The Canary Islands origin: a unifying model

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Abstract

A new model, partially based on the three most widely cited previous hypotheses, is proposed to explain the genesis of the Canary Islands. From the hotspot hypothesis it retains the notion that the islands originated from a thermal anomaly in the mantle. From the propagating fracture hypothesis it takes the critical role of regional fractures in the onset of magmatism. The uplifted block hypothesis contributes with the notion that the islands are in their present freeboard attitude due to the action of tectonic forces.

The main drawbacks of the three preceding hypotheses are solved within this unifying approach: the thermal anomaly is an upper mantle residue from an old plume, and therefore it does not carry (or does it in a highly diluted form) the typical geophysical and geochemical plume signatures; the fractures are well developed on the continental and oceanic crust, but not in the extremely thick sedimentary pile between the Canary Islands and Africa; and the Canary Islands uplift took place through transpressive shears, and not by means of purely reverse faults. This unifying model, which integrates the thermal and tectonic histories of the lithosphere and the sublithospheric mantle, is considered to be a valid approach to a number of volcanic areas where, as has been highlighted in recent years, pure hotspot or pure fracture models are found wanting to explain oceanic or (less frequently) continental volcanic lines.

Keywords: Canary islands; hotspots; fracture magmatism

1. Introduction

The Canary Islands are a *locus classicus* of the science of Volcanology. Extensively studied from the 19th century on, they feature characteristics that make them unique among the volcanic oceanic island groups. The present hypotheses on the Canary Islands origin have in common that they were born in the aftermath of the mobilist geologic revolution. Paramount among them is the mantle plume hypothesis, developed by Morgan (1971) on Wilson's (1963) hotspot concept. Equally anchored in the global frameworks of the seventies are the propagating fracture hypothesis (Anguita and Hernán, 1975) and the concepts of the Canary Islands as a local extensional ridge (Fúster, 1975) or as a set of uplifted tectonic blocks (Araña and Ortiz, 1986).

Of these four, only the plume hypothesis has been refurbished by its supporters during the last decade (Holik et al., 1991; Hoernle and Schmincke, 1993; Hoernle et al., 1995; Carracedo et al., 1998). It could therefore be concluded that this is the only presently accepted genetic model for the archipelago, but the real situation is slightly more complicated. Every hypothesis, including the several plume

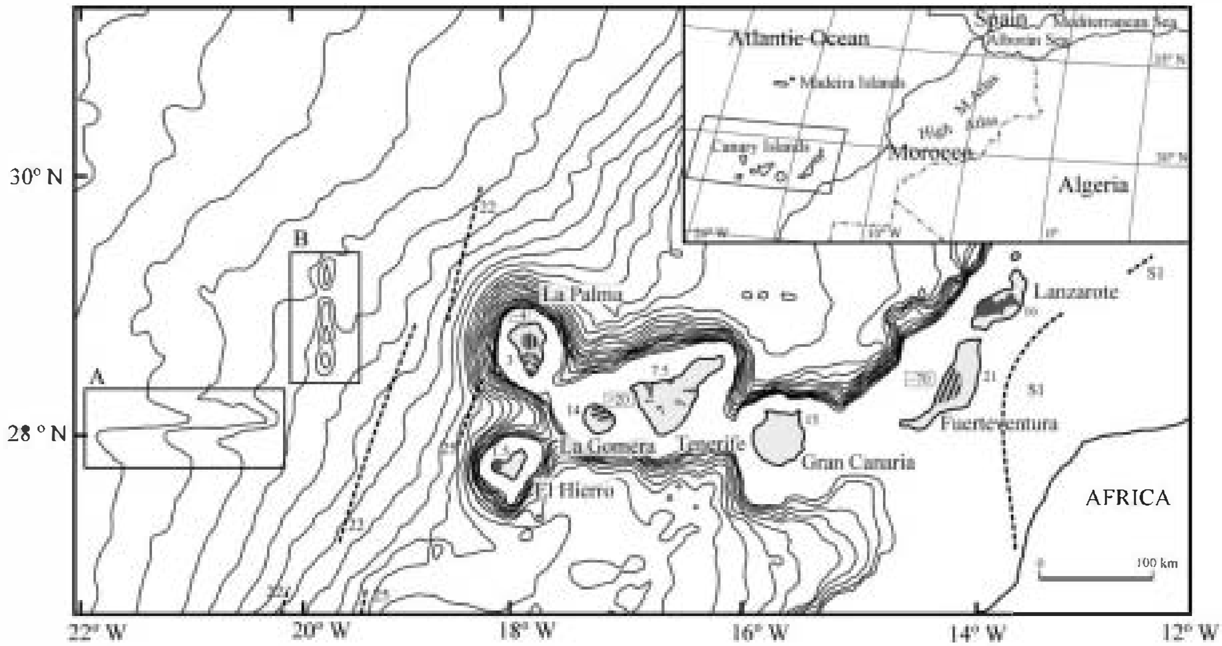

Fig. 1. A map of the Canary Islands showing some bathymetric (contours at 100 m intervals but only at depths greater than 2.5 km), chronological, and eruptive activity data. In dark grey, terrain covered by historical eruptions. Striped, basal complexes (stripe directions in the azimuth of the sheeted dike complex). Numbers indicate the ages (Ma) of the oldest subaerial outcrops; when in boxes, the ages of the basal complexes. Boxes A and B underline tectonic signatures: A is a straight, 300 km-long submarine canyon, and the site of a $M = 6.2$ quake which happened in 1959. B is a 200 km-long seamount line parallel to the strike of the sheeted dike complex of La Palma, the nearest island.

variants, suffered since it was proposed from inconsistencies with the local and regional geology: the fact is that the Canary Islands, like a number of other mid-plate volcanic chains, are not yet well understood. This has become even more evident as the amount of new data has increased at an ever growing pace. The list of new evidence arising in this decade is substantial, and includes new information on the sublithospheric mantle of the Canary Islands and surrounding regions; advances in the geochemistry of mantle source areas; the first thorough tectonic reconnaissance of several islands, and of the neighbouring Morocco areas as well; a number of new marine geophysics data sets; and the many recent geochronological investigations on Canary Islands rocks. These major advances now permit an overhauling of the former hypotheses; it is our contention that this holistic vision can be used as the basis of a new, unifying model in which the main obstacles formerly encountered by the previous ideas can be understood as problems derived too from single-sided approaches.

To evaluate the hypotheses that try to explain the geology of the islands, we must begin with a short geologic description of the archipelago (see Schmincke, 1973, 1976, 1982, for general background and further references). The Canary Islands are a roughly linear 500 km long chain (almost exactly the same size as the Hawaiian group) formed by seven islands (Fig. 1), all but one of which have been active in the last million year; four of them (three located at both ends of the chain, and one at its centre) show a record of eruptions in the last five centuries. As in other volcanic islands groups, the most complete sections consist of three types of units: (1) basal complexes (or pre-shield stage), composed of turbiditic sediments intruded by sheeted dike swarms, and by plutonics ranging from pyroxenites to carbonatites; (2) shield constructs; and (3) post-shield cones. The successive stages, which seem to represent one or more batches of new magma from the mantle, are commonly separated from each other by time gaps of several millions of years long; there are, moreover,

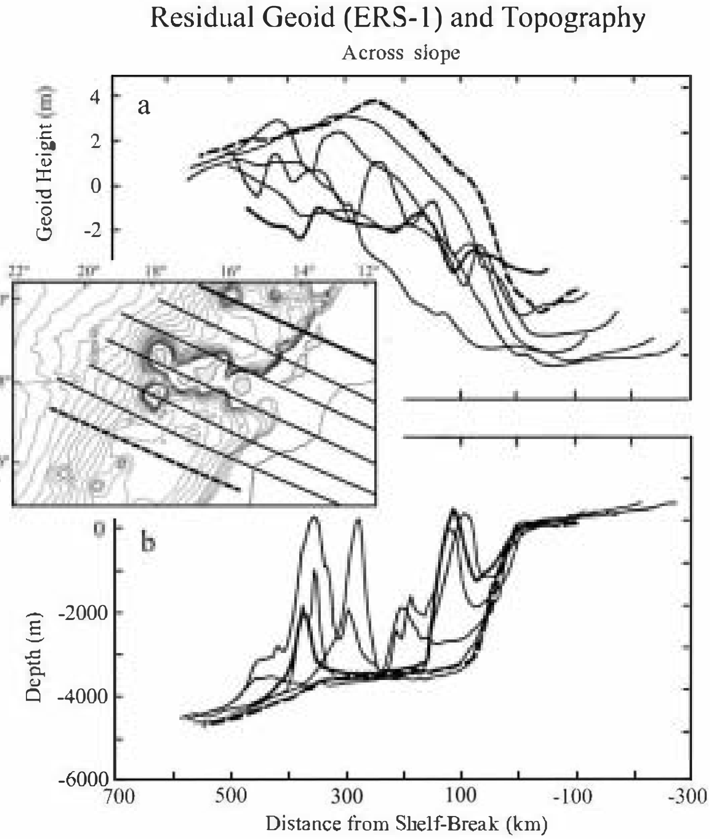

Fig. 2. Geoid height (a) and topography (b) around the Canary Islands. Note that the thicker and dashed lines correspond in both cases to the northernmost and southernmost sections. All geoid heights in the islands area are *lower* than the geoid at the southernmost section, far from the islands. As for the bathymetric baselines, they are almost identical among the islands and outside them (dashed line). After Watts (1994).

occasional but important time gaps between rocks of the same stage.

The rock types are really diverse, including melilitites, nephelinites, basanites, tholeiitic and alkali olivine basalts, tephrites, rhyodacites, rhyolites, pantellerites and comendites, trachytes, phonolites and carbonatites. In other words, the typical oceanic alkaline suite with saturated and undersaturated end-members. Most basalts are alkaline, though there are also minor tholeiitic rocks (for instance, the most voluminous historic eruption, at Lanzarote in the eastern end of the chain, produced tholeiitic basalts). Trachytes and phonolites are very common, and huge calderas have developed (in Gran Canaria and Tenerife only) at the end of the shield-building phase, while the post-shield activity produced essentially basanites and nephelinites. Sr–Nd–Pb isotopic analyses have been interpreted (Cousens et al., 1990; Hoernle and Tilton, 1991; Hoernle et al., 1991; Hoernle and Schmincke, 1993; Neumann et al., 1995) as meaning that the Canary Islands' magmas represent a multicomponent mixture of different reservoirs: a HIMU (lower mantle) component and another complex end-member with lithospheric (enriched mantle, or EM), asthenospheric (depleted mantle, or DM), and again HIMU components. In an effort to ascertain possible deep mantle (PHEM, or primitive helium mantle) sources, Kellogg and Wasserburg (1990), and Pérez et al. (1994) have also published (with mixed results, see Section 3.2) He isotopic ratios.

The geophysics of the archipelago and the intervening seas is characterised (Fig. 2) by the absence of a bathymetric swell or a geoid high (Jung and

Rabinowitz, 1986; Filmer and McNutt, 1989; Watts, 1994; but see the discussion by Grevemeyer, 1999, in Section 3.1). A number of discontinuities, interpreted as basement fractures, show up on the seismic sections (e.g. Hinz et al., 1982). As will be described in Section 3.5, some of these fractures are seismically active. As for the ocean crust magnetism (see Fig. 1), the M25 anomaly (Middle Jurassic) is located on the ocean crust near La Palma and El Hierro, the two westernmost islands. One “slope anomaly”, the S1 (175 Ma), has also been identified between the easternmost islands and the African continent. Moreover, areal magnetic anomalies, probably representing different basement blocks, are outstanding (Socías and Mezcua, 1996). The Jurassic age of the ocean crust on which the archipelago is built has been consistently confirmed (Hayes and Rabinowitz, 1975; Roest et al., 1992; Schmincke et al., 1998; Steiner et al., 1998).

Important tectonic structures can be observed in the islands, and especially in their basal complexes. They range from ductile shears (which have been interpreted by Fernández et al. (1997) as transtensive systems) to unequivocal compressional structures such as recumbent folds (Cendrero, 1969; Robertson and Stillman, 1979). From the islands' aeromagnetic map, Socías and Mezcua (1996) interpret the basement of the islands as consisting of large tilted blocks, a conclusion in any case evident in spectacular features noticeable on several islands, such as the heavily tilted basaltic series cropping out in La Gomera. These blocks have been differentially uplifted from the sea floor, as can be deduced from a number of submarine materials (sedimentary or volcanic) now cropping out at different heights. The amounts of uplift are variable but in general important (for example, 2 km for La Palma (Staudigel and Schmincke, 1984), 2–4 km for Fuerteventura (Robertson and Stillman, 1979), although just 0.4 km for Gran Canaria (Fúster et al., 1968)). This indicates that the islands rose up from the ocean floor as independent blocks or groups of blocks (Marinoni and Pasquarè, 1994), an assumption also supported by the bathymetry, which shows independent insular edifices separated by deep sea. Staudigel et al. (1986), and Araña and Ortiz (1986, 1991) have suggested that most of this uplift is due to the action of important normal faults, while Fernández et al. (1997) attribute the emergence to shear tectonics.

The archipelago has a long record of activity (e.g. Ancochea et al., 1990; Coello et al., 1992), but its oldest stages have been difficult to reconstruct due to problems inherent to isotopic dating. While Cantagrel et al. (1993) distrust K–Ar ages older than 25 Ma (their oldest age for Fuerteventura) because of a possible excess of argon, they supposed that the activity (represented by undatable layers) could have begun around 35 to 30 Ma. Contrasting with those authors, Le Bas et al. (1986), essentially on the basis of palaeontology and field relations, suggest for Fuerteventura a beginning at the Senonian, or around 80 to 70 Ma. A careful geochronology study (Balogh et al., 1999) has confirmed these old ages for the easternmost islands. Cantagrel et al. (1993) also dated the first subaerial activity around 20 Ma. This datum was corroborated by the 'Glomar Challenger' drillings (Schmincke, 1979), where no air fall tephra layers older than 19 Ma were found in the vicinity of the islands. One interesting chronological feature of the Canary Islands is that every comparable unit (be they the basal complexes, the shield volcanoes, or the post-shield constructs) is older in the eastern islands than in the western ones. For instance, the basal complex cropping out at La Palma was formed only 3–4 Ma ago (Staudigel et al., 1986), just a small fraction of the Fuerteventura complex age.

2. Existing hypotheses for the origin of the Canary Islands

2.1. The propagating fracture

Building on previous ideas (Dash and Bosshard, 1969; MacFarlane and Ridley, 1969; Bosshard and MacFarlane, 1970; Le Pichon and Fox, 1971; Grunau et al., 1975) about a geological connection between the Canary Islands and the Atlas Mountains (see sketch in Fig. 4), this hypothesis (Anguita and Hernán, 1975) proposed the existence of a leaky megashear which connected both areas. When experiencing a tensional phase, this transcurrent corridor would explain the Canary Islands volcanism through decompression melting; when subject to compression, important quiescent periods (and compressive structures) would ensue. Robertson and Stillman (1979) also supported this hypothesis.

