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Discussing the origin of "hotspot" volcanism

Canaries

The Canary Islands Hot Spot

José Mangas Viñuela

Departamento de Física-Geología, Edificio de Ciencias Básicas, Campus Universitario de Tafira, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain.

jmangas@dfis.ulpgc.es

The Canary archipelago comprises seven main volcanic islands and several islets that form a chain extending for ~ 500 km across the eastern Atlantic, between latitudes 27°N and 30°N, with its eastern edge only 100 km from the NW African coast (Figures 1 & 2). The Canary Islands developed in a geodynamic setting characterized by Jurassic oceanic lithosphere formed during the first stage of opening of the Atlantic at 180-150 Ma and lying close to a passive continental margin on a very slow-moving tectonic plate – the African plate. In addition, the archipelago lies adjacent to a region of intense active deformation comprising the Atlas mountains, a part of the Alpine orogenic belt.

Figure 1: The Canary Islands from space (NASA, Apollo).

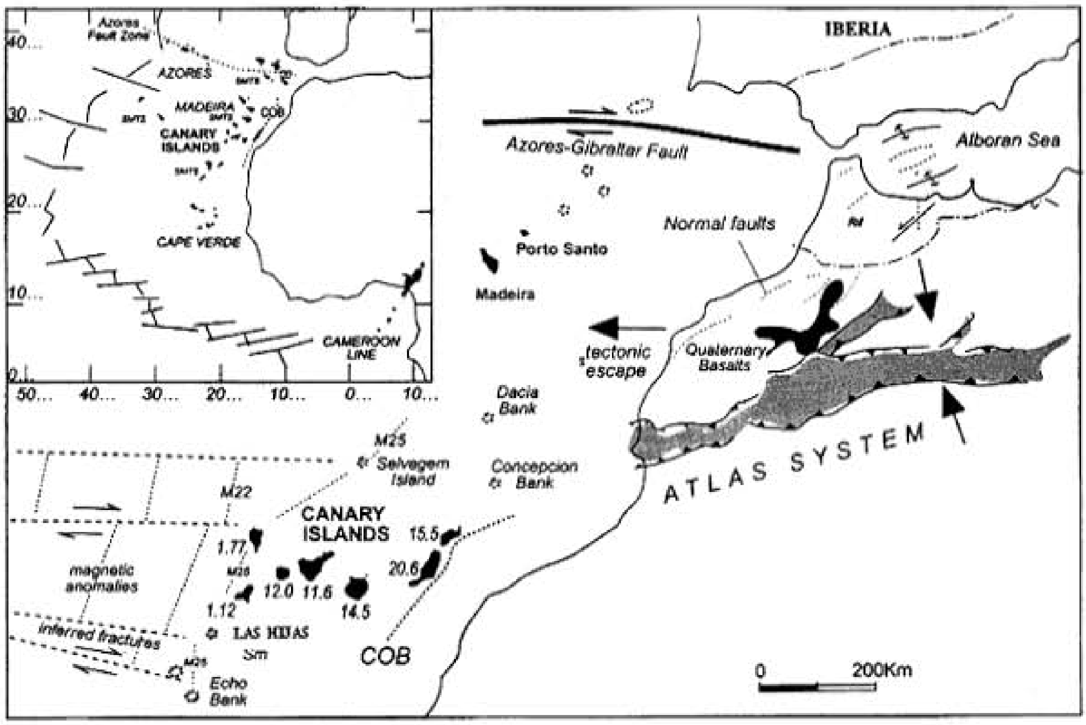


Figure 2: Geographic and geodynamic setting of the NW African continental margin with the Canary Islands and other archipelagos (from Carracedo et al., 2002).

Seismic refraction data and magnetic anomalies suggest that all the islands lie on oceanic crust and their limit is located between Lanzarote-Fuerteventura (Figure 3) and the coast of Africa (*Roest et al.*, 1992). The M25 magnetic anomaly (Middle Jurassic; ~ 56 Ma) is located on the ocean crust near La Palma and El Hierro, the two western-most islands. One “slope anomaly”, the S1 (175 Ma) anomaly, has also been identified between the easternmost islands and the African continent. The continent-ocean boundary is characterized by the presence of a 10-km-thick layer of sediments. The seismic sections show a number of discontinuities, interpretated as basement fractures, and some of them are seismically active. On the other hand, seismic data indicate a Moho depth of ~ 13 km beneath the islands.

