Mar Geophys Res (2006) 27:201–215
DOI 10.1007/s11001-006-9000-7

ORIGINAL PAPER

Linking the Canary and Cape-Verde Hot-Spots, Northwest Africa

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Received: 9 August 2004 / Accepted: 27 March 2006 / Published online: 26 September 2006

Abstract The Canary and Cape-Verde archipelagos are two groups of volcanic islands often cited as case examples of the surface expression of two distinct hot-spot plumes. However, several considerations that we enumerate suggest a link between the two archipelagos. Using seismic profiles we describe a continuous morphological basement ridge that exists between the two archipelagos. We then examine the stratigraphic record available from field data on Fuerteventura Island (Canary) and Maio Island (Cape-Verde) and from a few Deep Sea Drilling Project (DSDP) holes. The geological history of these volcanic islands is very similar since the formation of their oceanic basement during the Late Jurassic. They share the same and synchronious sedimentary evolution (subsidence, uplift and emersion) as well as very similar timing of volcanism and deformation. The two distinct hot-spots model does not appear adapted to account for the formation of these structures as it ignores the existence of the ridge, as well as most of the geological coincidences. By describing the coinciding geological incidents, we argue that it is misleading to treat these two regions apart.

Keywords Canary · Cape-Verde · Fuerteventura · Hot-spots · Maio

Introduction

The Canary and Cape-Verde archipelagos are two groups of volcanic islands located 1400 km apart along the African margin of the Central Atlantic Ocean (Fig. 1). They are often cited as case examples of the surface expression of two distinct hot-spot plumes. Their distribution does not define a line, as much oceanic islands of the Pacific Ocean do, but a cluster. This is considered as an indication of the steadiness of the African plate in the hot-spot reference frame (Burke and Wilson 1972).

These two archipelagos, probably because they are emerging, captivated the attention of the geologists. However they are not isolated as several other volcanic masses, mostly submarine, are found offshore Africa between Gibraltar Strait and the Gulf of Guinea, among which, from North to South are Dacia Seamounts, Salvage Islands, Saharan Seamounts, Tropic Seamount, Senghor Seamount (Fig. 1). Most of the studies concentrated on the late Tertiary evolution, when most of the exposed volcanic material was set up.

Robertson and Bernoulli (1982) proposed a synthesis on the region, with an attempt to compare the Cape-Verde and Canary geological events. Le Bas et al. (1986) later emphasised their similar magmatic history. But at that time the chronological data were lacking that would have encouraged further comparison. A genetic link between the two volcanic archipelagos has thus never been seriously considered. The idea that each archipelago was constructed from the volcanic products due to two distinct mantle plumes (Morgan 1971, 1983; Burke and Wilson 1972; Courtney and White 1986; Anguita and Hernan 2000) predominated, supported by their distance and the absence of identified structure between the two archipelagos.

However, stratigraphic studies show the islands, either from the Canary or the Cape-Verde Archipel, have recorded a very similar and synchronic geological

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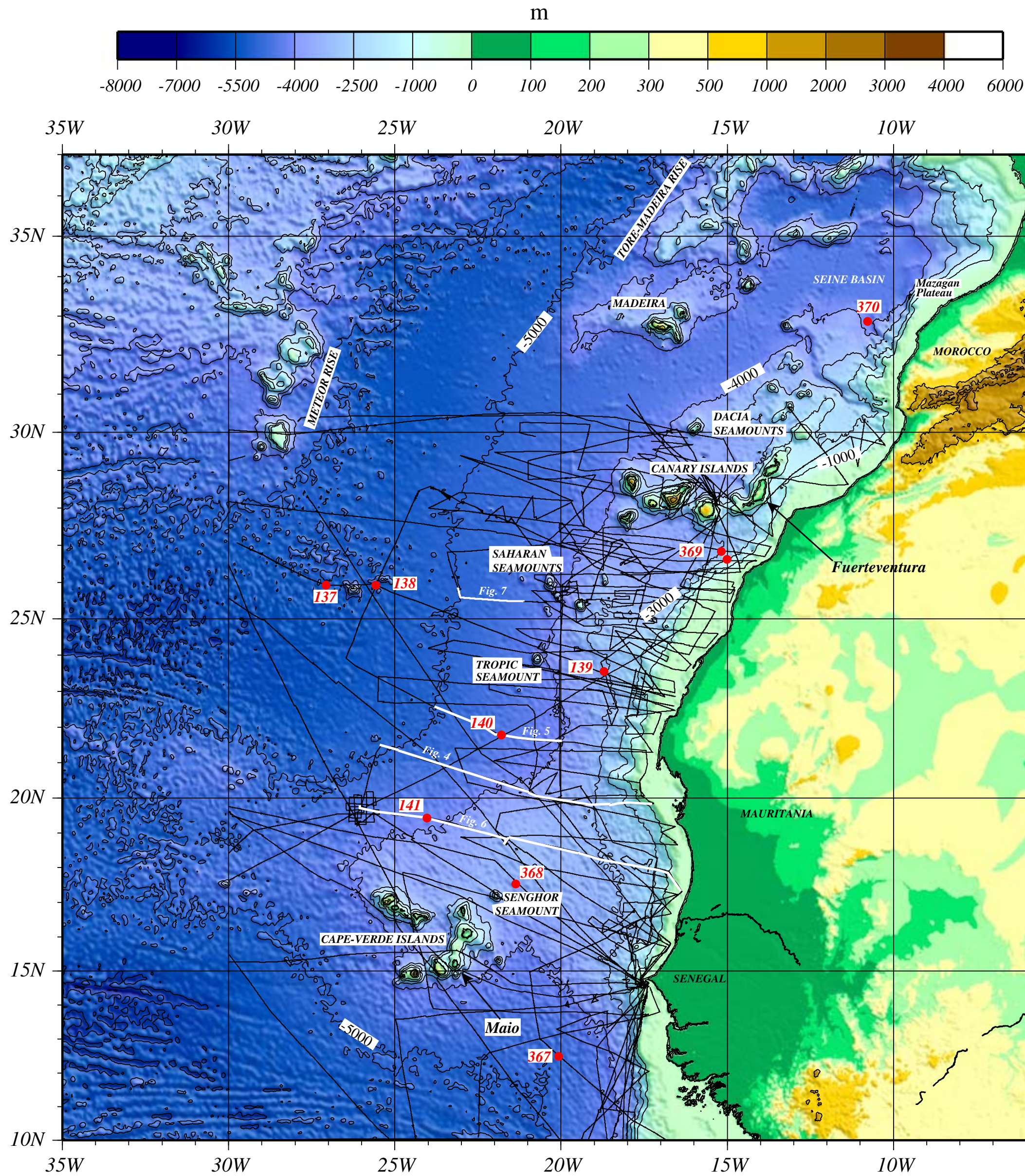

Fig. 1 General bathymetric and situation map (from Gibraltar to the Sierra Leone) showing the reflection seismic data and the DSDP holes used in this study

evolution. It is worth noting that both island groups surprisingly have had their basement uplifted to the surface before the main volcanic phases. Additionally the basement in the studied area presents an unexpected bulge that runs from the Canary to the Cape-Verde Islands (Olivet et al. 1984). When followed from the open sea towards the continent, the basement sinks progressively, according to the subsidence law of the oceanic lithosphere. Though, approaching the African coast but well before the awaited continental margin slope, it rises and forms a long and narrow bulge instead of keeping deepening progressively. Though almost totally hidden by the sedimentary blanket, this basement bulge is very large. Its size, elevation and extension, is comparable to that of todays nearby North-African Atlas.

We then decided to carry further forward the comparison between the two archipelagos, paying particular attention to the early stages of the geological evolution and keeping in mind the existence between them of this anomaly in the basement. We were encouraged in this work by recent chronological data that emphasize the synchronic evolution of the two archipelagos.