Although, it claimed the explanation of the cyclic structure of the Canary Islands volcanism in accordance with the compressive phases dated at the Atlas Mountains, the propagating fracture hypothesis did not explain the uplift of the insular blocks, and never overcame the absence of Cenozoic submarine faults between the islands and the termination of the South Atlas fault off Agadir (Watkins and Hoppe, 1979; Hinz et al., 1982). An added problem for this hypothesis was later shown: the volume of the islands ($\sim 1.5 \times 10^5$ km^3, (Schmincke, 1982)) greatly exceeded the theoretical possibilities of generating magma by stretching a lithosphere without an underlying thermal source (McKenzie and Bickle, 1988).

2.2. *The uplift of tectonic blocks*

The evidence of kilometres of uplift of different amounts for different islands was the basis for the hypothesis (Araña and Ortiz, 1986, 1991) that compressive tectonics (which led to ocean floor shortening and crustal thickening) was the main causal agent of the magmatism and uplift of the blocks forming the Canary Islands. The occasional relaxation of the tectonic stresses would permit the magmas to escape. While explaining both the present height of submarine formations above sea level and also the dynamics of the seismically active inter-island faults, this hypothesis did not propose a compelling process for magma genesis and for the spatial and temporal distribution of volcanism.

2.3. *The local Canary Islands rift*

The high dilation evident in Canary Islands basal complexes was the main evidence for the hypothesis of a regional extensional structure active in this area in Cenozoic times (Fúster, 1975). The Canary Islands rift has been considered again by Oyarzun et al. (1997), this time as a part of a huge rifted zone stretching from Cape Verde to Central Europe. But neither in its original form nor in the recent one can this idea contradict the overwhelming evidence that the ocean floor around the Canary Islands is Jurassic, so that the creative action of the putative rift would have to be limited to the islands themselves; moreover, since (as shown in Fig. 1) each of the three outcropping dike swarms has a different azimuth, the rift geometry is not easy to resolve. A last, but important, objection to this hypothesis is that the islands are separated by deep sea with no evidence of Cenozoic crust added to the Mesozoic one.

2.4. *The classic Canary Islands plume*

Following the success of the hotspot model in explaining the Hawaiian volcanism (Wilson, 1963), the Canary Islands were proposed (Morgan, 1971; Burke and Wilson, 1972; Schmincke, 1973; Vogt, 1974a,b; Khan, 1974; Morgan, 1983) to represent the surface expression of a column of fertile material which had risen through the mantle. The main problems faced by this first version of the hypothesis were emphasised by Anguita and Hernán (1975):

(1) Contrasting with the Hawaiian Islands, long time gaps (up to seven million years) frequently interrupted the magmatic activity. The classical plume model could not account for such long hiatuses (the longest time gap in Hawaii (Woodhead, 1992) spans just 1 Ma). (2) The onset of the subaerial volcanic activity showed a very irregular westward progression (cf. data in Fig. 1). Although the African plate velocity was far from being accurately measured, the fact was that no velocity value could account for all the ages in a classical fixed hotspot model. (3) At radical variance with the limitation of most recent activity to only one end of the Hawaiian chain, almost the whole Canary Islands line has erupted in recent times, which complicates the task of defining a location for the hotspot. Most authors choose to place it at La Palma or El Hierro, the westernmost islands, but this leaves unexplained the most important historical eruption, which took place at Lanzarote, the easternmost one.

To those initial criticisms, others were later added (by Hoernle and Schmincke, 1993):

(1) Contrary to the individually short-lived Hawaiian volcanoes, the Canary Islands present a long volcanic record, at least 30 (but more probably up to 80) Ma long on the oldest islands. Moreover, this activity is divided into separate magmatic cycles. (2) The thermal anomaly exhibits a very low melt productivity, in each island and in the whole archipelago; and this productivity is on the wane in each cycle. For Gran Canaria, the volume of magma produced in the Miocene made up 80% of the island, vs. only 18% in the Pliocene and just 2% in the Quaternary. Even allowing for the diminishing durations of the periods

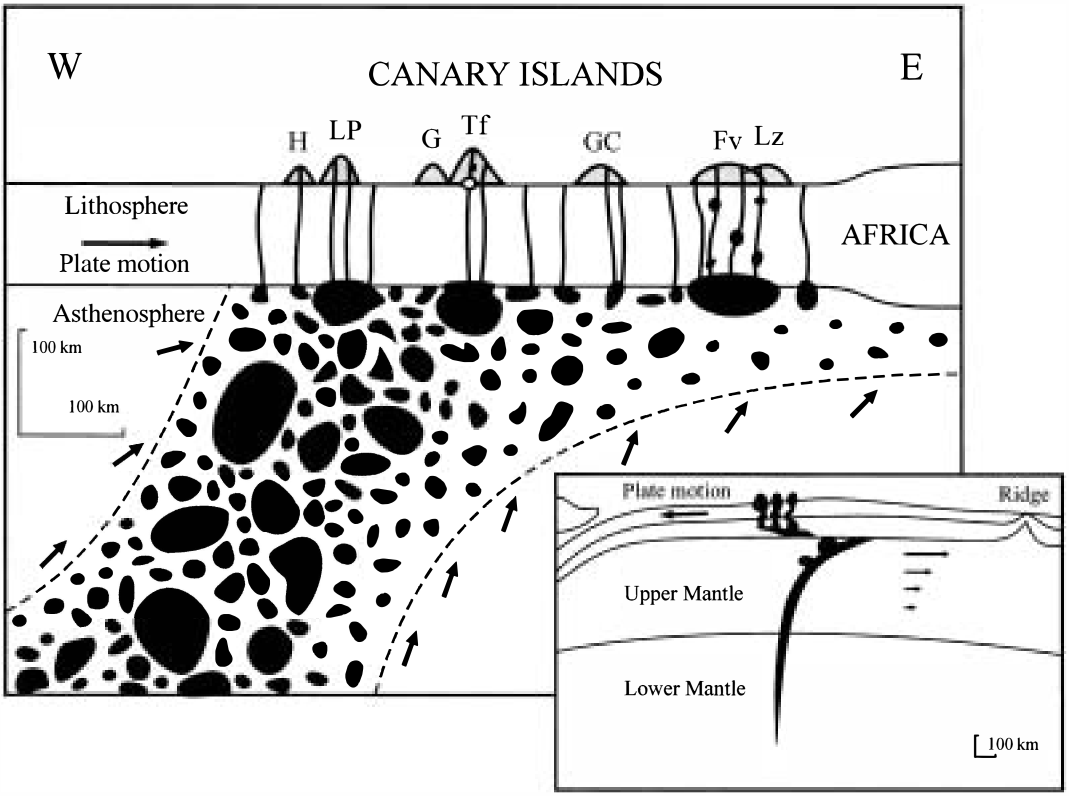

Fig. 3. The blob model for the Canary Islands, after Hoernle and Schmincke (1993). Inset: dipping plume model for the Hawaiian Islands after Ihinger (1995). Note that, due to upper mantle flow towards the spreading ridge (and contrary to the Canary model), the conduit dips against the lithosphere plate motion. See text for a different model (Cox, 1999).

implied, the seemingly evident waning of the activity is difficult to understand if an active flux of magma is coming up from the mantle underlying the islands. (3) The varied geochemistry (in time as well as in space) of the Canary Islands rocks also contrasts with the petrologic monotony of the Hawaii group.

No doubt that some of these problems could be solved with an ad hoc hotspot model: for instance, a plume with low melting rates ("Marquesan type" of Woodhead, 1992) under the quasi-stationary African plate would produce islands with long volcanic histories, low productivity and complex geochemistry. But even the weak plumes should behave as plumes, and many of the critical features, such as the long time gaps or the geophysical features, could not be explained away as side effects of the velocity of the African plate or the productivity of the plume.

Carracedo et al. (1998) have recently placed the Canary Islands plume under El Hierro, at the archipelago western end. These authors follow the suggestion of Holik et al. (1991), who identified a submarine reflector (apparently Late Cretaceous, and younger towards the south) near the African continental margin NE of the islands. They further proposed that this layer represents the first volcanic material emplaced by the putative Canary Islands plume. Several lines of evidence make this model difficult to accept: (1) While the model of Carracedo et al. (1998, their fig. 6) predicts that the onset of volcanism in Fuerteventura, some 600 km south of the reflector, happened around 25 Ma ago, palaeontology findings, marine geophysics data (Watkins and Hoppe, 1979), field relations (Robertson and Stillman, 1979; Le Bas et al., 1986; Cantagrel et al., 1993), and the most recent radiometric work (Balogh et al., 1999) all support for this island a minimum Eocene, but more probably Late Cretaceous age. (2) Holik et al. (1991) describe a bathymetric swell for their hotspot trace, while this feature does not exist in the Canary Islands (Jung and Rabinowitz, 1986; Filmer and McNutt, 1989; Watts, 1994; Watts et al., 1997; see Section 3.1), a contrast that suggests different origins. (3) The reflector is a continuous layer about 1000 m thick, whereas the islands are constructs several times that thickness separated by deep ocean: again the heterogeneity points to a disparate genesis. And (4) basal complexes (i.e. the deep roots of the islands) crop out at La Palma and Fuerteventura, at both ends of the chain, which means that, in contrast with the classical Hawaii-Midway-Emperor chain, the Canary line shows no trace of one-end subsidence. The criticism of Carracedo et al. (1998) about the non-applicability of the concept of one-end subsidence to volcanic groups built on slow-moving plates has at least two weak points: (1) Those authors propose a non-existent parallel with the Cape Verde group, where no age-progression at all has been found (e.g. Courtney and White, 1986; Abranches et al., 1990); and (2) Lanzarote is 500 km away from the supposed hotspot location: at roughly this distance from Loihi seamount (the location of the Hawaiian hotspot proper) we find Kauai, the westernmost island of the archipelago, in an advanced stage of subsidence. This contrast is of course irrespective of the plate velocity.

2.5. The blob model

Those inadequacies led to the appearance of a new plume model (Hoernle and Schmincke, 1993) of the "blob type", which had been previously introduced (Allègre et al., 1984) to explain isotopic mixing at spreading centres, then applied to geochemical modelling of the Galapagos volcanism (White et al., 1993). The Canary Islands blob model featured (Fig. 3) a dipping conduit which would underlie the whole archipelago, and whose dip to the west would be caused by the African plate viscous drag.

This model might overcome some of the shortcomings of the classical plume hypothesis. (1) The magmatic cycles and the gaps in activity would result from the successive arrival to the surface of fertile and sterile mantle material. (2) The ubiquity of the recent volcanism throughout the archipelago would be a consequence of the proposed geometry, with a fertile blob underlying each island with recent activity. (3) The geochemical diversity would also be easily explained as a consequence of the heterogeneity of the blobs.

Several drawbacks of this hypothesis derive from its very geometry: firstly, it is not clear whether the Hawaiian plume, which is the explicit model for the dipping conduit, dips in the same direction of the plate movement (Cox, 1999) or against it (Ihinger, 1995; inset on Fig. 3). Secondly, the African plate could be altogether stationary (see discussion on the African plate kinematics in Section 3.3) or, in any case, move too slowly to produce an effective viscous drag; and thirdly, the blobs should reach the westernmost islands first, and thus these should be the oldest ones. Other features that this model did not explain were the geophysics (the absence of a topographic swell and geoid high) and the tectonics, specifically the compressive features.

From a geochemical point of view, the blob model proposed a symmetry (alkaline–tholeiitic–alkaline) in each magmatic cycle that is far from being general, since the archipelago as a whole is essentially alkaline. And last, the blobs were unnecessary for other Atlantic volcanic islands, which did show clear hotspot signatures. Why should the Canary Islands require a plume different from the ones that explain such island groups as the Cape Verdes, Madeira, or Bermuda?

2.6. The upwelling sheet model

To probe the mantle underlying the Canary Islands crust, a seismic tomography study was performed (Hoernle et al., 1995). Previous data sets had provided ambiguous results: in one of the investigations (Anderson et al., 1992), the Canary Islands seemed to overlie the border of an upper mantle thermal anomaly elongated through parts of the NW African coast and central and western Europe, while in the other (Grand, 1994) the only anomalies under this area were restricted to the lower mantle (and centred under the Cape Verde Islands). The data of Hoernle et al. (1995) showed a sheet-shaped thermal positive anomaly, whose roots were detected down to a depth of 500 km (the maximum depth reached by the study) and which surfaced at NW Africa (oceanic

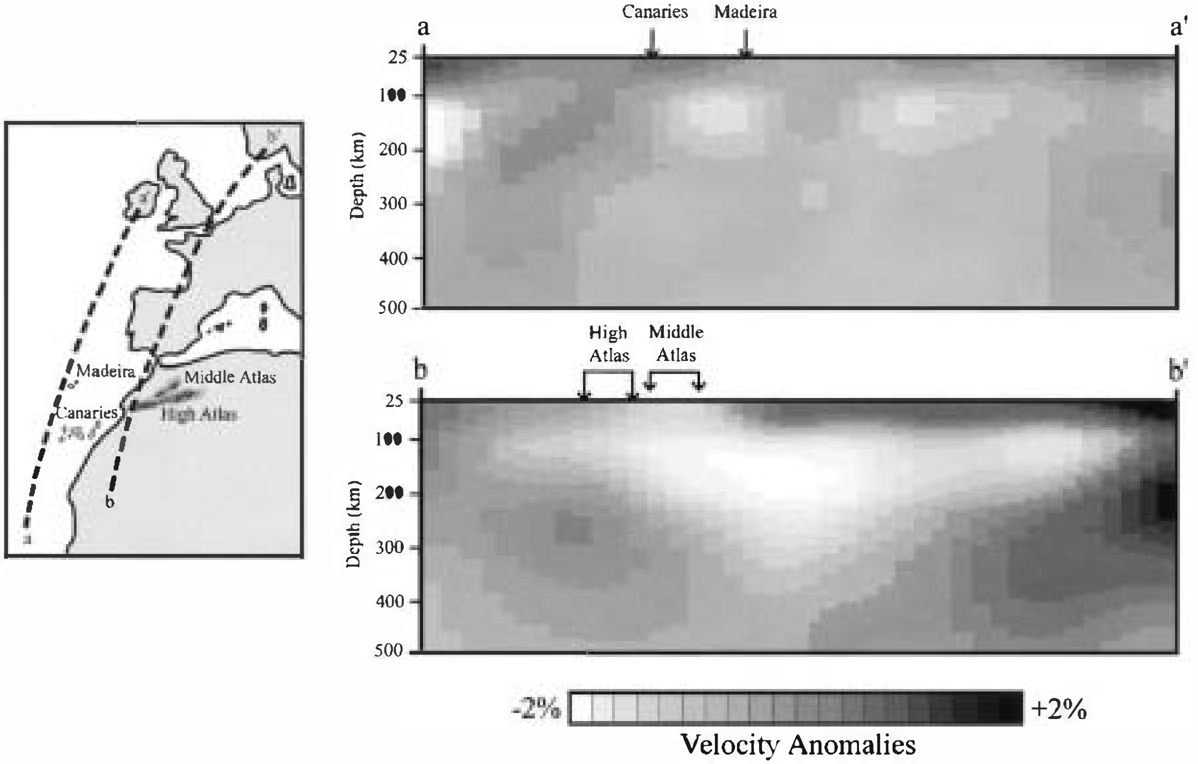

Fig. 4. Results of the seismic tomography experiment performed by Hoernle et al. and which are pertinent for the origin of the Canary Islands. In the a–a' section a cold lithosphere can be seen underlying the Canary Islands; the islands, moreover, overlie the border of a mild thermal anomaly of the upper mantle. In the b–b' section, a much more important thermal anomaly is located under the Atlas Mountains. Redrawn from Hoernle et al. (1995).

as well as continental), the Mediterranean, and central Europe, covering an overall area of 2500 × 4000 km.