Magmatism in the Canary Islands started during the Cretaceous and subaerial volcanism during the Miocene (Figure 3). The oldest stages have been difficult to reconstruct due to problems inherent in isotopic dating. Thus, *Cantagrel et al.* (1993) show K-Ar ages for the submarine magmatism of Fuerteventura around 35 – 30 Ma. In contrast with those authors, *Le Bas et al.* (1986), *Steiner et al.*, (1998) and *Balogh et al.* (1999), essentially on the basis of palaeontology, field relations and radiometric study, suggest the submarine magmatic activity of Fuerteventura began in the Senonian, or around 70 or 80 Ma. These dates contrast with the submarine stage age at La Palma, in the western part of the archipelago, which was formed at only 3 – 4 Ma (*Staudigel et al.*, 1986). Fuerteventura shows subaerial volcanism at 20.6 Ma and El Hierro younger than 1.12 Ma. All the islands except one (La Gomera) have been active in the last million years and four of them (Lanzarote, Tenerife, La Palma and El Hierro) have records of eruptions in the last five centuries.

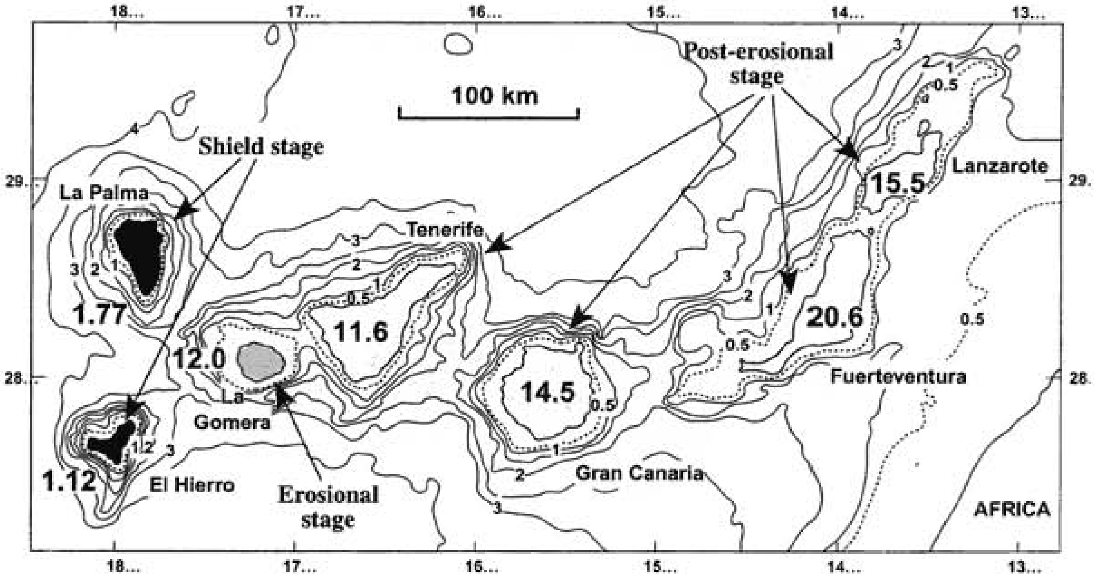


Figure 3: Oldest ages of the subaerial volcanism in the Canary Islands (Carracedo et al., 2002).

The origin of magmatism in the Canaries and its complicated space-time relationships have been a subject of debate for a long time. It is popularly believed that the origin of oceanic intraplate volcanism is related to mantle plumes. On the other hand, the long period of eruptive activity in this archipelago (> 20 Myr in some islands), their morphological and structural features, seismic signature and geochemical evolution (*Schmincke*, 1973; *Hoernle et al.*, 1995; *Hoernle & Schmincke*, 1993; *Carracedo et al.*, 1998; *Canas et al.*, 1998, and others) present problems for that model (Figure 4). The origin of the Canaries has been also attributed to:

1. ***A propagating fracture***: the extension to the Canary Islands of an offshore branch of the trans-Agadir fault, associated with the Atlas tectonic chain (*Anguita & Hernan*, 1975). Objections to this hypothesis are that there is no evidence of continuous faults connecting the two areas, the absence of volcanic constructs between the two zones, and the lack of explanation of the uplift of insular blocks.
2. ***A local extensional ridge***: there was a regional extensional structure active in the area in Cenozoic times (*Fuster*, 1975). Objections to this include that the ocean lithosphere around the Canaries is Jurassic, dike swarms in the submarine stages of Fuerteventura, Gomera and La Palma have different strikes, the rift geometry in each island is different and the islands are separated by deep sea with a lack of Cenozoic lithosphere added to the Mesozoic lithosphere.
3. ***Uplifted tectonic blocks***: Compressive tectonics give way to ocean-floor shortening and crustal thickening, and this process may be the main cause of magmatism and the uplift of blocks forming the Canary Islands. The occasional relaxation of tectonic stress would permit magma eruptions (*Araña & Ortiz*, 1986). An objection to this model is that it does not propose a convincing process for magma genesis and for the spatial and temporal distribution of volcanism in the archipelago.
4. ***A hot spot***: a mantle plume – the slow-moving hot spot model. Objections to this are that seismic tomography shows a cold lithosphere beneath the Canaries, subaerial volcanic activity shows an irregular westward progression and the thermal anomaly exhibits low melt production. There are long magmatic records (at least 39 Myr on Fuerteventura) which show time gaps in volcanic activity in some islands of up to several million years. There is no bathymetric swell in the Canaries area and no subsidence of the western islands.
5. ***A unifying model***: This suggests the origin of the magmas is a mantle anomaly. Tensional stages generate fractures that serve as conduits for magma liberation and compressive stages produce uplift of islands manifest as sets of flower structures. This model explains the magmatic and tectonic relationships from the Upper Cretaceous to the Miocene in both areas (*Anguita & Hernan*, 2000). The objections to this model are that there are still several open questions on the geology of the Canary Islands and Atlas Mountains. It is thus necessary to explain more about the space-time magmatic and tectonic relationships in each island, in the archipelago zone, and in the Atlas chain from the Miocene to present.

