

# Miocene shallow-water limestones from São Nicolau (Cabo Verde): Caribbean-type benthic fauna and time constraints for volcanism

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*Key words:* Caribbean Amphistegina, planktic foraminifera, Miocene, Cabo Verde Islands, volcanism, shallow-water limestones

## ABSTRACT

Shallow-water limestones of presumed Late Cretaceous and Eocene age, interbedded with basaltic lavas, were described by earlier authors from São Nicolau in the northwestern part of the Cabo Verde archipelago. If confirmed, these ages would imply late Mesozoic shallow-marine and subaerial volcanic activity in the Cabo Verde archipelago, and document a geological history very different from that known so far from other Cabo Verde Islands, from which no subaerial volcanic activity before the mid-Cenozoic is known. Our re-investigation of the foraminiferal fauna indicates a Late Miocene age for the presumed Late Cretaceous and Eocene limestones. The hypothesis of a long-lived hot spot, active by the Early Cretaceous, and of a major island-building stage in the Cabo Verde Islands during this period, is therefore not supported by the present bio- or chronostratigraphic data.

## RESUME

Dans l'île de São Nicolau, archipel du Cap Vert, des calcaires néritiques, intercalés dans des basaltes alcalins, ont été attribués au Crétacé supérieur et à l'Eocène. Un tel âge impliquerait une activité volcanique subaérienne ou sous-marine de faible profondeur dans l'archipel du Cap Vert dès le Mésozoïque et documenterait donc une histoire géologique différente des autres îles de l'archipel, où aucune activité volcanique n'est connue avant le Cénozoïque moyen. Une étude approfondie de la faune de foraminifères indique un âge Miocène supérieur aux calcaires présumés du Crétacé supérieur et de l'Eocène. L'hypothèse d'un *hot spot* de longue vie déjà actif pendant le Crétacé inférieur et d'une construction d'une île volcanique à cette époque n'est pas soutenue par les données bio- ou chronostratigraphiques.

## Introduction

The ten islands of the Cabo Verde group, rising from a water depth of 3 500 to 4 000 m, are located on a broad oceanic basement rise off west Africa that is floored by oceanic lithosphere of Early Cretaceous age (Fig. 1). During the Cenozoic, this oceanic lithosphere has been strongly altered by thermal and metasomatic events associated with silica-undersaturated mafic volcanism (de Paepe et al. 1974) and the uplift of the rise. Of these islands, Maio became famous because of the extensive occurrence of Mesozoic deep-water sediments (Colom 1954; Robertson 1984; Fourcade et al. 1990) associated with relict Atlantic ocean floor (Klerkx & de Paepe 1971; de Paepe et al. 1974). Such sediments are extremely rare on Atlantic volcanic islands and are, besides Maio, until now only known with certainty from Fuerteventura (Rothe 1968; Robertson & Bernoulli 1982; Steiner et al. 1998) and La Gomera (Cendrero

1971) in the Canary Islands. However, these sediments document deep-water sedimentation without volcanogenic input from nearby sources up to the Late Cretaceous in the areas of the future volcanic islands.

Shallow-water limestones of presumed Mesozoic and Early Cenozoic age have been mentioned so far only from São Nicolau in the northwestern part of the Cabo Verde archipelago where they are reported to be interbedded with basaltic lavas (Bebiano & Soares 1952). If confirmed, this occurrence would indicate a geological history very different from that of Maio and, as far as is known, the other Cabo Verde islands. As on Fuerteventura (Canary Islands) and other Atlantic islands, there is no compelling evidence for Late Cretaceous volcanicity on Maio, and magmatic activity appears to have started only in the Paleogene (Robertson 1984). In particular, the existence of extensive Late Cretaceous plateau lavas on São Nicolau

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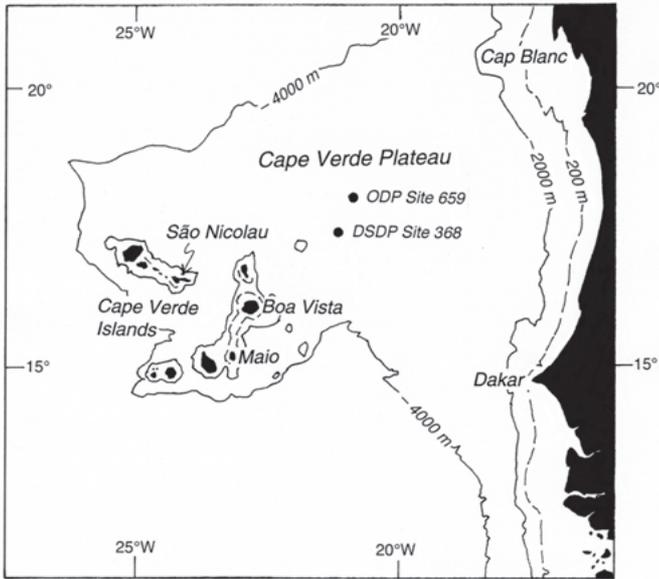


Fig. 1. Location of the Cabo Verde Islands and bathymetric map of the Cape Verde Plateau.

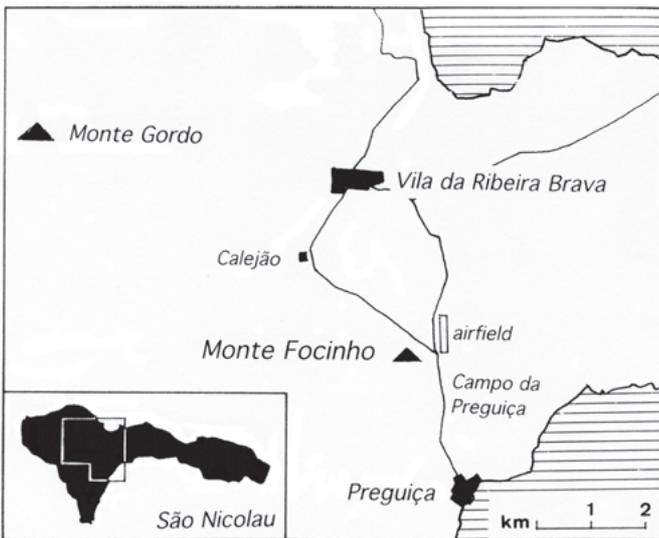


Fig. 2. Location of Monte Focinho, São Nicolau (Cabo Verde).