We started from structural analysis, added to new chronological data and field relationships that have been published since the work of Robertson and Bernouilli (1982) and that of Le Bas et al. (1986). The work exposed in this paper contains a bibliographic review, and an examination of existing seismic profiles. Similarly to the work of Robertson and Bernoulli (1982) it attempts to draw a homogeneous synthesis of the geological history over the whole region from the Canary Islands to the Cape-Verde Archipelago.

Using existing seismic profiles we first describe the continuous morphological basement ridge that does exist along the margin and that links the two archipelagos. We then examine the stratigraphic record available from field data on Fuerteventura Island (Canary) and Maio Island (Cape-Verde) and from a few Deep Sea Drilling Project (DSDP) holes. In the last part of our paper we emphasise the similarities of geological evolution recorded by the whole region since the Mesozoic and discuss the consequences.

Margin morphology

General morphology of the Central Atlantic African margin

The margin along the Atlantic coast of Northwest Africa is a passive margin. It extends from the Gibraltar Strait to the Gulf of Guinea, and presents a narrow continental plateau (Fig. 1). Three major segments can be distinguished according to the width of the marginal rise. A first short segment to the north is characterised by a steep slope and by the almost absence of a rise, the deep Seine abyssal plain lying directly at the foot of the slope. To the South it extends down to the Mazagan Cape. The second segment extends from North of the Dacia Seamounts, (North of- and prolonging the Canary Islands) to the Cape-Verde Islands. At the foot of its slope, the margin has a much wider rise. Its edge, that can tentatively be followed along the 4000 m bathymetric line, lies noticeably far from the shoreline. Along the last segment, to the south of the Cape-Verde archipelago, the margin becomes narrow again and passes, south of the Sierra Leone rise, to the transform margin of the Gulf of Guinea.

Though tenuous, WNW-ESE transform faults are the most obvious structures enlightened by the examination of both the bathymetry (Fig. 1) and free air gravity anomalies (Fig. 2) over the Central Atlantic African margin (CAAM). Some of the volcanic islands and aprons alignments and their bordering morphologic escarpment, like the western Canary Islands or the western Cape-Verde Islands, are parallel to the direction of those transform faults often considered as oceanic lithosphere flow lines. No other major structuration direction can be depicted except the margin parallel aprons and islands lines of the Torre-Madeira rise, of the eastern Canary Islands (Fuerteventura, Lanzarote) and of the eastern Cape-Verde Islands (Maio, Boa-Vista, Sal).

The study reported in this paper focused on the central Canary–Cape-Verde segment that shows significant volumes of Cenozoic extrusive material. Most obvious expression of this volcanism are the Canary and Cape-Verde volcanic islands that grew on a late Jurassic to early Cretaceous oceanic crust (Hayes and Rabinowitz 1975; Klitgord and Schouten 1986; Williams et al. 1990; Roest et al. 1992; Schminke et al. 1998). But other volcanic aprons exist, like the Dacia seamounts, 31° latitude North, and the Saharan seamounts around 26° latitude North and other isolated seamounts. Compared to other margins of the same age, the sea bottom all along this margin is anomalously shallow across a ca. 500 km wide band. It culminates at the Cape-Verde swell upon which the Cape-Verde Islands are superimposed.

The basement bulge along the Canary–Cape-Verde segment

From the African shore toward the West or Northwest the deepening of the seafloor is progressive and regular (Fig. 1). Nevertheless examination of already published single trace seismic (Uchupi et al. 1974, 1976) indicates the presence of a long basement bulge, parallel to the shoreline, levelled and therefore hidden by the sedimentary infilling. No clear and widespread unconformity, associated to this bulge, has been detected on the seismic profiles.

The outline of the basement bulge (Fig. 3) is primarily deduced from the basement depths and slopes we measured along the seismic profiles. Additionaly, it can be followed on a basement map calculated by subtracting the thickness of sediments coming from the 5 mn *digital total sediment thickness database for the world's oceans and marginal seas*, compiled by the National Geophysical Data Center (NGDC), from the bathymetry (Fig. 4).

The morphologic axis of the bulge passes through the Canary and Cap-Verde Archipelagos as well as through the Dacia and Saharan Seamounts. It marks a shift at its passage through the Kane Fracture Zone.

The top of the basement bulge is generally found shallower than 7 s two-way travel time (TWT) below

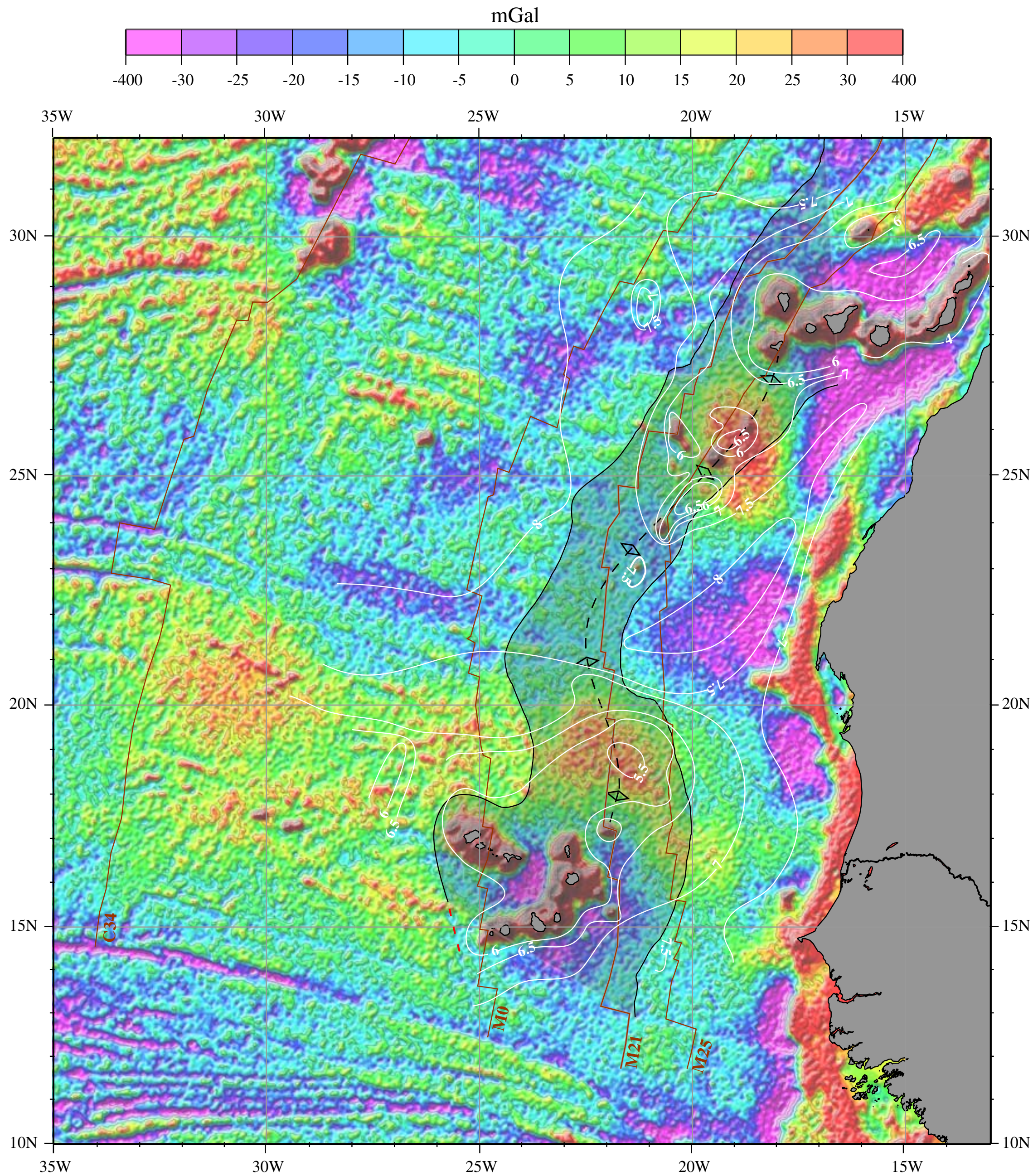

Fig. 2 Free air gravity anomaly map. Magnetic isochrones (black lines) M25, M21, M0 and A34 have been indicated as well as the outlines of the basement bulge in grey. White lines indicate depth to basement in seconds of reflection time. See text and Fig. 3 for explanations

