**Geochronology (Ar/Ar and K–Ar) of the South Atlantic post-break-up magmatism**

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**Abstract:** This work integrates the available geological information and geochronology data for the Cretaceous–Recent magmatism in the South Atlantic, represented by onshore and offshore magmatic events, including the oceanic islands along the transform faults and near the mid-ocean ridge. The analysis of the igneous rocks and their tectonic settings allows new insights into the evolution of the African and Brazilian continental margins during the South Atlantic opening. Following the abundant volcanism in the Early Cretaceous, the magmatic quiescence during the Aptian–Albian times is a common characteristic of almost all Brazilian and West African marginal basins. However, rocks ascribed to the Cabo Granite (104 Ma) are observed in NE Brazil. In West Africa, sparse Aptian–Albian ages are observed in a few coastal igneous centres. In the SE Brazilian margin, an east–west alkaline magmatic trend is observed from Poços de Caldas to Cabo Frio, comprising igneous intrusions dated from 87 to 64 Ma. Mafic dyke swarms trending NW also occur in the region extending from the Cabo Frio Province towards the Central Brazilian Craton. On the West African side, Early Cretaceous–Recent volcanism is observed in the Walvis Ridge (139 Ma), the St Helena Ridge (81 Ma) and the Cameroon Volcanic Line (Early Tertiary–Recent). Volcanic islands such as Ascencion (1.0–0.65 Ma), Tristão da Cunha (2.5–0.13 Ma) and the St Helena islands (12 Ma) most probably correspond to mantle plumes or hot spots presently located near the mid-Atlantic spreading centre. Within the South America platform and deep oceanic regions, the following volcanic islands are observed: the Rio Grande Rise (88–86 Ma), Abrolhos (54–44 Ma), the Vitória–Trindade Chain (no age), Trindade (2.8–1.2 Ma) and Fernando de Noronha (12–1.5 Ma). There are several volcanic features along the NW–SE-trending Cruzeiro do Sul Lineament from Cabo Frio to the Rio Grande Rise, but they have not been dated. The only known occurrence of serpentinized mantle rocks in the South Atlantic margin is associated with the Saint Peter and Saint Paul Rocks located along the São Paulo Fracture Zone. The Cameroon Volcanic Line in NW Africa is related to the magmatism that started in the Late Cretaceous and shows local manifestations up to the Present. The compilation of all available magmatic ages suggests an asymmetrical evolution between the African and South America platforms with more pre-break-up and post-break-up magmatism observed in the Brazilian margin. This is most likely to have resulted from the different geological processes operating during the South Atlantic Ocean opening, shifts in the spreading centre, and, possibly, the rising and waning of mantle plumes.

**Supplementary material:** A complete table with radiometric dates that have been obtained by universities, government agencies and research groups is available at: www.geolsoc.org.uk/SUP18596

This work integrates and summarizes the available information on the Cretaceous–Recent magmatism in the South Atlantic continental margins and oceanic islands that are related to the post-break-up divergence between the South American and African plates (Fig. 1). A brief analysis of the geological setting of the most important magmatic provinces formed after the South Atlantic break-up is presented below.

In the SE region of Brazil, there were two major magmatic events in the continental margin. The first one preceded and was partly coeval with the Gondwana rupturing event that resulted in the formation of the South Atlantic Ocean. This event is associated with the Early Cretaceous large-scale flood lava flows and related dyke swarms of the Paraná Continental Basalt Province, which is also registered as pre-rift and volcanic rocks in the continental margin. The SE Brazilian margins are also characterized by Mid-Cretaceous–Early Cenozoic felsic alkaline intrusive bodies. In addition, there are Cenozoic seamount chains in the western and eastern

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margins of the Atlantic Ocean intruded into the oceanic crust that are normally associated with ocean-island basalts (OIBs).

This chapter presents examples of the above-mentioned magmatism in eastern Brazil, West Africa and adjacent oceanic areas. The Saint Peter and Saint Paul Islets, located in the Equatorial Atlantic Ocean, are also discussed; although they are not volcanic, they constitute an exceptional example of the direct exposure of abyssal mantle rocks (Fig. 1).