would be in contrast with all we know from the Cabo Verde and Canary Islands. Although the existence of Cretaceous plateau lavas in the Cabo Verde Islands is very unlikely, the notion of Cretaceous shallow-water sediments is still lingering in the literature (e.g. Mitchell-Thomé 1976: 48, 1979). The reported Cretaceous ages (de Assunção et al. 1968), that, however, mainly refer to the Mid-Ocean-Ridge-Basalt (MORB) lavas of the Atlantic ocean floor exposed on Maio, have led Morgan (1981: 473–474), citing Assunção et al. (1968), to postulate for the Cabo Verde Islands a long-lived hot spot history

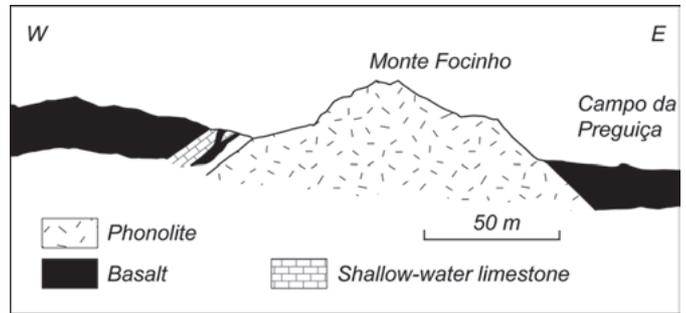


Fig. 3. Geological cross-section across Monte Focinho, São Nicolau (Cabo Verde) (after Bebiano & Soares 1952, modified).

from 120 to 50 Ma and a major island-building stage in the Cretaceous. In order to clarify the situation, one of us (DB) in 2003 sampled the limestone occurrences on São Nicolau in order to confirm or disprove the Cretaceous and/or Early Cenozoic age of the shallow-water limestones of Bebiano & Soares (1952). In this work, we shall demonstrate their Miocene age, and briefly discuss their faunal relationships to other occurrences in the central Atlantic area and the implications for the geological history of the Cabo Verde Islands.

#### Location of section and lithology

The occurrence of shallow-water limestones described by Bebiano & Soares (1952) is located on a ridge extending west of Monte Focinho in the neighborhood of the airfield of São Nicolau (Figs. 2 & 3). The limestones occur in two packages, the lower about three, the upper about five meters thick, separated by a dike crossing obliquely the section, and are intercalated within the plateau lavas that occupy much of the island. Although the two layers are only a few metres apart and are identical in lithology and facies, they were considered to be of widely differing ages by Bebiano & Soares (1952). The fossils collected from the higher limestone layer were regarded as of (?middle) Eocene (Lutetian) age, and those of the lower layer as Late Cretaceous (Senonian) based on solution molds of gastropods and bivalves. The limestones dip at about 30° to the west. Bebiano & Soares (1952) suggested that tilting is related to the phonolite intrusion of Monte Focinho (Fig. 3).

Both limestone intercalations are of the same facies and include the same fauna. They consist of crudely bedded, patchily cemented, coarse calcarenites. The skeletal fragments include cirripede and echinoderm remains, particularly echinoid spines, bivalves, gastropods, rotaliid foraminifera, red algae, and occasional corals. Planktic foraminifera are part of the fossil assemblage, and volcanic lithic and mineral grains are present in varying amounts.

The sediments show a grainstone texture; locally the particles are closely packed and show convex-concave contacts indicating pressure solution. There are two generations of calcite cement; a first generation of inclusion-rich crystals, overlain by

