lava flows (transitional tholeiite to basanite) filling canyons in the deeply eroded Miocene volcanic edifice. Upsection, the volcanic rocks become more evolved (ranging primarily from hawaiite to trachyte and tephrite to phonolite) and grade into tuffaceous rocks, massive breccia sheets (representing block and ash flows, lahars, and landslides), and volcanic plugs of highly evolved hauyne–phyric phonolites such as above Risco Blanco at the head of Barranco de Tirajana. The upper portions of the Roque Nublo group outcrop primarily in the center of the island, where the well-known Roque Nublo monolith, formed from a large breccia block, forms one of the highest peaks on the island. The Roque Nublo stratocone is likely to have reached an elevation of more than 3000 m and thus may have been similar in height to the present Pico de Teide volcano on Tenerife. Overlying an erosional unconformity in some parts of the island is a package of primarily basanitic to melilite nephelinite lava flows and dikes (~3.1–1.7 million years old), outcropping exclusively on the northeastern half of the island. Quaternary volcanism (occurring in the last 1.3 million

years), primarily nephelinitic to basanitic in composition, has been increasing over the last 600,000 years, suggesting that Gran Canaria may be entering a new late cycle of activity. The youngest dated volcanic structure on the island is the Bandama caldera and strombolian cone (~2000 years old).

Fuerteventura

Fuerteventura has the oldest exposed rocks of the Canary Islands and is closest (100 km) to the African coast, situated on up to 10 km of continental rise sediments derived from Africa. Four main lithological units are exposed on Fuerteventura (Fig. 5): (1) Mesozoic oceanic crust and sediments, (2) submarine volcanics and intrusives and sediments, (3) Miocene shield volcanoes, (4) and late or rejuventated Pliocene-Quaternary volcanic rocks and sediments. The Mesozoic oceanic crust, presumably uplifted as a result of extensive intrusive activity, is exposed along the western coast of the island and comprises a thick (~600-m) sedimentary sequence of Early Jurassic age with rare ocean crust volcanic rocks. Alkalic volcanic rocks with ages near the Cretaceous–Tertiary boundary may be associated with seamount volcanism unrelated to the formation of the Canary Islands.

The submarine volcanic rocks, comprising mafic pillow lavas and hyaloclastites, are unconformably overlain by littoral and shallow-water marine deposits (reefal bioclastic sediments, beach sandstones, and conglomerates), gently tilted to the west and apparently representing the transition from submarine to subaerial activity. A sequence of plutonic and hypabyssal intrusions, including an early syenite–ultramafic formation (alkali pyroxenites, amphibolites, and amphibole gabbros intruded by syenites) and later ijolite–syenite–carbonatite complexes (rarely exposed in intraplate island volcanoes), appear to be associated with the submarine volcanic complex.

Beginning about 20 million years ago, three adjacent basaltic shield volcanoes developed: the Central, Northern, and Southern or Jandía shields, comprising mainly alkali basaltic and trachybasaltic lavas, with minor trachytic differentiates. The extremely dense northeast–southwest dike swarm crossing the Miocene shields may be related to crustal stretching of as much as 30 km. Plutonic rocks (pyroxenites, gabbros, and syenites) and a basaltic-trachybasaltic dike swarm, which represent the hypabyssal roots of the evolving subaerial volcanic complexes, outcrop in the core of both the Central and Northern shields. Later plutonic activity includes concentric intrusions of gabbros and syenites, forming a spectacular ring complex.

Late-cycle volcanism extended from about 5.1 million to 134,000 years ago, the time of the last eruption dated on the island, although cones in the northern part of the island may be younger. Abundant littoral marine fauna developed during Pliocene equatorial climatic phases, and large volumes of aeolian sands derived from the Sahara covered most of the island at the end of the Pliocene.

Lanzarote

Lanzarote is the continuation to the northeast of Fuerteventura; these two islands are not geologically different, *sensu stricto,* because they are only separated by a narrow stretch of sea, which is shallower (less than 40 m) than the lowest sea level at maximum glacials. The oldest rocks in Lanzarote correspond to two main basaltic volcanoes, which developed as independent island volcanoes: the southern Ajaches volcano and the northern Famara volcano (Fig. 5). Isotope geochemistry suggests that both volcanoes represent late cycles of volcanism, and therefore that the shield cycle forming the bulk of this island may not be subaerially exposed. After a period of general quiescence of about 4 million years, a new cycle of rejuvenated activity resumed in the Quaternary with basaltic eruptive centers aligned in the northeast–southwest direction. The Corona volcanism in the northern part of the island (occurring 21,000 ± 6500 years ago) produced one of the largest known lava tubes, 6.8 km long with sections reaching 25 m in diameter. The tube formed as the lavas advanced along a wave-cut platform located 70 m below the present sea level. The last 2 km of the lava tube are at present submerged (−80 m) following sea-level rise after the last glaciation.