The relationship of this large mantle structure with a putative Canary Islands plume is unclear (Fig. 4). As featured in the Anderson et al. (1992) study, the archipelago lies precisely above the border of one of the thermal maxima, but this anomaly apparently does not penetrate the lithosphere or the lower mantle. It is interesting to stress that the two most important positive thermal anomalies detected in the area by Hoernle et al. (1995) lie near Madeira and near the volcanic Middle Atlas (sections a–a' and b–b' in Fig. 4). Though it has been proposed (Sleep, 1990) that families of plumes may result from the breaking up of tabular upwellings in their ascent through the mantle, the fact is that the Canary Islands plume stays elusive. This could be due to the poor accuracy of the present geophysical equipment, unable to detect structures smaller than about 100 km. But in theory (Davies, 1990), plume heads should be mushroom-shaped, and thus easier to detect. All that can be said from the existing data is that a large regional positive thermal anomaly occupies a broad area of the *upper* mantle in the vicinity of the Canary Islands, although not directly under them.

Besides its geochemical problems (which will be treated in Section 3.2), this last version of the plume model leaves unanswered the questions about the Canary Islands geophysics and tectonics; and, since no magmatic conduit has been located, all the rest of the problems for which the blob model was a theoretical solution (i.e. distribution of magmatism in space and time, magmatic cycles) must be considered as still pending.

3. Recent data on the origin of the Canary Islands

In this section, we present data acquired only in recent years, or else new with respect to the Canary Islands context, such as the Atlas Mountains data.

3.1. Geophysics

A number of interesting papers has been published on the physics of the Canary Islands lithosphere during recent years. First of these was Jung and Rabinowitz's (1986), where the Seasat-deduced geoid anomalies in the North Atlantic were systematically examined. These authors concluded that the residual geoid and bathymetric data correlate very well over the Azores, Bermuda, and Cape Verde; but that in other areas the overall correlations were not very significant. In fact, as confirmed by Watts (1994, his Fig.14), this study reveals that the Canary Islands are the only important North Atlantic island group not centred over a geoid anomaly.

These results were later corroborated by Filmer and McNutt (1989), who calculated a very high (8.0×10^{23} N m) flexural rigidity for the Canary Islands' lithosphere. This figure is five times bigger than the one deduced for Cape Verde, and one to two orders of magnitude larger than those of the Pacific volcanic islands. The authors interpreted this result as meaning that, contrasting with the lithosphere at true hot spots, the Canary Islands lithosphere had not been heated by a rising column of hot material. On the basis of the absence of a geoid high and a topographic swell (another well known plume signature: compare our Fig. 2 with the 1.9–2.4 km swell for Cape Verde (Courtney and White, 1986; McNutt, 1988; Monnereau and Cazenave, 1990)), Filmer and McNutt (1989) questioned the interpretation that the Canary Islands were a plume trace. Recently, Canales and Dañobeitia (1998) have proposed for the Canary Islands a "masked swell" caused by a NNE regional thermal anomaly: it seems quite probable that these authors are detecting the physical influence of the thermally anomalous mantle defined by Hoernle et al. (1995).

Sleep (1990) and Grevemeyer (1999) have, on the contrary, claimed the existence of a geoid high centred in the Canary Islands. Sleep (1990), though, only reinterpreted the data published by Jung and Rabinowitz (1986) who, as we have seen, make just the opposite claim. Grevemeyer (1999), following a method devised by Sandwell and MacKenzie (1989), compared the ratio of a geoid height to topography for eight Atlantic volcanic groups, and concluded that four of them, including the Canary Islands, presented an aspect ratio typical of a thermal swell. He then discussed the results of Filmer and McNutt (1989) (though not those of Jung and Rabinowitz (1986) or Watts (1994), whose conclusions were identical), implying that they were in error because those authors did not take into account the isostatic effect of the adjacent African margin. Nevertheless, a revision of his method (Sandwell and MacKenzie, 1989, p. 7406) leads to the conclusion that it is very sensitive to neighbouring geologic structures, and specifically to the edge effects produced by continental margins. This undermines the conclusions of Grevemeyer (1999), even if he cautions that a more detailed study is necessary to address the question of the geoid in the Canary Islands. This caution is especially adequate in the light of the following set of data.

Watts (1994) calculated a value of 20 km for the lithosphere elastic thickness under Tenerife and La Gomera. He then compared this datum with what would be expected for an unperturbed lithosphere of Jurassic thermal age, which should be 35 km thick. Watts (1994) inferred that this apparent weakening was most likely the result of thermal perturbations in the lithosphere caused by an underlying mantle plume, and he attributed the absence of a topographic swell and a geoid high to a high degree of variability in the geophysical properties of hotspots. Dañobeitia et al. (1994), however, *after correcting for the effect of the Moroccan margin*, obtained for the Canary Islands lithosphere a thickness of 35 km, or slightly smaller than their calculated unperturbed thickness of 40 km, but exactly the Watt's calculated unperturbed thickness. Further calculations led the same team (Canales and Dañobeitia, 1998) to propose a thickness range of 28–36 km, which they interpreted as a lack of thermal rejuvenation of the uppermost lithosphere. On the basis of geochemical calculations, Neumann et al. (1995) estimated a lithosphere thickness of 27 km under Lanzarote and they hypothesised that this was due to the effect of a thermal anomaly. But they surmised that the lithosphere is thicker under the chain's western end, so their conclusion clearly contradicts the location of the postulated plume under El Hierro or La Palma. And lastly, a high lithospheric strength has been deduced by Ye et al. (1999) from the Moho's nearly horizontal attitude, without significant crustal flexure towards the islands. This group evaluates these differences stating that the classic Hawaiian hotspot setting is not valid in the case of Gran Canaria.

The last geophysical feature investigated in the Canary Islands area is the possible existence of magmatic underplating, important (>4 km) under Hawaii (Lindwall, 1988) and the Marquesas (Caress et al., 1995). Watts et al. (1997) studied the flexure of the lithosphere under the load of Tenerife, and reached the conclusion that, in contrast to those archipelagos, the crust under at least part of Tenerife is not underplated by magmatic material. This is consistent with the suggestion (Hoernle and Schmincke, 1993) that the magmatic productivity of the Canary Islands melting anomaly is low. On the contrary, Ye et al. (1999) have located an 8–10 km thick underplated section under Gran Canaria. Unlike that under the Hawaiian Islands, the Gran Canaria underplating does not extend beyond the island coastline. This heterogeneity of the islands' roots, already pointed out by Banda et al. (1981), makes underplating, or its absence, an inconclusive argument for the origin of the islands.

3.2. Geochemistry

Kellogg and Wasserburg (1990) obtained for Canary Islands rocks $^{3}He/^{4}He$ ratios that are definitely small (5.8–7.5 times the atmospheric ratio, or R_A) when compared with the values (R_A between 11 and 48) obtained by Craig and Lupton (1976), and Kaneoka and Takaoka (1980), and Kurz et al. (1982) for Hawaii. At La Palma, Pérez et al. (1994) measured larger ^{3}He values (up to 9.6 R_A), on the limit of those attributed to hotspot islands; nevertheless, the rest of their measurements (4–6 R_A at Gran Canaria, and 6–7 R_A at Tenerife) are clearly outside these limits. Although Pérez et al. (1994) interpret their results as proof that a plume is contaminating the magma under La Palma with 6.1% of lower mantle helium, their data compare better with those for MORB (8–12 R_A) than with those measured at Loihi seamount, which range (Kurz et al., 1982) from 23 to 32 R_A. These results raise some questions about the real meaning of the whole geochemical array. Since the HIMU represents a *lower* mantle reservoir enriched in uranium (Hart et al., 1992; but see discussion by Anderson, 1999), then it is difficult to understand: (1) why the Canary Islands rocks are not (or only slightly) enriched in the PHEM source, as are other hotspots; and (2) why the anomalous mantle detected by means of tomography under the islands does not extend to the lower mantle. The last problem with the HIMU is the difference between the Canary Islands and Cape Verde carbonatites: while the first ones show the described complex geochemical assemblage, the Fogo (Cape Verde) carbonatites are pure HIMU (Hoernle and Tilton, 1991).

As for the $^{87}Sr/^{86}Sr$ relationship, it shows more ambiguous values, 0.7029 to 0.7035, with most clustering between 0.7030 and 0.7033 (Sun, 1980; Schmincke, 1982) or even 0.7035 for Tenerife (Ovchinnikova et al., 1995). These data fall in the hotspot field (0.7030–0.7050), though in its lowest range, and limiting with the MORB average ratio of 0.7025–0.7029 (White et al., 1987).

3.3. Canary Islands ages and the African plate kinematics

The main problem related to the ages of the Canary Islands rocks is the explanation of the chronological gaps. These periods without extrusive activity appear in most islands: they last 1.3 million years (from 2.9 to 1.6 Ma) in La Palma; two million years (from 12 to 10 Ma) in Lanzarote; three million years (from 3 to 0 Ma) in La Gomera; five million years (from 10 to 5 Ma) in Gran Canaria; and seven million years (from 12 to 5 Ma) in Fuerteventura. As already stated, the longest time gap in Hawaii (located on the island of Oahu (Woodhead, 1992) lasted for just 1 million years; but a minimum 5 million years gap exists in Maio, Cape Verde (Gerlach et al., 1988). Very long time gaps are also a distinct feature of the Cameroon line, where they can reach up to 12 million years in Principe and Pagalu (Fitton and Dunlop, 1985). In theory, plume activity should be more or less continuous, while tectonic-controlled volcanism could be rather episodic, since it is dependent on changes in the lithosphere stress regime. The blob model for hotspots was put forward (Hoernle and Schmincke, 1993) to solve this problem, but its limitations when applied to the Canary Islands' case have already been stated.

The movement of the African plate is related to this age problem and has also an essential bearing on the genetic hypotheses for the Canary Islands. Unfortunately, this movement is a matter of contention, since there is not even agreement on whether there has been movement at all during recent times. While Burke and Wilson (1972), Briden and Gass (1974), Steiner (1975), and Minster and Jordan (1978) proposed a nearly stationary African plate, Duncan (1981) and Morgan (1983) have reconstructed a very slow moving plate, with velocities around 1 cm a^{-1}. Watts (1994) cited a velocity of 20 mm a^{-1}, but he did not mention the source of this value. Recently, Burke (1996) presented evidence for the plate being essentially at rest with respect to the underlying mantle since about 30 Ma, though O'Connor et al. (1999) propose a velocity of 20 $\pm$ 1 mm a^{-1} for the same period. In any case, a plot of the islands' oldest ages vs. distances leads to graphs (Carracedo et al., 1998, their fig. 2) of arguable geological meaning, since outcrops of comparable age (for instance, the beginning of shield-building emissions) are not found, or are not useful for dating, in most islands.

These complex time vs. distance relationships are more similar to those of volcanic lines with strong tectonic control, like Samoa (Woodhead, 1992), the Cameroon line (Fitton and Dunlop, 1985; Halliday et al., 1988), or the Cook-Austral chain (McNutt et al., 1997). In the case of the Canary Islands, and bearing in mind that the African plate could be stationary, the real question to discuss is rather why any progression in ages does exist at all. This point will be treated in Section 6.

3.4. Tectonics on the islands

The importance attributed to tectonics in the Canary archipelago has varied from major (for Hausen, 1956, 1958) to minor (e.g.Fúster et al., 1968; Schmincke, 1968). Tectonics is now considered to be important to understanding the evolution of the Canary Islands. The most important of the "classic" tectonic features in the archipelago is the outstanding unconformity present in Fuerteventura basal complex between an overturned Cretaceous sedimentary and volcanic succession and gently dipping mid-Tertiary sediments. Robertson and Bernoulli (1982) suggested that these folds were generated by dextral motion along a shear zone; or, alternately, that they could indicate a compressive stress field acting twice, in post-Cretaceous and post-Miocene times. Now, considering (Stillman, 1987) that the injection of the basal complexes dike swarms requires important dilations, and bearing in mind that the last period of injection was Oligocene–Miocene (see our Fig. 9), a succession of compressional and dilational stress fields could be deduced. Whether this alternation of compression and extension is able to explain eruptive periods separated by time gaps has been the matter of a long debate. An interesting alternative has been pointed by Staudigel et al. (1986), which explained the N–S strike of the dikes of the La Palma basal complex as a result of a regional N–S compressive field. In this case, the magmas would not result from extension, but from the compression caused by the collision of Africa against Eurasia.

An important piece of evidence for a causal relationship between tectonics and magmatism in the Canary Islands has been the identification of ductile shear zones in the Fuerteventura basal complex (Casillas et al., 1994; Fernández et al., 1997; Muñoz et al., 1997). Carbonatite bodies intrude along these shears, thus indicating a transtensive stress field. The shears show NW and NE conjugate azimuths that can be solved by transtension with a horizontal σ_3 striking E–W. The slip could exceed 1 km, and their age is bracketed between Late Oligocene and Early Miocene. Judging by their dimensions, age, and field relationships, it seems reasonable to think that these deformations were instrumental in the intrusion of Fuerteventura's last basal complex materials: the carbonatite bodies have been dated (Cantagrel et al., 1993; Balogh et al., 1999) at 23 Ma, or Early Miocene.

Another step in confirming the connection between tectonics and magmatism has been a thorough tectonic study of Lanzarote (Marinoni and Pasquarè, 1994), in which these authors located more than 200 faults and over 40 volcanic alignments with the same general strike (NNW) as the faults. Most of the faults were of the strike-slip type (right- as well as left-handed), although normal and reverse examples were also present. There had been two different phases of activity, in Pliocene and Pleistocene times. Anguita et al. (1991) also detected faults and an important number of WNW-aligned Pliocene cones and dikes, which run across the centre of Gran Canaria.