the sea surface. Yet variations exist along strike. The bulge crest is sometime found very shallow, as in the neighbourhood of the volcanic seamounts. Conversely, north of its passage through the Kane Fracture Zone, around 21–22° latitude North, the basement reaches depths close to 8 s TWT (Fig. 3). Actually, additional observations along a section perpendicular to the shore indicate that the whole crust portion, from sea-bottom to basement is found deeper along a narrow band at this latitude located just North of the prolongation of the Kane Fracture Zone. From the African shore to about 35° W the Kane Fracture Zone marks the southern limit of a relatively deeper zone.

The interface between the basement and the sediments, as seen with reflection seismic, presents interesting variations of texture. These variations are contrasted enough to distinguish several different textural domains. We draw a textural map of the

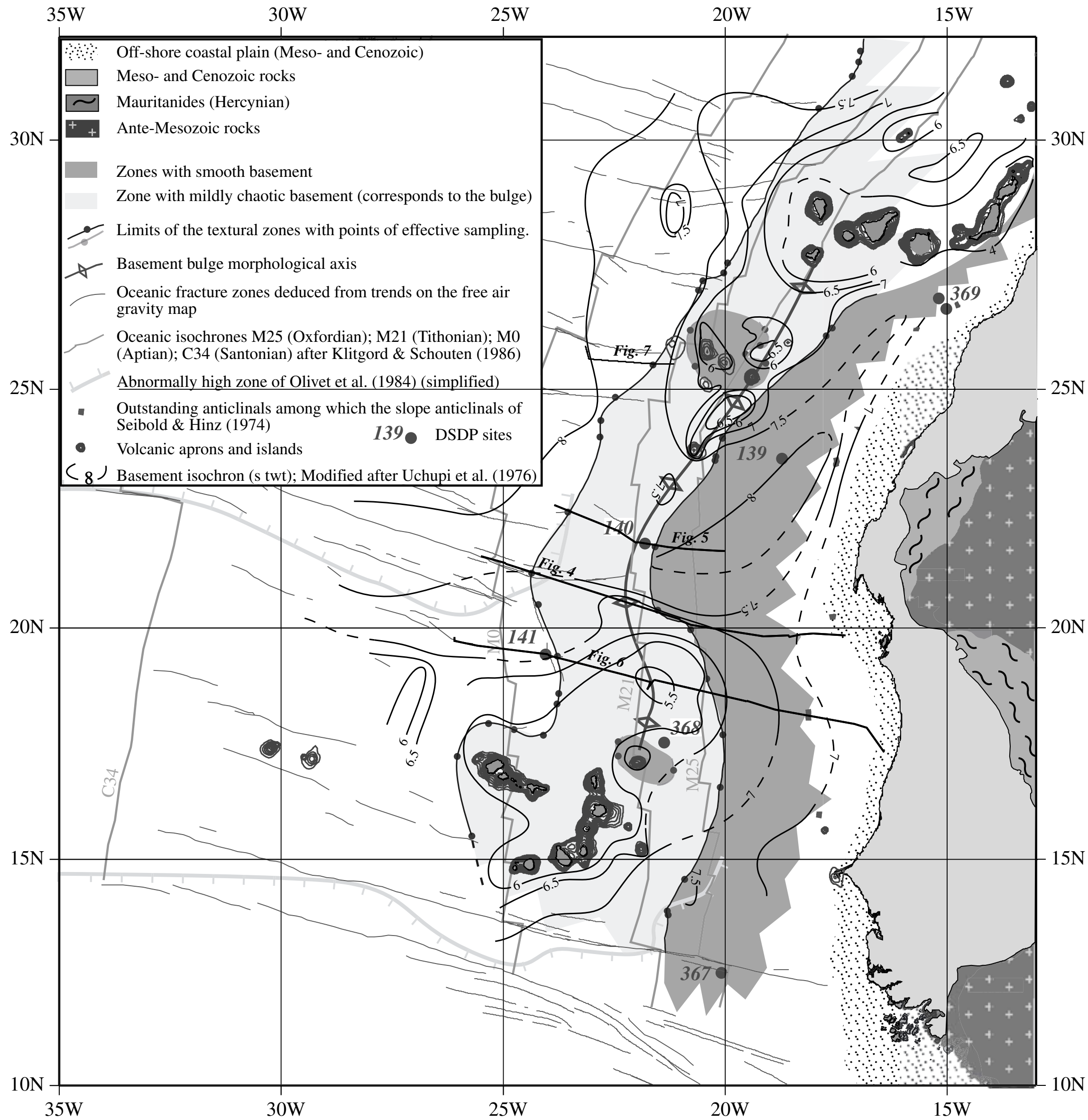

Fig. 3 Structural map and localisation of the basement bulge based on seismic-reflection

basement from Canary to Cape-Verde Islands in spite of the low density of the data that reach the basement (Fig. 3). The resulting textural limits show some coincidences with the outlines of the basement bulge.

The reflective texture of the basement can be followed on the line drawings published by Uchupi et al. (1974, 1976), as well as on Lamont and on recent unpublished DAKHLA multichannel seismic profiles (Figs. 5–8). The bulge is characterised by a chaotic basement reflector with relatively small amplitude variations. To the West, toward the ocean, the basement reflector is much more chaotic and shows greater amplitude variations. In contrast, to the East, between the basement bulge and the shore, the basement reflector is remarkably smooth and constant, showing only long wavelength variations. It is worth noting that the limits of these textural domains are not parallel to the isochrones of Klitgord and Schouten (1986).

Patches of smooth basement are found inside the zone characterised by chaotic basement, in the basement bulge (Fig. 3). Because of the heterogeneous seismic coverage, the distribution and outlines of those patches are not known into all the details, but we found it restricted to zones where volcanic aprons are observed: around Senghor Seamount and around the Saharan Seamounts. The basement surrounding the volcanic emerged islands is generally obscured by the numerous secondary volcanic aprons or sills and by