### Continental magmatism

The Meso-Cenozoic magmatism registered in the Brazilian territory can be associated with two major magmatic events that occurred in the South American Platform during the continental break-up as follows.

- Pre- and syn-rift tholeiitic magmatism, with radiometric ages of approximately 133–120 Ma (Ar/Ar), which is associated with the fragmentation of West Gondwana, the opening of the South Atlantic Ocean and the implantation of the Brazilian continental margin rift basins (Mizusaki *et al.* 2002).
- Post-break-up alkaline magmatism that occurred during the drifting of the South American and African plates from the Mid-Cretaceous to the Late Tertiary, culminating in a platform uplifting phenomena and the formation of small sedimentary basins in onshore SE Brazil in the Late Tertiary (Asmus 1984; Riccomini *et al.* 2004).

The tholeiitic magmatism in the Serra Geral Formation of the Paraná Basin is equivalent to the offshore volcanic rocks flooring the continental margin rift basins and heralds the break-up processes that formed the South Atlantic Ocean (Asmus 1984; Mohriak 2003). The Early Cretaceous dyke swarms are scattered in the State of Rio de Janeiro and São Paulo, along the Santos, Campos and Espírito Santo basins (Fig. 2). Some of them are well exposed on sea-cliffs, on outcropping areas along the coastline or in adjacent regions (e.g. in São
Sebastião Island, Ubatuba, Búzios Island, Tijuca Massif, Paracambi, Petrópolis, Ponta Negra, Cabo Frio, Arraial do Cabo and Armação de Búzios).

There are two distinct dyke orientations: N50°E and N10°W (Guedes et al. 2005). Most of the dykes are oriented at approximately N50°E. These dykes are wide, from 8 to 10 m, locally 47 m, and composed primarily of gabbro and diabase. They exhibit horizontal columnar joints of 50 cm up to 1 m in diameter and are considered to be the feeders of the continental flood basalts. In contrast, the basaltic lava flows are found at the basement of the Cenozoic sedimentary basin of the Pelotas, Santos, Campos and Espírito Santo basins in eastern Brazil (Mohriak 2003), and also occur in the conjugate African basins from Angola to Namibia (Marzoli et al. 1999).

The tectonomagmatic events that shaped the continental margin after the break-up are divided into the volcanic features observed onshore and offshore. Continental magmatism (tholeiitic basalts and intrusions with alkaline affinities) evolved into mid-ocean ridge basalts (MORBs) as a result of the South Atlantic opening and plate divergence. Magmatic lineaments affecting the oceanic crust are observed along the Brazilian and West African margins (e.g. along the Cameroon Volcanic Line and in the Sumba or Angolan Lineament in offshore Angola).

Most of the Paraná flood basalts and their related dykes have compositions at the limit between basalt and andesite (Peate et al. 1992; Guedes et al. 2005). Among the dykes, most of them are the low-Ti type, but there are some present of the high-Ti type. The dykes of Arraial do Cabo indicate Early Cenozoic ages with highly rugose age plateaus (Benno et al. 2003), so it is believed that they are dated at approximately 135 Ma, based on the well-defined Ar/Ar ages (Stewart et al. 1996). The dyke direction is defined primarily by the local stress field during their intrusion, regardless of the weak zones of the host rock when the stress is relatively low, at less...
than approximately four times the tensile yield stress of the host rock.

The mafic dykes of the State of Rio de Janeiro, particularly along the Cabo Frio between the Santos and Campos basins (Fig. 3), show intrusions according to hydraulic shear fracturing (Solberg et al. 2005; Motoki et al. 2009b), which is represented by the left-sense strike-slip displacement between the blocks separated by the dyke, the left lateral-sense en echelon linkages (Fig. 3e), the tabular xenoliths along the dyke contact plane (Fig. 3f), and a conjugate dyke system with a direction of N50°E and N10°W.