3.5. Tectonics on the seafloor

Submarine tectonic structures have been detected in the Canary Islands area from the time of the first marine geophysics surveys in the 1970s. Some of them (e.g. an E–W graben located east of Lanzarote (MacFarlane and Ridley, 1969) seem to be submarine extensions of the subaerial structures. In the open sea, the marine geophysicists have found an array of tectonic structures, such as antiforms, synforms and unconformities (Dillon, 1974; Uchupi et al., 1976; Dañobeitia and Collette, 1989). Outstanding among the antiforms is a huge (~200 km wide) anticline (the "Slope Anticline") whose axis follows the slope and shelf some 150 km south of the islands, and is parallel to their general trend (e.g. Watts, 1994, his Fig. 11).

Most submarine fractures are transcurrent (Le Bas et al., 1986) or normal (MacFarlane and Ridley, 1969; Bosshard and MacFarlane, 1970; Banda et al., 1992) faults. A 80 km shift of the S1 magnetic lineation east of Lanzarote (Roeser, 1982; see our Fig. 1) also suggests the presence of marine fracture zones. More complex tectonic settings include (see Fig. 4 of Hinz et al., 1982) flower structures, an accepted (Harding, 1985) signature of transcurrent dynamics. A large seismic event permitted Mezcua et al. (1992) to detect between Tenerife and Gran Canaria a submarine fault some 50 km-long, with transcurrent (left-lateral) and reverse components. From it they deduced a compressional stress field with σ_1 around N170E. This fault is therefore of the same kind as the left-handed transcurrent faults associated with folds located at the Essaouira basin (northern border of the Atlas) by Piqué et al. (1998). Here we find the first hint of a genetic kinship between the Canary Islands and the Atlas Mountains.

Beyond the indisputable dynamic character of the zone, the real question is whether a physical connection in the shape of a continuous fracture links the islands with the South Atlas lineament. No Cenozoic faults appear in the two published seismic profiles that offer hard data on this critical question [2]. In one of them, Watkins and Hoppe (1979) see no evidence of tectonic activity in this area which could be attributable to movements along the South Atlas fault during the Alpine orogeny. On the other profile, Hinz et al. (1982) state, likewise, that the area was not affected by any major faulting after the Dogger; nevertheless, they illustrate (in their Fig. 2) faults and folds affecting the Aptian, and describe four (Aptian, Eocene, Oligocene and Miocene) erosional unconformities. These add to other similar structures detected in the same zone, such as an array of folds (McMaster and Lachance, 1968; Summerhayes et al., 1971; Goldflam et al., 1980) and a Pleistocene angular unconformity (Dillon, 1974).

To sum up, the oceanic basement and sedimentary cover between the Canary Islands and the African continent were tectonically unstable from Cretaceous times on, but this tectonic activity is not expressed as a fault or a set of faults. The wide seismic gap depicted by Medina and Cherkaoui (1991, their Fig. 2; see our Fig. 10) between the Canary Islands and Africa seems to confirm the lack of active faults there, and suggests that the present deformation is mainly aseismic. This aspect will be considered again in Sections 4.4 and 5.

4. The northwestern Africa geologic framework

Clear syntheses on the geology of the Atlas Mountains can be found in Jacobshagen et al. (1988a,b), Froitzheim et al. (1988), Brede et al. (1992), and Giese and Jacobshagen (1992). This chain was built through the tectonic inversion of a Triassic and Jurassic intracratonic rift (the "Atlas gulf" of Jacobshagen et al., 1988a) associated with the opening of the North Atlantic (Fig. 5). The cause for the inversion was most probably the convergence of the African and Eurasian plates during the Cenozoic. The Atlas Mountains data most relevant to the Canary Islands' origin are given in the following sections.

4.1. Geophysics

The seismic tomography data by Hoernle et al. (1995) are useful not only to understand the Canary Islands' evolution, but also for the study of the Atlas Mountains. Their b–b' section (our Fig. 4), the one which shows the maximum thermal contrast, cuts through the western High Atlas. There, and near the

[2] Stets and Wurster (1982), cited as proving the non-existence of a fracture, do not offer data; as for Weigel et al. (1978) and Weigel et al. (1982), their sections bear no data relevant to this question.

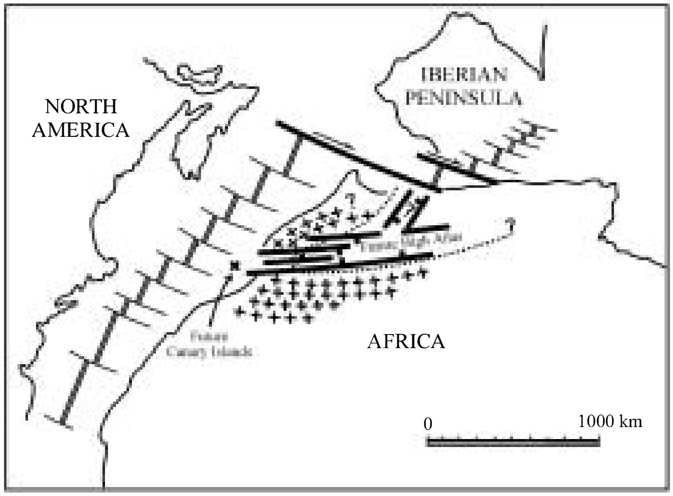

Fig. 5. The ultimate cause for the origin of the Canary Islands may well be the formation in Jurassic times of this failed arm rift in the place of the present High Atlas, during the opening of the central Atlantic Ocean. Redrawn from Lee and Burgess (1978).

neighbouring Middle Atlas, the anomaly seems to reach the surface. These data had been anticipated by (1) the uncompensated isostatic state of the chain (Wigger et al., 1992), and (2) the location of high conductivity (Menvielle and Le Mouël, 1985; Schwartz et al., 1992) and low-seismic velocity (Schwartz and Wigger, 1988) layers deep in the Atlas Mountains crust. These were later independently confirmed by Seber et al. (1996), who identified (their Fig. 7) low-velocity layers from 35 to 150 km beneath the High and Middle Atlas, and the Antiatlas (see situation in Fig. 7) as well. But the critical set of data is still the one obtained by Hoernle et al. (1995). Although the only mention of NW Africa made by those authors is a statement (p. 38) on the lack of volcanoes in the Atlas Mountains (see the section on volcanism below), the anomalous mantle they detected, and which underlies the eastern central Atlantic *and* NW Africa, clearly suggests that the Canary Islands magmas and the parental magmas of the Cenozoic Atlas volcanoes have the same origin.

The area is seismically active. The focal mechanism solutions are strike-slip and/or thrust (Medina and Cherkaoui, 1991). Cherkaoui et al. (1991) present an analysis of the focal mechanism of the great 1960 Agadir earthquake (see location in Fig. 7) compatible with the dextral-reverse movement of a N49E fault, though Harmand and Moukadiri (1986) and Gomez et al. (1996) propose a left-lateral strike-slip fault as the cause; the last two interpretations are coincident with that of Mezcua et al. (1992) for the Canary Islands' quake of 1989.

4.2. Tectonics

Giese and Jacobshagen (1992) and Beauchamp et al. (1999) have proposed that the Atlas chain is the result of an important (>30 km) shortening, during which the Jurassic rift faults became thrusts, newly formed thin-skinned thrusts added to that thick-skin tectonics, and the crust under the High Atlas thickened to 38–39 km. Most authors (e.g. Fraissinet et al., 1988) propose four tectonic phases. Some authors suggest that the inversion is an all-Tertiary event, but others (Froitzheim et al., 1988; Beauchamp et al., 1999; see our Fig. 9) have claimed it to have begun in the Cretaceous. These uncertainties notwithstanding, the coincidence in time and geometry between the stress fields experienced by the Atlas chain and by the Canary Islands is evidenced by their parallel geological structures, such as, for instance, the angular unconformity between Cretaceous and Cenozoic series.

As for the types of faults, Mattauer et al. (1977), Proust et al. (1977) and Binot et al. (1986) propose that all post-Cretaceous Atlas faults are thrusts. But Herbig (1988) and Jacobshagen (1992) find also strike-slip faults (mostly sinistral), a conclusion

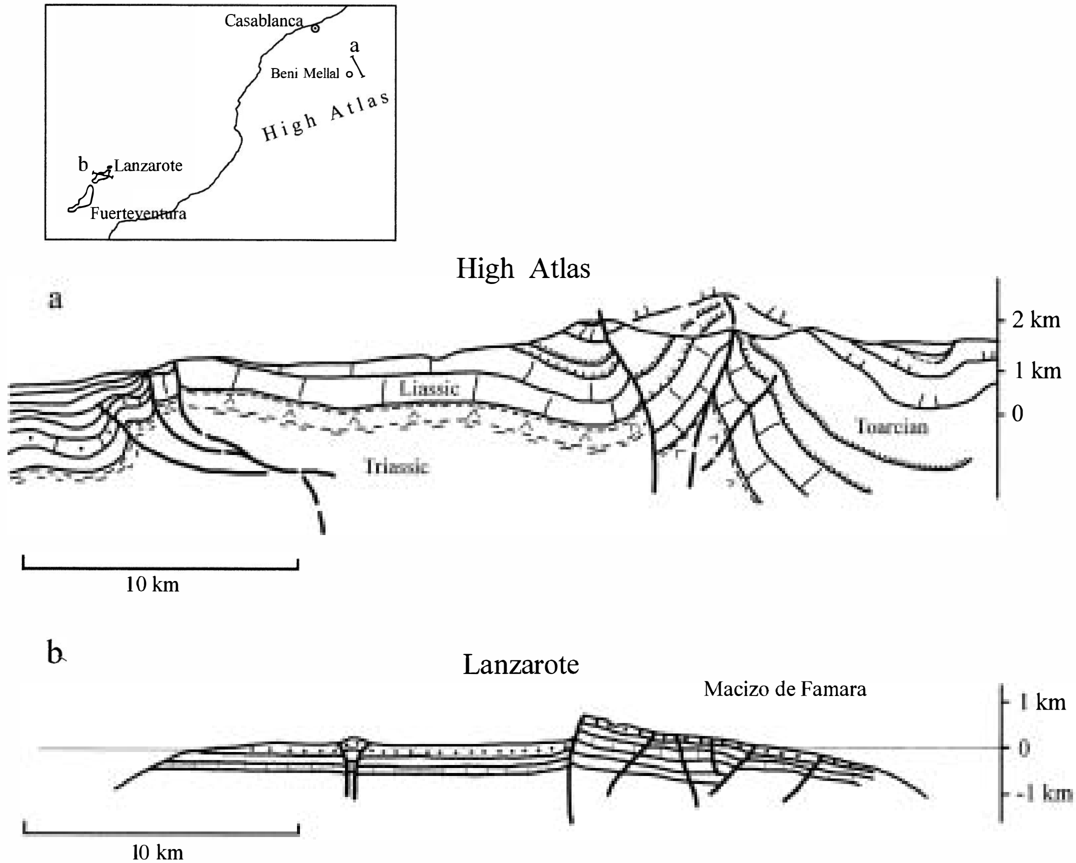

Fig. 6. (a) A flower structure cropping out in the High Atlas (after Laville and Piqué, 1992). (b) An E–W section (along the parallel 29°N) across Lanzarote, an island of medium size, at the same horizontal and vertical (2 ×) scales. The tectonic structures are from Marinoni and Pasquarè (1994).

which seems to agree better with (1) the seismic plane solutions, and (2) the frequent flower structures (Fig. 6) found in the chain (Binot et al., 1986; Froitzheim et al., 1988; Laville and Piqué, 1992; Saadallah et al., 1996). Most faults strike NNE (in the High Atlas), NE (in the Middle Atlas), or NW (dispersed though less marked), although abundant N–S structures were detected in a morphometric survey (Deffontaines et al., 1992). The most recent volcanoes (see below) are aligned nearly N–S.

The South Atlas lineament, a classic (Russo and Russo, 1934) as well as complex structure, merits a study on its own. The extreme position of Stets and Wurster (1982) who reject its very existence outright, is not shared by most authors. Proust et al. (1977) and Jacobshagen et al. (1988a) describe it as a discontinuous NNE structure. A microtectonic study by Proust et al. (1977) defined it as a megashear active from Palaeozoic times on, first as a right-lateral, then left-lateral, then (during the Tertiary) a reverse fault, and now represented as a set of en echelon structures. All tectonicists working on the Atlas Mountains agree that this lineament should be studied as a part of a newly defined strike-slip sinistral megastructure more than 1000 km long, the Trans-Alborán Fault system (Bousquet and Montenat, 1974; Sanz de Galdeano, 1990; see location in Fig. 7), which runs along the High Atlas (where it is called the Tizi-n′Test fault) and Middle Atlas and crosses the Alborán (Mediterranean) Sea up to the Spanish town of Alicante. Jacobshagen (1992) stresses, though, that this structure is

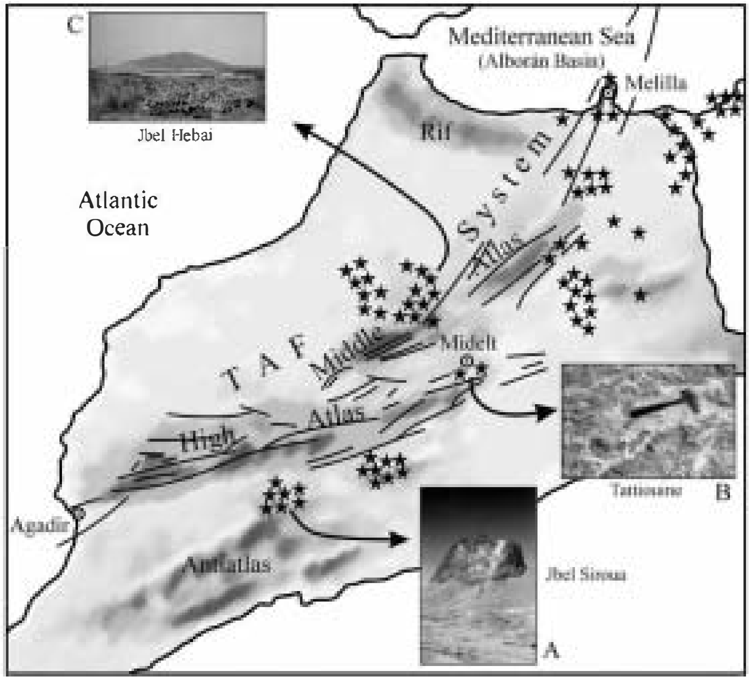

Fig. 7. The volcanoes (stars) of the Atlas Mountains. (A) is a phonolitic plug of Jbel Siroua, in the Antiatlas; (B) a carbonatite outcrop at Tattiouine, near Midelt, northern High Atlas; and (C) a monogenetic basaltic cone from Jbel Hebri, Middle Atlas. Volcanoes and faults (TAF = Trans-Alborán Fault) from Jacobshagen et al. (1988a,b).

not continuous, but that it consists of partial, relaying fragments.