Hoernle et al. (1995) cite evidence from seismic tomography and isotope geochemistry of a large region of upwelling in the upper mantle extending from the eastern Atlantic (Canary Islands and North Africa) to the western Mediterranean. This anomaly has the shape of a sheet and *Oyarzun et al.* (1997) propose that this is a thermal anomaly representing the remnant of a "fossil" plume, now present under the African margin and Europe. The apparent lack of a Canarian lithospheric swell was cited by several authors as an argument against the presence of a hot spot in the Canaries. However, *Canales & Dañobeitia* (1998) analysed a number of seismic lines in the vicinity of the archipelago and demonstrated the existence of a subdued (~ 500 m maximum elevation) lithospheric depth anomaly around the Canary Islands. They proposed that this anomaly could be related to a swell that is otherwise obscured by the weight and perhaps also mechanical effects of the thick sedimentary cover along the NW African continental margin and by the weight of the volcanic rocks of the islands themselves.

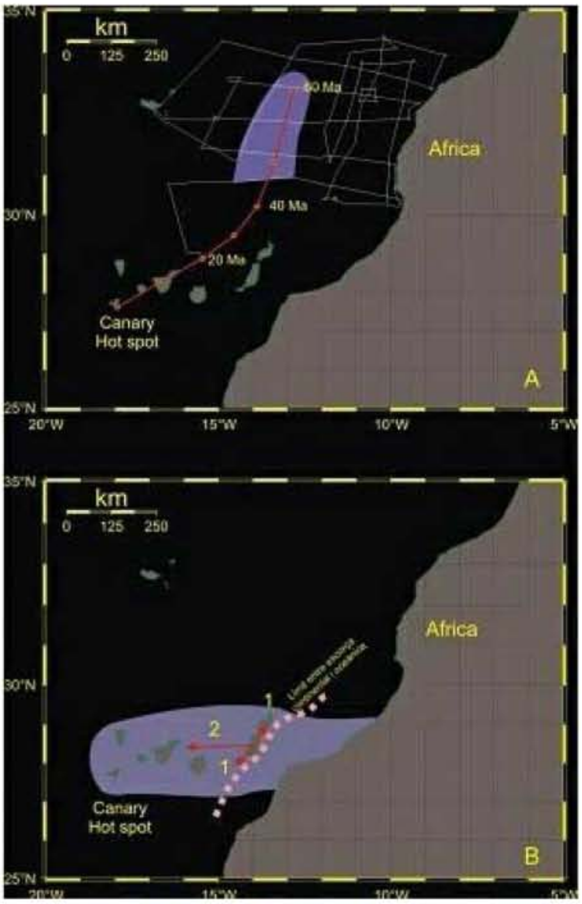


Figure 4: The hot spot model for the Canary archipelago (Hollik et al., 1991; Carracedo et al., 1998). Hollik et al. (1991) identified a submarine reflector (apparently Late Cretaceous and younger towards the south) near the African continental margin, NNE of the Canary islands (upper panel). This was the first magmatic material emplaced. However, the model of Carracedo et al. (1998) predicts that the first magmatic rocks were produced at ~ 25 Ma in the Fuerteventura area and that progression of volcanism was from east to west (lower panel) (from Urgeles, 2000).

A wealth of geological data made available in recent years has led to the conclusion that the Canaries, like the Hawaiian archipelago, show submarine stages, followed by shield-building, declining, erosive and rejuvenation stages (Walker, 1990). The stages shown by the Canary Islands are (Figures 5 & 6):

1. seamount and emergent, containing submarine sediments, volcanic rocks (mainly alkali basaltic pillow basalts and hyaloclastites), dyke swarms and mafic and ultramafic plutonic intrusions which form the cores of these islands (Figure 7);
2. shield-building, characterized by subaerial alkaline basalts and trachybasalts lava flows (Figure 8);
3. declining, containing rocks with trachytic and phonolitic compositions (Figure 9); and
4. rejuvenation, containing nephelinites, basanites and basalts lava flows (Figure 10).