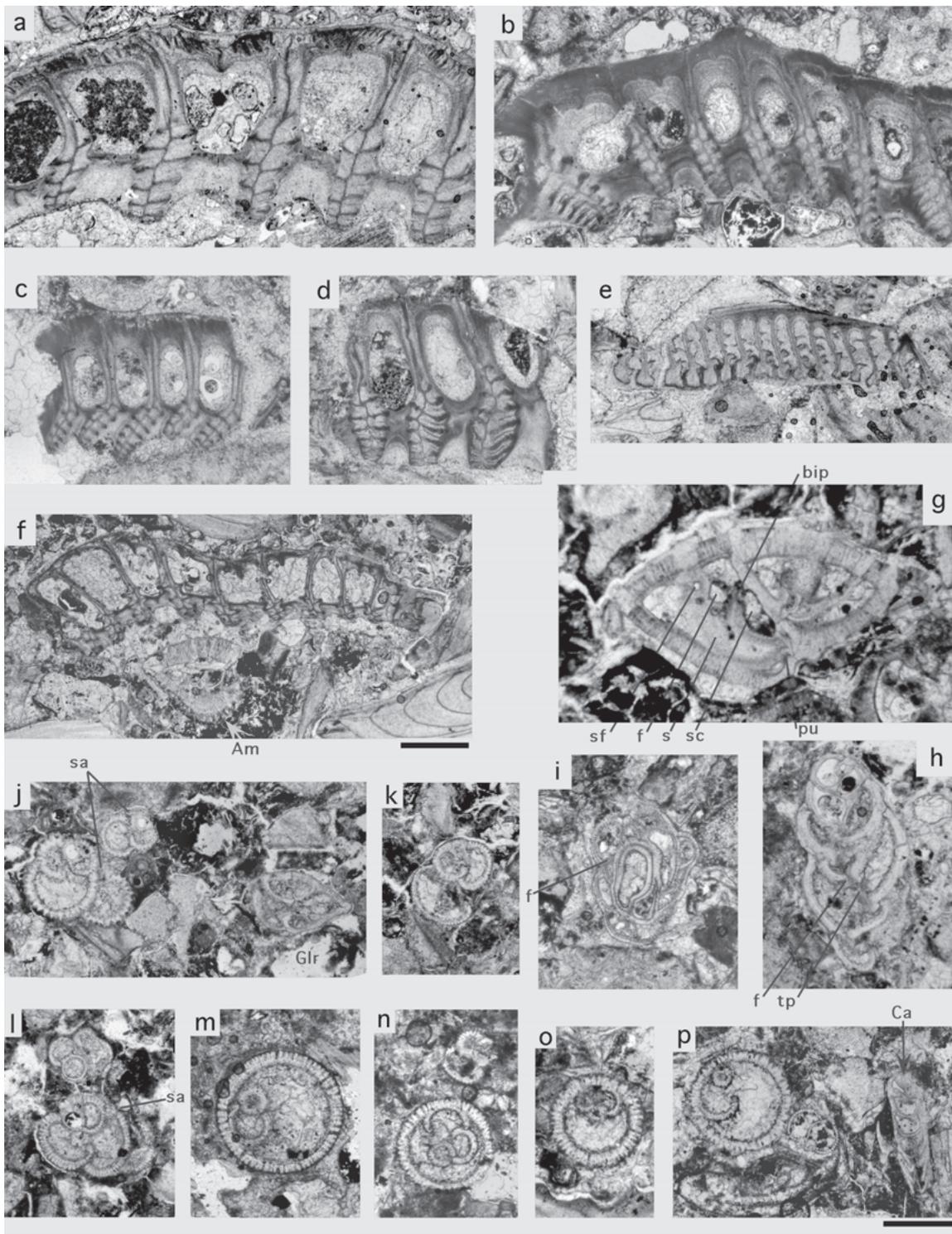


Fig. 4. Cirripeds and foraminifera from Miocene shallow-water limestones, Monte Focinho, São Nicolau (Cabo Verde). a–f) *Balanus* sp. (cirripeds), fragments of lateral walls showing glandular structures; with *Amphistegina tuberculata* in f. g) *Eponides repandus* (FICHTEL & MOLL), approximately axial section; note the bipartitor, the diagnostic generic character. h) *Fursenkoina* sp., approximately axial section; note toothplate extending between successive foramina. i) *Acervulina* sp., random section; note foramen with peristome. j) *Globigerinoides* sp. with *Globorotalia* sp., random sections; note supplementary sutural apertures. k, l) *Globigerinoides* sp., random sections; note supplementary sutural apertures. m–p) *Orbulina* sp., random sections showing early spiral chambers enclosed in ultimate spherical chamber; with *Cassidulinoides* sp. in p, showing toothplate in an almost axial section. Abbreviations: Am, *Amphistegina tuberculata*; bip, bipartitor; Ca, *Cassidulinoides* sp.; f, main foramen; Glr, *Globorotalia* sp.; pu, pseudumbilicus; s, septum; sa, supplementary sutural apertures; sc, “spiral canal”; sf, supplementary areal foramen; tp, toothplate. Thin sections. Scale bars: 0.5 mm (a–f); 0.25 mm (g–p).