4.3. Volcanism

There are a number of volcanic areas in the Atlas Mountains and adjacent zones (Fig. 7): the best studied of them are one in the Middle Atlas with about 90 volcanic constructs (monogenetic cones, maars) aligned on an approximate N170E direction; a second one on the Antiatlas, with two huge volcanic centres (Jbel Siroua and Jbel Sarhro) which crop out some 20 km from the southern High Atlas border; and a third one which consists of few cones but large intrusions, and it is located on the northern border of the High Atlas. We see that the statement on the supposed lack of volcanism in the Atlas Mountains (Hoernle et al., 1995) is inaccurate even if limited to the High Atlas. The absence of volcanics on the High Atlas *axis* could be explained by the cited thickening of the crust under this part of the chain. As for the Antiatlas volcanoes, they could be related to the very shallow dipping structure (detected through its seismic low velocity (Schwartz and Wigger, 1988) and high conductivity (Schwartz et al., 1992), which crosses the High Atlas roots and seems to connect both volcanic provinces (Giese and Jacobshagen, 1992, their Fig. 4).

All the volcanics are alkaline, but very different rocks crop out in each area: basanites and alkali basalts with some nephelinites in the Middle Atlas (Harmand and Cantagrel, 1984); phonolites and trachytes with minor hawaiites, rhyolites and comendites in the Antiatlas (Berrahma, 1989); and nephelinites plus a gabbro to carbonatite complex in the High Atlas (Le Bas et al., 1986). Ages vary widely. The oldest magmatism (the syenites, carbonatites and nephelinites cropping out near the town of Midelt in the High Atlas (Lancelot and Allègre, 1974) is Eocene to Oligocene (45–35 Ma) but the next active period, in the nearby Middle Atlas, did not take place until the Miocene (14–6 Ma, nephelinites). The activity finished with Pleistocene basalts, basanites and nephelinites (1.8–0.5 Ma). The ages of the Antiatlas volcanic province are rather poorly known, but they seem to spread from the Upper Miocene to the Pliocene: 10.8–2.1 Ma for the Jbel Siroua phonolites (Berrahma, 1989), while Jbel Sarhro is mainly composed of Miocene, Pliocene and Pleistocene rhyolitic ash-flows, and hauyne trachyte lavas (de Sitter et al., 1952).

All those rock types (even the less frequent, such as the carbonatites, the comendites, or the hauyne trachytes) are represented in the Canary Islands. The rock ages (beginning in Early Cenozoic, with the bulk activity centred in the Miocene–Pliocene) are roughly similar as well. The time gaps represent another chronological parallel: there are two intervals (of 20 and 4 Ma) without volcanic activity in the Middle Atlas; another, less well defined (10.8–8.2 Ma?) in Jbel Siroua. This discontinuous magmatism has given rise to different tectonogenetic hypotheses: Harmand and Cantagrel (1984), Berrahma (1989) and Aït Brahim and Chotin (1990) tried to connect the active periods with tectonic phases; for instance, Harmand and Cantagrel (1984) claim that volcanism and compression are coeval, but the loose time-stratigraphic control limits the validity of this and similar hypotheses.

4.4. Regional models

Gomez et al. (1996) proposed that the whole Meseta block (the lithospheric subplate north of the Atlas Mountains) is escaping towards the Atlantic along the Trans-Alborán Fault as a consequence of the compression from the north, a scheme already advanced by Olsen and Schlische (1990). Another tectonic synthesis (Froitzheim et al., 1988) takes into account both compression and lateral response, and on the basis of the frequent flower structures found puts forward the hypothesis that the Atlas Mountains has been subjected during the whole Cenozoic to transpressive and transtensive movements. A third hypothesis (Michard et al., 1975; Brede et al., 1992) emphasises a slight (~5°) Cenozoic clockwise rotation of the Meseta block (Brede et al., 1992, their Fig. 15) as a side effect of the collision against the Eurasian plate. This would cause a propagation of stresses towards the NE, noticeable in: (1) a slight delay in the Middle Atlas uplift with respect to the High Atlas (Choubert and Faure-Muret, 1962); and (2) a delay in the movements along the Trans-Alborán Fault, which began its activity at least in the Oligocene in Morocco, but not until Late Miocene in SE Spain (Jacobshagen, 1992).

All three models do find support in the Atlantic and Canary Islands data. (1) The escape hypothesis of Gomez et al. (1996) could explain why the Meseta Atlantic shelf shows signs of instability, such as folding, transtensive faulting and a possible Oligocene angular unconformity (Summerhayes et al., 1971; Piqué et al., 1998). (2) Transpression is the stress field indicated by the fault plane solution of the last earthquake in the Canary Islands (Mezcua et al., 1992). It could be as well an effective mechanism for the islands' tectonic uplift (the Canary Islands as flower structures? see below). (3) The propagation (and liberation) of stresses along relaying lithospheric fractures is the simplest way to explain why the western Canary Islands are younger than the eastern ones.

5. A unifying model

A mantle thermal anomaly under North Africa, the Canary Islands, and western and central Europe was defined through seismic tomography (Hoernle et al., 1995). This anomaly has the shape of a sheet, and not of a plume, and does not enter the lower mantle. Both features preclude it from being a plume (or at least a plume from the core-mantle boundary: see discussion in Anderson, 1998). What is its origin? Following an idea first suggested by Wigger et al. (1992) for the Atlas Mountains, and then on a wider scale by Oyarzun et al. (1997), we propose that the thermal anomaly is the remnant of a "fossil" plume. This hot material would have arrived in the upper mantle near the end of the Triassic (~200 Ma), being instrumental in the opening of the central Atlantic (May, 1971). Its outcrops (tholeiitic dikes, sills and lava flows covering about 7 million km^2 of North and South America, NW Africa and SW Europe) are widespread enough to catalogue it as the largest of known LIPs (Large Igneous Provinces), or even as a super-plume (Wilson, 1997). Oyarzun et al. (1997) designated this putative plume the Central Atlantic Plume, while Marzoli et al. (1999) prefer the name of Central Atlantic Magmatic Province. Some geochemical

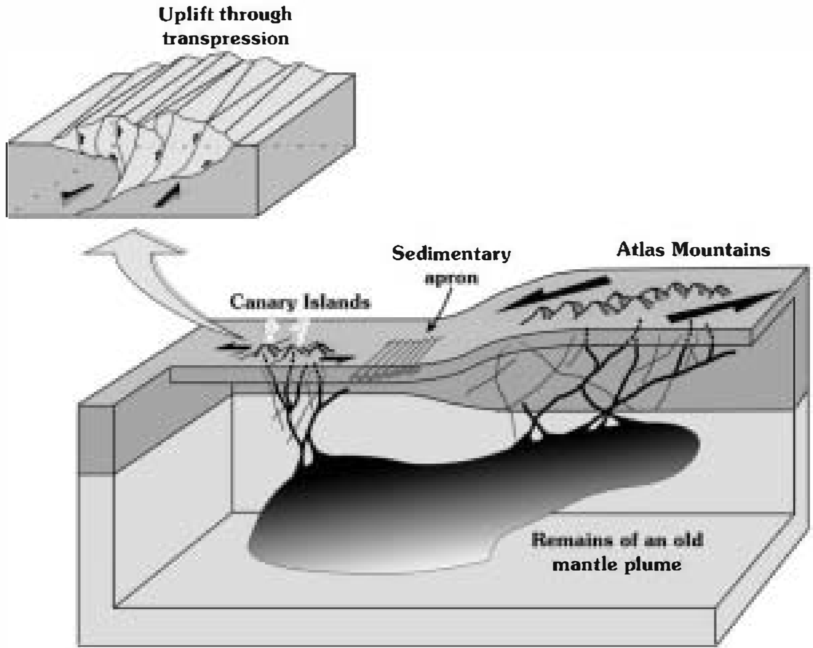

Fig. 8. Cartoon illustrating the unifying hypothesis on the origin of the Canary Islands. The inset represents a transpressive phase, when the islands would emerge as flower structures.

evidence for this old plume is the EM component found in Lanzarote basalts and interpreted (Ovchinnikova et al., 1995) as a contribution from continental lithospheric mantle: a remainder of Pangea.

As for its subsequent (Cretaceous–Cenozoic) evolution, Oyarzun et al. (1997) and Moreira et al. (1999) put forward an eastward migration of the remnants of the plume head, now detected under the African margin and Europe. Magmatism occurred where and when an efficient fracture system provided a pathway. These places were the central European rift system, the volcanic provinces of the westernmost Mediterranean (Balearic and Alborán basins), Iberia, the Canary Islands and Cape Verdes (Hoernle et al., 1995).

The model we propose: (1) integrates the Atlas Mountains volcanoes with the rest of this magmatic province, a logical step since they share the same thermal anomaly with them; and (2) explains—through the Canary Islands and the Atlas Mountains common tectonic features—not only the time–space magmatic relationships of the archipelago but its uplift as well. In this unifying hypothesis, the magmatism in the Canary Islands is explained through the tapping of the old thermal anomaly by the fractures inherited from the Mesozoic failed arm rift (Fig. 8). The strongest evidence for it is: (1) that the Atlas Mountains and the Canary Islands show the same types of structures even when considering the details. For instance, transcurrent faults have not only the same set of strikes (NE, NW and N–S), but also share the characteristic of being left- and right-handed as well. Those common features support the interpretation that all of them are being caused by the same stress field; and (2) that there is an alternation in time of the periods of magmatism in the islands, and of compression in the Atlas Mountains and Atlantic (Fig. 9). During the tensional periods, the fractures would serve as conduits for the magma (Cousens et al., 1990, p. 326; Anderson, 1999, p. 23), while in the compressive epochs they would cause the uplift of the islands as sets of flower structures.

This hypothesis gathers together the main aspects of the three most important lines of research on the origin of the Canary Islands: (1) The hotspot is vindicated, since the origin of the magmas is a mantle thermal anomaly, even if it is not presently coming from the lower mantle. (2) The propagating fracture is

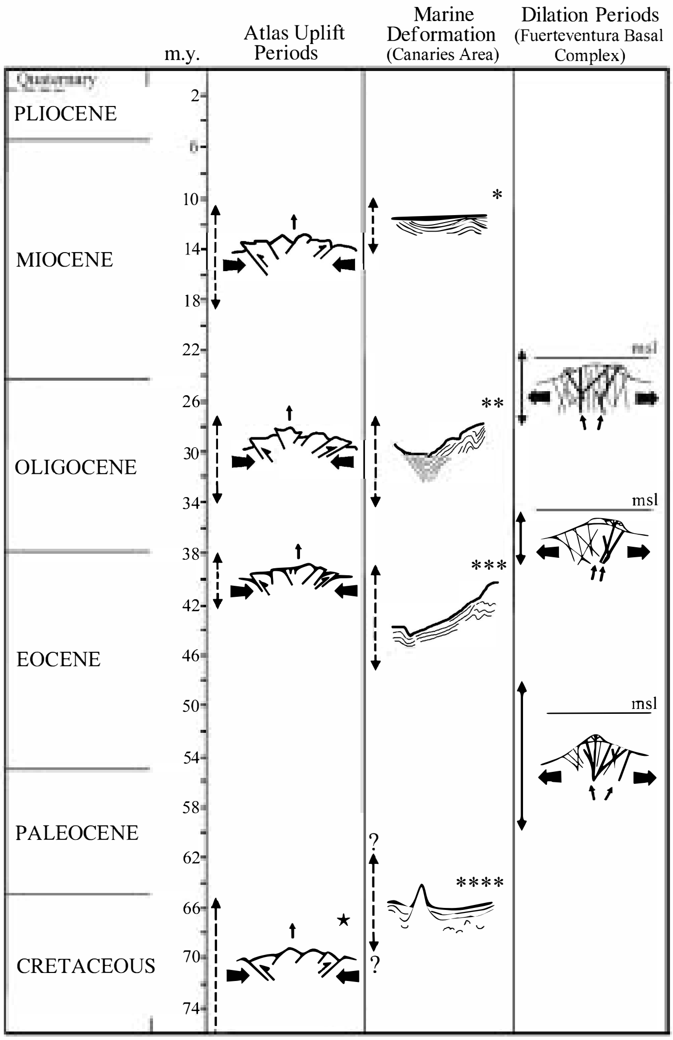

Fig. 9. A calendar of tectonic and magmatic events in the Atlas chain, the Canary Islands and the intervening Atlantic Ocean. Atlas uplift periods as cited in Uchupi et al. (1976), excepting (★) after Froitzheim et al. (1988). Marine deformations in the Canary area after: (*) McMaster and Lachance (1968); (**) Uchupi et al. (1976); (***) Summerhayes et al. (1971); (****) Dañobeitia and Collette (1989). The first three are coincident in time with erosional unconformities described by Hinz et al. (1982). Dilation periods in the Fuerteventura basal complex after Stillman (1987). Though based on real sections, sketches are only approximate renderings.

necessary to tap the magmas from the thermal anomaly, but with a more complicated geometry than originally proposed. (3) The islands' uplift is acknowledged as a real tectonic process in the archipelago, though it is proposed that the main movement is transcurrent instead of reverse.

Besides the Atlantic–European–Mediterranean rift system, the analogues to the process proposed are multiple:

- The mid-ocean ridge system. As shown for instance by Hofmann and White (1982) and Zhang and Tanimoto (1992) or Anderson et al. (1992), this planetary system works essentially by passive upwelling: the plates spread apart and material wells up at the ridge, much in the same way as the fossil Atlantic plume is drained through the fractures.
- The asthenosphere, frequently fed by mantle

plumes (e.g. Sleep, 1990) that supply hot, deep, mushroom-shaped material which spreads laterally in the upper mantle. Our Fig. 4 (a part of the Fig. 2 of Hoernle et al., 1995) clearly shows that the only hot material at typical asthenosphere depths below a large expanse of the central eastern Atlantic and northwestern Africa is the one supplied by the old plume.

- Many continental rifts, including classical examples such as the Late Palaeozoic eastern North America (Phipps, 1988) and Oslo rifts (Pedersen and van der Beek, 1994). Neither of them seem to have been associated with active plumes.
- Many problematic "hotspot chains", such as Samoa (Woodhead, 1992), the Marquesas (McNutt et al., 1989), Cook-Austral (McNutt et al., 1997), Fernando de Noronha (Gerlach et al., 1987), or the Cameroon line (e.g. Halliday et al., 1988; Lee et al., 1994). The Cameroon line, astride the ocean–continent boundary, is an excellent example of the limits of the assertion by Vink et al. (1984) on the difficulty ("mechanical impossibility" when cited by Carracedo et al. (1998) encountered by fractures on continental crust to propagate into oceanic crust. The Cameroon Line could be, moreover, the best known parallel to the "fossil plume" hypothesis. To explain the Pb, Nd and Sr systematics, Halliday et al. (1988) proposed that the Cameroon Line rocks are contaminated by the old St. Helena hotspot.
- Some "pure" hotspot volcanic groups, like the Cape Verde. The 5 Ma time gap (Gerlach et al., 1988) is a telltale sign of the tectonic forcing on the magmatism of this group proposed by Vogt (1974a), de Paepe et al. (1974), and Klerkx and de Paepe (1976), and documented by Williams et al. (1990).

