Geol. Mag. **135** (*5*), *1998, pp. 591–604. Printed in the United Kingdom* © *1998 Cambridge University Press*

Hotspot volcanism close to a passive continental margin: the Canary Islands

J. C. CARRACEDO*†, S. DAY†, H. GUILLOU‡, E. RODRÍGUEZ BADIOLA§, J. A. CANAS¶ & F. J. PÉREZ TORRADO#

* Estación Volcanológica de Canarias, IPNA, CSIC, La Laguna, Tenerife, Canary Islands, Spain
† Benfield Greig Centre for Hazard Research, University College London, UK
‡ Centre des Faibles Radioactivités, CEA-CNRS, Gif sur Yvette, France
§ Museo Nacional de Ciencias Naturales, CSIC, Madrid, Spain
¶ ETSICC, Universidad Politécnica de Cataluña, Spain
# Facultad de Ciencias del Mar, ULPGC, Las Palmas, Gran Canaria, Canary Islands, Spain

(*Received* 8 January 1998; *accepted* 27 April 1998)

Abstract – The Canarian Archipelago is a group of volcanic islands on a slow-moving oceanic plate, close to a continental margin. The origins of the archipelago are controversial: a hotspot or mantle plume, a zone of lithospheric deformation, a region of compressional block-faulting or a rupture propagating westwards from the active Atlas Mountains fold belt have been proposed by different authors. However, comparison of the Canarian Archipelago with the prototypical hotspot-related island group, the Hawaiian Archipelago, reveals that the differences between the two are not as great as had previously been supposed on the basis of older data. Quaternary igneous activity in the Canaries is concentrated at the western end of the archipelago, close to the present-day location of the inferred hotspot. This is the same relationship as seen in the Hawaiian and Cape Verde islands. The latter archipelago, associated with a well-defined but slow-moving mantle plume, shows anomalies in a plot of island age against distance which are comparable to those seen in the Canary Islands: these anomalies cannot therefore be used to argue against a hotspot origin for the Canaries. Individual islands in both archipelagoes are characterized by initial rapid growth (the 'shield-building' stages of activity), followed by a period of quiescence and deep erosion (erosion gap) which in turn is followed by a 'post-erosional' stage of activity. The absence of post-shield stage subsidence in the Canaries is in marked contrast with the major subsidence experienced by the Hawaiian Islands, but is comparable with the lack of subsidence evident in other island groups at slow-moving hotspots, such as the Cape Verdes. Comparison of the structure and structural evolution of the Canary Islands with other oceanic islands such as Hawaii and Réunion reveals many similarities. These include the development of triple ('Mercedes Star') rift zones and the occurrence of giant lateral collapses on the flanks of these rift zones. The apparent absence of these features in the post-erosional islands may in part be a result of their greater age and deeper erosion, which has removed much of the evidence for their early volcanic architecture. We conclude that the many similarities between the Canary Islands and island groups whose hotspot origins are undisputed show that the Canaries have been produced in the same way.

1. Previous interpretations of the Canary Islands

The Canarian Archipelago is, apart perhaps from the Hawaiian Islands, the most extensively studied group of oceanic islands in the world. However, although these issues have been the subject of a long debate, the origin and evolution of the Canarian Archipelago are far from being as well explained and modelled as those of the Hawaiian Islands. Several circumstances may account for the difficulty in defining a model for the genesis and evolution of the Canary Islands. The complexities of the geology of the Canaries, in the east of the archipelago in particular, are such that it may not be possible to reach a conclusive solution in favour of one of the various possible alternatives on the basis of the limited data available.

* Author for correspondence: jcarracedo@ipna.csic.es

Definitive evidence for the relative roles of regional tectonics and mantle plumes in the genesis of the islands may come from large-scale seismological and structural studies of the deep structure of the surrounding oceanic crust and lithosphere and from constraints provided by geochemical and isotopic features of the magmas involved. Nevertheless, it may be interesting to analyse, as we do in this work, the existing geological information from the islands themselves, especially the timing of eruptive activity in the islands and their morphological and structural features. This may help to establish some clear constraints that narrow down the range of acceptable models for the genesis and development of the Canary Islands.

Comparison of the geology and evolution of these islands with more typical hotspot-induced groups like the Hawaiian, Cape Verde and Réunion islands provides insights into factors controlling the geology of

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

oceanic islands and helps in the understanding of the processes involved in the genesis and development of the Canarian Archipelago. In this paper we will compare the Canary Islands with the Hawaiian Islands in particular, because of the wealth of data available for the latter group and because they have come to be regarded as paradigmatic hotspot-related islands. The Hawaiian Islands are located in the middle of an oceanic plate (the Pacific plate) which is moving rapidly with respect to the underlying mantle hotspot. Many aspects of the geology and geological history of the Hawaiian Islands are related to these features and their highly productive hotspot, which are by no means applicable to all oceanic island groups. In the future it may be more appropriate to compare the geology of the Canary Islands with those of other island groups on a slow-moving plate, such as the Cape Verde islands: unfortunately the geology and geochronology of these islands are relatively little-known at present.

The Canary Islands are located in a very different geodynamic setting from that of the Hawaiian Islands: in the case of the Canary Islands, on old (Jurassic) oceanic lithosphere, close to a continental margin, and on a tectonic plate which is moving very slowly in relation to an underlying mantle hotspot. The absolute motion of the African plate over fixed hotspots has been estimated (O'Connor & Duncan, 1990) for the Walvis Ridge at about 7° in latitude and 34° in longitude for the last 60 Ma. In the region of the Canaries these values may be as low as 2.4° and 5°, respectively, for the same period. The active life of most oceanic volcanoes is generally limited by the displacement of the corresponding plate to a few million years. In contrast, the Canary Islands, the Cape Verde Islands (Mitchell *et al.* 1983) and the oceanic sector of the Cameroon line (Lee *et al.* 1994), all of which lie on the slow-moving African plate, are rare examples of long-lived oceanic volcanic islands.

The Cape Verde islands, located 500 km off the west African continental margin, exhibit all the characteristic geophysical features of a mantle plume-induced volcanic archipelago, including a prominent lithospheric swell estimated at between 400 km (Grunau *et al.* 1975) and 1500 km (Courtney & White, 1986) across and as much as 1500 m high at its centre (Courtney & White, 1986). In contrast, the eastern Canary Islands are as little as 100 km from the edge of the African continental shelf and the archipelago as a whole is not associated with a comparable lithospheric swell. This apparent lack of a swell was used by Filmer & McNutt (1988) as an argument against the presence of a hotspot in the Canaries and has also been noted by other authors (Hoernle & Schmincke, 1993; Watts, 1994). However, Canales & Dañobeitia (1998) analysed a number of seismic lines in the vicinity of the archipelago and demonstrated the existence of a subdued (*c.* 500 m maximum elevation) lithospheric depth anomaly around the Canary Islands. These authors proposed that this anomaly could be related to a swell that was otherwise obscured by the weight (and perhaps also mechanical effects (Watts & Marr, 1995)) of the thick sedimentary cover along the northwest African continental margin and by the weight of the volcanic rocks of the islands themselves.

Morgan (1971) and McDougall (1971) simultaneously presented the hotspot and membrane tectonics ideas to explain the origin of oceanic volcanic island chains. Accordingly, the models proposed for the origin of the Canary Islands were immediately polarized into these two apparently self-excluding categories. However, the early models proposed have two important limitations: (1) they were too dependent on limited radiometric data, later substantially revised, and (2) these models were based upon information from the eastern and central islands (see Fig. 1a). The western islands of La Palma and El Hierro, which we considered to be crucial to the understanding of the archipelago, were very poorly known at that time.

Geological (structural and geochronological) work carried out in the western Canaries has revealed the presence of development patterns and structural features which are in apparent contrast to those of the eastern islands. We examine these studies in a subsequent section and show that these apparently contrasting features, previously interpreted as reflecting variations in the nature and rigidity of the lithosphere (Carracedo, 1996*a*), may be related to the different stages of evolution of the Canaries.

2. Age of the Canary Islands volcanism

The extensive K/Ar dating carried out in the Canaries, with about 450 K/Ar ages published from lava flows, gives a remarkable control of the subaerial volcanic history of this archipelago. The age of the earliest exposed volcanic rocks as well as the periods of volcanic activity and alternating gaps are clearly delineated (Fig. 1a).

Detailed geochronological work using accurate dating techniques and cross-checking against palaeomagnetic reversals has proved that some of the previous age determinations in these islands have substantial errors, sometimes of several million years (McDougall & Schmincke, 1976). Such errors are especially significant in the islands of La Palma and El Hierro, where most of the subaerial lavas are of Quaternary age (Guillou *et al.* 1996). Recent studies have shown that ages from stratigraphic sequences, consistent with the general volcanic stratigraphy and the corresponding polarities of the standard geomagnetic polarity timescale, are the most reliable (Carracedo, 1979; Guillou *et al.* 1996).