The dykes present in the oriental terrane of the Brazilian Orogeny are subparallel to the structure of the basement; therefore, the intrusion mechanism was attributed to the magma fill in the pre-existing weak zone of the host rock (e.g. Schmitt & Stanton 2007) following the so-called fracture-fill model (e.g. Delaney et al. 1986; Delaney & Gartner 1997). However, the basement orthogneiss of the Cabo Frio and Arraial do Cabo areas is an original member of the Congo Craton. This terrane is known locally as the Cabo Frio Terrane (Schmitt et al. 2004, 2008), and the orthogneiss occurs at N10°W–N30°W. This direction is

![Fig. 3. Mode of field occurrence of basaltic dykes of the Cabo Frio area: (a) wide and continuous dyke; (b) narrow parallel dykes; (c) left-handed branching; (d) en echelon linkage of left-lateral sense shear stress; (e) en echelon linkage of small dyke of left lateral sense; and (f) very high aspect ratio tabular xenolith.](image-url)
quite different from the mafic dyke orientation, which is N55°E. The wall rocks of these dykes are metamorphic rocks of the Ribeira Orogenic Belt, which correspond to the late stage of the Pan-African continental collision zone. These wall rocks include the orthogneiss of the Occidental Terrane, the paragneiss of the Paráiba do Sul Unit, the orthogneiss of the Oriental Terrane, the paragneiss of the Costeiro Unit, the paragneiss of Búzios Unit, the orthogneiss of Região dos Lagos Unit and the amphibolite of the São Mateus Unit (Campos Neto 2000; Heilbron et al. 2000; Heilbron & Machado 2003; Schmitt et al. 2004). According to recent zircon U–Pb geochronology, their metamorphic ages are Cambrian (approximately 550 Ma for the charnockite unit in Niterói). The orthogneiss of Região dos Lagos has an intrusive age of 1970 Ma and a metamorphic age of 530 Ma. They are intruded by the Andorinha post-tectonic granite dykes and a related granitic pluton of 510 Ma, and they are cut by the tectonic breccia of the last stage of this orogeny.

The break-up between the West African and the Brazilian plates followed the suture or weakness zones inherited from the previous continental collision. The mafic dykes and the Early Cretaceous rift basin border faults are characterized by similar structural trends, particularly along the Santos, Campos and Espírito Santo basins in SE Brazil. These mafic dykes are related to the igneous centres and long fissures that most probably fed the flood basalts in the onshore and offshore regions during the break-up episode.

At the initial stage of continental rifting, parallel dykes intruded along the spreading axis zone by hydraulic tensile fracturing under moderate extensional tectonism (Fig. 4a). The dyke swarm of the Ponta Grossa Arc in the Paraná State of SE Brazil corresponds to this stage. The dyke orientation is parallel to the spreading axis, which corresponds to S1 of the intrusion time. At the advanced stage, a large deviatoric stress caused by a strong extension can occur in off-rift axis zones (Fig. 4b). In the Early Cretaceous, the studied area corresponded to the western lateral off-rift axis zone of magmatism. The spreading axis at that time must have been present at the continental slope. The orientation direction of the mafic dykes is N50°E and N10°W, directions that are oblique to the continental rifting axis. The conjugate orientations of the dykes indicate that the S1 direction during the intrusion was N20°E.

Following the continental break-up and divergence of the continental margins, Mid-Cretaceous dykes and intrusive bodies were emplaced in the Brazilian and African regions. These features are the main subject of this paper and are described herein.

In Brazil, some lineaments are subparallel to the Early Cretaceous NW-trending dykes of the Ponta Grossa Arch and occur along the Paraíba Arch that separates the Paraná Basin from the São Francisco Basin. Alkaline and kimberlite intrusions are recorded along this lineament, which extends from the coastline towards the Central Brazilian Shield (Mohriak 2003, 2004). Other lineaments are subparallel to the coastline between the Santos and Campos basins, such as the east–west-trending Poços de Caldas–Cabo Frio Lineament, which is characterized by Mid-Cretaceous–Early Tertiary intrusive rocks onshore, and intrusive and extrusive rocks offshore. The frequency of the radiometric ages from post-break-up rock samples (described in detail below) from the South Atlantic (Fig. 5) can be divided into four main classes: the Upper Cretaceous, with more than 40 radiometric ages for the intervals 60–80 Ma; the Miocene–Recent, with 10–20 samples; and the less frequent radiometric ages for the Miocene–Recent, with the Mid-Cretaceous (90–105 Ma). The oldest magmatic event that post-dates the inception of the oceanic crust in NE Brazil is registered in the Cabo de Santo Agostinho magmatic province, which is onshore near the Pernambuco–Paraíba coastal basins (Fig. 1).