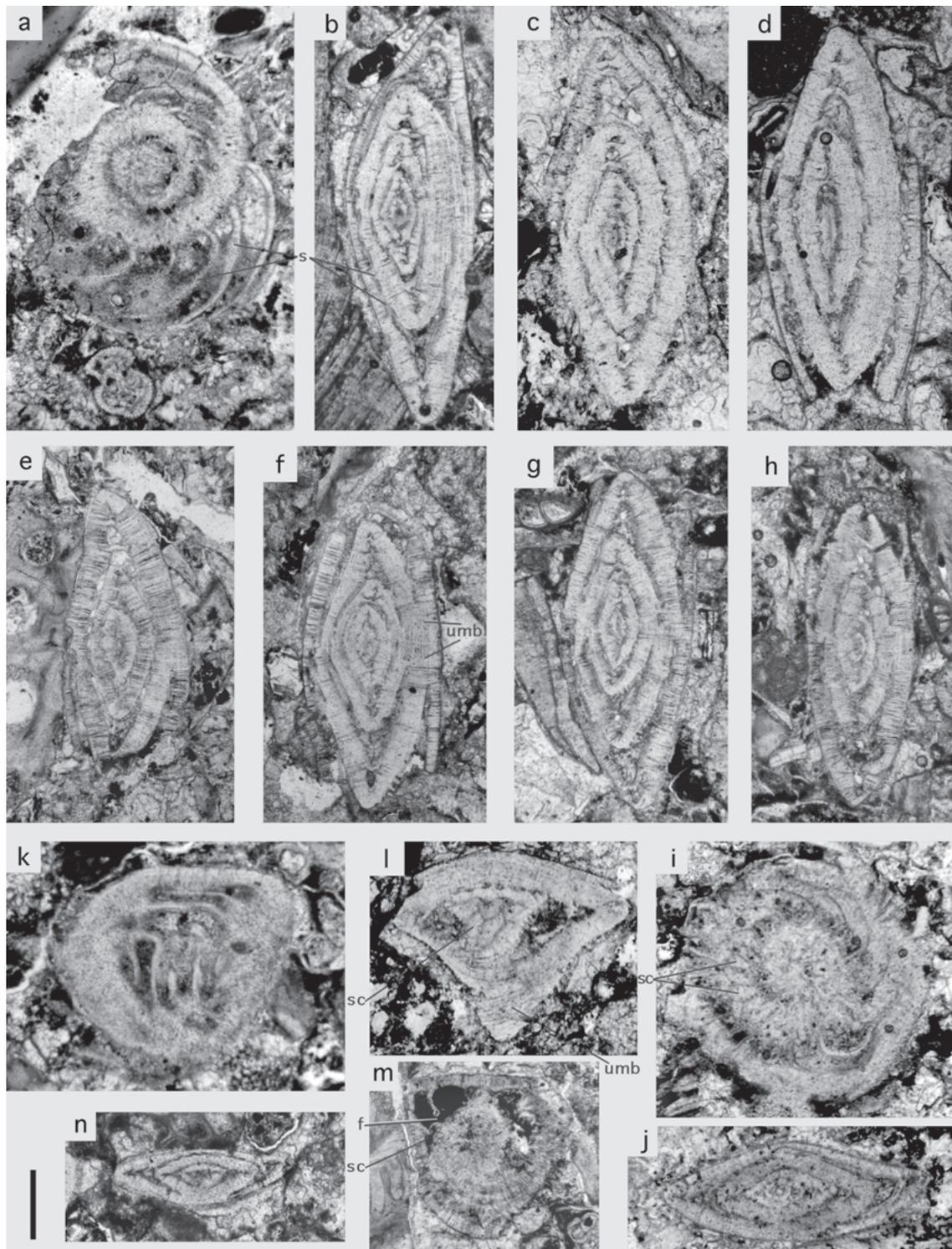


Fig. 5. *Amphistegina* from Miocene shallow-water limestones, Monte Focinho, São Nicolau (Cabo Verde). a–j) *Amphistegina canaensis*, megalospheric specimens; section almost perpendicular to shell axis through dorsal part of shell in a, showing main septa bent backward in a low arc; approximately axial section, centered in b; non-centered, approximately transverse sections near to the axial plane, more or less oblique in c–h, the section is exactly parallel to the shell axis and sufficiently near to it to show the faintly convex ventral umbo in g. i) Section perpendicular to shell axis, through ventral part of shell showing the sutures of the stellar chamberlets. j) oblique, centered section showing small megalosphere. k–m) *Amphistegina tuberculata*, megalospheric specimens, oblique sections, showing stellar chamberlet sutures, diagnostic for the genus *Amphistegina*, the main foramen and the heavy, prominent umbo, characteristic for the megalospheric specimens of *A. tuberculata*. n) *Amphistegina* cf. *bowdenensis*, megalospheric specimen, almost axial section. Note the wider spiral and the more flattened test as compared to inner whorls of *A. canaensis* in f, g, and j. Abbreviations: f, foramen; s, septum; sc, stellar chamberlets; umb, umbo. Thin sections. Scale bar: 0.25 mm.

a second generation of clear blocky calcite. Aragonitic skeletal fragments and corals are dissolved, and their molds are partially cemented by the second generation of clear, sparry calcite. Volcanic fragments are often surrounded by a rind of nontronite that also occurs in patches throughout the rocks.

## Age and depositional environment

### *Benthic fauna*

The benthic fauna is dominated on the one hand by cirripeds (*Balanus* sp.) (Figs. 4a–f), forming a filter-feeding population of rapidly growing organisms permanently attached to a hard substrate. The calcified fragments of their shells accumulated, together with the debris of coralline red algae, below steep rocky slopes and formed beds of coarse carbonate sands. By contrast, the shells of *Amphistegina* species, free-living benthic foraminifera with symbiotic algae, constitute another significant contribution to the carbonate sediment. Other benthic foraminifera occur in very low numbers. We have identified *Eponides repandus* (FICHTEL & MOLL), *Fursenkoina* sp. and the permanently attached *Acervulina* sp. (Figs. 4g–i).

The species of the genus *Amphistegina* and its relatives constitute one of the Cenozoic groups of benthic foraminifera of which the ecological and biogeographical significance at specific level is well recognized but calls urgently for taxonomic revision. Today, we observe six species in the Indo-Pacific ocean (Larsen 1976; Hottinger et al. 1993) but only one (*A. gibbosa* D'ORBIGNY) was found until now in the Caribbean (Collins 1999: Appendix: 106). During the Late Miocene-Pliocene, the diversity of *Amphistegina* species seems to be inverted, few species in the Indo-Pacific, many in the Caribbean. This inversion may not be due to monographic artifacts only, although the latter may amplify the phenomenon.

Most of the fossil species have been described and defined exclusively by their external morphology, without taking into account the dimorphism (or eventually trimorphism) of the generations within a species, nor have the diameters of the megalospheres been measured. The latter is the most important measure for evolutionary progress within a phyletic line. Under these conditions, the current knowledge about the distribution of taxa in the fossil record from Oligocene to Recent is unreliable.

The amphisteginids from São Nicolau (Fig. 5) are cemented in the carbonate rock and therefore can be studied only in random sections. Whatever thin sections from Neogene carbonate rocks in the Neotethys were available for comparison, none showed *Amphistegina* species with similar, wide spirals or with comparable heavy umbos. In the Dominican Republic, however, Bermudez (1949) described a number of Neogene amphisteginid species with comparable characters. In the material collected by a team of scientists of the Basel Museum of Natural History from sections in Neogene deposits of the Dominican Republic (Saunders et al. 1986), a series of very rich amphisteginid populations is documented with numerous free

shells. Some are topotypes of Bermudez' species. We have sectioned some of them (Fig. 6), permitting direct comparison with the material of São Nicolau. On this basis, we have identified as the dominant species *A. canaensis* BERMUDEZ and as accessory components of the communities *A. tuberculata* BERMUDEZ and *A. cf. bowdenensis* BERMUDEZ. A monographic revision of these and other species of the genus *Amphistegina* will be given elsewhere, as soon as sufficient and appropriate free shell material from Neogene Neotethyan deposits will be available.

The *Amphistegina* species from the Dominican Republic, in particular from the Rio Gurabo section, represent a deepening-upward series of communities extending from the Cercado Formation through the Gurabo and into the Mao Formation. According to Saunders et al. (1986), the Miocene-Pliocene boundary is located 400 m above the base of the section, in the middle of the Gurabo Formation. The age extension down-section and to the top of the section is not exactly known but might not extend to more than a stage.

From bottom to top of the Rio Gurabo section, the ecological gradient seems to be fairly uniform. According to the successive foraminiferal communities, in the Dominican Republic, the observed ecological gradient with which the amphisteginids are associated extends through the complete photic realm and beyond into deeper water, where planktic shells accumulate and where the larger agglutinated forms of the Caribbean Neogene (*Textulariella*, *Cuneolinella*, etc.) become abundant. *Amphistegina canaensis* and *A. tuberculata* are frequent in the Cercado and Gurabo formations; their bathymetric ranges extend a little beyond the lower depth limit of the very shallow *Parasorites* and other soritids and archaiasines present in the same section (Hottinger 2001). They belong thus to the upper part of the photic zone. *Amphistegina bowdenensis*, however, reaches its maximum frequency with 79% of all amphisteginids at 680 m above the base of the section, at the level marking the end of the photic zone, where plankton shells appear in the sediment. Its small-sized, much compressed shells match the morphology of *A. papillosa* marking the deepest *Amphistegina* communities in the Indo-Pacific.