Figure 1a shows a plot of published radiometric ages from lavas of the Canary Islands. Two groups are clearly defined: (1) the islands of Lanzarote,

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

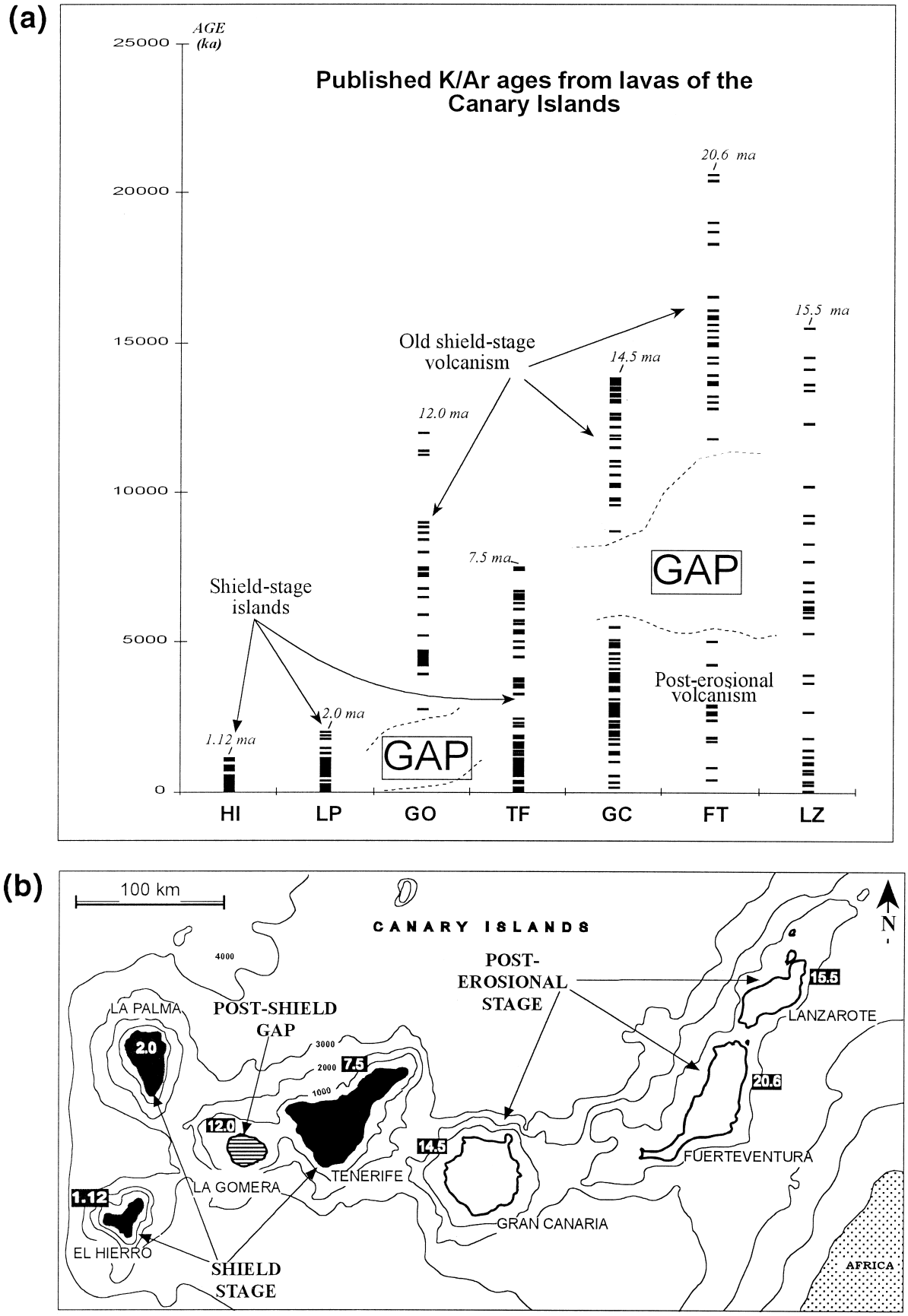


Figure 1. (a) Published K–Ar ages from volcanic rocks of the Canary Islands. (b) Oldest published K–Ar ages of the subaerial volcanism of the Canary Islands. As observed in the Hawaiian Islands, the Canaries can be separated into three groups: islands in the shield-stage of development, in the gap stage and in the post-erosional stage.

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

Fuerteventura, Gran Canaria and La Gomera, with subaerial volcanism 12 Ma or older and well-defined hiatuses in the volcanic activity, and (2) the islands of Tenerife, La Palma and El Hierro, with exposed volcanic rocks 7.5 Ma old or younger and essentially uninterrupted volcanic histories.

The oldest subaerial volcanic rocks of Tenerife consistently yield ages under 7.5 Ma (Ancochea *et al.* 1990; Carracedo, 1979; Abdel-Monem, Watkins & Gast, 1971; Feraud *et al.* 1985). This age can therefore be estimated, with all probability, as the oldest limit for the emergence of the island of Tenerife.

2.a. Gaps in volcanic activity

Detailed radiometric dating of previously defined magneto-stratigraphic units in the Canaries (Watkins, 1974; Carracedo, 1979; Carracedo & Soler, 1995; Guillou *et al.* 1996; Carracedo *et al.* 1997*a*) have shown the presence of gaps or hiatuses in the eruptive activity in several of the Canaries that can be excluded as related to sampling. It appears that these eruptive gaps occur only in the early (Middle–Lower Miocene)-emerged islands of Lanzarote, Fuerteventura, Gran Canaria and La Gomera (Fig. 1a). In contrast, volcanic activity has continued uninterrupted from the time of subaerial emergence to the present day in the late (uppermost Miocene–Quaternary)-emerged islands of Tenerife, La Palma and El Hierro.

Similar interruptions are observed in the prototypical hotspot islands of the Hawaiian Archipelago, where they constitute a key stratigraphic feature separating the shield-stage volcanism from the post-erosional or rejuvenated-stage volcanism (Langenheim & Clague, 1987; Walker, 1990). We may conclude that, as in the Hawaiian Islands, the periods of volcanic quiescence allow the separation of the Canaries into different categories (Fig. 1b): (a) the islands of Lanzarote, Fuerteventura and Gran Canaria, at present with post-erosional rejuvenated-stage volcanism; (b) the island of La Gomera, presently in the gap stage, and (c) the islands of Tenerife, El Hierro and La Palma, in the pre-gap shield stage. Tenerife is probably approaching the period of volcanic quiescence, while La Palma and El Hierro are in the most active phase of shield-stage volcanism.

Much of the previous mapping of the Canary Islands has involved the definition of numbered Volcanic Series. In the older islands (Fuerteventura, Lanzarote, Gran Canaria), 'Series I' corresponds to the shield-building stage subaerial volcanic rocks (Fúster *et al.* 1968; Fúster, Fernández Santín & Sagredo, 1968). These are followed after a long erosional interval by relatively small-volume 'Series II', and in some cases 'Series III' and 'Series IV', which correspond to our 'post-erosional volcanism'. In contrast, in the younger islands such as El Hierro (Fúster *et al.* 1993), the same authors define as many as four 'Series' which are not separated by long erosional intervals and which all lie within the early phases of the 'shield-building' stage (Guillou *et al.* 1996). Thus, the use of 'Series' as a stratigraphic unit is inconsistent between islands and likely to lead to confusion. We therefore propose discarding numerically based 'Series' and use instead the 'shield-building' and 'post-erosional' stratigraphic distinction developed in the Hawaiian Islands (see MacDonald & Abbott, 1970, for a review of stratigraphic units and concepts in the Hawaiian Islands). We also propose discarding the generally used distinction between 'eastern' and 'western' groups in the Canarian Archipelago in favour of an age-based criterion, to recognize the location of the older island of La Gomera in the middle of the younger ('western') Canaries group.

2.b. Pre-shield stage rocks

The subaerial shield-stage volcanic rocks are the oldest rocks exposed above sea level in the Hawaiian Islands. It has, however, long been recognized that these must be preceded by a 'seamount stage' of submarine volcanism, represented in the present by Loihi Seamount to the southeast of Hawaii (Fornari *et al.* 1988). In the Canarian islands of Fuerteventura, La Gomera and La Palma the shield volcanism rests upon variably deformed and uplifted sequences of submarine sediments, volcanic rocks (mainly pillow basalts), dyke swarms and plutonic intrusions which form the cores of these islands. These have been interpreted as uplifted blocks of 'oceanic basement' in the pre-Plate Tectonic sense (Hausen, 1958; Fúster *et al.* 1968). However, this interpretation is inconsistent with the observation that the igneous rocks are younger than the oceanic sedimentary sequences (Robertson & Stillman, 1979). The hypothesis was then modified to suggest that the 'basal complex' of Fuerteventura developed in an off-axis spreading centre analogous to the southeast Iceland rift zone (Stillman *et al.* 1975; Stillman, 1987). However, more recent studies in Fuerteventura (Stillman, 1997) have demonstrated that the submarine volcanic rocks pass up through littoral volcanic rocks into the oldest subaerial shield-building rocks, although unconformities break up the sequence in many places. This therefore implies that the 'basal complex' of Fuerteventura represents the seamount stage of the growth of this island. A similar conclusion had previously been reached for the 'basal complex' of La Palma by Staudigel (Staudigel & Schmincke, 1984). We therefore propose that the previously used term 'basal complex' for these pre-shield submarine igneous sequences be discarded and replaced by the general term ' seamount series'. The presence of these rocks above sea level is in strong contrast to the Hawaiian Islands (although similar rocks are to be found in the Cape Verde islands, notably on Maio (Stillman *et al.* 1982)). We relate this to the dif-

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

ferent uplift and subsidence histories of the islands (see below).

2.c. Alternation of activity between islands: are age–distance plots useful at low plate velocities?

It is customary to plot the ages of islands in hotspot-related archipelagoes against the distance from the present-day location of the mantle plume generating them. Such plots show a good age–distance correlation for archipelagoes such as the Hawaiian Islands, located on lithosphere that is moving rapidly relative to the underlying mantle plume (see Langenheim & Clague, 1987, for a recent version of the age–distance plot of the Hawaiian Islands–Emperor Seamount chain). Kauai, the oldest island still to have a significant part of its bulk above sea level, is less than 6 Ma old but lies 580 km from the hotspot at which it initially formed and on the periphery of the hotspot topographic swell. In contrast, the oldest rocks on Fuerteventura are just over 400 km from the youngest island, El Hierro (Figs 1b, 2). We note here, however, that these lateral motions together with the small movement of even the oldest islands in the Canaries relative to the possible dimensions of a plume source mean that neither a perfect age–distance correlation nor single, well-defined episodes of shield and post-erosional activity are to be expected. Thus, the occurrence of anomalies in the age–distance plot of the Canary Islands, such as those represented by the pair La Gomera–Tenerife and the pair Fuerteventura–Lanzarote (Fig. 2), is not a strong argument against generation of the Canary Islands by a mantle plume. Neither are these time–distance anomalies in themselves a strong argument in favour of a 'blob-type' heterogeneous plume (Hoernle & Schmincke, 1993), although of course there may be strong geochemical arguments in favour of such a model.