The above analogues lend support to the view that lithospheric rupture is needed as much as a thermal perturbation for the onset of magmatism. This idea, advanced by Nicolas et al. (1994) for rifts, could be, as shown, of wider application. In the case of the Canary Islands, it explains most of the geological, geophysical and geochemical features of the archipelago, such as:

(1) The persistence of magmatic activity for a lengthy (>50 Ma) period.

(2) The diversity of geochemical reservoirs present in the Canary Islands magmas: the HIMU and PHEM components (and the slightly enriched $^{87}Sr/^{86}Sr$ ratio as well) would represent the original plume material, mixed with different proportions of lithospheric components in each new batch of magma.

(3) The absence of a clear gravity high and bathymetric swell, since there is no active mantle currents underneath the islands.

(4) The tectonic seismicity around the islands and the many structures noticeable in the seismic profiles.

(5) The multi-Ma gaps in magmatic activity, which would be a consequence of regional or local compressive stress fields.

(6) The seismic tomography data showing a cold lithosphere, but a mildly hot upper mantle under the archipelago.

(7) The diminishing volume of magmas erupted in each successive cycle: the fractures are draining a "fossil" magmatic source.

(8) The outstanding petrologic coincidences between the Canary Islands and the Atlas Mountains. This relationship was first noticed by Le Bas et al. (1986), but they considered both areas to be "too far apart" to be related. Now the regional mantle tomography has shown that the distance was not too large to sustain a common lineage.

(9) The islands uplift, including the tectonically tilted blocks evident in many islands, and which could be best interpreted as parts of flower structures. In the High Atlas, these tectonic forms measure up to 25 km wide (Laville and Piqué, 1992, and our Fig. 6), i.e. the approximate size of El Hierro, La Gomera, La Palma, or of the blocks defined (Marinoni and Pasquarè, 1994) as the uplifted units in Lanzarote. The submarine flower structures noticeable in the seismic sections are of the same order of magnitude (~10 km wide (Hinz et al., 1982, their Fig. 4). As for the vertical uplifts, they reach more than 1 km, which is again in the estimated range of tectonic island uplift.

6. Discussion

The main obstacle for the acceptance of a genetic relationship between the Canary Islands and the Atlas chain has been the lack of continuous faults connecting both areas. The plot of all seismic foci in the zone

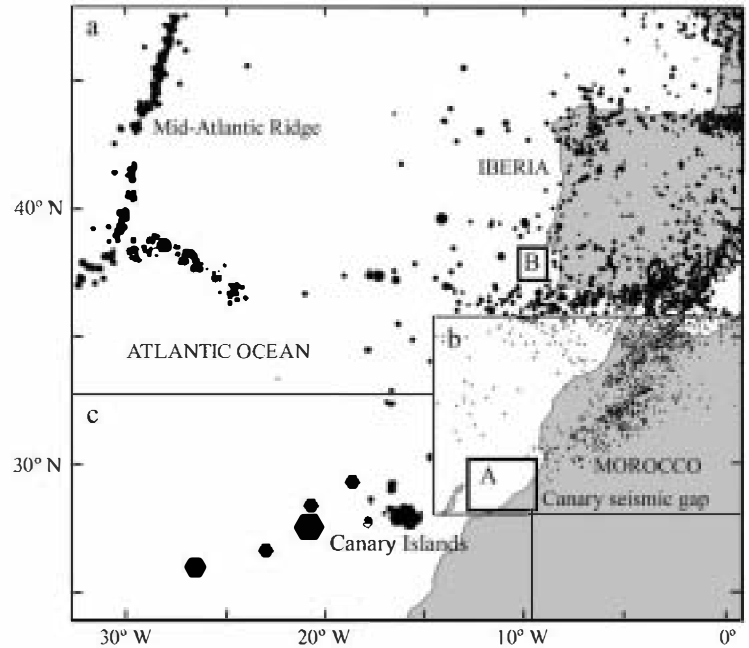

Fig. 10. Recent seismicity in the Canary Islands and surrounding areas. Since no author plots the African and Atlantic foci together, different sources have been used: (a) is from Andeweg et al. (1999); (b) from Medina and Cherkaoui (1991); and (c) from Wysession et al. (1995). Boxes indicate (A) the Canary Islands, and (B) the Lisbon seismic gaps. Both are proposed to be due to the unusual mass of sediments deposited on the continental slope and rise. In (a) and (c), the size of the signs correlates with seismic magnitude.

(Fig. 10) permits identification of an outstanding seismic gap (A) between the islands and the High Atlas chain. This seismic dead zone interrupts an otherwise continuous earthquake line extending from the Alborán Basin to a point in the Atlantic Ocean some 800 km WSW of the Canary line. We support the idea, first advanced by Medina and Cherkaoui (1991), that the cause of the gap is that the huge sedimentary mass deposited at this area (>12 km thick after Hinz et al. (1982, their Fig. 2)) absorbs by ductile flow (Bott, 1981) the stresses exerted on it, much the same as the gap in the Lisbon fault (Fig. 10b). In considering the feasibility of this idea, two points should be kept in mind: (1) that this sedimentary apron has experienced a severe strain, as highlighted by the abundant antiforms and several erosional and angular unconformities described in Section 3.5; and (2) that the tectonic seismicity reappears in the Canary Islands realm (Mezcua et al., 1992) *and* oceanwards (Medina and Cherkaoui, 1991; Wysession et al., 1995).

The seismic gap is also consistent with the absence of volcanic constructs between the Canary Islands and the Atlas Mountains, which could be explained as due to the lack of faults that could tap the thermal anomaly. The abundance of sediments in this area of the African continental shelf and slope would be a logic consequence (and a proof as well) of its working as a triple junction (Dewey and Burke, 1973; Weigel et al., 1982) during the Jurassic (see Fig. 5). A further trace of this old line can be noticed in a submarine canyon west of El Hierro (see Fig. 1A), the site of a 1959 $M =$ 6.2 earthquake (Medina and Cherkaoui, 1991).

The following points still warrant further analysis:

- Why do the islands show tectonic lineaments with such different azimuths? The sheeted dike units in the three outcropping basal complexes are, for instance, oriented N20E (Fuerteventura), N70E (La Gomera), and due North (La Palma). Can all be referred to a common stress field, as proposed by Stillman (1987)? The N–S strike of most dikes in La Palma basal complex is coincident with one important tectonic strike of the Atlas Mountains

(Deffontaines et al., 1992, their Fig. 6), and also with a seamount line 200 km west of La Palma (see Fig. 1b). All these data can be explained by the present compressive stress field created by the collision of the African and Eurasian plates. Unfortunately, we do not have other so clear frameworks for the stress situations prevailing in the Canary Islands area from the end of Mesozoic times on. In general, we ignore what relations did exist between the building of each individual construct and its structural lineaments.

- What is the real significance of the triple junctions defined by Navarro (1974) and Navarro and Farrujía (1989) at Tenerife and El Hierro, and only much later adopted by Carracedo (1994) and later references, in none of which he acknowledged the origin of the idea)? Wyss, who in 1980 described these *Mercedes* star-shaped rifts for Hawaii and Maui, the two youngest Hawaiian islands, conceded that Iceland rifts do not show this symmetric pattern because of the dominant stress field. The fact that most of the Canary Islands are not three-armed would be an additional proof that, like Iceland, they were built in the presence of regional stress fields. This conclusion applies to the shields (for instance, the radial dike pattern observed by Schmincke (1968) in Gran Canaria) and to the pre-shield stages as well. Staudigel et al. (1986) detected an all-radial (not three-armed) dike pattern superposed on the N–S tectonic one on the La Palma basal complex. The insistent efforts (Carracedo, 1994, 1996; Carracedo et al., 1998) to promote the three-armed geometry as fundamental for understanding the origin of the archipelago seem out of place to the present authors.
- What is the meaning of the reflector detected by Holik et al. (1991) north of the Canary Islands? Except for its stratigraphic position, it is similar to the Triassic–Jurassic volcanic layers left by the Central Atlantic super-plume (for instance, in the North American Atlantic coast (Kelemen and Holbrook, 1995) when the Atlantic opened.
- The Mio–Pliocene magmatic activity in the Atlas chain appears to propagate in two opposite ways: towards the north (Pliocene and Pleistocene volcanism in southern Spain) and towards the west (the progression of volcanism from the eastern towards the western Canary Islands). If this migration is real, what is its cause? Perhaps it is an effect of the rotation of the Maghreb subplate relative to the African plate (Brede et al., 1992); or simply (Anderson, 1999) a natural tendency, partly based on buttressing, of volcanoes to propagate into chains. One last (but important) open question on the geology of the Canary Islands.

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References

Abranches, M.C., Storetvedt, K.M., Serralheiro, A., Lovlie, R., 1990. The palaeomagnetic record of the Santiago volcanics (Republic of Cape Verde); multiphase magnetization and age consideration. Phys. Earth Planet. Inter. 64, 290–302.

Aït Brahim, L., Chotin, P., 1990. Oriental Moroccan Neogene volcanism and strike-slip faulting. J. Afr. Earth Sci. 11, 273–280.

Allègre, C.J., Hamelin, B., Dupré, B., 1984. Statistical analysis of isotopic ratios in MORB: the mantle blob cluster model and the convective regime of the mantle. Earth Planet. Sci. Lett. 71, 71–84.

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. J. Volcanol. Geotherm. Res. 44, 231–249.

Anderson, D.L., 1998. The scales of mantle convection. Tectonophysics 284, 1–17.

Anderson, D.L., 1999. A theory of the Earth: Hutton and Humpty Dumpty and Holmes. In: Craig, J.Y., Hull, J.H. (Eds.), James Hutton—Present and Future. Geol. Soc. London, Spec. Publ., 150, pp. 13–35.

Anderson, D.L., Tanimoto, T., Zhang, Y., 1992. Plate tectonics and hotspots: the third dimension. Science 256, 1645–1651.

Andeweg, B., De Vicente, G., Cloetingh, S., Giner, J., Muñoz, A., 1999. Local stress field and intraplate deformation in spatial and temporal interplay of regional stress sources. Tectonophysics 305, 153–164.

Anguita, F., García, L., Colombo, F., González, A., Vieira, R., 1991. Roque Nublo caldera: a new stratocone caldera in Gran Canaria, Canary Islands. J. Volcanol. Geotherm. Res. 47, 45–63.

Anguita, F., Hernán, F., 1975. A propagating fracture model versus a hot-spot origin for the Canary Islands. Earth Planet. Sci. Lett. 27, 11–19.

Araña, V., Ortiz, R., 1986. Marco geodinámico del volcanismo canario. An. Física, Vol. Esp. 82, 202–231.

Araña, V., Ortiz, R., 1991. The Canary Islands: Tectonics, magmatism and geodynamic framework. In: Kampunzu, A.B., Lubala, R.T. (Eds.), Magmatism in Extensional Structural Settings—the Phanerozoic African Plate, Springer, New York, pp. 209–249.

Balogh, K., Ahijado, A., Casillas, R., Fernández, C., 1999. Contributions to the chronology of the Basal Complex of Fuerteventura, Canary Islands. J. Volcanol. Geotherm. Res. 90, 81–101.

Banda, E., Dañobeitia, J.J., Suriñach, E., Ansorge, J., 1981. Features of crustal structure under the Canary Islands. Earth Planet. Sci. Lett. 55, 11–24.

Banda, E., Ranero, C.R., Dañobeitia, J.J., Rivero, A., 1992. Seismic boundaries of the eastern Central Atlantic Mesozoic crust from multichannel seismic data. Geol. Soc. Am. Bull. 104, 1340–1349.

Beauchamp, W., Allmendinger, R.W., Barazangi, M., Demnati, A., El Alji, M., Dahmani, M., 1999. Inversion tectonics and the evolution of the High Atlas Mountains, Morocco, based on a geological–geophysical transect. Tectonics 18, 163–184.

Berrahma, M., 1989. Études pétrologiques des laves récentes du massif du Siroua. PhD thesis, Université Laval, Québec, Canada, 234p.

Binot, F., Dresen, G., Stets, J., Wurster, P., 1986. Die Tizi-n'Test-Verwerfungszone im Hohen Atlas (Marokko). Geol. Rundsch. 75, 647–664.

Bosshard, E., MacFarlane, D.J., 1970. Crustal structure of the western Canary Islands from seismic refraction and gravity data. J. Geophys. Res. 75, 4901–4918.

Bott, M-H.P., 1981. Crustal doming and the mechanism of continental rifting. Tectonophysics 73, 1–8.

Bousquet, J.C., Montenat, C., 1974. Présence de décrochements NE–SW plio-quaternaires dans les Cordillères bétiques orientales (Espagne). Extension et signification générale. C. R. Acad. Sci. Paris 278, 2617–2620.

Brede, R., Hauptmann, M., Herbig, H.G., 1992. Plate tectonics and intracratonic mountain ranges in Morocco—the Mesozoic–Cenozoic development of the Central High Atlas and the Middle Atlas. Geol. Rundsch. 81, 127–141.

Briden, J.C., Gass, I.G., 1974. Plate movement and continental magmatism. Nature 248, 650–653.

Burke, K., 1996. The African plate. S. Afr. J. Geol. 99, 339–409.

Burke, K., Wilson, J.T., 1972. Is the African plate stationary? Nature 239, 387–390.

Canales, J.P., Dañobeitia, J.J., 1998. The Canary Islands swell: a coherence analysis of bathymetry. Geophys. J. Int. 132, 479–488.

Cantagrel, J.M., Fúster, J.M., Pin, C., Renaud, U., Ibarrola, E., 1993. Age Miocène inférieur des carbonatites de Fuerteventura (23 Ma: U–Pb zircon) et le magmatisme précoce d'une île océanique (îles Canary Islands). C. R. Acad. Sci. Paris 316, 1147–1153.

Caress, D.W., McNutt, M.K., Detrick, R.S., Mutter, J.C., 1995. Seismic imaging of hot-spot related crustal underplating beneath the Marquesas Islands. Nature 373, 600–603.

Carracedo, J.C., 1994. The Canary Islands: an example of structural control on the growth of large oceanic island volcanoes. J. Volcanol. Geotherm. Res. 60, 225–241.

Carracedo, J.C., 1996. Morphological and structural evolution of the western Canary Islands: hotspot-induced three-armed rifts or regional tectonic trends? J. Volcanol. Geotherm. Res. 72, 151–162.