Holocene eruptions are probably limited to the historical 1730–1736 and 1824 events. During the 1730–1736 Timanfaya eruption, which lasted for 68 months, over 30 volcanic vents, aligned along a 14-km-long, N 80° E–trending fissure, were formed in five main multi-event eruptive phases. The Timanfaya eruption began with the eruption of basanite and alkali basalt during the first half-year and then erupted tholeiite for the rest of the eruption. In stark contrast to Hawaii, where tholeiites represent the most common rock type during the shield stage of volcanism but are generally absent in the rejuvenated stage, the late-cycle Timanfaya eruption produced the most tholeiitic rocks found thus far in the Canary Islands.

OTHER VOLCANOES OF THE CANARY VOLCANIC PROVINCE

The Selvagen Islands and neighboring large seamounts, located north and northeast of the Canary Islands, are
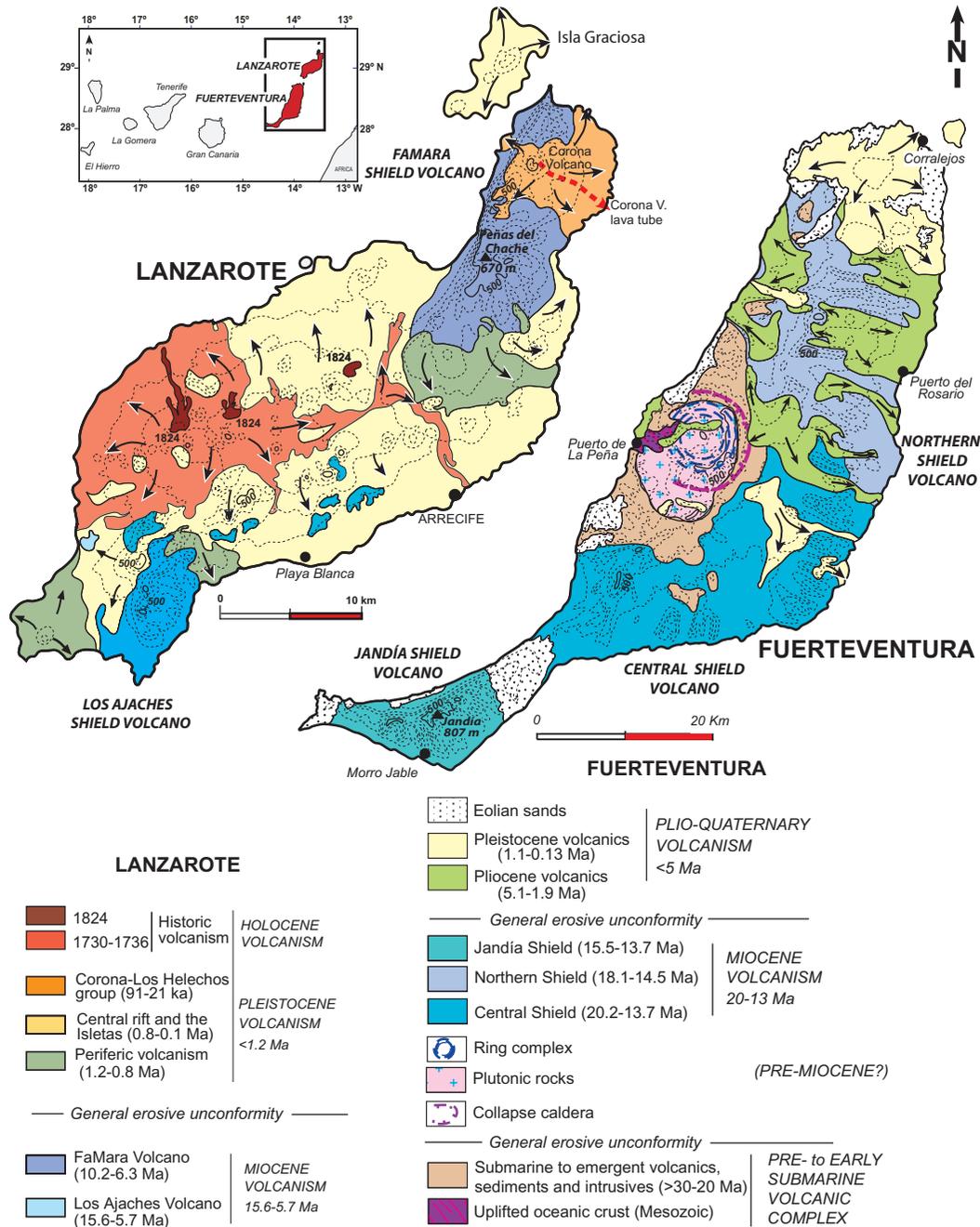
FIGURE 5 Simplified geological map of the eastern Canaries: Lanzarote and Fuerteventura. Modified from Carracedo *et al.* (2002).