Similar anomalies in age–distance plots to those found in the Canary Islands also exist in other volcanic archipelagoes located on slow-moving plates. In the Cape Verde islands, although a general southward and westward trend in age exists in the eastern and southern islands of the archipelago (Sal, Boa Vista, Maio, Santiago, Fogo, Brava, with Sal being the morphologically oldest island and Quaternary volcanism concentrated in Fogo and Brava), the focus of late Quaternary volcanism has shifted back from Brava to Fogo in a manner possibly analogous to the late Miocene switch in activity from La Gomera to Tenerife in the Canaries. Furthermore, the northwestern group of islands in the Cape Verdes, from Sao Nicolau to Santo Antao, appears to define a separate, northwest directed age trend. All of these islands are, however, located within 500 km of one another, and all are located on the top of the broad lithospheric swell which is the primary signature of the Cape Verde mantle plume (Courtney & White, 1986). It may therefore be inappropriate to expect perfect age–distance correlations within hotspot-related island groups in slow-moving plates, where the distances between islands are such that all lie close to the mantle plume involved.

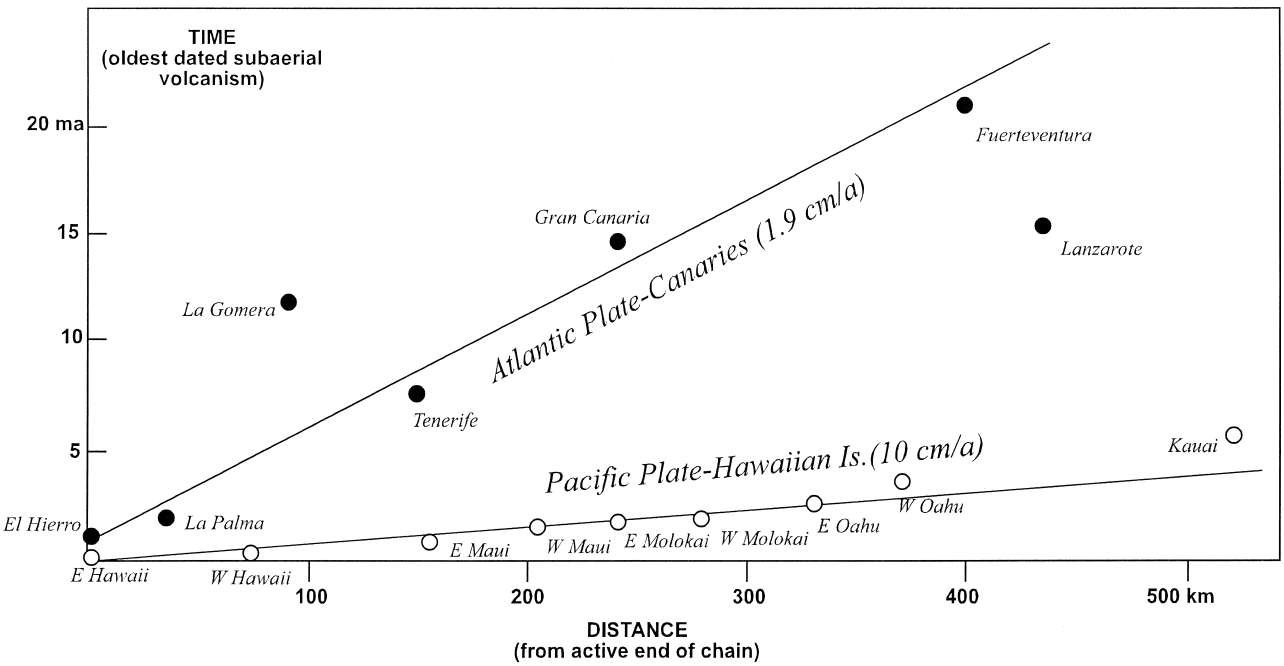


Figure 2. Distances of the successive islands in the Canarian and Hawaiian archipelagoes from their respective active end of chain plotted against the oldest subaerial published ages of the different volcanoes. The Hawaiian volcanoes fit in a straight distance vs. time line corresponding to a plate velocity of about 10 cm/a. The Canaries fit in a similar line corresponding to a plate velocity of about 1.9 cm/a, with the exception of La Gomera and Lanzarote, as explained in the text.

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

3. Production rates and evolution of magmas in the Canary Islands

Although the Canaries and the Hawaiian islands share a common trend of two-stage subaerial evolution – high effusion rate, shield-stage volcanism, followed by multiple, intermittent and essentially asynchronal post-erosional eruptive episodes – they differ greatly in the type of magmas involved. In the Hawaiian Islands the pre-gap volcanism is characterized by tholeiitic basalts, with late minor volumes of alkali basalts and associated differentiated magmas. During the rejuvenated stage, silica-poor magmas (alkali basalts, basanites and nephelinites) predominate. In the Canaries, no such contrast is evident and magma compositions are much more varied in both stages. The rocks of the pre-gap shield volcanism are predominantly basaltic (picrites, tholeiites and basanites) but with associated differentiated lavas (phonolites and trachytes). Highly differentiated felsic rocks occur in large volumes in the shield-stage volcanism of both Tenerife and Gran Canaria, and to a lesser extent in the other islands. Post-erosional rejuvenated volcanism repeats a similar trend but with much smaller volumes of rock involved in most cases, although the Pliocene Roque Nublo stratovolcano in Gran Canaria (Pérez Torrado, Carracedo & Mangas, 1995) represents perhaps the most voluminous episode of post-erosional volcanism in any island in the world. Wide variations in alkalinity occur in the post-erosional stage volcanism, sometimes within individual eruptions. The variation from basanites to alkali basalts seems to be a common feature in Holocene volcanic eruptions in the Canaries but exceptional variations from basanites to alkali basalts and tholeiites in a single eruption have been observed in the 1730–36 eruption of Lanzarote (Carracedo, Rodríguez Badiola & Soler, 1992). The latter is one of only two historic eruptions to have occurred in a post-erosional stage island in the Canaries (the other is the small eruption of 1824, also on Lanzarote).

A similar lack of contrast between shield-stage and post-erosional magma compositions may also be evident in other island groups on slow-moving plates. In the Cape Verde islands, magma compositions in all stages of activity are alkaline and, commonly, extremely so. The only systematic trend identified by Davies *et al.* (1989) was spatial: they found that rocks in the northwestern islands (Sao Vicente, Santo Antao) were systematically more silica-undersaturated than those from the islands (Sal, Brava) which in their shield stage of activity were located above the inferred mantle plume head. The spatial and temporal patterns of compositional variation in hotspot-related island groups on slow-moving plates may therefore, in general, be more complex than in island groups on fast-moving plates such as the Hawaiian Islands.

A second well-documented distinction between the shield-building and post-erosional stages in the Hawaiian Islands is the much greater rate of magma supply in the former. This is clearly reflected both in the far greater volumes of the Hawaiian shields as compared to the products of the post-erosional magmatism in each island and in the much higher frequency of eruptions during the shield-building stage of each volcano. Moore & Clague (1992) estimated average magma supply rates during the entire (shield-building) history of the island of Hawaii to be of the order of 0.02 km^3/year.

This includes the hiatuses between growth of individual shield volcanoes, and peak magma production rates may be much higher. However, magma production rates may be difficult or impossible to evaluate in the Canary Islands. Two main reasons for this are: (1) the discontinuous character of volcanism, in which eruptive gaps, inherently difficult to date, may predominate over periods of activity, making true evaluation of magma production rates untrustworthy unless large time intervals are compared, and (2) the occurrence of giant lateral collapses which may repeatedly remove large fractions of the mass of an island, especially during the shield-building stage, and redistribute it over distances of hundreds or even thousands of kilometres. Several megaturbidites deposited in the Madeira abyssal plain within the past 1 Ma have been shown to have originated in the Canarian Archipelago (Weaver *et al.* 1992).

The former problem is exemplified by the case of Lanzarote, where the 1730–36 eruption is perhaps the largest to have occurred in the archipelago in historic time by as much as an order of magnitude in volume. However, the previous eruption of note in Lanzarote is that of Montaña Corona, dated at 53 ka (Guillou, unpub. data) using the high-precision Cassignol technique (Guillou *et al.* 1996). In the same period, as many as 100–1000 eruptions may have taken place in the shield-building stage islands of El Hierro, La Palma and Tenerife. Some of these eruptions, such as those of Tanganasoga on El Hierro (Fúster *et al.* 1993, Carracedo *et al.* 1997*a*) and the Volcán Fuego on La Palma (Carracedo *et al.* 1997*b*) were of comparable or greater volume than the 1730–36 Lanzarote eruption.

Eruption rates during the subaerial shield-building stage which are two to three orders of magnitude greater than those during the post-erosional stage are therefore implied by considering a period of the order of tens of thousands of years. But even this may not be a sufficient averaging period because of the switching of activity between shield-stage islands on timescales of the order of hundreds of thousands of years and the occurrence of episodes of relatively intense post-erosional volcanism such as that which produced the Roque Nublo volcano on Gran Canaria (Pérez Torrado, Carracedo & Mangas, 1995).