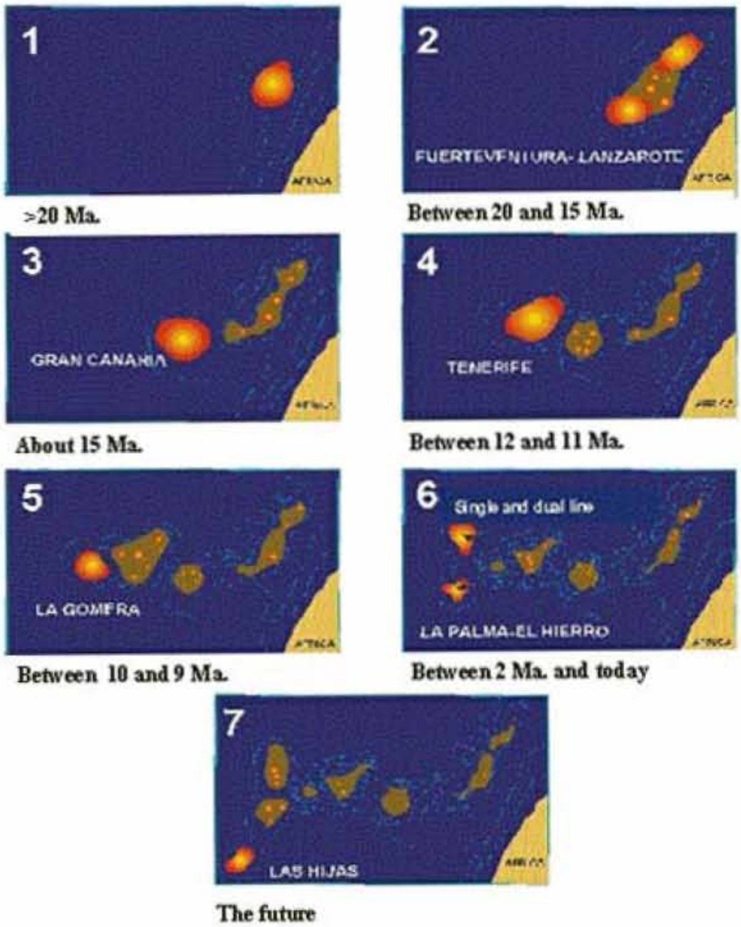


Figure 5: Genetic evolution of the Canary Islands from Miocene to present (Carracedo, 1999).

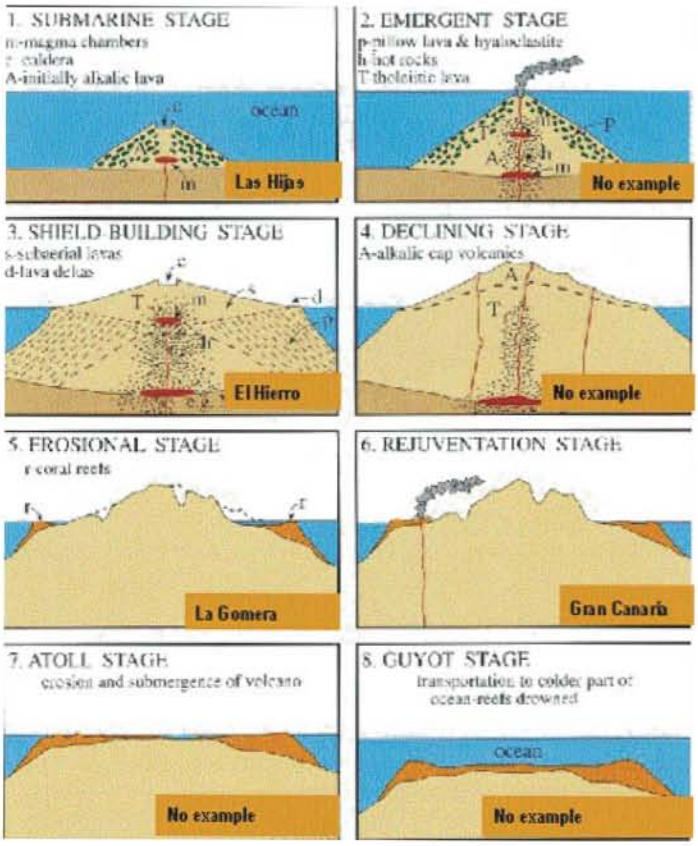


Figure 6: Formation stages of volcanic islands associated with "hot spots" (modified from Walker, 1990).

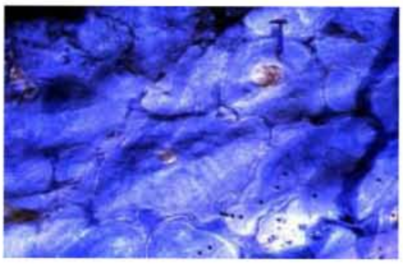


Figure 7: Basaltic pillow lavas of the submarine stage from La Palma island (Barranco Las Angustias).