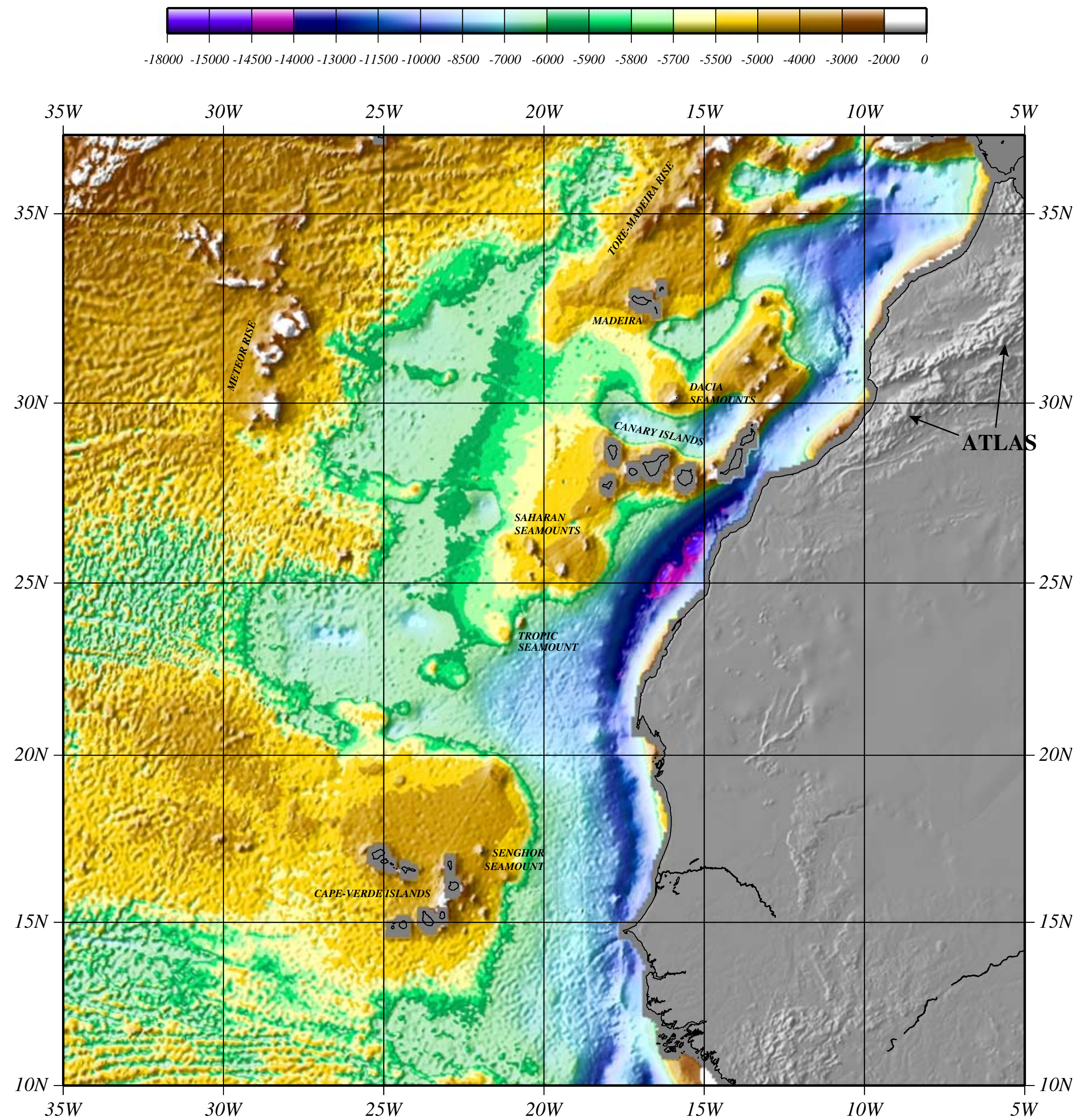

Fig. 4 Map of the basement calculated by subtracting the thickness of sediments, coming from the digital database of the NGDC ''total sediment thickness database for the world's oceans and marginal seas'', from the bathymetry

thicker or more opaque sediments. Therefore it is difficult to describe the basement in direct proximity to these islands and to know if, similarly, smooth basement characterises the surroundings of volcanic islands.

The basement bulge outlines can also be compared to the free air gravity map (Fig. 2). No single and continuous gravimetric anomaly is specifically associated to the bulge. However the basement bulge coincides with a discontinuous positive anomaly bordered by two discontinuous bands of negative anomalies. The correlation between the highest positive anomalies and the zones where the basement is the shallowest is reasonable.

At the latitude of the Cape-Verde archipelago the positive anomaly (above 10 mGal) extends further West, until 35°West, along a 5° wide zone elongated parallel to the fracture zones. In this zone the basement appears slightly overhanging and its reflectors show smoother texture than that of the surrounding oceanic crust. Olivet et al. (1984) already made these observations and described a basement bulge in this zone. Examination of the data shows the basement bulge we describe in the present paper, although in the continuation of that described by Olivet et al. (1984), is distinct from it. West of the Cape-Verde Islands there is a discontinuity between these two bulges formed by

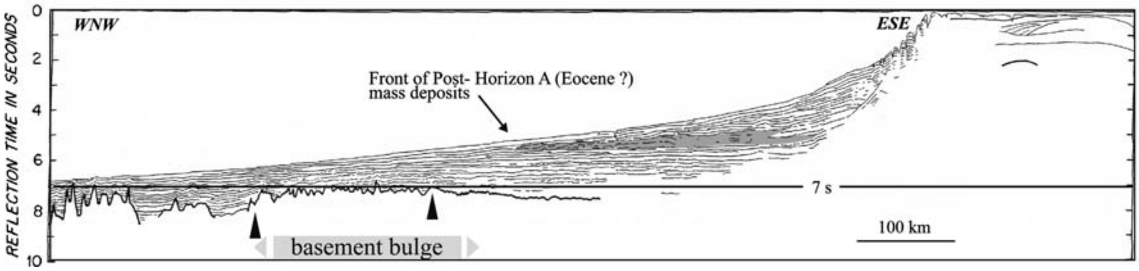

Fig. 5 Line drawing of seismic reflection profile 111 (modified after Uchupi and Emery 1974; Uchupi et al. 1976; Localisation see Fig. 1 or 3). The basement is underlined by the thick black line at the foot of the sedimentary series. The transparent interval, highlighted by grey shadowing, is thought to represent Post-Eocene mass deposits. The thick arrows correspond to the limit between zones showing different texture of the basement reflector

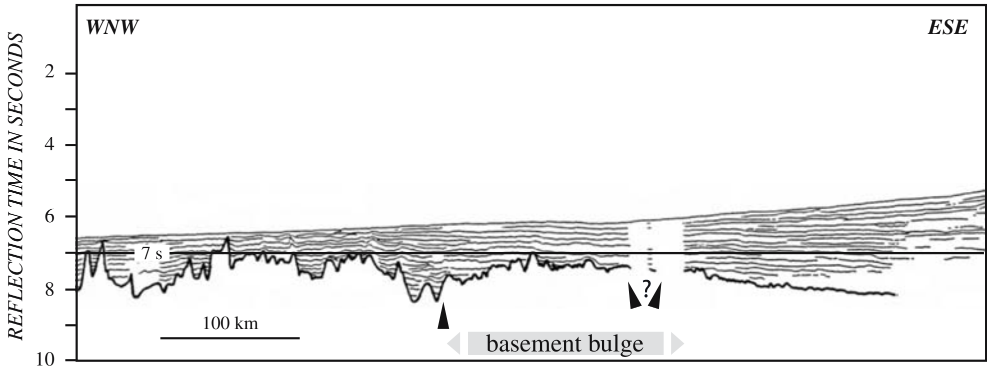

Fig. 6 Line drawing of part of the seismic reflection profile 113 (modified after Uchupi and Emery 1974; Uchupi et al. 1976; Localisation see Fig. 1 or 3). The continental platform is at the right, toward the East. The basement is underlined by the thick black line at the foot of the sedimentary series. Its texture is more and more chaotic from East to West. The basement bulge is at the borderline between the smooth basement on the left and the chaotic typical oceanic basement. The thick arrows correspond to the limit between zones showing different texture of the basement reflector