The island of El Hierro probably presents the best geochronological control in the Canary Islands. The

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

uncomplicated development of the island, which is still in its juvenile stage of shield growth, and the abundant and accurate K/Ar ages combined with magnetic stratigraphy (Guillou *et al.* 1996), allow the closest possible approach to the reconstruction of the entire emerged volcanic history of any of the Canaries. The present emerged volume of the island, of about 140–150 km^3, has been produced in the last 1.12 Ma, giving an apparent average magma production rate of 0.12–0.13 km^3/ka. However, if we take into consideration the three consecutive giant lateral collapses that affected the island, each clearly exceeding 100 km^3, the magma production rate for this juvenile stage of growth of El Hierro increases to > 0.4 km^3/ka.

A similar evaluation of shield-stage magma production rates in the presently post-erosional islands is highly problematic. This is because it is impossible to evaluate the volume removed by lateral collapses (Canals *et al.* 1997; Stillman, 1997); it is difficult to determine even the number of collapses in these deeply eroded islands, let alone the volumes of individual collapses.

4. Contrasting structural features in the older and younger islands?

Recent onshore and offshore studies of the younger islands of Tenerife, La Palma and El Hierro (Holcomb & Searle, 1991; Canals *et al.* 1997; Carracedo, 1994, 1996*a*; Carracedo *et al.* 1997*a*; Watts & Masson, 1995; Guillou *et al.* 1996; Day, Carracedo & Guillou, 1997) have revealed the existence of volcanological, structural and geomorphological features (triple-armed active rifts and giant landslides) typical of hotspot islands. These features, are difficult to identify in the older islands of the archipelago.

Among the most distinctive of these features are triple-armed active rifts, described in detail in previous works (Carracedo, 1994, 1996*a*), and clearly observable in the islands of Tenerife and El Hierro and in the Mauna Kea Volcano (Fig. 3). While these are easily related to the radially symmetric stress patterns associated with hotspots (Walker, 1992; Carracedo, 1994), triple-armed rifts are difficult to relate to regional fractures, as recently discussed (Carracedo, 1996*b*). Giant slope collapses, another characteristic feature of hotspot-induced oceanic islands (Hawaii, Réunion, etc.), have recently been identified in the western islands (Fig. 4), and their onshore and offshore features described (Holcomb & Searle, 1991; Carracedo, 1994, 1996*a*,*b*; Watts & Masson, 1995; Guillou *et al.* 1996). In the younger Canaries, the link between giant collapses and the volcanic rifts is clear (Carracedo, 1994, 1996*a*,*b*).

The apparent contrast in structural features observable in the younger and older Canaries may, however, reflect only different stages of development of the islands. Recent studies in Fuerteventura in particular

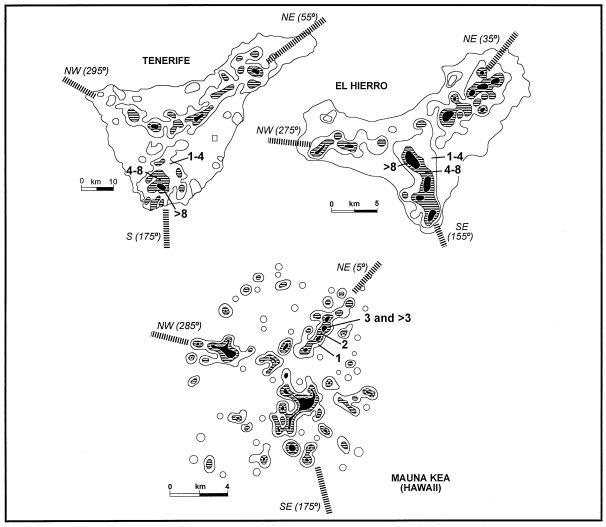


Figure 3. Distribution of emission vents in island-volcanoes. Numbers indicate concentration of eruptive vents (vents/km^2). The islands of Tenerife and El Hierro, and the Mauna Kea Volcano evolved unbuttressed, and the rifts have preserved the regular, three-armed geometry. Many other Hawaiian volcanoes and the Cumbre Vieja Volcano in La Palma have evolved to asymmetric configurations as the rifts were constrained in their progress. The distribution of Mauna Kea vents is from Porter (1972).

(Ancochea *et al.* 1996; Stillman, 1997) have identified triple-rift geometries in the shield volcanoes making up the subaerial stage of growth of the island, and west-directed lateral collapse structures. At similar stages of evolution the islands appear to have similar structural features. We consider the multiple rifts and giant landslides to be characteristic features of the shield-stage of development, both in the Canaries and other intraplate oceanic islands of a hotspot-related origin. At this time of active volcanism and frequent eruptions, high aspect ratio, rift-growth-controlled, unstable volcanoes develop. Modifications during the erosional gaps, that in the Canaries are considerably longer than in most of the other archipelagoes of similar origin, hinder recognition of these features in the older islands. Onshore erosion obscures landslide scars, and offshore sedimentation from the nearby continent and younger islands covers the corresponding debris avalanche and debris flow deposits. The characteristic triple rifts may evolve and lose their symmetrical configuration due to buttressing of successive nearby volcanoes even within the shield stage. Intense erosion of the predominantly pyroclastic facies present in the rift zones may erode these features during eruptive quiescence in the erosional gaps.

Furthermore, as has been observed in the Hawaiian Islands, eruptions occur during the rejuvenated or post-erosional stage at vents whose distribution is unrelated to the pre-existing rifts (Langenheim & Clague, 1987). The deep, densely intruded core of the old, thermally aged and eroded rifts may in fact act as effective barriers rather than preferential paths for new

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

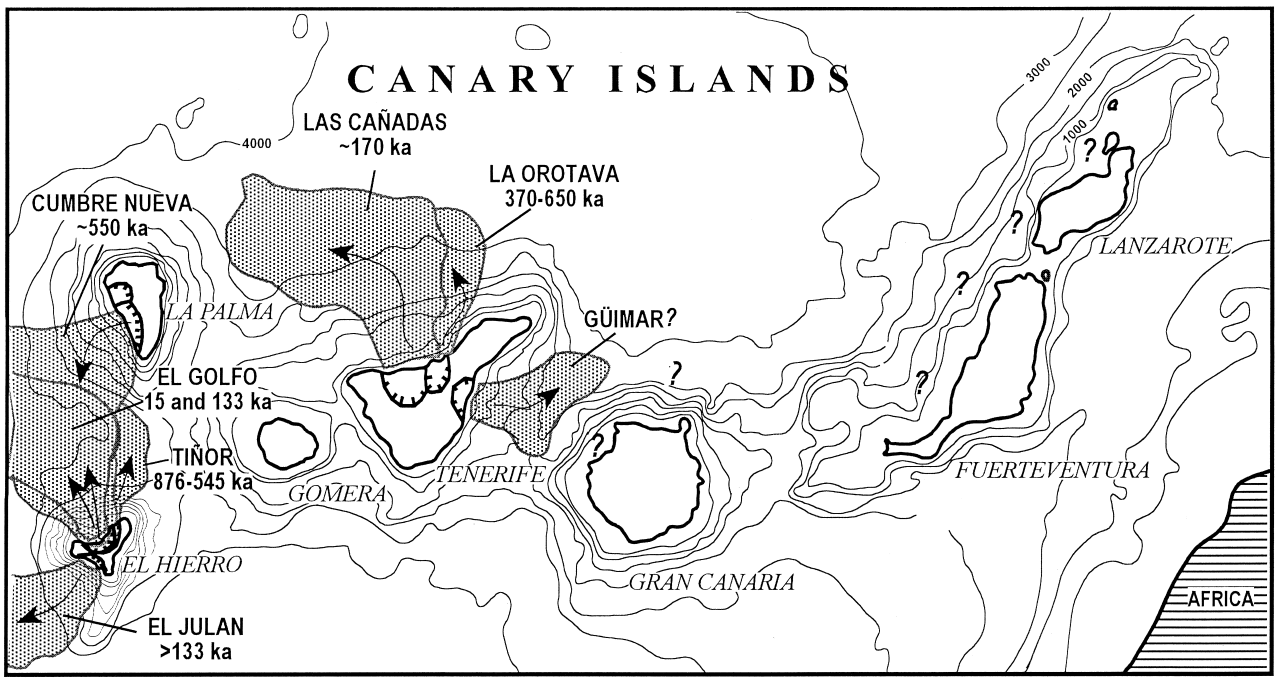


Figure 4. Giant landslides and associated submarine deposits in the Canary Islands. The ages of the landslides in La Palma and El Hierro are estimated from on-shore geological and geochronological data. The giant landslides of Tenerife are from Watts & Masson (1995).

eruptive conduits, explaining this decoupling of rejuvenated volcanism from the shield-stage rifts. Therefore, rejuvenated-stage volcanism may have helped erosion in largely obscuring the structural features of the shield stage in the older Canaries, accounting for the present apparent contrast in the structure of the older and younger islands.

5. Subsidence history of the Canarian islands

The most striking movements relative to sea level in the Canarian islands are recorded by the early seamount series rocks which are now uplifted to up to 1.5 km above sea level (Staudigel & Schmincke, 1984) and furthermore have been deeply incised by syn- and post-uplift erosion. In all the islands where seamount series rocks are exposed, this uplift is accompanied by tilting and/or thrusting away from centres of continued intrusion. It is therefore likely that the uplift is accomplished by large-scale endogenous growth of the volcanic edifices due to emplacement of intense dyke swarms and larger plutons within them. In contrast, the bulk of the subaerial shield-building stage and the subsequent periods are in general characterized by much evidence for a high degree of stability.