Thus, the benthic fauna of São Nicolau does not contribute to an exact age assignment of its host sediment but suggests nevertheless the Late Miocene as the period of its deposition. On the other hand, the dominant components of the benthic fauna suggest the production of the carbonates on exposed, steep rocky walls covered by cirripeds and coralline algae, similar to environments observed in Marseille (Hottinger 1983). Fragments and free shells from the total height of the wall may have accumulated in depths corresponding to the lower limit of the photic zone where *A. bowdenensis* may have constituted a more or less autochthonous faunal element.

The Cape Verde Islands represent the easternmost outpost of the extant Caribbean foraminiferal faunal province (Langer & Hottinger 2000). This province may be characterized by the presence of the shallow-water genera *Archaias*, *Cyclorbiculina* and by *Amphistegina gibbosa*. Stony corals (Veron 1995) and

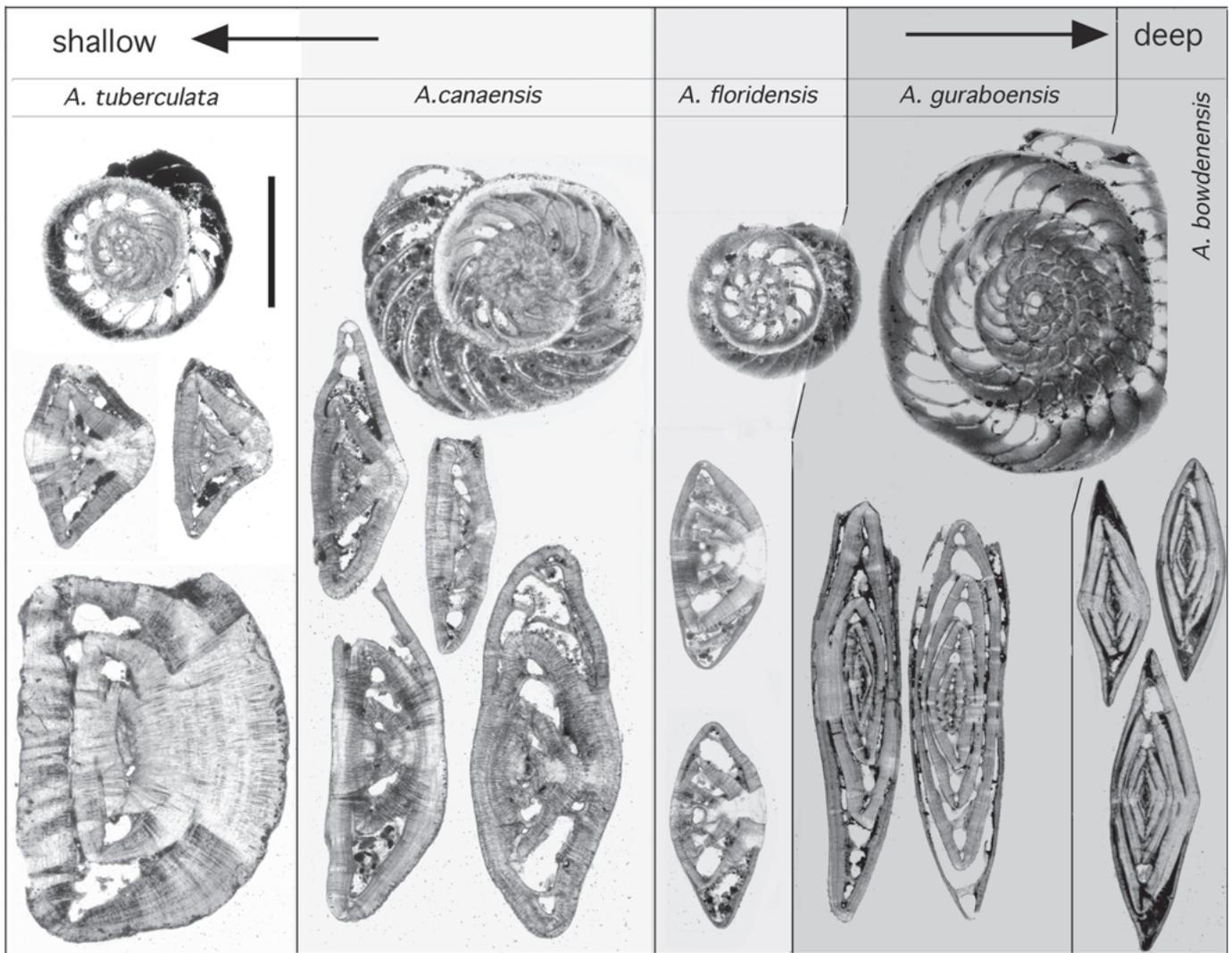


Fig. 6. Selected Caribbean species of *Amphistegina* (Foraminifera) in the depth gradient of the deepening-upward Gurabo section (Cercado to Mao Formations), Dominican Republic (Late Miocene to Pliocene according to Saunders et al. 1986). Equatorial and axial sections of free specimens. Progressive shading of the background corresponds to progressive depth of deposition. Thin sections. Scale bar: 1 mm.

many other groups of marine organisms represent even more important indicators of faunal provincialism, but the large-sized, benthic, K-strategist foraminifera have the greatest potential to closely document the provinces through geologic time: similar Caribbean faunal provinces of shallow-water organisms have been observed for the Late Cretaceous (*Sulcoperculina* and its orbitoidal derivatives), in the Eocene (*Eoconuloides-Boreloides*, *Cyclorbiculinoidea*, *Yaberinella* and Eocene “lepidocyclinids”), and in the Late Miocene (the larger alveolar-agglutinated forms such as *Cuneolinella* and numerous amphisteginid species (Bermudez 1949) as well as *Androsinopsis* (Hottinger 2001) and *Miosorites*). At present, it is unclear whether the so-called Caribbean faunal province is a phenomenon of long duration, ranging from Late Cretaceous to Recent or if it is repetitive. The presence of “Caribbean” faunal elements in the eastern outpost of the province in the Late

Miocene is a first indication of the temporal extension of the recent “Caribbean” province and its trans-Atlantic extension over the Late Miocene to Recent interval.