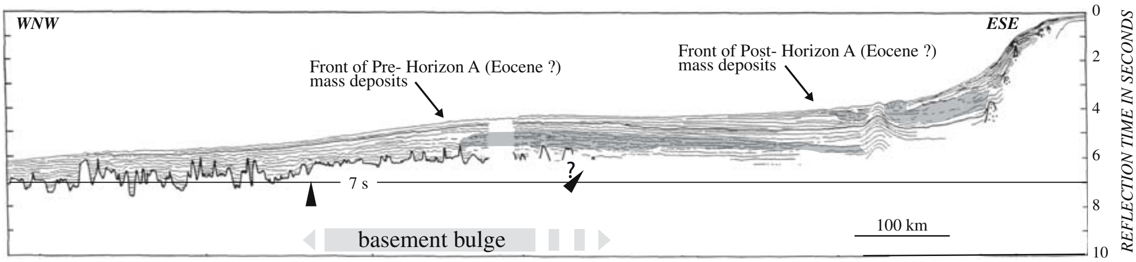

Fig. 7 Line drawing of seismic reflection profile 109 (modified after Uchupi and Emery 1974; Uchupi et al. 1976; Localisation see Fig. 1 or 3). The basement is underlined by the thick black line at the foot of the sedimentary series. Transparent intervals as well as intervals showing ruguous surface are shadowed in grey. They are thought to represent mass deposits coming from the continental slope. While the oldest (Pre-Eocene) mass deposits extend far to the west, the latest ones (Post-Eocene) are restricted to the slope and its foot. The thick arrows correspond to the limit between zones showing different texture of the basement reflector

a topographic slope toward the West and by a textural change (blue line, Fig. 3) cross cutting the basement bulge of Olivet et al. (1984).

Therefore a basement bulge roughly parallel to the shore does exist almost continuously, although the depth of its apex varies longitudinally. It is found from Dacia Seamounts, its northern extremity, to the Cape-Verde archipelago, its southern end.

Lithostratigraphy

Cape-Verde Islands

The oceanic basement and its pelagic sedimentary cover have been uplifted and crop out on the island of Maio, through a window, below the tertiary volcanic edifice (Fig. 3) (Stillman et al. 1982; Robertson 1984).

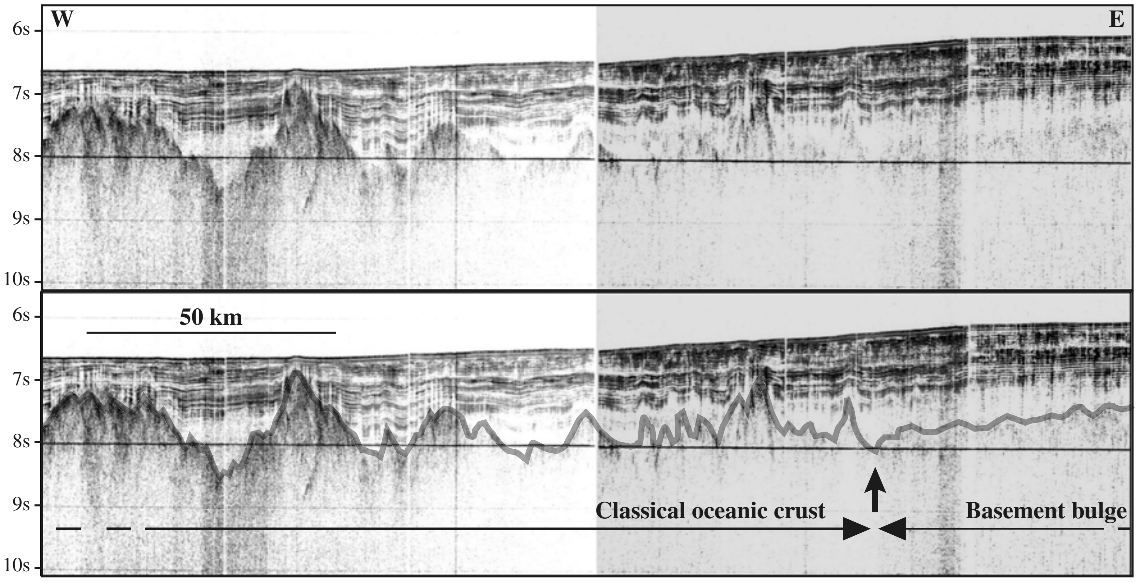

Fig. 8 Detail of a seismic reflection profile and its interpretation (localisation see Fig. 1 or 3). The basement reflector is typically oceanic (very rough) at the left hand side. It is smoother at the right hand side, though still slightly chaotic, typical of the basement bulge area

This allows a study of the island's early geological (Mesozoic) history and of the relationship between the Mesozoic island core and the Tertiary volcanic complex which uncomformably overlies it (Fig. 9).

The oceanic basement on Maio (Bathala Formation) is composed of the typical oceanic cortege of mafic pillow lavas, lava breccias, hyaloclastites and interlava sediments. The overlying sediments provided biostratigraphical data that permit to assign a Late Jurassic to Early Cretaceous age to this basement (Bernard-Griffiths et al. 1975; Grunau et al. 1975; Mitchell et al. 1983; Robertson 1984, for a review of the biostratigraphical work). This age is confirmed by the nearby DSDP Site 367 (Fig. 3) that provided an Oxfordian age to the oceanic basement.

The overlying sediments are composed of 180–350 m of fossiliferous pelagic limestones (Morro Formation) dated Tithonian to lower Cretaceous. More heterogeneous shales overlie these limestones, siltstones and thin-bedded limestones dated Albian to Cenomanian (Carquiejo Formation). These (maximum thickness 90 m) were deposited close to, then below, the calcite compensation depth (CCD) in a pelagic environment with terrigeneous or calcareous influxes due to turbiditic currents.

Pyroclastic tuffs, sandstones and conglomerates of the Coruja formation are following above this pelagic succession. Rudites found in this formation include well-rounded clasts of ocean floor basalts but also of granular plutonics similar to alcaline plutonic rocks found in the central intrusive complex of Maio. These shallow marine facies and the presence of igneous materials originating from an aerial volcanic edifice mark a major change in the deposit environment. But this change is not accompanied by any observable angular discordance between the underlying pelagic sediments and these shallow marine sediments (Stillman et al. 1982; Robertson 1984). Except rare and poorly preserved planktonic foraminifera, no fossils are found in this formation which is therefore badly dated. Whole rock K/Ar determination, possibly altered by later intrusions, suggests a minimum mid-Miocene age (Knill and Mitchell 1984), while planktonic foraminifera indicate a Tertiary age (Robertson 1984). Their 300 m thickness gives only a minimum as they are truncated by an erosion surface.

The following sequence is separated from the Coruja Formation by an angular discordance. It comprises Tertiary to Quaternary gently dipping lavas and mainly non-marine volcaniclastic sediments (Stillman et al. 1982). According to K–Ar and Ar/Ar studies, most of this late volcanic activity seems to have occurred between 20 and 7 Ma (Mitchell et al. 1983).