Evidence for the position of contemporary sea levels, in the form of marine abrasion platforms, littoral and beach sedimentary deposits, coastal volcanic deposits such as hyaloclastite-based lava deltas and Surtseyan tuff rings, and erosional palaeocliffs, is widespread in the Canary Islands. These markers occur close to present sea level, within the range of eustatic sea level change. Marine abrasion platforms up to several million years old are present in the oldest islands of Fuerteventura and Lanzarote. Schmincke, Sumita & Funck (1997) argue for the stability of Gran Canaria with respect to sea level over the whole of the last 14 Ma on land and marine evidence. These authors describe late Miocene to Recent age nearly horizontal seismic reflectors north of Gran Canaria, extending to northern Tenerife. Even in the very young island of La Palma, still in the shield-building stage, a beach shoreface sand deposit between about 0.5 Ma and 0.2 Ma old is to be found close to present sea level at El Time. Surtseyan tuff rings occur at present sea level in the Taburiente volcanic edifice at Santa Cruz de La Palma and in the cliff-forming series of the Cumbre Vieja volcano: likely ages for these are about 1 Ma and 100 ka, respectively. It appears that, in common with the other islands, La Palma is extremely stable and has undergone neither subsidence nor uplift since the end of the seamount series uplift.

The lack of post-emergence subsidence in the Canary Islands is in very strong contrast to the rapid subsidence seen during the shield stage and later in the Hawaiian Islands (Moore, 1987). However, islands in the Cape Verde archipelago such as Maio (Stillman *et al.* 1982) also show evidence for no post-emergence subsidence in the form of uplifted seamount-stage rocks. Littoral volcanic landforms and well-developed old marine abrasion platforms crop out close to and above the present sea level. A lack of post-emergence subsidence may be a general feature of islands associated with slow-moving hotspots.

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

6. Constraints upon proposed models for the origin of the Canary Islands

6.a. The Canary Islands and the Alpine Orogenic Belt

A potentially very important difference between the Canarian Archipelago and most other hotspot-related island groups is that the Canaries are located adjacent to a region of intense active deformation, comprising the Atlas Mountains, Rif Mountains, Alboran Sea and Betic Cordillera provinces of the Alpine orogenic belt. A number of models have been proposed in the past which relate the magmatism which produced the islands to deformation of the oceanic lithosphere to the west and southwest of these continental deformation provinces, and consequent decompression melting of the underlying asthenosphere (Anguita & Hernán, 1975; Araña & Ortiz, 1991). These models explicitly sought to provide an alternative to hotspot-type models for the Canarian Archipelago. Thus the proposal that magmatism in the Canarian Archipelago may be related to the tectonic evolution of the western end of the Alpine chain acquired general significance in the years following the first enunciation of contrasting hypotheses to explain the origin of oceanic volcanic island chains (Morgan, 1971; McDougall, 1971).

Anguita & Hernán (1975) proposed that NNW–SSE directed extension, perpendicular to the overall 080 trend of the archipelago, was responsible for decompression melting of the asthenosphere, and correlated periods of intense magmatic activity in the islands with preceding periods of compression-related uplift in the High Atlas mountains. They postulated that extension in the region of the archipelago occurred as the Atlantic Ocean lithosphere deformed to accommodate membrane–tectonic stresses set up by the preceding phases of compressional deformation to the east. The model is therefore based on a fracture or fractures propagating from the Atlas to the Canaries. It proposes that this fracture is sufficient to tap melts from the asthenosphere and trigger volcanism as it propagates westwards. The timing of the lithospheric fracturing would be related, as mentioned earlier, to orogenic pulses associated to the Atlas tectonism (Fig. 5).

This model, however, was based on age determinations that were subsequently substantially revised. The island of Fuerteventura is a lineation of volcanic complexes with similar oldest subaerial ages of about 20 Ma (Ancochea *et al.* 1996). The island of Lanzarote is the prolongation of Fuerteventura to the northeast (parallel to the continental edge), separated by a narrow stretch less than 100 m deep. The age of the volcanic complexes that form Lanzarote decreases towards the northeast (Abdel-Monem, Watkins & Gast, 1972; Coello *et al.* 1992). Therefore, the initial spread of volcanism in the Canaries would be opposite in direction to a fracture propagating from the Atlas. The other aspect to note is the age relationship of La Gomera and Tenerife. As already mentioned, the island of Tenerife probably started to grow east of La Gomera when this island was already fully developed and approaching the gap stage. This 'anomaly' is difficult to relate to a fracture propagating from the Atlas, but is conceivable in the context of a very slow-moving mantle plume, where a blob may have been decoupled from plumbing La Gomera and diverted by this island edifice against the general spreading trend.

The Anguita & Hernán (1975) propagating fracture model has some points of resemblance to the 'hot line' model originally proposed for the Cameroon Line by Fitton & Dunlop (1985). It is noteworthy, however, that re-analysis of the age data for the initial stages of growth of islands in the oceanic part of the Cameroon Line (Lee *et al.* 1994) has led to a revised model in which the development of these islands is related to a mantle plume.

The long periods of quiescence or gaps (see Fig. 1a) have been repeatedly asserted by Anguita & Hernán (1975) to be one of the main pieces of evidence against a hotspot model for the Canaries. These authors assert in a later paper that in a hotspot model all the Canaries, with the exception of La Palma and El Hierro, should be long inactive (Anguita & Hernán, 1986). They do not take into account the fact that the presence of long periods of interruption of the volcanic activity is precisely a characteristic of hotspot-related island chains, otherwise, the shield/post-erosional stratigraphic distinction could not be made in island groups such as the Hawaiian Islands. The comparatively longer duration of gaps in the Canarian Archipelago is probably a consequence of the slow rate of motion of the Canarian hotspot and the properties of the oceanic lithosphere on which the islands have formed.

A strong objection to this model is related to the production of magma required to build the Canary Islands by lithospheric extension in the absence of an asthenospheric anomaly. Quaternary basanites and alkali basalts occur in the Middle Atlas of Morocco (Harmand & Cantagrel, 1984). However, if the extension–melt production relationships proposed in decompression melting models, such as that of McKenzie & Bickle (1988), are only even approximately applicable to the Canary Islands, the small degrees of lithospheric extension associated with the Atlas tectonics, although perhaps sufficient to produce the small-volume volcanic sequences in the Atlas mountain basins, will be insufficient in the absence of elevated (plume-generated) asthenospheric temperatures to produce the very large volumes of igneous rocks within the archipelago itself.

A further important objection to propagating-fracture models for the Canaries is related to the propagation of tectonic stresses from continental to oceanic lithosphere. In the simplest hypothesis of Anguita & Hernán (1975) the Canary Islands would be originated

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

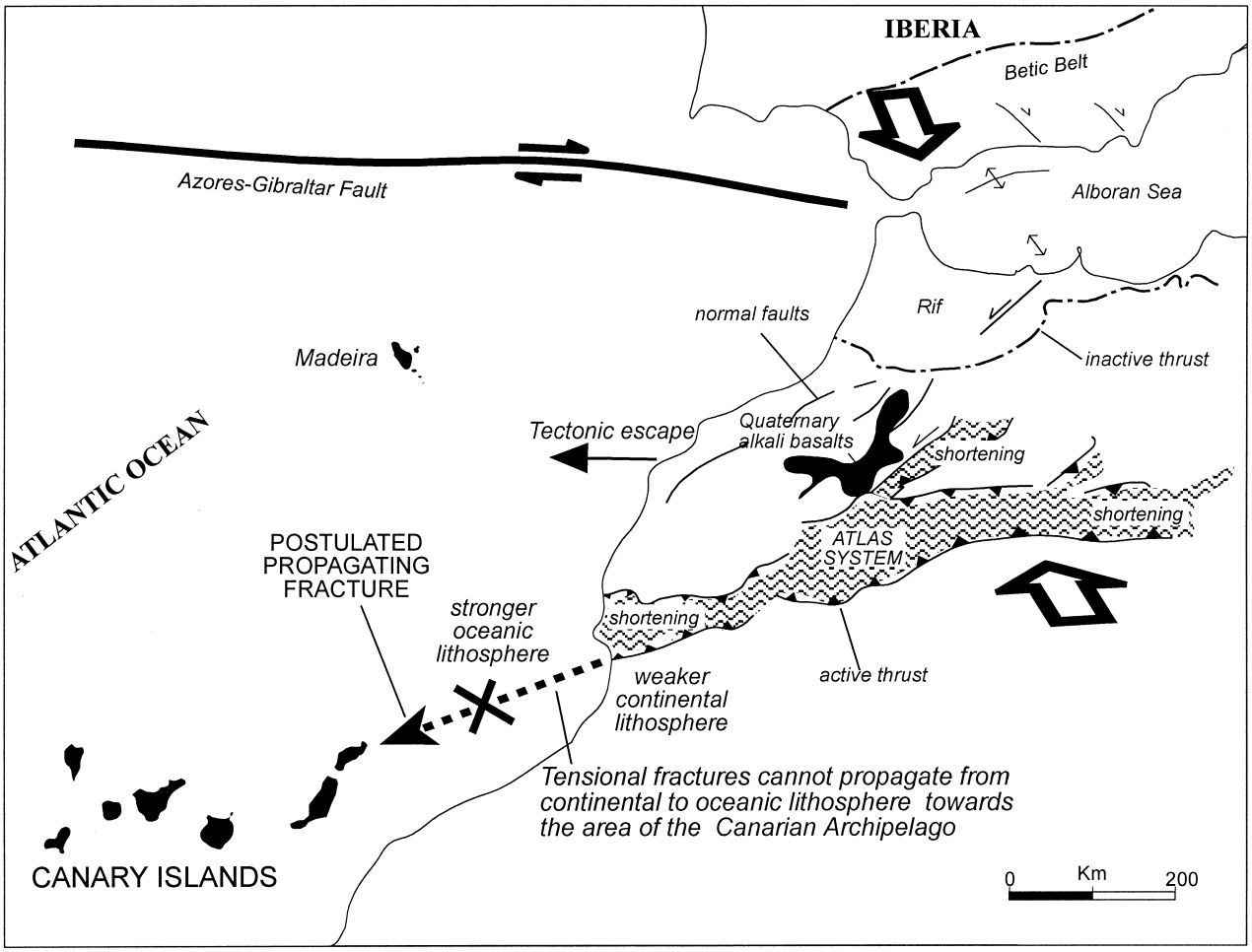


Figure 5. Geodynamic setting of the Canary Islands. The figure shows some of the main objections to relating the origin of the Canary Islands to the Atlas tectonism, as explained in the text.