**NE Brazil: the Cabo de Santo Agostinho Granite**

The Cabo de Santo Agostinho region is located on the southern coast of Pernambuco State, and is famous for its geological, historical and touristic aspects, which are all located in the same geographical area (Fig. 6). The region is renowned for its Cabo de Santo Agostinho Granite (or just Cabo Granite), a semi-circular body with an area of approximately 4 km², representing a rare example of a Mid-Cretaceous granite in Brazil (102 ± 1 Ma, Ar/Ar). It is the southernmost and youngest pluton of the hot-spot trace that connects several granitic intrusions which occur in the conjugate margin (Nigeria and Cameroon). Long et al. (1986) suggests that the Ascension plume was responsible for melting the feldspathic arenites in the continental crust at pressures of 5–6 kbar. The Cabo Agostinho pluton is located at the point where the Ascension plume intersects the NE Brazilian coastline. Tectonic reconstructions also indicate that the basaltic–rhylitic magmatism observed in the area is associated with the plume.

The Cabo Granite presents one main petrographic facies with an equigranular, medium-grained texture hosting microgranite autoliths. The rocks of the Cabo Granite comprise an acidic, alkaline, volcano-plutonic association that was generated by
a partial melting of the continental crust (Nascimento & Souza 2009). Petrographically, the rocks are classified as alkali-feldspar granites, including orthoclase, quartz and sodic plagioclase, as well as amphibole (riebeckite–arfvedsonite), magnetite, allanite, fluorite and zircon. Concomitant with the emplacement of the Cabo Granite, an important basic–acidic (basaltic–rhyolitic) volcanism was occurring in the adjoining area. Therefore, approximately 102 Ma ago, the region was the locus of a relatively voluminous volcano-plutonic magmatism that most probably extended to the offshore

Fig. 4. Schematic illustration for the genesis of Early Cretaceous parallel dyke swarms: (a) hydraulic tensile fracturing in an initial stage of continental rifting on the central axis zone under moderate spreading tectonism and deviatory stress; and (b) hydraulic shear fracturing at an advanced stage on lateral zones under strong extension tectonism and high deviatory stress.

Modified from Motoki et al., 2009.
rifts (Pernambuco–Paraiba Basin). The magmatism in West Africa extended over time, affecting the oceanic and continental crusts with volcanic episodes in the Tertiary and Quaternary times, as will be discussed below for the Cameroon Line.

Alkaline magmatism in SE Brazil: from the Cretaceous to the Tertiary

According to geological studies conducted by universities and government agencies, the continental alkaline magmatism in SE Brazil (Fig. 7) occurs as plugs, stocks, dykes and sills that present several trends, from a general ENE direction for the dykes to NW–SE and east–west lineaments, as evidenced by the geological and geophysical datasets in the continental crust adjacent to the Santos and Campos basins (e.g. Sadowski & Dias Neto 1981). These alkaline complexes most probably represent the roots of extinct Cretaceous volcanoes (Motoki et al. 2008d). Over time, the volcanic superstructures have eroded and only the plutons remain, as is also observed present day along the Cameroon Line, where volcanoes have been deeply eroded in some segments.

In the State of Rio de Janeiro and its adjacent areas, along the longitude 42°W–ESE lineament, there are a dozen felsic alkaline intrusive rock bodies forming a WNW–ESE lineament called the Poços de Caldas–Cabo Frio alkaline rock alignment (Sadowski & Dias Neto 1981; Thomaz-Filho & Rodrigues 1999; Riccomini et al. 2004). This lineament includes several intrusions, such as Itaitaia (Brotzu et al. 1979), Morro Redondo (Brotzu et al. 1989), Tinguá (Derby 1897), Mendanha (Motoki et al. 2007c), Itaúna (Motoki et al. 2008d), Tanguá, Rio Bonito, Soarinho (Motoki et al. 2010), Morro dos Gatos, Morro de São João (Brotzu et al. 2008; Mota et al. 2009) and Cabo Frio Island (Motoki & SicHEL 2008; Motoki et al. 2008a). These igneous intrusive complexes (Fig. 8) have various ages that span the interval from 85 to 55 Ma.