Repetition of the Mesozoic stratigraphical succession is achieved through a thrust fault (Stillman et al. 1982). It is considered as contemporaneous to the folding responsible for most of the sedimentary strata dip. As the Coruja Formation lies conformably above older sediments, thrusting and folding are younger than deposition of this formation. The south to southwest directed compression (Stillman et al. 1982) is thus post Late Cretaceous. Mitchell et al. (1983) reported a

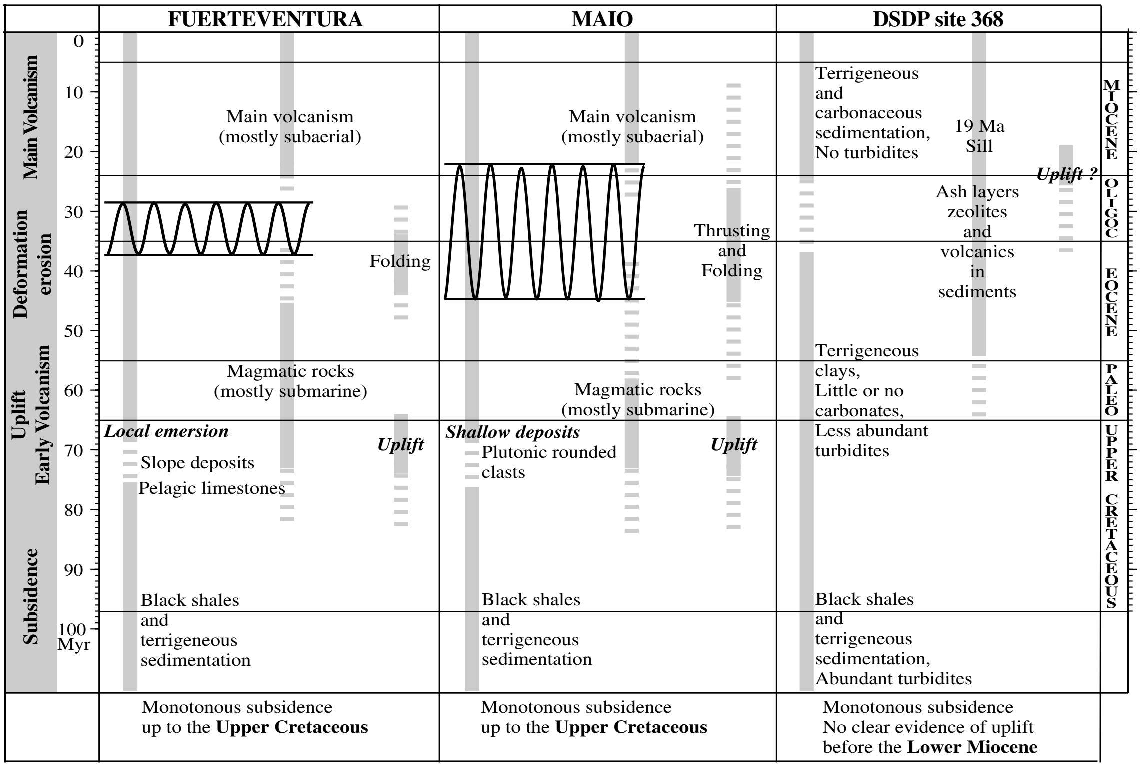

Fig. 9 Synthetic chronologic diagram. From left to right the columns correspond to the stratigraphy, the magmatism, and the deformation and uplift. The undulating black line indicates the time of the major angular unconformity seen, on the field, on Fuerteventura and Maio. The width of these undulating lines does not correspond to the duration of the geological process but to the doubt concerning the effective age of the unconformity. (after for Maio: Bernard-Griffiths et al. 1975; Grunau et al. 1975; Stillman et al. 1982; Mitchell et al. 1983; Knill and Mitchell 1984; Robertson 1984. Fuerteventura: and Robertson and Stillman 1979b; Robertson and Bernoulli 1982; Le Bas et al. 1986; Cantagrel et al. 1993; Boutin 1994; Ancochea et al. 1996; Fernandez et al. 1997; Hoernle 1998; Schminke et al. 1998; Steiner et al. 1998; Balogh et al. 1999. DSDP: Hayes et al. 1972; Uchupi et al. 1974; 1976; Lancelot and Seibold 1978; Arthur et al. 1979; Schminke and von Rad 1979)

K–Ar age of 9 Ma for a dyke cut by the main thrust plane which could then be as young as Late Miocene. Normal faulting and associated updoming of the Central Intrusive Complex post date all this deformation. The deformation, evidenced in the field by thrusts and normal faults, is therefore not responsible for the Late Cretaceous uplift of the island (Stillman et al. 1982; Robertson 1984).

Canary Islands

On the island of Fuerteventura, similar to what is observed on the island of Maio, the oceanic basement and its Mesozoic to early-Tertiary sedimentary cover has been uplifted and crops out below the Tertiary volcanic rocks (Robertson and Stillman 1979a; Robertson and Bernoulli 1982; Steiner et al. 1998), (Fig. 9). In this basal complex the strata are generally steeply dipping or vertical. The oldest sediments, and thus the seafloor basalts directly underlying them, have been dated ante-Oxfordian by biostratigraphical data (Steiner et al. 1998). A Toarcian age is proposed by combining those biostratigraphical data with various geological and geophysical considerations (Steiner et al. 1998). Xenoliths of MORB gabbros and basalts were found on the neighbour islands of Gran Canaria, La Palma and Lanzarote whose Ar/Ar and Sm/Nd datings confirmed Jurassic (180 Ma) ages (Hoernle 1998; Schminke et al. 1998).

The base of the Mesozoic sedimentary sequence is composed of 800 m of terrigeneous (clayey to silty) and carbonate or noncarbonate pelagic sediments deposited at proximity to the CCD. The top of this series is dated Berriasian. Following this are 600 m of sandy turbidites and black shales whose top is dated early to middle Albian. Above this Mesozoic sequence are 150 m of slope deposits pelagic limestones, mainly chalks, showing extensive soft-sediments slumping. These sediments, indicating great gravitational instability, are dated from late Albian to Campanian.

The first volcanic material appears, like on the island of Maio, through apparent conformity with the underlying sediments. Confirming the hypothesis of

Boutin (1994) that Fuerteventura emerged as early as the end of Cretaceous, these volcanics were erupted into waters that were already relatively shallow (Robertson and Stillman 1979b). Submarine alkaline basaltic pillow lavas and hyaloclastics compose these volcanics. Le Bas et al. (1986) report an outcrop of basaltic Hyaloclastics intercalated with Senonian chalks which indicates a Late Cretaceous date for the beginning of this island-building volcanism. K–Ar and Ar–Ar analyses of Balogh et al. (1999) confirmed this early start of magmatism with plateau ages of 63 and 64 Ma indicating the minimum age of some syenite intrusions. Le Bas et al. (1986) reported K/Ar ages of 35–48 Ma for some basalt dykes. Balogh et al. (1999) reported similar Eocene ages for plutonic intrusions. Robertson and Bernoulli (1982), found volcaniclastic sandstones intercalated with middle Oligocene bioclastic limestones. All this reveals continued sedimentation and eruptive submarine volcanism from Late Cretaceous to early Oligocene.

Le Bas et al. (1986) gave a pre-Oligocene age to the deformation responsible for the overturned position of the Mesozoic sedimentary pile. Fernandez et al. (1997) evidenced ductile shear zones and brittle faults indicating vertical shortening and EW elongation in igneous rocks belonging to the basal complex of Fuerteventura. This deformation occurred between 21 and 30 Ma, after the emplacement of syenites and carbonatites and before that of the complexes of gabbro and syenite ring-dykes which where not affected by the deformation. Nevertheless, Balogh et al. (1999) found syenite intrusions as old as 64 Ma. These recent results could enlarge the time window of ductile deformation proposed by Fernandez et al. (1997) to 64–21 Ma. In spite of these recent radiochronological dating, and based on field work considerations, Fernandez and Ahijado (2002, personal communication) still maintain their 21–30 Ma window for the EW extensional deformation. Furthermore older inverse structures are also observed in the old plutonic rocks that are displaced by the extensional ones (Fernandez, 2002, personal communication).

A succession of flat lying subaerial volcanic flows and pyroclastic deposits dated Miocene to Quaternary overlies the basal complex sequence through an angular discordance. Radiochronological studies of those young volcanic stages indicate a period of intense activity around 20–25 Ma (Le Bas et al. 1986; Cantagrel et al. 1993; Ancochea et al. 1996; Balogh et al. 1999). Although no volcanism younger than lower Miocene is known on the west flank of Fuerteventura, quaternary eruption centres and volcanic rocks are known on its northeastern flank. Historic eruptions have occurred on the nearby Lanzarote Island, a few kilometres to the north, and on other islands of the Canarian archipelago.