located on the same bathymetric high as the Canary Islands and have similar geochemical (major and trace element and Sr–Nd–Pb–Hf isotopic) compositions to the Canary Island magmatic rocks, but distinct compositions from the Madeira Island rocks to the north (Fig. 1), consistent with their derivation from a similar source as the Canary Islands. Therefore, these volcanic structures are also included in the Canary volcanic province and

can provide clues to the earlier history and origin of the Canary Islands.

The Selvagen Islands, located about 200 km north of the Canary Islands, form the summits of two shield volcanoes that ascend from 4000 m water depth, merging at depths between 500 and 1000 m. The main island of Selvagem Grande (163 m; area of 2.4 km²) is located on the summit of the northeast volcano, and a group of

small islands, the largest being Selvagem Pequena (49 m; 0.2 km^2), is located on the summit of the second volcano. A basanitic to phonolitic intrusive complex (29 million years in age) is exposed on Selvagem Pequena belonging to the shield cycle of activity. Despite its small size, three magmatic stages have been identified on Selvagem Grande: (1) a late Oligocene (occurring 26–24 million years ago) tephritic to phonolitic shield cycle intrusive complex, (2) a Middle to Late Miocene (occurring 12–8 million years ago) mafic alkaline late cycle, and (3) a Pliocene (occurring 3.4 million years ago) mafic alkaline late cycle.

Seven large seamount complexes are located to the northeast of the Canary Islands. Many of the seamounts in the northeastern portion of the volcanic province are guyots with flat tops from which beach cobbles were obtained by dredging, indicating that these guyots were former islands that were eroded to sea level by wave action and then subsequently subsided beneath sea level. Age-dated samples from four seamounts can be placed in shield and late cycles using geochemical criteria (e.g., Pb isotopic composition). When only the oldest ages from the shield-stage volcanic rocks are considered, there is an age progression with ages increasing from southwest to northeast through the Canary volcanic province, consistent with motion of the African plate in this region over a relatively fixed magma source at a rate of ~1.2 mm/year over the last ~70 million years.

MODELS FOR THE ORIGIN OF THE CANARY VOLCANIC PROVINCE

A wide variety of models have been proposed to explain the origin of the Canary Islands and the Canary volcanic province. These include volcanism resulting from decompression melting (1) along a leaky transform fault or propagating fracture (i.e., most likely an extension of the South Atlas fault system), (2) beneath rising lithospheric blocks as a result of tectonic shortening, (3) beneath a suture zone running along the Atlantic margin of northwestern Africa, or (4) of an upwelling mantle plume. The first three sets of models rely upon structures that cut through the lithosphere to cause and to control the location of the volcanism, whereas the origin and location of volcanism in accordance with the fourth model is largely independent of the lithosphere. The curved northeast–southwest alignment of the Canary and Madeira volcanic provinces clearly deviates from the east–west orientation of fracture zones in the East Atlantic crust. Furthermore, there is no evidence for such faults in the Canary or Madeira volcanic provinces or for suture zones in these areas. In addition, movements along structures cutting thick Mesozoic litho-

sphere would only generate very small volumes of melt as a result of the passive upwelling of normal asthenospheric mantle. Finally, there is no explanation why two roughly parallel curved fracture zones would form and propagate in the same curved direction and at the same average rate for at least 70 million years in this region.

The hotspot or mantle plume model, however, can adequately explain the parallel age progressions of oldest shield-cycle volcanism along curved southwest to northeast paths for the Canary and Madeira volcanic provinces. The age progressions of ~12 mm/year for both volcanic provinces are consistent with the rotation of the African plate around a common Euler pole (at 56° N, 45° W between 0 and 35 million years ago, and at 35° N, 45° W between 35 and 64 million years ago at an angular velocity of ~0.20° ± 0.05°/million years) above relatively fixed but distinct (based on differences in geochemistry for the two volcanic provinces) magmatic sources (i.e., mantle plumes). Strong additional support for the existence of a mantle plume comes from seismic tomography, which has imaged a mantle plume to the core–mantle boundary (at 2900 km) beneath the Canary Islands. The long history of volcanism on individual volcanoes could result through small amounts of melting of plume material flowing in the asthenosphere to the east and northeast beneath the older volcanoes.