#### *Planktic foraminifera*

Planktic foraminifera are generally rare in our samples, however, a few key species, listed in Table 1 and illustrated in Figure 7, are present. The planktic foraminifera, identified in thin section, give the most reliable ages, whereas the benthic foraminifera give a general Late Miocene age. In the Atlantic, *Globorotalia menardii* is known from the base of Zone N14 onward (late Middle Miocene) following the low-latitude standard zonation of Blow (1969, 1979), slightly modified by Kennett & Srinivasan (1983) and Curry et al. (1995). In Hole 1006A, ODP Leg 166 (Bahamas) this species appears slightly

Table 1. Distribution of planktic foraminifera in thin sections from the Miocene shallow-water limestones of São Nicolau (Cabo Verde). VR, very rare; R, rare; C, common; A, abundant.

Systematics	Thin section Nr. (Foraminiferal abundance)						
	1 (R)	2 (R)	4 (C)	5 (A)	6 (VR)	7 (R)	8 (R)
<i>Dentoglobigerina altispira</i>				x			
<i>Globigerina bulloides</i>	x	x	x	x			
<i>Globigerinoides conglobatus</i>			cf.				
<i>Globigerinoides extremus</i>				x			
<i>Globigerinoides obliquus</i>			x	x		x	
<i>Globigerinoides trilobus</i>		x	x	x		x	
<i>Globigerinoides</i> spp.					x		x
<i>Globoquadrina dehiscens</i>				x		x	x
<i>Globorotalia menardii</i>			x	x		x	
<i>Globorotalia plesiotumida</i>				x			
<i>Orbulina universa</i>			x				
<i>Sphaeroidinellopsis</i> sp.			x	x			

above the First Occurrence (FO) of *Zeaglobigerina nepenthes* (Kroon et al. 2000, Spezzaferri et al. 2002). According to Berggren et al. (1995), this species first appears at 11.8 Ma. The last occurrence (LO) of *Globoquadrina dehiscens* is recorded in ODP Leg 166 in Zone N17 in the Late Miocene (Spezzaferri et al. 2002) at 5.8 Ma (numerical age from Berggren et al. 1995). The sediments from São Nicolau should therefore have been deposited during an interval spanning from 11.8 to 5.8 Ma. If the presence of *Globigerinoides conglobatus* would be confirmed by additional studies, the interval for the deposition of the sediments in São Nicolau could be restricted from 6.2 to 5.8 Ma (Late Miocene), because this species occurs from 6.2 Ma to the present.

In summary, our biostratigraphical data clearly document a Late Miocene age for the calcarenites of Monte Focinho, in contrast to the Late Cretaceous and Eocene ages postulated by Bebiano & Soares (1952). Because the calcarenites are conformably intercalated within the basaltic sequence of Monte Focinho, the volcanics must also be of Miocene age.

#### *Sr-isotope chronology*

As calcium carbonate incorporates Sr but not Rb, there will be no significant contribution of  $^{87}\text{Sr}$  from the decay of  $^{87}\text{Rb}$ , and the  $^{87}\text{Sr}/^{86}\text{Sr}$  values need not be corrected to account for the decay of  $^{87}\text{Rb}$ . A calcitic fossil fragment from the calcarenites yielded a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.70817 \pm 7$ . The NBS standard value at the time of isotope analysis was 0.71025 (Bernoulli et al. 2004).

Because the Sr isotope composition of ocean water has become more and more radiogenic since the Eocene, measurement of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in Eocene and younger carbonate sediments yields (1) the youngest age of sedimentation and (2) the oldest age of diagenesis during the time interval from the Eocene to the Recent (Swart et al. 1987), provided the carbonate minerals are precipitated from seawater and no other source of Sr is involved. The highly radiogenic Sr isotope value we measured in a calcitic bioclast is much higher than Cretaceous or Eocene seawater values (Jones et al. 1994); however, it does not match the biostratigraphic age of the sample. The

measured value of 0.708168 would correspond to an age of 25 to 30 Ma in the time scale of Koepnick et al. (1988), an age obviously in conflict with the biostratigraphic age based on planktic and benthic foraminifera and differing from the biostratigraphic age by at least 12 My. Because the biostratigraphic age is well documented, we assume interaction with basalt-derived fluids, shifting the Sr isotope ratio to a lower, less radiogenic value.

#### **Discussion and conclusions**

The early, Cretaceous history of the present region of the Cabo Verde Islands is documented so far only on Maio. On Maio, a sequence of tilted and uplifted Early Cretaceous Atlantic ocean floor dips steeply away from a central alkaline plutonic complex of pyroxenites, essexites, syenites, and carbonatites (Serralheiro 1970; Stillman et al. 1982). In contrast to the strongly silica-undersaturated alkaline rocks of Cenozoic age, the oldest rocks of the ocean floor sequence are pillow lavas of MORB character (de Paepe et al. 1974; Batalha Formation of Stillman et al. 1982; Robertson 1984), overlain by pelagic nannofossil limestones (Morro Formation) of Maiolica facies, ranging in age from the Valanginian to the Barremian (Stahlecker 1934; Fourcade et al. 1990). By the mid-Cretaceous (Albian-Cenomanian), the ocean floor had subsided to near or below the calcite compensation depth with the deposition of anoxic black shales (Carqueijejo Formation, Robertson 1984). According to Robertson (1984), the thin interbeds of limestones and siltstones are pelagic sediments and distal terrigenous turbidites, respectively, and lack volcanic material. The alkaline igneous rocks are distinctly younger than this oceanic sedimentary sequence and the oceanic crust underlying it.