DSDP sites

Of the nine DSDP Site (137, 138, 139, 140, 141, 367, 368, 369 and 397; Hayes et al. 1972; Lancelot and Seibold 1978; Arthur et al. 1979; Schminke and von Rad 1979) existing inside the region we study (Fig. 3) only one, DSDP Site 367, reached the oceanic basement. Situated close to the island of Maio, its basement has a similar Late Jurassic age (Lancelot and Seibold 1978).

From Late Jurassic to Berriasian, the sedimentation is characterised by calcareous limestones and by very low amounts of terrigeneous components. Concordantly with oceanic crust subsidence models, this calcareous sequence is followed by a period dominated by terrigeneous clayey sedimentation after the sea floor passes below the CCD. This stage is reached around the Valanginian. Since that period until the Early Upper Cretaceous, terrigeneous clayey sedimentation dominated, while anoxic conditions facilitated the formation of black shales (Fig. 9).

Termination of the anoxic conditions happened during Upper Cretaceous (Cenomanian to Turonian). Green terrigeneous clays and silty clays, containing almost no carbonates, succeed to black shales (this period corresponds with the general Upper Cretaceous transgression and to the massive carbonate deposits in northern Europe). These deposits, indicative of deep basin conditions, below the CCD, prevailed in the basins up to the early Neogene. The occurrence of chert-rich layers is characteristic of this period. They correlate with ‘‘horizon A’’, a prominent reflector observed on seismic profiles (Uchupi et al. 1974, 1976).

Except DSDP Site 137 and 138 that keep on being characterised by deep pelagic sediments, all other sites record a return to carbonaceous sedimentation since Early to Middle Miocene time. This change can be due either (or both) to a lowering of the CCD, or (and) to a tectonic uplift of certain sites. Sedimentation on DSDP Site 368, in the Cape-Verde basin (which is a terrace actually) during this period is markedly poor in terrigeneous elements relative to the other sites closer to the margin.

Turbidites are found at DSDP Site 368 above Lower Cretaceous. Their abundance decreases gradually upward and stops at the end of Paleogene (Lancelot and Seibold 1978) while it persisted during Neogene in site 367.

Ash layers and zeolites, evidences for volcanic activity, have been observed in most of the sites of the region. Zeolites are present in Lower Eocene sediments of site 367 on the Cape-Verde rise and in late Cretaceous sediments of DSDP Site 140 and undated sediments of DSDP Site 141. Scattered volcanic glass and zeolites are also present in the early Paleogene of DSDP Site 368, in the Cape-Verde basin and in the late Paleogene of Site DSDP 369. Volcanic products are found everywhere since Neogene until now. Zeolites or volcanic glass are found since the late Middle Miocene in the Cape-Verde Basin (DSDP Site 367), and since Early Middle Miocene in the sites 368, 369 and 397. Several diabase sills, among which one has been dated 19 Ma, were found interbedded with Albian-Turonian black shales of DSDP Site 368. A basalt has been drilled in DSDP Site 141 whose age is not known but could be Paleogene (Hayes et al. 1972).

Discussion

Chronology

As Robertson and Bernouilli (1982), and chronological data published since their work (Mitchell et al. 1983; Knill and Mitchell 1984; Robertson 1984; Le Bas et al. 1986; Cantagrel et al. 1993; Boutin 1994; Ancochea et al. 1996; Hoernle 1998; Schminke et al. 1998; Steiner et al. 1998; Balogh et al. 1999) reinforce the feeling, we were struck by the similarities in the geological evolution of the Canary and Cape-Verde archipelagos (Fig. 9). After the classical thermal cooling driven deepening of the sedimentary environment a sustained uplift, leading locally to emersion, is observed at the end of Cretaceous. This uplift is recorded on Maio (Stillman et al. 1982) as on Fuerteventura (Robertson and Stillman 1979b) and in both island this event is not associated with any apparent unconformity. Contemporaneous with this uplift, and thus older than any unconformity, are the first records of volcanic materials. Almost all of the emerging volume of actual islands would not be due to this early volcanic episode but to Tertiary volcanism. Yet, on Maio and Fuerteventura, uplift from depth superior to the carbonate compensation depth (CCD) to the surface was achieved before the Tertiary volcanism. The abyssal depth prior to the uplift was certainly several thousands of meters as 5000 m is the average depth for 50 Ma oceanic crust (Parsons and Sclater 1977), the age reached by the crust at the end of Cretaceous.

During or before this first volcanic stage sediments were brought from pelagic to shallow marine environment without tilting or any visible deformation. Deformation postdated this stage and mostly stopped before the Tertiary volcanism that constitutes most of the volume of all the Canary and Cape-Verde Islands. Though most studies focussed on the last tertiary stage, we would like to emphasise Maio and Fuerteventura islands were already emerging or sub-emerging at this date.

Relative chronology is well established as four steps of geologic evolution are recorded in the volcanic islands: (1) subsidence following the cooling of the oceanic crust, (2) uplift and early volcanism in Late Cretaceous, (3) Oligocene to Early Miocene deformation and erosion, then (4) Cenozoic volcanism, whose peak activity is dated Middle Miocene. Yet biochronological or radiochronological data are not always precise enough to provide a good absolute chronology of the geological succession. The transition from the early (stage 2) uplift to the Tertiary volcanism is particularly crudely dated.

Very little is known about the chronological evolution of the submarine seamounts between the Canary and Cape-Verde Islands. To our knowledge, no radiochronological ages have been published. Although seismic lines around the Saharan and Tropic Seamounts show local unconformity or even sills very high in the sedimentary series that suggest an activity during the Cenozoic at least. We did not find any such sign around Senghor Seamount, but a diabase sill has been dated 19 Ma in DSDP site 368, less than 80 km northeast of Senghor Seamount.

No clear indication exists in the DSDP reports concerning a pre-Tertiary uplift, volcanism or deformation. On many seismic profiles perpendicular to the margin transparent and/or chaotic intervals are observed spread at the foot of the slope (Figs. 5 and 7). They are often laterally associated with scarps indicating destruction of parts of the margin steepest portion (Seibold and Hinz 1974). These chaotic intervals are interpreted as mass deposits following periodic landslides from the slope (Seibold and Hinz 1974; Uchupi et al. 1974, 1976; Lancelot and Seibold 1978; See description of DSDP hole 139 (Hayes et al. 1972) that reaches such a transparent seismic interval). We examined the timing and extension of these mass deposits in the whole area. Each few times we identified these deposits on the sections, they were restricted to the zone between the shore and the basement bulge axis since the Tertiary (posterior to horizon A of Uchupi et al. 1976), while older mass deposits (deeper than horizon A) were seen oceanward beyond the axis (Figs. 5 and 7). As Lancelot and Seibold (1978) did in DSDP 368 cores, according to the idea that mass deposits do not go up the slope, we suggest that the turbidites spreading has certainly been confined by the basement bulge. We therefore used this distribution of mass deposits to date the uplift of the basement bulge. Like this, along the bulge the uplift occurred sometime between the upper Cretaceous and the Miocene. It is today difficult to precise this chronology but, so far, it coincides with the uplift observed in the volcanic islands. Transition from shales containing turbidites to calcareous oozes is dated post lower Miocene in the Cape-Verde rise (DSDP Site 368) with a 19 Ma old sill supposed to pre-date the uplift (Duncan and Jackson 1978; Lancelot and Seibold 1978).

Collier and Watts (2001) similarly observed differential distribution of sediments seaward and landward of what they call ''the Canary Islands ridge'' prior to the onset of important volcanic loading of the lithosphere. They proposed the existence of a significant submarine barrier as early as upper Cretaceous or even, the Lower Cretaceous and Jurassic.