by an offshore extension of the Trans-Agadir Fault. Seismic, magnetic and geological studies carried out off the coast of Morocco (Dillon & Sougy, 1974) concluded that the Anti-Atlas feature abruptly terminated along the coast, without any evidence of an offshore continuation of this structure. Furthermore, the propagation of such a feature from continental into oceanic lithosphere may be mechanically impossible. Analysis of strength differences between continents and oceans has been an important issue in the study of the development of plate boundaries. Vink, Morgan & Zhao (1984) considered strength differences between continents and oceans and reached the conclusion that continents are always weaker. Steckler & ten Brink (1986) and ten Brink (1991) analysed the total integrated strength of continental and oceanic lithosphere. Applying their conclusions to the African margin in the Atlas region it is evident that the >150 Ma old oceanic lithosphere is considerably stronger than the continent, precluding any fracture propagating from the Atlas towards the Canaries.

Araña & Ortiz (1991) proposed an alternative model in which shortening of the lithosphere, on high-angle reverse faults, produces decompression melting of the asthenosphere beneath the rising blocks. Evidence is present for localized uplift by up to perhaps 5 km on some islands, notably in the seamount series of La Palma (Staudigel & Schmincke, 1984) and in the Basal Complex of Fuerteventura (Ancochea *et al.* 1996). However, the model of Araña & Ortiz (1991) requires the systematic and continuous uplift of all the islands by distances of the order of tens of kilometres to produce decompression melting on the scale and degree of partial melting needed to account for the volume and composition of the Canarian magmas (McKenzie & Bickle, 1988), most especially those which characterize the early stage of subaerial magmatism in the older islands. There is no evidence to suggest the occurrence of uplift on this scale in the Canaries. Finally, in this model the initiation of volcanism should be nearly synchronous along the entire archipelago, instead of the observed general progression oceanwards of the oldest subaerial volcanism.

6.b. The hotspot model

The association of the Canarian Archipelago with an asthenospheric hotspot was originally proposed by

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

Burke & Wilson (1972) and has since been proposed repeatedly (Schmincke, 1973; Carracedo, 1979; Feraud *et al.* 1985; Holik, Rabinowitz & Austin, 1991; Hoernle & Schmincke, 1993; Watts, 1994; Carracedo, 1994, 1996*a*). However, the applicability of the hotspot model to the Canaries has commonly been questioned on the grounds that the archipelago lacks some of the geophysical features associated with the prototypical hotspot-related island groups.

The hotspot model was first defined in the Hawaiian Islands, where a very productive and vigorous mantle plume and a fast-moving plate combined to generate the prototypical hotspot-induced island chain. However, as in the case of the Canaries, these prototypical circumstances cannot always be expected to be present, making the identification of the hotspot signature more difficult. The wide variation in the characteristics of mid-plate oceanic islands has been noted by Watts (1994), who related these variations to absolute plate motions and the long-term thermal and mechanical properties of the lithosphere. These circumstances may play a role in precluding a simple relationship between the elastic thickness of the lithosphere and the characteristic regional anomalies (topographic swells, gravity/geoid highs).

The Canary and Cape Verde Islands seem to be the only regions of convection-generated tensional stress fields in northwest Africa, as shown by global scale models derived from convection-generated stresses in the lithosphere inferred from satellite and surface gravity data (Liu, 1980). Recent work compiling intraplate seismicity in the Atlantic in the period 1918–1990 (Wysession *et al.* 1995) shows that seismicity within the African plate offshore from the Atlantic coast is also concentrated in two areas: within the Cape Verde swell and in a region of similar extent around the Canaries. The authors interpret this seismicity as being related to plume-generated magmatic activity.

Seismic studies carried out off the coast of Morocco (Holik, Rabinowitz & Austin, 1991) identified a velocity inversion between a body of 4.7 km/s seismic velocity and the underlying 3.1 km/s sediments and a deep crustal layer with anomalous velocities of 7.1–7.4 km/s. They interpreted this sequence as being igneous in origin, with a group of shallow intrusive and volcanic rocks being emplaced within and above sediments (to produce the velocity inversion) and being fed from deep crustal intrusions (to produce the anomalous deep layer). They proposed that the development of this igneous province was due to passage of a hotspot that rejuvenated the ancient crust off Morocco from approximately 60 Ma (1 in Fig. 6) onwards. They trace the underplated igneous body to the north of the Canary Islands following a broad bathymetric arch across the continental rise west of the Fuerteventura–Lanzarote ridge that connects with the western part of the Canarian Archipelago. The arrival of the hotspot at this end of the island chain would have taken place, according to Holik, Rabinowitz & Austin (1991), at about 10 Ma.

In a different model of the same general 'hot spot' type, Watts (1994) postulated a narrow asthenospheric feature encircling the Canaries and probably extending below the African continent (2 in Fig. 6).

7. Conclusions

We conclude that, in contrast to the propagating fracture model, not only do hotspot-type models not conflict with available geological information, but in fact they explain many of the apparent inconsistencies pointed out in the development of the Canaries.

In our model, we postulate that the Canaries originated by an asthenospheric plume (Canas *et al.* 1994). The first volcanic manifestations of this hotspot would have been localized at the continental–oceanic boundary west of Fuerteventura (see Fig. 6). Sediment thickness at continental margins exceeding 10 km should be a major factor in modifying the strength of the lithosphere. Lower overburden and conductivity of the sediments are associated with significant weakening of the lithosphere (Vink, Morgan & Zhao, 1984). The gravity anomaly study of Watts & Marr (1995) provides independent evidence for the weakness of the continent–ocean transition zone at the eastern end of the Canary Islands.

The thick sedimentary sequence in the continental margin off Cape Juby may have thus provided a favourable location for the first Canarian volcanism, defining the volcanic complex lineation parallel to the coast described by Ancochea *et al.* (1996). In this initial stage – the earlier non-folded submarine volcanism of Fuerteventura dated at about 36 Ma (Abdel-Monem, Watkins & Gast, 1972) and 39 Ma (Coello *et al.* 1992) and of Eocene–Oligocene age according to palaeontological evidence (Robertson & Stillman, 1979) – volcanism may have been spreading to the northeast and southwest along the weak continental–ocean crust transition zone, producing the Fuerteventura–Lanzarote ridge (A in Fig. 6). As described by Dillon & Sougy (1974), interaction between the Canary Islands volcanism and the African continental margin is apparent off Cape Juby, where strongly magnetic volcanic seamounts extend in the lower continental slope along lines continuous with the Canary trend.

As discussed above, the assertion that the volcanic activity progresses from Lanzarote to Fuerteventura and oceanwards is inconsistent with the presently accepted geochronological and geological information, and reflects an unfounded link between the Canaries and the Atlas tectonism. After this initial stage, slow motion of the hotspot may have initiated the general westward trend followed by the Canaries (B in Fig. 6). The succession of the islands is broadly