SEE ALSO THE FOLLOWING ARTICLES

Canary Islands, Biology / Eruptions / Seamounts, Geology

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CAPE VERDE ISLANDS

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Cape Verde's natural heritage is unique. The physical environment of these islands creates a multiplicity of habitats with a great wealth of fauna and flora. Nevertheless, this biodiversity is naturally restricted to the narrow geographical limits of the islands and is extremely vulnerable to disturbances caused by human activities. The threatened island endemics are thus likely to benefit from conservation management programs that are urgently needed if Cape Verde's natural levels of diversity are to be maintained.

PHYSICAL ENVIRONMENT

Geography and Geomorphology

The Cape Verde archipelago is grouped together with the Azores, Madeira, the Selvagens, and the Canary Islands in the Macaronesian region, which is situated in the North Atlantic Ocean, close to the West African coast and the West Mediterranean region. The Cape Verde archipelago consists of ten volcanic islands and several islets situated between 14°45′–17°10′ N and 22°40′–25°20′ W (Fig. 1). It lies 1500 km south of the Canary Islands, and a mere 570 km separate Boavista Island from the African mainland (the coast of Senegal). The archipelago is spread over 58,000 km² of ocean and has about 1050 km of coastline.

The Cape Verde Islands are usually classified in three groups: Northern Islands, Eastern Islands, and Southern Islands (Table 1). However, other classification groups are also considered: the Windward Islands (Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, and Boavista), and the Leeward Islands (Maio, Santiago, Fogo, and Brava).
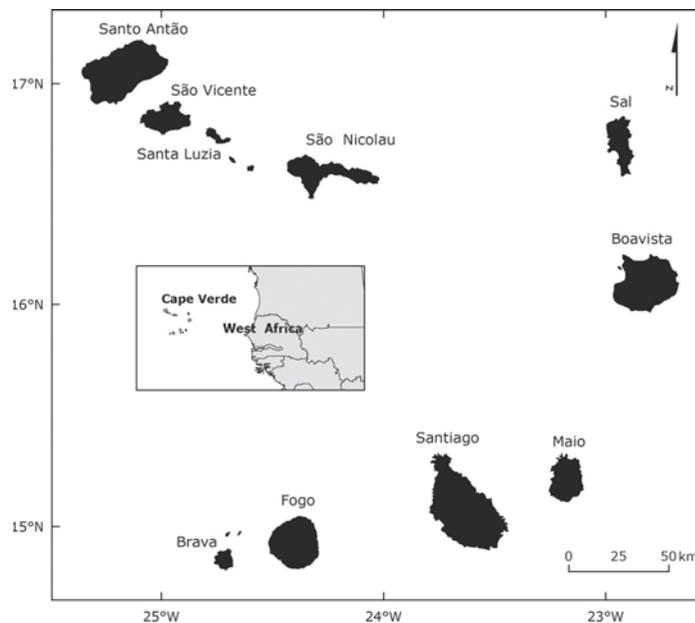
FIGURE 1 Cape Verde Islands: geographic location.

Santiago is the largest island and is home to more than half of Cape Verde's total population (434,625 inhabitants as of the 2000 census), whereas the smallest island—Santa Luzia—is uninhabited.

The northern and southern groups are characterized by high mountains and offer a wide range of habitats in relatively small areas. Slopes can be extraordinarily steep (average gradients of 25° to 41°), with active fluvial erosion. The eastern group is composed of flat islands, and such peaks as do exist reach only a few hundred meters in height and are surrounded by relatively broad extents of plain land, where deposition is dominant. Fogo Island contains Cape Verde's tallest mountain—Pico do Fogo—which rises to 2829 m (Table 1).

TABLE 1
Some Geophysical Features of the Cape Verde Islands

Island Group	Island Names	Area (km²)	Max. Altitude (m)	Population (as of 2000)
Northern	Santo Antão	779	1979	47,170
	São Vicente	227	725	67,163
	Santa Luzia	35	395	0
	São Nicolau	343	1304	13,661
Eastern	Sal	216	406	14,816
	Boavista	620	387	4209
	Maio	269	436	6754
Southern	Santiago	991	1392	236,627
	Fogo	476	2829	37,421
	Brava	64	976	6804