Carracedo, J.C., Day, S., Guillou, H., Rodríguez, E., Canas, J.A., Pérez, F.J., 1998. Hotspot volcanism close to a passive continental margin. Geol. Mag. 135, 591–604.

Casillas, R., Ahijado, A., Hernández-Pacheco, A., 1994. Zonas de cizalla dúctil en el complejo basal de Fuerteventura. Geogaceta 15, 117–120.

Cendrero, A., 1969. The volcano-plutonic complex of La Gomera (Canary Islands). Bull. Volcanol. 34, 537–561.

Cherkaoui, T.E., Medina, F., Hatzfeld, D., 1991. The Agadir earthquake of February, 29, 1960. Examination of some of the parameters. In: Symp. on the seismicity, the seismotectonics and the seismic risk of the Ibero-maghrebian region. Publ. Inst. Geogr. Nac., vol. 8. Monografía, Madrid, pp. 130–146.

Choubert, G., Faure-Muret, A., 1962. Évolution du domaine atlasique marocain depuis les temps paléozoïques. Livre Mém. Paul Fallot, Soc. Géol. Fr. 1, 447–527.

Coello, J., Cantagrel, J.M., Hernán, F., Fúster, J.M., Ibarrola, E., Ancochea, E., Casquet, C., Jamond, C., Díaz, J.R., Cendrero, A., 1992. Evolution of the eastern volcanic ridge of the Canary Islands based on new K–Ar data. J. Volcanol. Geotherm. Res. 53, 251–274.

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. Geophys. J. R. Astron. Soc. 87, 815–868.

Cousens, B.L., Spera, F.J., Tilton, G.R., 1990. Isotopic patterns in silicic ignimbrites and lava flows of the Mogan and lower Fataga Formations, Gran Canaria, Canary Islands: temporal changes in mantle source composition. Earth Planet. Sci. Lett. 96, 319–335.

Cox, R.T., 1999. Hawaiian volcanic propagation and Hawaiian swell asymmetry: evidence of northwestward flow of the deep upper mantle. Tectonophysics 310, 69–79.

Craig, H., Lupton, J.E., 1976. Primordial neon, helium and hydrogen in oceanic basalts. Earth Planet. Sci. Lett. 31, 369–385.

Dañobeitia, J.J., Collette, B.J., 1989. Estudio mediante sísmica de reflexión de un grupo de estructuras submarinas situadas al norte y al sur del archipiélago canario. Acta Geol. Hisp. 24, 147–163.

Dañobeitia, J.J., Canales, J.P., Dehghani, G.A., 1994. An estimation of the elastic thickness of the lithosphere in the Canary Archipelago under admittance function. Geophys. Res. Lett. 21, 2649–2652.

Dash, B.P., Bosshard, E., 1969. Seismic and gravity investigations around the western Canary Islands. Earth Planet. Sci. Lett. 7, 169–177.

Davies, G.F., 1990. Mantle plumes, mantle stirring and hotspot chemistry. Earth Planet. Sci. Lett. 99, 94–109.

Deffontaines, B., Chotin, P., Aït Brahim, L., Rozanov, M., 1992. Investigation of active faults in Morocco using morphometric methods and drainage pattern analysis. Geol. Rundsch. 81, 199–210.

de Paepe, P., Klerkx, J., Hertogen, J., Plinke, P., 1974. Oceanic tholeiites on the Cape Verde Islands: petrochemical and geochemical evidence. Earth Planet. Sci. Lett. 22, 347–354.

de Sitter, L.U., de Sitter-Koomans, C.M., Heetveld, H., 1952. Les phonolites du Jebel Saghro (Maroc Occidental). Geol. Mijnb. 14, 267–276.

Dillon, W.P., 1974. Structure and development of the southern Moroccan continental shelf. Mar. Geol. 16, 121–143.

Duncan, R.A., 1981. Hotspots in the southern oceans - An absolute frame of reference for motion of the Gondwana continents. Tectonophysics 74, 29–42.

Fernández, C., Casillas, R., Ahijado, A., Perelló, V., Hernández-Pacheco, A., 1997. Shear zones as a result of intraplate tectonics in oceanic crust: The example of the Basal Complex of Fuerteventura (Canary Islands). J. Struct. Geol. 19, 41–57.

Filmer, P.E., McNutt, M.K., 1989. Geoid anomalies over the Canary Islands group. Mar. Geophys. Res. 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 alkali basalt. Earth Planet. Sci. Lett. 72, 23–38.

Fraissinet, C., Zouine, M., Morel, J.L., Poisson, A., Andrieux, J., Faure-Muret, A., 1988. Structural evolution of the southern and northern Central High Atlas in Paleogene and Mio–Pliocene times. In: Jacobshagen, V.H. (Ed.), The Atlas System of Morocco. Lecture Notes Earth Science, vol. 15. Springer, Berlin, pp. 273–291.

Froitzheim, N., Stets, J., Wurster, P., 1988. Aspects of western High Atlas tectonics. In: Jacobshagen, V.H. (Ed.), The Atlas System of Morocco. Lecture notes Earth Science, vol. 15. Springer, Berlin, pp. 219–244.

Fúster, J.M., 1975. Las Islas Canarias: un ejemplo de evolución temporal y espacial del vulcanismo oceánico. Est. Geol. 31, 439–463.

Fúster, J.M., Hernández-Pacheco, A., Muñoz, M., Rodríguez, E., García, L., 1968. Geology and volcanology of the Canary Islands: Gran Canaria. Inst. Lucas Mallada (CSIC), Madrid, 1–243.

Gerlach, D.C., Stormer, J.C., Mueller, P.A., 1987. Isotopic geochemistry of Fernando de Noronha. Earth Planet. Sci. Lett. 85, 129–144.

Gerlach, D.C., Cliff, R.A., Davies, G.R., Norry, M., Hodgson, N., 1988. Magma sources of the Cape Verdes Archipelago: isotopic and trace element constraints. Geoch. Cosmoch. Acta 52, 2979–2992.

Giese, P., Jacobshagen, V., 1992. Inversion tectonics of intracontinental ranges: High and Middle Atlas, Morocco. Geol. Rundsch. 81, 249–259.

Goldflam, P., Hinz, K., Weigel, W., Wissmann, G., 1980. Some features of the northwest African margin and Magnetic Quiet Zone. Philos. Trans. R. Soc. London A294, 87–96.

Gomez, F., Barazangi, M., Bensaid, M., 1996. Active tectonism in the intracontinental Middle Atlas Mountains of Morocco: synchronous crustal shortening and extension. J. Geol. Soc. London 153, 389–402.

Grand, S.P., 1994. Mantle shear structure beneath the Americas and surrounding seas. J. Geophys. Res. 99, 11 591–11 621.

Grevemeyer, I., 1999. Isostatic geoid anomalies over mid-plate swells in the central North Atlantic. J. Geodyn. 28, 41–50.

Grunau, H.R., Lehmer, 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). In: Progress in Geodynamics. R. Soc. Neth. Acad. Arts Sci., pp. 90–108.

Halliday, A.N., Dickin, A.P., Fallick, A.E., Fitton, J.G., 1988. Mantle dynamics: a Nd, Sr, Pb and O isotopic study of the Cameroon Line volcanic chain. J. Petrol. 29, 181–211.

Harding, T.P., 1985. Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion. Am. Assoc. Pet. Geol. Bull. 65, 582–600.

Harmand, C., Cantagrel, J.M., 1984. Le volcanism alcalin Tertiaire et Quaternaire du Moyen Atlas (Maroc): chronologie K/Ar et cadre géodynamique. J. Afr. Earth Sci. 2, 51–55.

Harmand, C., Moukadiri, A., 1986. Synchronisme entre tectonique compressive et volcanism alcalin: example de la province Quaternaire du Moyen Atlas (Maroc). Bull. Soc. Géol. Fr. 8, 595–603.

Hart, S.R., Hauri, E.H., Oschmann, L.A., Whitehead, J.A., 1992. Mantle plumes and entrainment: isotopic evidence. Science 256, 517–520.

Hausen, H., 1956. Contributions to the geology of Tenerife. Soc. Sci. Fenn. Commun. Phys.-Math. 18, 1–247.

Hausen, H., 1958. On the geology of Fuerteventura (Canary Islands). Soc. Sci. Fenn. Commun. Phys.-Math. 22, 1–211.

Hayes, D.E., Rabinowitz, P.D., 1975. Mesozoic magnetic lineations and the Magnetic Quiet Zone off northwest Africa. Earth Planet. Sci. Lett. 28, 105–115.

Herbig, H.G., 1988. Synsedimentary tectonics in the northern Middle Atlas (Morocco) during the Late Cretaceous and Tertiary. In: Jacobshagen, V.H. (Ed.), The Atlas System of Morocco. Lecture Notes Earth Science, vol. 15. Springer, Berlin, pp. 321–337.

Hinz, K., Dostmann, H., Fritsch, J., 1982. The continental margin of Morocco: seismic sequences, structural elements and geological development. In: von Rad, U., Hinz, K., Samthein, M., Seibold, E. (Eds.), Geology of the Northwest African Margin. Springer, Berlin, pp. 34–59.

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 Canary hotspot. J. Petrol. 34, 599–626.

Hoernle, K., Tilton, G.R., 1991. Sr–Nd–Pb isotope data for Fuerteventura (Canary Islands) basal complex and subaerial volcanics: applications to magma genesis and evolution. Schweiz. Mineral. Petrogr. Mitt. 71, 3–18.

Hoernle, K., Tilton, G., Schmincke, H.U., 1991. Sr–Nd–Pb isotopic evolution of Gran Canaria: evidence for shallow enriched mantle beneath the Canary Islands. Earth Planet. Sci. Lett. 106, 44–63.

Hoernle, K., Zhang, Y.S., Graham, D., 1995. Seismic and geochemical evidence for large-scale mantle upwelling beneath the eastern Atlantic and western and central Europe. Nature 374, 34–39.

Hofmann, A.W., White, W.M., 1982. Mantle plumes from ancient oceanic crust. Earth Planet. Sci. Lett. 57, 421–436.

Holik, J.S., Rabinowitz, P.D., Austin, J.A., 1991. Effects of Canary

hotspot volcanism on structure of oceanic crust off Morocco. J. Geophys. Res. 96, 12 039–12 067.
Ihinger, P.I., 1995. Mantle flow beneath the Pacific plate: evidence from seamount segments in the Hawaiian-Emperor chain. Am. J. Sci. 295, 1035–1057.
Jacobshagen, V.H., 1992. Major fracture zones of Morocco: the South Atlas fault and the TransAlborán fault systems. Geol. Rundsch. 81, 185–197.
Jacobshagen, V., Brede, R., Hauptmann, M., Heinitz, W., Zylka, R., 1988a. Structure and post-Palaeozoic evolution of the central High Atlas. In: Jacobshagen, V.H. (Ed.), The Atlas System of Morocco. Lecture Notes Earth Science, vol. 15. Springer, Berlin, pp. 245–271.
Jacobshagen, V., Görler, K., Giese, P., 1988b. Geodynamic evolution of the Atlas System (Morocco) in post-Palaeozoic times. In: Jacobshagen, V.H. (Ed.), The Atlas System of Morocco. Lecture Notes Earth Science, vol. 15. Springer, Berlin, pp. 481–499.
Jung, W.Y., Rabinowitz, P.D., 1986. Residual geoid anomalies of the north Atlantic ocean and their tectonic implications. J. Geophys. Res. 91, 10 383–10 396.
Kaneoka, I., Takaoka, N., 1980. Rare gas isotopes in Hawaiian ultramafic nodules and volcanic rocks: constraint on genetic relationships. Science 208, 1366–1368.
Kelemen, P.B., Holbrook, W.S., 1995. Origin of thick, high-velocity igneous crust along the U.S. east coast margin. J. Geophys. Res. 100, 10 077–10 094.
Kellogg, L.H., Wasserburg, G.J., 1990. The role of plumes in mantle helium fluxes. Earth Planet. Sci. Lett. 99, 276–289.
Khan, M.A., 1974. Dynamic implications of mantle hotspots. Nature 251, 596–597.
Klerkx, J., de Paepe, P., 1976. The main characteristics of the magmatism of the Cape Verde Islands. Ann. Soc. Géol. Belg. 99, 347–357.
Kurz, M.D., Jenkins, W.J., Hart, S.R., 1982. Helium isotopic systematics of oceanic islands and mantle heterogeneity. Nature 297, 43–47.
Lancelot, J.R., Allègre, C.J., 1974. Origin of carbonatite magma in the light of the Pb–U–Th isotope system. Earth Planet. Sci. Lett. 22, 233–238.
Laville, E., Piqué, A., 1992. Jurassic penetrative deformation and Cenozoic uplift in the Central High Atlas (Morocco): a tectonic model. Structural and orogenic inversions. Geol. Rundsch. 81, 157–170.
Le Bas, M.J., Rex, D.C., Stillman, C.J., 1986. The early magmatic chronology of Fuerteventura, Canary Islands. Geol. Mag. 123, 287–298.
Le Pichon, X., Fox, P.J., 1971. Marginal offsets, fracture zones and the early opening of the North Atlantic. J. Geophys. Res. 76, 6294–6308.
Lee, C.W., Burgess, C.J., 1978. Sedimentation and tectonic controls in the Early Jurassic Central High Atlas trough, Morocco. Geol. Soc. Am. Bull. 89, 1199–1204.
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 Planet. Sci. Lett. 123, 119–138.
Lindwall, D.A., 1988. A two-dimensional seismic investigation of crustal structure under the Hawaiian Islands near Oahu and Kauai. J. Geophys. Res. 92, 13 687–13 707.
MacFarlane, D.J., Ridley, W.I., 1969. An interpretation of gravity data for Lanzarote, Canary Islands. Earth Planet. Sci. Lett. 6, 431–436.
Marinoni, L.B., Pasquarè, G., 1994. Tectonic evolution of the emergent part of a volcanic ocean island: Lanzarote, Canary Islands. Tectonophysics 239, 111–135.
Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., De Min, A., 1999. Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. Science 284, 616–618.
Mattauer, M., Tapponnier, P., Proust, F., 1977. Sur les mécanismes de formation des chaînes intracontinentales. L'exemple des chaînes atlasiques du Maroc. Bull. Soc. Géol. Fr. 19, 521–526.
May, P.R., 1971. Pattern of Triassic–Jurassic diabase dikes around the North Atlantic in the context of the predrift position of the continents. Geol. Soc. Am. Bull. 82, 1285–1292.
McKenzie, D., Bickle, M.J., 1988. The volume and composition of melt generated by extension of the lithosphere. J. Petrol. 29, 625–679.
McMaster, R.L., Lachance, T.P., 1968. Seismic reflectivity studies on northwestern African continental shelf: Strait of Gibraltar to Mauritania. Am. Assoc. Pet. Geol. Bull. 52, 2387–2395.
McNutt, M.K., 1988. Thermal and mechanical properties of the Cape Verde Rise. J. Geophys. Res. 93, 2784–2794.
McNutt, M.K., Fischer, K., Kruse, S., Natland, J., 1989. The origin of the Marquesas fracture zone ridge and its implications for the nature of hot spots. Earth Planet. Sci. Lett. 91, 381–393.
McNutt, M.K., Caress, D.W., Reynolds, J., Jordahl, K.A., Duncan, R.A., 1997. Failure of plume theory to explain midplate volcanism in the southern Austral islands. Nature 389, 479–482.
Medina, F., Cherkaoui, T., 1991. Focal mechanisms of the Atlas earthquakes, and tectonic implications. Geol. Rundsch. 80, 639–648.
Menvielle, M., Le Mouël, J.L., 1985. Existence d'une anomalie de conductivité dans le Haut Atlas marocain et concentration des courants telluriques à l'échelle régionale. Bull. Soc. Géol. Fr. 8, 553–558.
Mezcua, J., Buforn, E., Udías, A., Rueda, J., 1992. Seismotectonics of the Canary Islands. Tectonophysics 208, 447–452.
Michard, A., Westphal, M., Bossert, A., Hamzeh, R., 1975. Tectonique de blocs dans le socle Atlaso-Mésétien du Maroc; une nouvelle interprétation des données géologiques et paléomagnétiques. Earth Planet. Sci. Lett. 24, 363–368.
Minster, W.J., Jordan, T.H., 1978. Present-day plate motions. J. Geophys. Res. 83, 5331–5354.
Monnereau, M., Cazenave, A., 1990. Depth and geoid anomalies over volcanic hotspot swells: a global survey. J. Geophys. Res. 95, 15 429–15 438.
Moreira, M., Doucelance, R., Kurz, M.D., Dupré, B., Allègre, J.C., 1999. Helium and lead isotope geochemistry of the Azores archipelago. Earth Planet. Sci. Lett. 169, 189–205.
Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, 42–43.
Morgan, W.J., 1983. Hotspot tracks and the early rifting of the Atlantic. Tectonophysics 94, 123–139.