Figure 8: Basaltic lava flows of the shield-building stage from Gran Canaria (the cliffs of Güigüi).

Figure 9: Unconformity between a trachy-phonolitic cone sheet of the declining stage and horizontal volcanic rocks of the rejuvenation stage from Gran Canaria (Barranco de Tejeda).

Figure 10: Line of strombolian cones in Timanfaya National Park associated with the rejuvenation stage of Lanzarote.

The successive stages are commonly separated from each other by time gaps several million years long and there are sometimes time gaps withing a single stage. In addition, the landscape of the Canaries is characterized by collapse structures – vertical collapse calderas (such as the Caldera de Tejeda in Gran Canaria), gravitational collapse scarps and embayments (Figure 11) such as El Golfo, Julán y Las Playas and El Hierro (Figure 12) and rift zones (Figure 13), locally known as "dorsales" (such as the Cumbre Vieja volcano in La Palma).

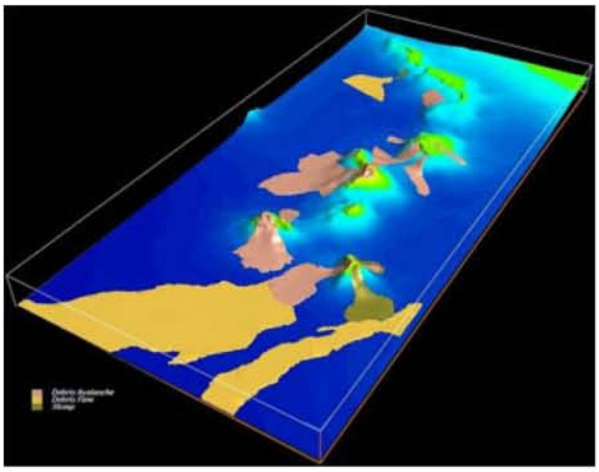


Figure 11: Debris avalanches, debris flows and slumps in the Canaries zone (M. Canals, 2003). Click on image for enlargement.

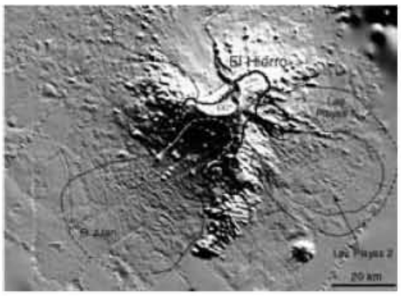


Figure 12: Giant landslides of El Hierro (M. Canals, 2003).

Figure 13: Aerial view of the southern part of La Palma and Cumbre Nueva rift (Photo: S. Socorro).

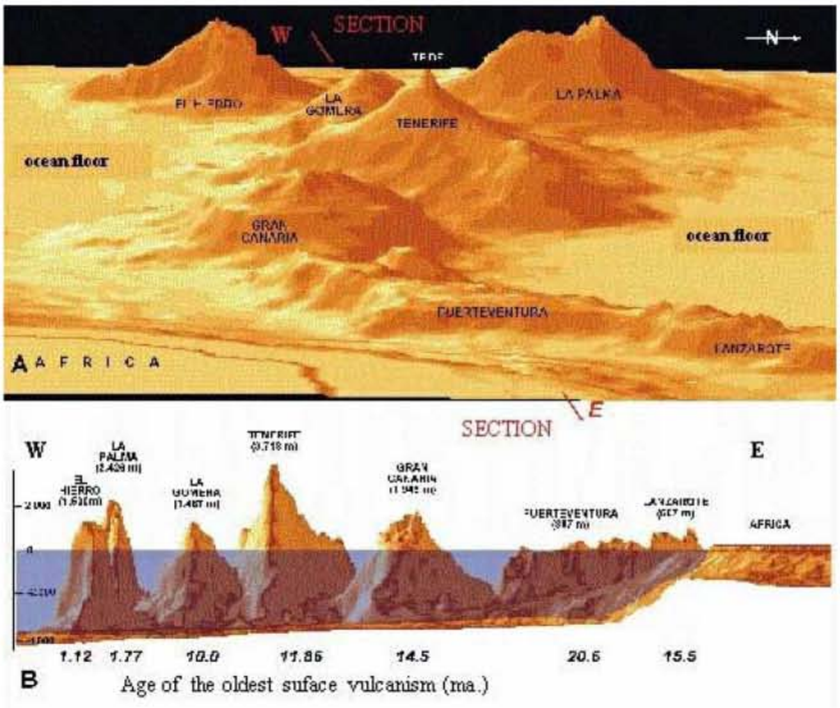
The Canaries also show some interesting differences with the Hawaii Islands, however:

1. the geochemical evolution of their magmas (alkaline suite),
2. the formation of central stratovolcanoes (Roque Nublo in Gran Canaria and Teide in Tenerife (Figure 14),
3. the island tectonics, *e.g*., ductile shears associated with transtensive systems (*Fernandez et al*., 1997; Figure 15), compressional structures such as recumbent folds (*Robertson & Stillman*, 1979), blocks differentially uplifted from the sea floor – 2 km for La Palma and 2 – 4 km for Fuerteventura, and tectonic lineaments with different azimuths in each island, and
4. the small or zero subsidence – in several islands there are marine structures and deposits of different ages up to several million years old that appear to have remained close to present-day sea level.