Basement bulge origin

Neither the nature of the bulge we described in this paper, nor the links between the geological history of Canary and Cape-Verde oceanic Islands, are understood today. Some genetic models have been proposed that concern the Canary hot-spot or the Cape-Verde hot-spot, rarely the two of them, but never take into account their synchronic evolution.

Holik et al. (1991) observed a bathymetric swell North of the Canary Islands and proposed that its cause was the effect of a hot-spot drifting toward the South. The increased crustal thickness they detect along the swell is interpreted to be the result of underplating and assimilation of existing oceanic crust caused by the Canary thermal anomaly. The latter bathymetric swell being situated in the northern prolongation of the basement bulge we describe in this paper, it is attractive to interpret the bathymetric swell as the northern end effect of the Canary–Cape-Verde basement bulge.

Holik et al. (1991) described a high velocity Unit of Chaotic Facies (UCF) all along the bathymetric swell and interpreted it as being of igneous origin. The seismic we worked on did not allow us to distinguish any equivalent to this UCF south of the Canary either because it does not exist or (and ?) because of the poor quality of the old seismic we used (recent DAKHLA seismic lines do not cross the entire bulge). The only comparable chaotic seismic intervals are mass deposits considered as gravity slides or turbidites that spread at the foot of the slope. As described above, these mass deposits sometime reach the bulge but are not restricted straight above the bulge axis as the UCF of Holik et al. (1991) is.

If the bathymetric swell marks the northern end of the basement bulge, the latter can be followed over 2000 km, from 33° North, the limit given by Holik et al. (1991), to 13° North, South of the Cape-Verde Islands. Such a long ridge can not be explained by the drift of the hot-spot situated today in the middle of the ridge, in the Canary, whose trace concerns only the North of the zone (Holik et al. 1991). Therefore either the interpretation by Holik et al. (1991) is wrong, the ridge is not the trace of a hot-spot, or the ridge south of the Canary Islands is an other, independent, ridge. It can not be the trace of the Cape-Verde hot-spot whose evolution, calculated, as suggested by Holik et al. (1991), using the poles proposed by Morgan (1983), does not match with the position of the basement bulge.

Explaining the whole basement bulge with the hot-spot origin therefore requires more than one plume. Two distinct hot-spot plumes were already suggested for the origin of the volcanic Canary and Cape-Verde Islands (Morgan 1971, 1983; Burke and Wilson 1972; Courtney and White 1986). But our review emphasises the very close chronological evolution of the Canary and the Cape-Verde archipelagos. Therefore at least two hot-spot plumes are required but, additionally, they should have been closely synchronised. An explanation to this synchronism has still to be found, or the plume related origin of these hotspots needs to be revised.

A 7.1–7.4 km/s velocity layer, detected by sonobuoys refraction experiment, has been described by Holik et al. (1991) at the base of the crust below the bathymetric swell north of Canaries. It is interpreted as a crustal high velocity layer corresponding to volcanic underplating. On the other hand Weigel et al. (1978) interpreted a 7.6 km/s velocity layer, below the Conception Bank north of Lanzarote, as a low velocity mantle below a crust flexured by the volcanic load. According to Weigel et al. (1982) and Holik et al. (1991), the bathymetric swell or its underlying high-velocity layer would be too distant from the ocean continent transition to be related to rifting processes.

This ridge is neither a flexural bulge due to sedimentary loading of the proximal margin. Its wavelength, its size and the distance from the depotcentre, are not compatible. A flexural bulge would be wider and should be found farther from the shore (Watts 1994; Collier and Watts 2001; Ali et al. 2003), even for an elastic thickness as weak as 5 km while Young and Hill (1986), Watts (1994) and Collier and Watts (2001) favour 15–35 km as the most probable values.

An alternative hypothesis is the Canary–Cape-Verde ridge being a consequence of tectonics between the African and European plates. The Canary–Cap-Verde ridge could have been eventually an oceanic westward prolongation of the South Atlas front. In Late Cretaceous time it would temporarily have connected the Atlas front with a transform zone (whose existence has still to be demonstrated) around the Cape-Verde Plateau before being abandoned, the boundary jumping more to the North, to the Azores-Gibraltar transform zone. From then and during the whole Cenozoic, it would have influenced the distribution of magmatism and concentrated it along the Canary–Cap-Verde lineament.

Most of the (post-rift) deformation has been dated Cenozoïc in the Atlas, though compressive events have been occuring from time to time since Cretaceous (Obert 1981, 1984; Wildi 1983; Guiraud 1997, 1998; Bracene et al. 2003; Ellouz et al. 2003). These early compressive events are of various ages in the Atlas region but some of them could be contemporaneous with the late Cretaceous uplift recorded in the Canary and Cape-Verde Islands.

The effects of compressive deformation on an intraoceanic boundary can be observed in the central Indian Ocean (see for example Krishna et al. 1998 or 2001). The long (150–300 km) basement undulations with 1–2 km relief, that characterise the longest wavelength of deformation observed in the Indian Ocean, resemble the basement bulge observed offshore Africa, except that, in the free air gravity anomalies, these long ondulations are clearly identified in the Indian Ocean but hardly visible in Africa. This could be a consequence of time elapsed since deformation was active along the African coast. Shorter wavelengths, characterised by tight foldings and faulting, particularly numerous in the Indian Ocean, are almost absent in the seismic sections of the Canary–Cape-Verde region we examined.

Conclusions

The origin of the Canary and Cape-Verde Islands is most often assumed to result from the activity of two distinct hot-spot plumes. However several considerations suggest a link between the two archipelagos.

Their geological history is very similar since the formation of their oceanic basement during the Late Jurassic. They share the same sedimentary evolution (subsidence, uplift and emersion) as well as very similar timing of volcanism and deformation. In particular, on both Archipelagos, uplift is achieved in Late Cretaceous time without any tilting or deformation. It predates the Cenozoic main volcanism and unconformity.

A basement ridge can be followed along the African margin, from 33° North to 13° North. It is evidenced by a morphological expression but is also accompanied by textural characteristics seen on seismic reflection but by only faint trends seen on the free air gravity anomaly map. It passes through and joins the Cape-Verde and Canary Islands but also several other, mostly submarine, volcanic masses.

Many questions about this ridge remain unanswered. Additional reflexion and wide angle seismic could help answer them. The main question concerns the nature of the bulge. In particular we do not know if the thickness of the crust changes below the ridge, if igneous materials, younger than Jurassic mid-ocean ridge products, are present and, more particularly and as suggested further north, if underplating lies at the base of the crust.

So far the two distinct hot-spots origin for the Canary–Cape-Verde region does not appear to be adapted. It ignores the existence of the bulge as well as many geological coincidences that suggest a common origin. The Canary–Cape-Verde geological structure resembles more a hot line or dotted line than two hot-spots. But no other convincing explanation has been proposed that links the two archipelagos. A tectonic origin seems today the most appropriate explanation, though it has still to be tested. Nevertheless, by enumerating Canary and Cape-Verde coinciding geological incidents, we aim, at least, to argue that it is misleading to treat these two regions apart.

Either due to tectonic or any other process the scale of the basement bulge is comparable to that of terrestrial mountains ranges. Additionally, this range is not isolated in the Eastern Central Atlantic region, the Tore-Madeira Rise and Meteor Rise are of very similar scale and could have been formed around the same period. All this suggests to consider the geological history of the Canary and Cape-Verde Islands as part of that of the Eastern Central Atlantic ocean as a whole.

Acknowledgements This work was founded on the ideas of J.L. Olivet. We benefited from many discussions with him and also D. Aslanian, M. Sahabi, M. Moulin, W. Roest and L. Géli, all of whom are either members of or visitors to the Département Géosciences Marines in Ifremer.

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