Pyroclastic rocks associated with agglomerates, conglomerates and sandstones (Coruja Formation) overlie the pelagic succession and suggest the emergence of the island of Maio. Clasts of plutonic rocks in these rudites indicate magmatism and unroofing of a volcano to substantial depth (Stillman et al. 1982). This and the occurrence of uplifted oceanic sediments suggest that prior to emergence, large intrusive complexes

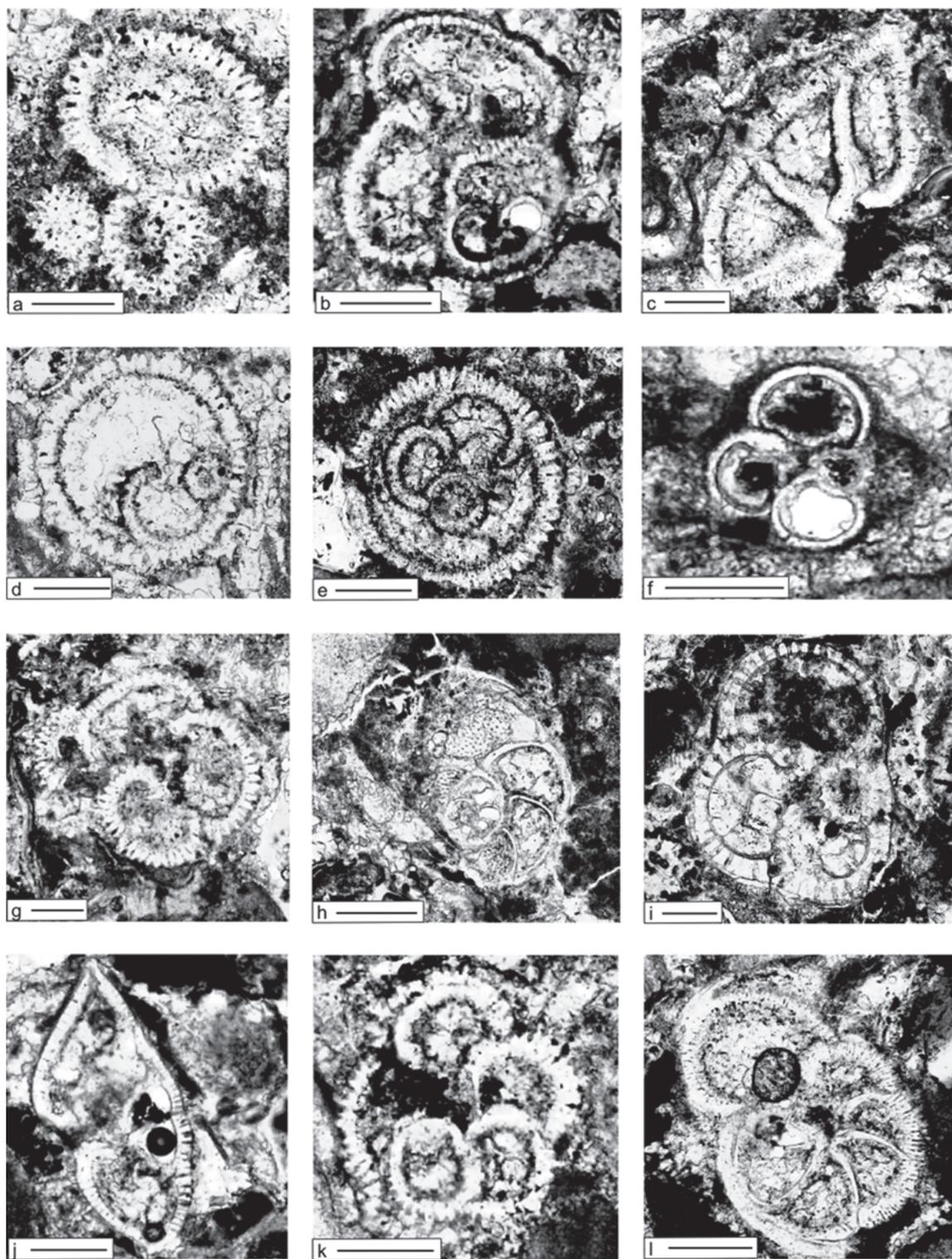


Fig. 7. Planktic foraminifera from Miocene shallow-water limestones, Monte Focinho, São Nicolau (Cabo Verde). a) *Globigerinoides trilobus* (REUSS), thin section Snic 2; b) *Globigerinoides obliquus* BOLLI transitional to *G. extremus* BOLLI & BERMUDEZ, thin section Snic 4. c) *Globorotalia* cf. *menardii* (PARKER, JONES & BRADY), thin section Snic 5. d) *Orbulina universa* D'ORBIGNY, note the juvenile *Globigerina* inside the test, thin section Snic 4. e) *Orbulina universa* D'ORBIGNY, thin section Snic 5. f) *Globigerinita* sp., thin section Snic 5. g) *Globigerinoides obliquus* BOLLI, thin section Snic 5. h) *Globorotalia menardii* (PARKER, JONES & BRADY), note the well-preserved wall texture in the last chambers, thin section Snic 4. i) *Sphaeroidinellopsis* sp., thin section Snic 4. j) *Globorotalia menardii* (PARKER, JONES & BRADY), thin section Snic 5. k) *Dentoglobigerina altispira* CUSHMAN & JARVIS, thin section Snic 5. l) *Globorotalia* cf. *plesiotumida* BANNER & BLOW, thin section Snic 5. Thin sections. Scale bars: 0.1 mm.

grew within the volcanoes during their seamount stage. The age of the Coruja Formation and of the earliest intrusive rocks is, however, weakly constrained. Stillman et al. (1982) thought that it could still be Late Cretaceous, but there exists no positive evidence for this until now (Fourcade et al. 1990). The rare planktic foraminifera reported seem to indicate an Early, partly Late Cenozoic age (Grunau et al. 1975; Robertson 1984). Although Stillman et al. (1982) and Robertson (1984) did not recognize an angular unconformity with the underlying Carqueijo Formation, a marked contrast exists between the abyssal plain deposits of the Carqueijo Formation, that lacks volcanic material, and the volcanoclastic succession of the Coruja Formation. The Basem Complex of Maio (Stillman et al. 1982), including the Mesozoic sediments, the intrusives and the Carqueijo Formation, is unconformably overlain by coarse conglomerates and marine sands (Pedro Vaz Conglomerate) of presumably Middle Miocene age and finally by the Neogene–Quaternary subaerial plateau basalts and cinder cones.