Figure 14: Northwest littoral area of Tenerife and view of the Teide stratovolcano.

Figure 15: Shear zone associated with the submarine stage of Fuerteventura (Caleta de la Cruz, west coast). Carbonatites, syenites and gabbros are deformed and intruded by later basaltic dykes.

The volume and distribution of the volcanoes provides interesting information about the evolution of the archipelago. The islands rest on an oceanic floor that deepens progressively westward, reaching a depth of 4,000 m in the area of La Palma and El Hierro (Figure 16A).



Shaded relief images (Figure 16B), which give an empty ocean view of the Canarian chain, clearly show that the elevation and emerged volume of the islands increase as their age decreases, with a generally westward trend. The islands of Fuerteventura and Lanzarote, and the chain of seamounts off Cape Juby, are parallel to the continental margin, whereas most of the remaining islands of the archipelago follow a general east-west trend.

Figure 16: Shaded relief view of the Canary Islands from the east (A) and east-west cross-section (B) (from Carracedo et al., 2002).

The dual line of La Palma and El Hierro forms a north-south trend and are thought to be associated with changes in plate motion. In addition, *Rihm et al.* (1998) demonstrate the presence of a group of apparently young seamounts (the Las Hijas seamounts) located 70 km SE of El Hierro, perhaps destined to become the next Canarian islands.

The rock types in the Canary Islands are diverse and include melilitites, nephelinites, basanites, tholeiitic and alkali basalts, tephrites, rhyiodacites, rhyolites, pantellerites, comendites, trachytes, phonolites and carbonatites. In other words, they comprise a typical oceanic alkaline suite with saturated and undersaturated end members. Most basalts are alkaline in the shield-building stages, trachytes and phonolites are very common in the declining stages, while the rejuvenation stages produced essentially basanites and nephelinites.

Total alkali vs. silica (TAS) diagrams of volcanic rocks from the Canary Islands (Figure 17) show that they fall in the alkaline, silica-undersaturated field. There is a generally bimodal grouping into basalt-basanite and trachyte-phonolite compositions. Figure 17 also shows that most samples correspond to moderately alkaline (alkali basalt-trachyte) or highly alkaline (basanite-phonolite) rocks.