Muñoz, M., Sagredo, J., Rincón, P.J., Vegas, R., 1997. Emplazamiento en una zona de cizalla dúctil-frágil transtensiva para el plutón de Pájara, Fuerteventura, Islas Canarias. Geogaceta 21, 171–174.

Navarro, J.M., 1974. Estructura geológica de la isla de Tenerife y su influencia sobre la hidrogeología. Actas del I Congreso Internacional sobre Hidrología en Islas Volcánicas, Lanzarote, 13 pp.

Navarro, J.M., Farrujía, I., 1989. Bases para el planeamiento hidrológico insular: aspectos geológicos e hidrogeológicos. Plan Hidrológico Insular de Tenerife. Cabildo Insular de Tenerife, Sección de Planificación Hidráulica, 135 pp.

Neumann, E.R., Wulff-Pedersen, E., Johnsen, K., Andersen, T., Krogh, E., 1995. Petrogenesis of spinel harzburgite and dunite suite xenoliths from Lanzarote, eastern Canary Islands: implications for the upper mantle. Lithos 35, 83–107.

Nicolas, A., Achauer, U., Daignieres, M., 1994. Rift initiation by lithospheric rupture. Earth Planet. Sci. Lett. 123, 281–298.

O'Connor, J.M., Stoffers, P., van den Bogaard, P., McWilliams, M., 1999. First seamount age evidence for significantly slower African plate motion since 19 to 30 Ma. Earth Planet. Sci. Lett. 171, 575–589.

Olsen, P.E., Schlische, R.W., 1990. Transtensional arm of the early Mesozoic Fundy rift basin: Penecontemporaneous faulting and sedimentation. Geology 18, 695–698.

Ovchinnikova, G.V., Belyatskii, B.V., Vasil'eva, I.M., Levskii, L.K., Grachev, A.F., Araña, V., Mitchavila, J., 1995. Sr–Nd–Pb isotope characteristics of the mantle sources of basalts from the Canary Islands. Petrology 3, 172–182.

Oyarzun, R., Doblas, M., López, J., Cebriá, J.M., 1997. Opening of the central Atlantic and asymmetric mantle upwelling phenomena: implications for long-lived magmatism in western North Africa and Europe. Geology 25, 727–730.

Pedersen, T., van der Beek, P., 1994. Extension and magmatism in the Oslo rift, southeast Norway: no sign of a mantle plume. Earth Planet. Sci. Lett. 123, 317–329.

Pérez, N.M., Wakita, H., Nakai, S., Sano, Y., Williams, S.N., 1994. ^{3}He/^{4}He isotopic ratios in volcanic hydrothermal discharges from the Canary Islands, Spain: implications on the origin of the volcanic activity. Mineral. Mag. 58A, 709–710.

Phipps, S.P., 1988. Deep rifts sources for alkaline intraplate magmatism in eastern North America. Nature 334, 27–31.

Piqué, A., Le Roy, P., Amrhar, M., 1998. Transtensive synsedimentary tectonics associated with ocean opening: the Essaouira-Agadir segment of the Moroccan Atlantic margin. J. Geol. Soc. London 155, 913–928.

Proust, F., Petit, J.P., Tapponnier, P., 1977. L'accident du Tizin'Testet le rôle des décrochements dans la tectonique du Haut Atlas occidental (Maroc). Bull. Soc. Géol. Fr. 19, 541–551.

Robertson, A.H.F., Bernoulli, D., 1982. Stratigraphy, facies, and significance of Late Mesozoic and Early Tertiary sedimentary rocks of Fuerteventura (Canary Islands) and Maio (Cape Verde Islands). In: von Rad, U., Hinz, K., Samthein, M., Seibold, E. (Eds.), Geology of the Northwest African Continental Margin. Springer, Berlin, pp. 498–525.

Robertson, A.H.F., Stillman, C.J., 1979. Submarine volcanic and associated sedimentary rocks of the Fuerteventura Basal Complex, Canary Islands. Geol. Mag. 116, 203–214.

Roeser, H.A., 1982. Magnetic anomalies in the Magnetic Quiet Zone off Morocco. In: von Rad, U., Hinz, K., Sarnthein, M., Seibold, E. (Eds.), Geology of the Northwest African Continental Margin. Springer, Berlin, pp. 61–68.

Roest, W.R., Dañobeitia, J.J., Verhoef, J., Collette, B.J., 1992. Magnetic anomalies in the Canary Basin and the Mesozoic evolution of the central north Atlantic. Mar. Geophys. Res. 14, 1–24.

Russo, P., Russo, L., 1934. Le grand accident sud-atlasien. Bull. Soc. Géol. Fr. 5, 375–384.

Saadallah, A., Belhaï, D., Djellit, H., Seddik, N., 1996. Coulissage dextre entre zones internes et externe des Maghrébides, et structuration en fleur de la dorsale calcaire du Djurdura (Algérie). Geodyn. Acta 9, 177–188.

Sandwell, D.T., MacKenzie, K.R., 1989. Geoid height versus topography for oceanic plateaus and swells. J. Geophys. Res. 94, 7403–7418.

Sanz de Galdeano, C., 1990. La prolongación hacia el sur de las fosas y desgarres del norte y centro de Europa: una propuesta de interpretación. Rev. Soc. Geol. Esp. 3, 231–241.

Schmincke, H.U., 1968. Faulting versus erosion and the reconstruction of the Mid-Miocene shield volcano of Gran Canaria. Geol. Mitt. 8, 23–50.

Schmincke, H.U., 1973. Magmatic evolution and tectonic regime in the Canary, Madeira and Azores islands groups. Geol. Soc. Am. Bull. 84, 633–648.

Schmincke, H.U., 1976. The geology of the Canary Islands. In: Kunkel, G. (Ed.), Biogeography and Ecology of the Canary Islands. Junk, pp. 67–184.

Schmincke, H.U., 1979. Age and crustal structure of the Canary Islands. A discussion. J. Geophys. 46, 217–224.

Schmincke, H.U., 1982. Volcanic and chemical evolution of the Canary Islands. In: von Rad, U., Hinz, K., Samthein, M., Seibold, E. (Eds.), Geology of the Northwest African Margin. Springer, Berlin, pp. 273–306.

Schmincke, H.U., Klügel, A., Hansteen, T.H., Hoernle, K., van den Bogaard, P., 1998. Samples from the Jurassic ocean crust beneath Gran Canaria, La Palma and Lanzarote (Canary Islands). Earth Planet. Sci. Lett. 163, 343–360.

Schwartz, G., Wigger, P.J., 1988. Geophysical studies of the Earth's crust and upper mantle in the Atlas System of Morocco. In: Jacobshagen, V.H. (Ed.), The Atlas System of Morocco. Lecture Notes Earth Science, vol. 15. Springer, Berlin, pp. 339–357.

Schwartz, G., Mehl, H.G., Ramdani, F., Rath, V., 1992. Electrical resistivity structure of the eastern Moroccan Atlas System and its tectonic implications. Geol. Rundsch. 81, 221–235.

Seber, D., Barazangi, M., Tadili, B.A., Ramdani, M., Ibenbrahim, A., Ben Sari, D., 1996. Three-dimensional upper mantle structure beneath the intraplate Atlas and interplate Rif Mountains of Morocco. J. Geophys. Res. 101, 3125–3138.

Sleep, N.H., 1990. Hotspots and mantle plumes: some phenomenology. J. Geophys. Res. 95, 6715–6736.

Socías, I., Mezcua, J., 1996. Levantamiento aeromagnético del archipiélago canario. Instituto Geográfico Nacional, Publ. Técn., Madrid 35, 1–28.

Staudigel, H., Schmincke, H.U., 1984. The Pliocene seamount

series of La Palma (Canary Islands). J. Geophys. Res. 89, 11 195–11 215.
Staudigel, H., Féraud, G., Giannerini, G., 1986. The history of intrusive activity on the island of La Palma (Canary Islands). J. Volcanol. Geotherm. Res. 27, 299–322.
Steiner, M.B., 1975. Mesozoic apparent polar wander and Atlantic plate tectonics. Nature 254, 107–109.
Steiner, C., Hobson, A., Favre, P., Stampfli, G.M., Hernandez, J., 1998. Mesozoic sequence of Fuerteventura (Canary Islands): witness of Early Jurassic sea-floor spreading in the central Atlantic. Geol. Soc. Am. Bull. 110, 1304–1317.
Stets, J., Wurster, P., 1982. Atlas and Atlantic—structural relations. In: von Rad, U., Hinz, K., Samthein, M., Seibold, E. (Eds.), Geology of the Northwest African Continental Margin. Springer, Berlin, pp. 69–85.
Stillman, C.J., 1987. A Canary Islands dyke swarm: Implications for the formation of oceanic islands by extensional fissural volcanism. In: Halls, H.C., Fahrig, W.F. (Eds.), Mafic Dyke Swarms. Geol. Assoc. Can. Sp. Pap., 34, 243–255.
Summerhayes, C.P., Nutter, A.H., Tooms, J.S., 1971. Geological structure and development of the continental margin of northwest Africa. Mar. Geol. 11, 1–25.
Uchupi, E., Emery, K.O., Bowin, C.O., Phillips, J.E., 1976. Continental margin off western Africa: Senegal to Portugal. Am. Assoc. Pet. Bull. 60, 809–878.
Vink, G.E., Morgan, W.J., Zhao, W.L., 1984. Preferential rifting of continents: a source of displaced terrains. J. Geophys. Res. 89, 10 072–10 076.
Vogt, P.R., 1974a. Volcano spacing fractures and thickness of the lithosphere. Earth Planet. Sci. Lett. 21, 235–252.
Vogt, P.R., 1974b. Volcano height and plate thicknesses. Earth Planet. Sci. Lett. 23, 337–348.
Watkins, J.S., Hoppe, K.W., 1979. Seismic reflection reconnaissance of the Atlantic margin of Morocco. In: Talwani, M., Hays, W., Ryan, W.B.F. (Eds.), Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment. Am. Geophys. Union, Washington, pp. 205–217.
Watts, A.B., 1994. Crustal structure, gravity anomalies and flexure of the lithosphere in the vicinity of the Canary Islands. Geophys. J. Int. 119, 648–666.
Watts, A.B., Peirce, C., Collier, J., Dalwood, R., Canales, J.P., Henstock, T.J., 1997. A seismic study of lithospheric flexure in the vicinity of Tenerife, Canary Islands. Earth Planet. Sci. Lett. 146, 431–447.
Weigel, W., Goldflam, P., Hinz, K., 1997. The crustal structure of the Conception Bank. Mar. Geophys. Res. 3, 381–392.
Weigel, W., Wissmann, G., Goldflam, P., 1982. Deep seismic structure (Mauretania and central Morocco). In: von Rad, U., Hinz, K., Samthein, M., Seibold, E. (Eds.), Geology of the NW African Continental Margin. Springer, Heidelberg, pp. 132–159.
White, W.M., McBirney, A.R., Duncan, R.A., 1993. Petrology and geochemistry of the Galapagos Islands: Portrait of a pathological mantle plume. J. Geophys. Res. 98, 3–19 563.
Wigger, P., Asch, G., Giese, P., Heinsohn, W.D., El Alami, S.O., Ramdani, F., 1992. Crustal structure along a traverse across the Middle and High Atlas Mountains derived from seismic refraction studies. Geol. Rundsch. 81, 237–248.
Williams, C.A., Hill, I.A., Young, R., White, R.S., 1990. Fracture zones across the Cape Verde Rise, NE Atlantic. J. Geol. Soc. London 147, 851–857.
Wilson, J.T., 1963. A possible origin of the Hawaiian Islands. Can. J. Phys. 41, 863–870.
Wilson, M., 1997. Thermal evolution of the central Atlantic passive margins: Continental break-up above a Mesozoic super-plume. J. Geol. Soc. London 154, 491–495.
Woodhead, J.D., 1992. Temporal geochemical evolution in oceanic intra-plate volcanics: a case study from the Marquesas (French Polynesia) and comparison with other hotspots. Contrib. Mineral. Petrol. 111, 458–467.
Wyss, M., 1980. Hawaiian rifts and recent Icelandic volcanism: expressions of plume generated radial stress fields. J. Geophys. 47, 19–22.
Wysession, M.E., Wilson, J., Bartkó, L., Sakata, R., 1995. Intraplate seismicity in the Atlantic Ocean basin: a teleseismic catalog. Bull. Seismol. Soc. Am. 85, 755–774.
Ye, S., Canales, J.P., Rihm, R., Dañobeitia, J.J., Gallart, J., 1999. A crustal transect through the northern and northeastern part of the volcanic edifice of Gran Canaria, Canary Islands. J. Geodyn. 28, 3–26.
Zhang, Y.S., Tanimoto, T., 1992. Ridges, hotspots and their interaction as observed in seismic velocity maps. Nature 355, 45–49.