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

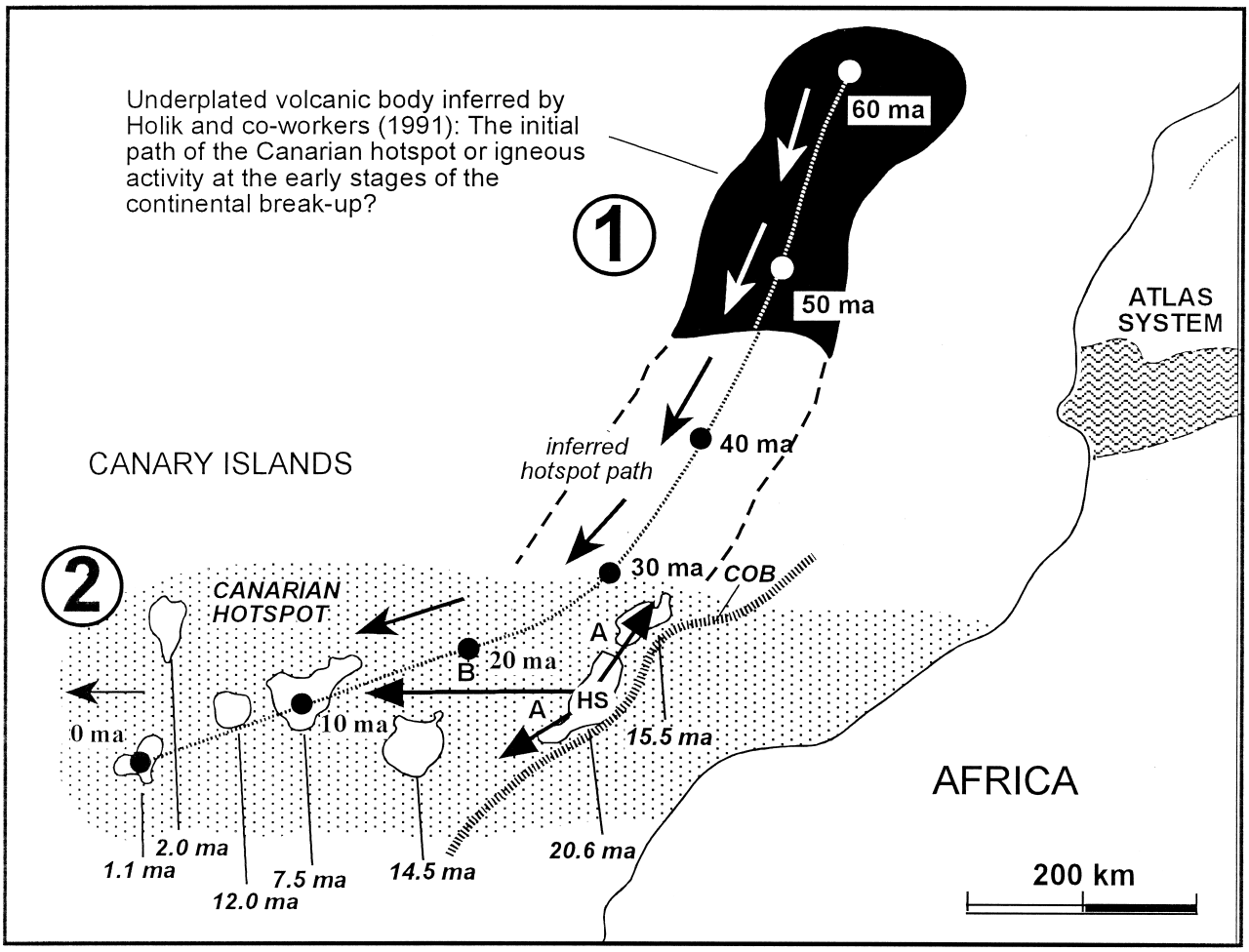


Figure 6. Figure illustrating the origin of the Canaries in relation to a hotspot. HS: initial activity of the CHS, close to the continental–oceanic boundary. A: initial progression of volcanism along the continental–oceanic boundary (COB). B: general progression of volcanism induced by the displacement of the African plate. Ages in italics: the oldest dated subaerial volcanism of each island. The two scenarios (1 and 2) are explained in the text.

congruent with the westward progression of the hotspot; for reasons discussed above a perfect age–distance correlation is not to be expected because of the very low velocity of the African plate relative to the plume reference frame.

Acknowledgements. The ideas presented in this paper have been greatly clarified and developed through our discussions with Uri ten Brink, Tony Watts, Tim Minshull, Robin Holcomb, Bruce Nelson and Hubert Staudigel. Stimulating comments from Hans Schmincke also helped us to focus our arguments. We thank all of them for their assistance in various stages of the preparation of this paper.

References

Abdel-Monem, A., Watkins, N. D. & Gast, P. W. 1971. Potassium–argon ages, volcanic stratigraphy, and geomagnetic polarity history of the Canary Islands: Lanzarote, Fuerteventura, Gran Canaria and La Gomera. *American Journal of Science* **271**, 490–521.

Abdel-Monem, A., Watkins, N. D. & Gast, P. W. 1972. Potassium–argon ages, volcanic stratigraphy, and geomagnetic polarity history of the Canary Islands: Tenerife, La Palma, and Hierro. *American Journal of Science* **272**, 805–25.

Ancochea, E., Brändle, J. L., Cubas, C. R., Hernán, F. & Huertas, M. J. 1996. Volcanic complexes in the eastern ridge of the Canary Islands: the Miocene activity of the island of Fuerteventura. *Journal of Volcanology and Geothermal Research* **70**, 183–204.

Ancochea, E., Fúster, J. M., Ibarrola, E., Cendrero, A., Coello, J., Hernán, F., Cantagrel, J. M. & Jamond, C. 1990. Volcanic evolution of the Island of Tenerife (Canary Islands) in the light of new K–Ar data. *Journal of Volcanology and Geothermal Research* **4**, 231–49.

Anguita, F. & Hernán, F. 1975. A propagating fracture model versus a hotspot origin for the Canary Islands. *Earth and Planetary Science Letters* **27**, 11–19.

Anguita, F. & Hernán, F. 1986. Geochronology of some Canarian dike swarms: contribution to the volcano-tectonic evolution of the Archipelago. *Journal of Volcanology and Geothermal Research* **30**, 155–62.

Araña, V. & Ortiz, R. 1991. The Canary Islands: Tectonics, magmatism and geodynamic framework. In *Magmatism in extensional structural settings (The Phanerozoic African plate)* (eds A. B. Kampunzu and R. T. Lubala), pp. 209–563. Barcelona, Spain: Springer-Verlag.

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

BURKE, K. & WILSON, J. T. 1972. Is the African plate stationary? *Nature* **239**, 387–90.

CANALES, J. P. & DAÑOBEITIA, J. 1998. The Canary Islands swell: a coherence analysis of bathymetry and gravity. *Geophysical Journal International* **132**, 479–88.

CANALS, M., ALIBES, B., URGELES, R. & ALONSO, B. 1997. Landsliding on the Canary islands. The missing submarine sediment record. *International Workshop, Volcanism & Volcanic Hazards in Immature Intraplate Oceanic Islands. La Palma, Canary Islands, Abstract Volume,* 106–9.

CANAS, J. A., PUJADES, L. G., BLANCO, M. J., SOLER, V. & CARRACEDO, J. C. 1994. Coda-Q distribution in the Canary Islands. *Tectonophysics* **246**, 245–61.

CARRACEDO, J. C. 1979. *Paleomagnetismo e historia volcánica de Tenerife.* Aula de Cultura, Cabildo Insular de Tenerife, 82 pp.

CARRACEDO, J. C. 1994. The Canary Islands: An example of structural control on the growth of large oceanic-island volcanoes. *Journal of Volcanology and Geothermal Research* **60**, 225–41.

CARRACEDO, J. C. 1996*a*. A simple model for the genesis of large gravitational landslide hazards in the Canary Islands. In *Volcano Instability on the Earth and other Planets* (eds X. McGuire, X. Jones and X. Neuberg), pp. 125–35. Geological Society Special Publication no. 110

CARRACEDO, J. C. 1996*b*. Morphological and structural evolution of the western Canary Islands: Hotspot-induced three-armed rifts or regional tectonic trends? *Journal of Volcanology and Geothermal Research* **72**, 151–62.

CARRACEDO, J. C. & SOLER, V. 1995. Anomalously shallow palaeomagnetic inclinations and the question of the age of the Canarian Archipelago. *Geophysical Journal International* **122**, 393–406.

CARRACEDO, J. C., DAY, S., GUILLOU, H. & PÉREZ TORRADO, J. F. 1997*a*. El Hierro Geological Excursion Guidebook. *International Workshop, Volcanism & Volcanic Hazards in Immature Intraplate Oceanic Islands. La Palma, Canary Islands, September 1997*.

CARRACEDO, J. C., DAY, S., GUILLOU, H. & GRAVESTOCK, P. 1997*b*. *Geological colour map (1:33 000) of the Cumbre Vieja Volcano, La Palma, Canary Islands.* Pub. CSIC & Cons. Política Territorial, Gobierno Canarias.

CARRACEDO, J. C., RODRÍGUEZ BADIOLA, E. & SOLER, V. 1992. The 1730–1736 eruption of Lanzarote: an unusually long, high magnitude fissural basaltic eruption in the recent volcanism of the Canary Islands. *Journal of Volcanology and Geothermal Research* **53**, 239–50.

COELLO, J., CANTAGREL, J. M., HERNÁN, F., FÚSTER, J. M., IBARROLA, E., ANCOCHEA, E., CASQUET, C., JAMOND, C., DÍAZ DE TERÁN, J. R. & CENDRERO, A. 1992. Evolution of the eastern volcanic ridge of the Canary Islands based on new K–Ar data. *Journal of Volcanology and Geothermal Research* **53**, 251–74.

COURTNEY, R. C. & WHITE, R. S. 1986. Anomalous heat flow and geoid across the Cape Verde Rise: evidence for dynamic support from a thermal plume in the mantle. *Geophysical Journal of the Royal Astrophysical Society: Volcanology and Geothermal Research* **87**, 815–67.

DAVIES, G. R., NORRY, M. J., GERLACH, D. C. & CLIFF, R. A. 1989. A combined chemical and Pb–Sr–Nd isotope study of the Azores and Cape Verde hotspots: the geodynamic implications. In *Magmatism in the Ocean Basins* (eds A. D. Saunders and M. J. Norry), pp. 231–55. Geological Society Special Publication no. 42:

DAY, S. J., CARRACEDO, J. C. & GUILLOU, H. 1997. Age and geometry of an aborted rift flank collapse: the San Andrés fault system, El Hierro, Canary Islands. *Geological Magazine* **134**, 523–37.

DILLON, W. P. & SOUGY, J. M. A. 1974. Geology of West Africa and Canary and Cape Verde Islands. In *The Ocean Basics and Margins* (eds A. E. M. Nairn and F. G. Stehli), pp. 315–90. New York: Plenum Press.

FERAUD, G., GIANNERINI, G., CAMPREDON, R. & STILLMAN, C. J. 1985. Geochronology of some Canarian dike swarms: Contribution to the volcano-tectonic evolution of the Archipelago. *Journal of Volcanology and Geothermal Research* **25**, 29–52.

FILMER, P. E. & MCNUTT, M. K. 1988. Geoid anomalies over the Canary Islands group. *Marine Geophysical Research* **11**, 77–87.

FITTON, J. G. & DUNLOP, H. M. 1985. The Cameroon line, West Africa, and its bearing on the origin of oceanic and continental alkalic basalts. *Earth and Planetary Science Letters* **72**, 23–38.

FORNARI, D. J., GARCIA, M. O., TYCE, R. C. & GALLO, D. G. 1988. Morphology and structure of Loihi Seamount based on Seabeam sonar mapping. *Journal of Geophysical Research* **93**, 15227–38.