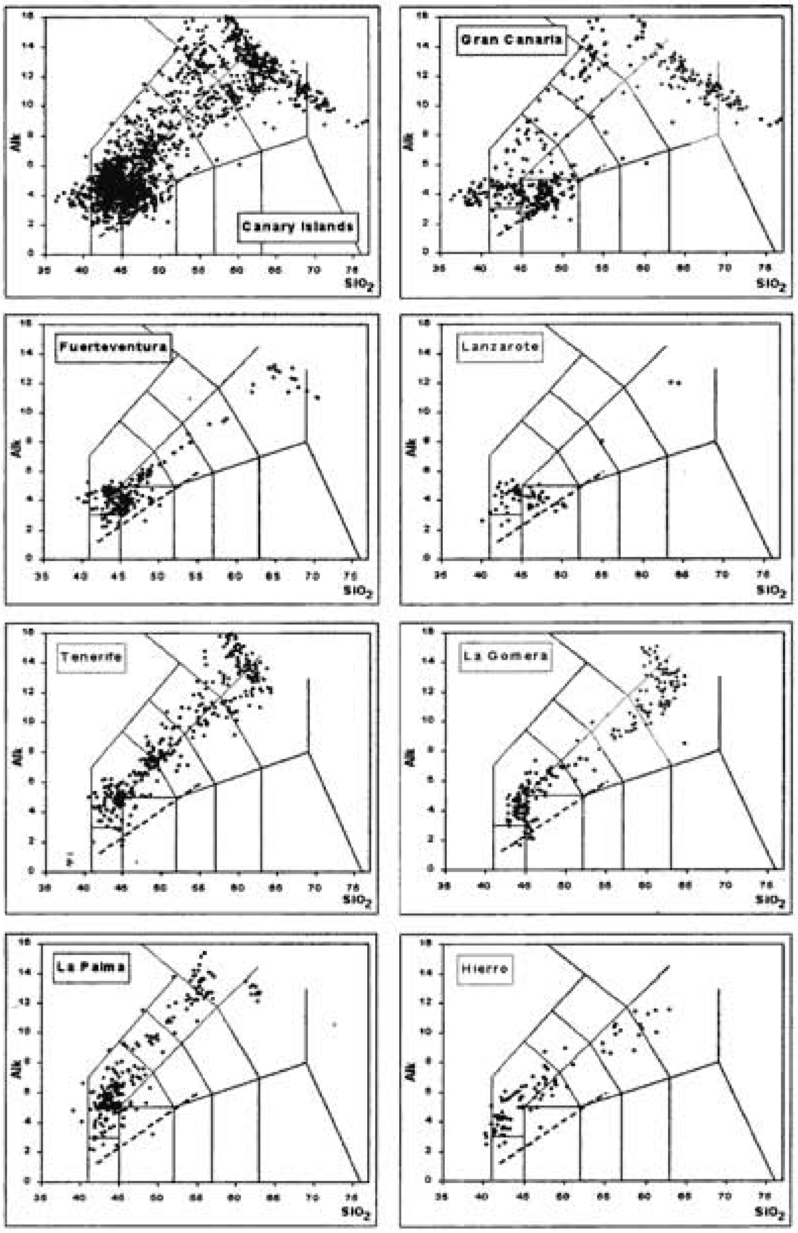


Figure 17: Total alkali versus silica diagrams (TAS) with analyses of Canaries volcanic rocks (Carracedo et al., 2002).

Rocks of tholeiitic affinity have been recognized only in the oldest units of Gran Canaria and in the most recent lavas of Lanzarote. Ultra-alkaline rocks appear mainly in Gran Canaria (ol-melilitites and nephelinites) and Fuerteventura (ol-nephelinites), corresponding to the rejuvenation stage. There are notable differences in the alkalinity and abundance of rock types between the islands. Gran Canaria has rocks embracing all compositions from the most to the least alkaline, whereas in the other islands the alkalinity of lava flows is mostly homogeneous. The most alkaline is La Palma, whereas Tenerife is less so, being on the boundary between highly and moderately alkaline. El Hierro, La Gomera, Fuerteventura and Lanzarote show the least overall alkalinity – all are moderately alkaline. The islands with the least abundance of felsic rocks (< 1%) are Lanzarote and El Hierro, with ~ 3% on La Palma, La Gomera and Fuerteventura, and the central islands (Gran Canaria and Tenerife) having the largest abundance (>10%).

Mg variation diagrams of Canarian rocks show similar trends in all the islands (Figure 18), with decreasing MgO in basic rocks (basalts, basanites; < 6%) and the trachytic-phonolitic rocks (MgO < 1%). Both CaO and FeO decrease slightly, while Al_2O_3 rises considerably and TiO_2 has a tendency to increase slightly.

Trace-element data show the most incompatible elements increasing from the basalts to the trachybasalts and basaltic trachyandesites, with a reduction in Ti and P, possibly due to Fe-Ti oxides and apatite crystallization (Figure 19). The trace- and radiogenic-isotope contents are characteristic of HIMU OIBs, although with some variations depending on the age of the various units (*Weaver*, 1991; *Hoernle et al.*, 1991; *Thirwall et al.*, 1997).