So far, all attempts to date volcanic rocks by the K-Ar method of the Cabo Verde Islands have given only Cenozoic ages (Bernard-Griffiths et al. 1975; Grunau et al. 1975; Mitchell et al. 1983). These ages may be partly reset (Bernard-Griffiths et al. 1975). Nevertheless, because the clastic sediments of the Coruja Formation that include the oldest fragments of magmatic rocks contain only Cenozoic foraminifera, there is no positive evidence for Cretaceous volcanic activity. That the Cabo Verde volcanoes were emergent not later than the Early to Middle Miocene ( $\pm 18$  Ma) is suggested by ash layers of this age at the nearby Deep Sea Drilling Sites 368 (Lancelot et al. 1977) and 659 (Ruddiman et al. 1988); however, Lancelot et al. (1977: 251) also noted that “none of our data show evidence of pre-Miocene [subaerial] volcanic activity in the area [of Site 368, Cape Verde Rise]”. Sills of alkaline diabase intruded into mid-Cretaceous sediments at Site 368 are also of Miocene age (19 Ma, Duncan & Jackson 1977).

Likewise, in the Canary Islands that show a similar evolution of oceanic island formation (see e.g. Gutiérrez et al. 2006), only scarce pre-Miocene radiometric data are reported (Le Bas et al. 1986, Carracedo et al. 2002 and references therein). Gutiérrez et al. 2006, based on K-Ar and Ar-Ar data, suggest a Oligocene to early Miocene age for the submarine building and later emergence of Fuerteventura. Even though an Oligocene to Miocene age is now demonstrated for submarine volcanic rocks of Fuerteventura (Gutiérrez et al. 2006) that were interpreted earlier as of Late Cretaceous (Robertson & Stillman 1979) or early Palaeogene age (Le Bas et al. 1986), we cannot exclude a priori that submarine volcanic activity started before the Oligocene because no deep-water (> 1000 m) volcanic facies were found on Fuerteventura until now (Gutiérrez et al. 2006). Also in Cabo Verde, submarine volcanic activity and uplift of the Cape Verde Rise started with all certainty before the Miocene (Stillman et al. 1982). Clear evidence for Early Cenozoic magmatism exists, however, only to the south along the Guinea margin. There, a cluster of magnetic

seamounts occurs on the Sierra Leone Rise along the Guinea Fracture Zone. In this area, lamprophyric lavas of Early Eocene age (53–55 Ma) were dredged on Krause Seamount (Jones et al. 1991). Nadir Seamount, also located on the fracture zone, has been recognized as an alkaline volcano of middle to late Paleocene age (58.6 Ma), rising 3000 m from the sea floor and culminating 860 m below sea level (Bertrand et al. 1993). The alkali basalts and trachybasalts dredged from this seamount are chemically very similar to early dykes of the Basal Complex of Fuerteventura or alkali basalts from the Cabo Verde Islands (Bertrand et al. 1993) and are also typical Ocean Island Basalts. The extrusion of the dated Paleocene and Eocene rocks, dredged from the surface of the volcanoes, must have been preceded by earlier magmatic activity, possibly already in the Late Cretaceous. Although there is no proof that the magmatic rocks of the Canary Islands, Cabo Verde and the Guinean Margin are synchronous, they might reflect a similar tectonic and magmatic history. In particular, both Maio and Fuerteventura have similar spans of oceanic sedimentation followed by alkaline magmatism and uplift (Le Bas et al. 1986).

Two hypotheses have been advanced to explain the magmatic evolution of the Cabo Verde (and Canary) oceanic islands: (1) The volcanic activity results from deep-seated plumes of concentrated heat rising from the lower mantle and leading to partial melting in the mantle (Morgan 1971, 1972). For the Cabo Verde islands, Morgan (1981: 473–474), based on the Cretaceous ages reported by Assunção et al. (1968), postulated a long-lived hot spot history from 120 to 50 Ma and a major island-building stage as early as the Cretaceous. (2) Magmatic activity is related to tectonic activity along old fracture zones reactivated in relation to the rearrangement of plate motions (Le Pichon & Fox 1971). Indeed, the Cabo Verde Islands lie among a series of fracture zones (Williams et al. 1990). Bertrand et al. (1993) pointed out that most of the volcanic centers of the central Atlantic lie in the eastward extension of fracture zones and that this could reflect thermal instabilities within the upper mantle related to their interference with a hot-spot track. The broad bathymetric anomaly of +2 km associated with the Cabo Verde Rise suggests in fact the presence of a hot-spot swell (Crough 1983), and a hot spot origin of the Cabo Verde Islands is now assumed by many authors (e.g. Courtney & White 1986); however, according to later studies, its history would begin only in the Cenozoic (McNutt 1988; Hoernle et al. 2002). This is also suggested by the radiometric data from Maio that cluster around 7–15 Ma (Mitchell et al. 1983), the first appearance of volcanic ash layers at nearby Deep Sea Drilling Sites in the Early or Middle Miocene (Lancelot et al. 1977; Ruddiman et al. 1988) and seismic stratigraphy in the area east of Maio and Boa Vista (Ali et al. 2003). Our data are in agreement with a Cenozoic age of volcanism; they do not support the existence of a long-lived hot spot active at 120 Ma, as postulated by Morgan (1981): The magmatic rocks of the Basal Complex of Maio are oceanic tholeiites and part of the Early Cretaceous ocean floor (Klerkx

& Paepe 1971; Paepe et al. 1974) and unrelated to the much younger Cabo Verde magmatic history; the evolution of volcanic seamounts did certainly not start before the latest Cretaceous or the earliest Cenozoic, and the plateau basalts of the island of São Nicolau and probably most of the other islands are Miocene and still younger in age. Pre-Miocene subaerial volcanic rocks are thus, until now, not documented for the archipelago, and Cretaceous intraplate volcanic activity is still not demonstrated.

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