FÚSTER, J. M., CENDRERO, A., GASTESI, P., IBARROLA, E. & LOPEZ RUIZ, J. 1968. Geología y Volcanología de las Islas Canarias: Fuerteventura. Instituto "Lucas Mallada", C.S.I.C., Madrid, 239 pp.

FÚSTER, J. M., FERNÁNDEZ SANTÍN, S. & SAGREDO, J. 1968. *Geología y Volcanología de las Islas Canarias: Lanzarote.* Instituto "Lucas Mallada", C.S.I.C., Madrid, 177 pp.

FÚSTER, J. M., HERNÁN, F., CENDRERO, A., COELLO, J., CANTAGREL, J. M., ANCOCHEA, E. & IBARROLA, E. 1993. Geocronología de la isla de El Hierro (Islas Canarias). *Boletín de la Real Sociedad Española de Historia Natural (Seccion Geología)* **88**, 85–97.

GRUNAU, H. R., LEHNER, P., CLEINTUAR, M. R., ALLENBACH, P. & BAKKER, G. 1975. New radiometric ages and seismic data from Fuerteventura (Canary Islands), Maio (Cape Verde Islands), and Sao Tomé (Gulf of Guinea). *Progress in Geodynamics. Royal Netherlands Academy of Arts and Science*, 90–118.

GUILLOU, H., CARRACEDO, J. C., PÉREZ TORRADO, F. & RODRÍGUEZ BADIOLA, E. 1996. K–Ar ages and magnetic stratigraphy of a hotspot-induced, fast grown oceanic island: El Hierro, Canary Islands. *Journal of Volcanology and Geothermal Research* **73**, 141–55.

HARMAND, C. & CANTAGREL, J. M. 1984. Le volcanisme alcaline Tertiaire et Quaternaire du Moyen Atlas (Maroc): chronologie K/Ar et cadre géodynamique. *Journal of African Earth Sciences* **2**, 51–5.

HAUSEN, H. 1958. On the geology of Fuerteventura (Canary Islands). *Societas Scientiarum Fennica, Commentationes Physico-Mathematicae* **22-1**, 1–211.

HOERNLE, K. & SCHMINCKE, H. U. 1993. The role of partial melting in the 15-Ma geochemical evolution of Gran Canaria: a blob model for the Canarian hotspot. *Geotechnology* **10**, 19–32.

HOLCOMB, R. T. & SEARLE, R. C. 1991. Large landslides from oceanic volcanoes. *Marine Geotechnology* **10**, 19–32.

HOLIK, J. S., RABINOWITZ, P. D. & AUSTIN, J. A. 1991. Effects of Canary hotspot volcanism on structure of oceanic crust off Morocco. *Journal of Geophysical Research* **96**, 12039–67.

LANGENHEIM, V. A. M. & CLAGUE, D. A. 1987. The Hawaiian–Emperor volcanic chain. Part II:

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press

Stratigraphic framework of volcanic rocks of the Hawaiian Islands. In *Volcanism in Hawaii* (eds W. Decker, T. L. Wright and P. H. Stauffer), pp. 55–84. U.S. Geological Survey Professional Paper 1350, vol. 1.

Lee, D. C., Halliday, A. N., Fitton, J. G. & Poli, G. 1994. Isotopic variations with distance and time in the volcanic islands of the Cameroon line: evidence for a mantle plume origin. *Earth and Planetary Science Letters* **123**, 119–38.

Liu, H.S. 1980. Convection generated stress field and intraplate volcanism. *Tectonophysics* **65**, 225–44.

MacDonald, G. A. & Abbot, A. T. 1970. *Volcanoes in the sea – The geology of Hawaii.* Honolulu: University of Hawaii Press, 441 pp.

McDougall, I. 1971. Volcanic island chains and seafloor spreading. *Nature* **231**, 141–4.

McDougall, I. & Schmincke, H. U. 1976. Geochronology of Gran Canaria, Canary Islands: Age of shield building volcanism and other magmatic phases. *Bulletin of Volcanology* **40**, 57–77.

McKenzie, D. & Bickle, M. J. 1988. The volume and composition of melt generated by extension of the lithosphere. *Journal of Petrology* **29**, 625–79.

Mitchell, J. G., Le Bas, M. J., Zielonka, J. & Furnes, H. 1983. On dating the magmatism of Maio, Cape Verde islands. *Earth and Planetary Science Letters* **64**, 61–76.

Moore, J. G. 1987. Subsidence of the Hawaiian Ridge. In *Volcanism in Hawaii* (eds W. Decker, T. L. Wright and P. H. Stauffer), pp. 85–107. U. S. Geological Survey Professional Paper 1350, vol. 1.

Moore, J. G. & Clague, D. A. 1992. Volcano growth and evolution of the island of Hawaii. *Geological Society of America Bulletin* **104**, 1471–84.

Morgan ,W. J. 1971. Convection plumes in the lower mantle. *Nature* **230**, 42–43.

O'Connor, J. M. & Duncan, R. A. 1990. Evolution of the Walvis Ridge-Rio Grande Rise hotspot system: implications for African and South American plate motions over plumes. *Journal of Geophysical Research* **95**, 17475–502.

Pérez Torrado, F., Carracedo, J. C. & Mangas, J. 1995. Geochronology and stratigraphy of the Roque Nublo Cycle, Gran Canaria, Canary Islands. *Journal of the Geological Society, London* **152**, 807–18.

Porter, S. C. 1972. Distribution, morphology and size frequency of cinder cones on Mauna Kea. *Geological Society of America Bulletin* **84**, 607–12.

Robertson, A. H. F. & Stillman, C. J. 1979. Submarine volcanic and associated sedimentary rocks of the Fuerteventura Basal Complex, Canary Islands. *Geological Magazine* **116**, 203–14.

Schmincke, H. U. 1973. Magmatic evolution and tectonic regime in the Canary, Madeira, and Azores Island groups. *Geological Society of America Bulletin* **84**, 633–48.

Schmincke, H. U., Sumita, M. & Funck, T. 1997. Growth and destruction of Gran Canaria: Evidence from land studies, bathymetry, offshore seismic studies and drilling during ODP Leg 157. *International Workshop, Volcanism & Volcanic Hazards in Immature Intraplate Oceanic Islands. La Palma, Canary Islands, Abstract Volume*, 10–12.

Staudigel, H. & Schmincke H. U. 1984. The Pliocene seamount series of La Palma/Canary Islands. *Journal of Geophysical Research* **89**, 11190–215.

Steckler, M. S. & ten Brink, U. S. 1986. Lithospheric strength variations as a control on new plate boundaries: examples from the northern Red Sea region. *Earth and Planetary Science Letters* **79**, 120–32.

Stillman, C. J. 1987. A Canary island dyke swarm: implications for the formation of oceanic islands by extensional fissural volcanism. In *Mafic dyke swarms* (eds H. C. Halls and W. F. Fahrig), pp. 243–55. Geological Association of Canada Special Paper no. 34.

Stillman, C. J. 1997. The episodic growth and partial destruction of pre-shield-lava Fuerteventura. *International Workshop, Volcanism & Volcanic Hazards in Immature Intraplate Oceanic Islands. La Palma, Canary Islands, Abstract Volume*, 56–8.

Stillman, C. J., Furnes, H., Le Bas, M. J., Robertson, A. H. F. & Zielonka, J. 1982. The geological history of Maio, Cape Verde Islands. *Journal of the Geological Society, London* **139**, 347–61.

Stillman, C. J., Fúster, J. M., Bennell Barker, M. J., Muñoz, M., Smewing, J. D. & Sagredo, J. 1975. Basal Complex of Fuerteventura is an oceanic intrusive complex with rift-system affinities. *Nature* **257**, 469–70.

ten Brink, U. S. 1991. Volcano spacing and plate rigidity. *Geology* **19**, 397–400.

Vink, G. E., Morgan, W. J. & Zhao, W. L. 1984. Preferential rifting of continents: a source of displaced terranes. *Journal of Geophysical Research* **89**, 10072–6.

Walker, G. P. L. 1990. Geology and volcanology of the Hawaiian Islands. *Pacific Science* **44**, 315–47.

Walker, G. P. L. 1992. Coherent intrusion complexes in large basaltic volcanoes- a new structural model. *Journal of Volcanology and Geothermal Research* **50**, 41–54.

Watkins, N. D. 1974. Paleomagnetism of the Canary Islands and Madeira. *Geophysical Journal of the Royal Astrophysical Society* **32**, 249–67.

Watts, A. B. 1994. Crustal structure, gravity anomalies and flexure of the lithosphere in the vicinity of the Canary Islands. *Geophysical Journal International* **119**, 648–66.

Watts, A. B. & Marr, C. 1995. Gravity anomalies and the thermal and mechanical structure of rifted continental margins. In *Rifted Ocean-Continent Boundaries* (eds E. Banda *et al.*), pp. 65–94. Kluwer Publishing.

Watts, A. B. & Masson, D. G. 1995. A giant landslide on the north flank of Tenerife, Canary Islands. *Journal of Geophysical Research* **100**, 24487–98.

Weaver, P. P. E., Rothwell, R. G., Ebbing, J., Gunn, D. E. & Hunter, P. M. 1992. Correlation, frequency of emplacement and source directions of megaturbidites on the Madeira Abyssal Plain. *Marine Geology* **109**, 1–20.

Wysession, M. E., Wilson, J., Bartkó, L. & Sakata, R. 1995. Intraplate seismicity in the Atlantic Ocean Basin: A teleseismic catalog. *Bulletin of the Seismological Society of America* **85**, 755–74.

https://doi.org/10.1017/S0016756898001447 Published online by Cambridge University Press