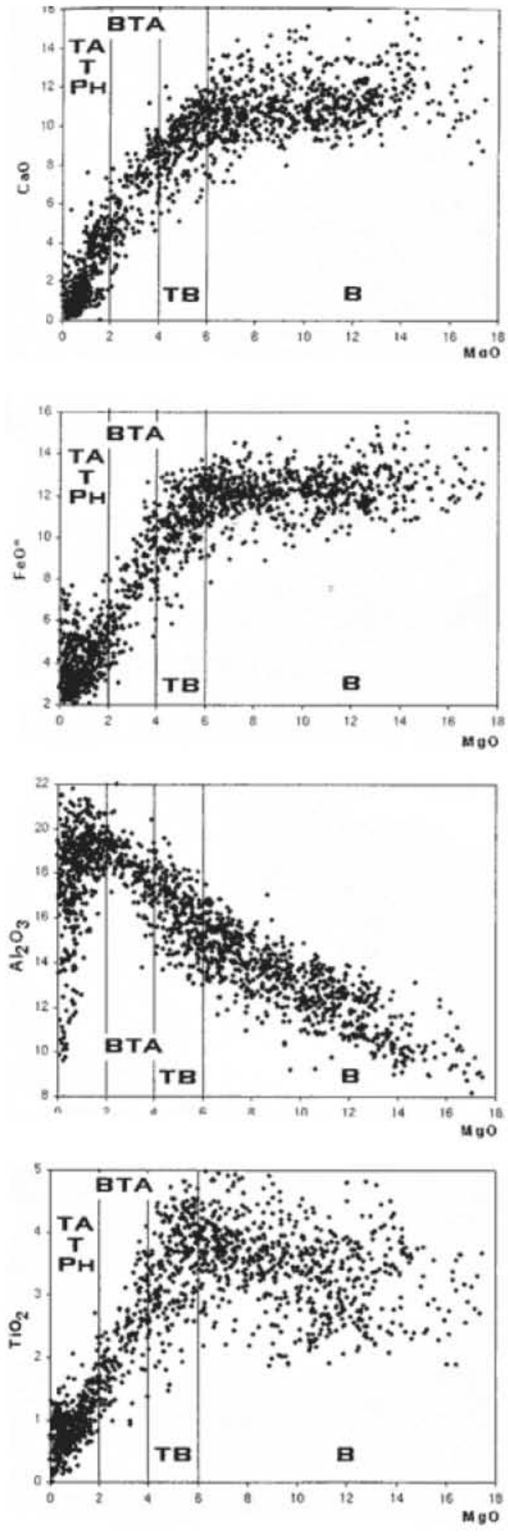


Figure 18: Plots of MgO vs. major oxides from Canary Islands volcanic rocks (Carracedo et al., 2002).

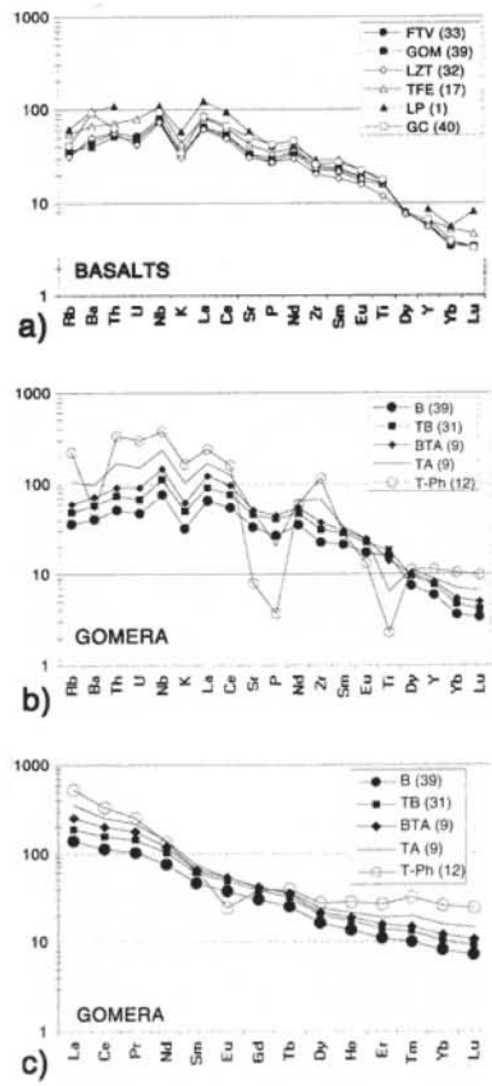


Figure 19: Plots of incompatible trace elements normalized to primitive mantle (Carracedo et al., 2002).

Sr-Nd-Pb isotopic analyses have been interpreted as indicating that the magmas of the Canary Islands represent a multicomponent mixture of different reservoirs – a HIMU component and a second end-member with lithospheric (EM), asthenospheric (DM) and additional HIMU components (*Cousens et al.*, 1990; *Hoernle & Tilton*, 1991; *Hoernle et al.*, 1991; *Hoernle & Schmincke*, 1993; *Neuman et al.*, 1995).

Summary

The Canary archipelago developed at a passive continental margin, on Jurassic oceanic lithosphere and a slow-moving tectonic plate. There are several genetic hypotheses for the Canary Islands, including a propagating fracture, a local extensional ridge, uplifted tectonic blocks and an unifying model but it is generally assumed that the archipelago originated from residual old plume material in the upper mantle. The first alkaline magmatic manifestations of this hot spot occurred at Fuerteventura during the Upper Cretaceous (~ 70 Ma), submarine volcanism started in the Eocene-Oligocene (~ 39 Ma) and subaerial volcanism in the Miocene (~ 20.6 Ma). There is a general progression of the oldest volcanism, thought to be induced by westward motion of the African plate and thus El Hierro island has the oldest dated subaerial Quaternary (~ 1.1 Ma) volcanism. The chain has been active along its entire length during the last million years, however.

Canary Island volcanism involves submarine stages, followed by shield-building, declining, erosive and rejuvenation stages. Three groups of islands are currently in the rejuvenation stage – Fuerteventura, Lanzarote, Gran Canaria and Tenerife. La Gomera is in the erosional stage, and La Palma and El Hierro are in the declining stage.

The Canary Islands show some interesting differences with other oceanic islands such as the formation of central stratovolcanoes, island tectonics that include ductile shears and compressional structures, and small or zero subsidence.

For more information about the geology of the Canary Islands, see:

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