The alkaline intrusions present some residual relief bodies, in part formed by plutons of an alkaline nature, and are lined up according to a WSW–ENE trend. For example, the Itaitaia–Passo Quatro complexes, with peaks up to 2800 m above sea level, represent the highest elevations on the Atlantic side of South America. Over a distance of 500 km, they were emplaced into the northern segment of the Neoproterozoic Ribeira belt. Poços de Caldas, with an area of approximately 800 km², is the largest alkaline complex in Brazil and one of the largest in the world.

In addition, the Cananeia and Jacupiranga intrusions, located between Paraná and the São Paulo states, are well known for their complex lithologies...
and are of economic importance as Ti-rich minerals are sought in the carbonatites from Jacupiranga. In São Paulo, there are several alkaline complexes, the most important of which are the intrusive bodies observed in Ponte Nova, Passa Quatro and São Sebastião Island.

Most of the intrusions are constituted by main stocks, with sizes varying from less than 1 km up to 15 km in diameter. They are composed of nepheline syenite and alkaline syenite, with associated small bodies of phonolite and trachyte. Rarely, coarse-grained mafic alkaline rocks are found in the Morro de São João Intrusive Complex (Brotzu et al. 2008; Mota et al. 2009) and Cabo Frio Island. The fine-grained rocks that originated from the magma of a similar composition are observed to be lamprophyre dykes. These rocks are globally scarce in occurrence but relatively common in the State of Rio de Janeiro, and are quarried for their high-quality ornamental construction material (Petrakis et al. 2010). The alkaline intrusive complexes form geomorphological features (Fig. 9) with relative heights of between 300 and 900 m that are locally called alkaline massifs. The occurrence of alkaline massifs is attributed to the strong erosive resistance of nepheline syenite, alkaline syenite, phonolite and trachyte. However, their constituent minerals, especially nepheline and alkaline feldspar, are vulnerable to chemical weathering in the humid, tropical climate.

The origin of the felsic alkaline magmas is not yet clearly understood. In the field, highly felsic nepheline syenite and alkaline syenite are found with rare occurrences of mafic alkaline rocks. However, intermediate alkaline rocks are very scarce. Therefore, it is difficult to accept the fractionation crystallization model of mafic alkaline magma. In addition, there are a small number of silica-saturated rocks in the contact zone of the Mendanha (Motoki et al. 2007a) and Cabo Frio Island intrusions (Motoki et al. 2008b). The existence of pseudoleucite in the nepheline syenite, with a relatively low SiO₂ content, indicates that the relatively less-differentiated felsic alkaline magma is K-rich and that it becomes Na-rich by means of fractionation crystallization.

Based on the chemical analyses and their petrological interpretation, Motoki et al. (2010) proposed a three-stage magma evolution model (Fig. 10a, b). The relatively less differentiated nepheline syenite magma has a high K₂O/(Na₂O + K₂O) ratio; however, the leucite-crystallizing magma and the
residual magma have a lower K\textsubscript{2}O/(Na\textsubscript{2}O + K\textsubscript{2}O) ratio. The first phase is called stage 1 and continues until the arrival of the residual magma composition at the cotectic curve. During the slow cooling of the magma, leucite crystals transform into pseudoleucite. Examples of stage 1 are observed in the Tanguá and Morro de São João complexes. The next process is alkaline feldspar crystallization. This crystallized alkaline feldspar is expected to be moderately potassic, with the K\textsubscript{AlSi\textsubscript{3}O\textsubscript{8}}/Na\textsubscript{AlSi\textsubscript{3}O\textsubscript{8}} proportion ranging from 0.6/0.4 to 0.7/0.3. Through the fractionation of the alkaline feldspar, the residual magma changes from K-rich to Na-rich, sliding on the cotectic curve. Examples of this phase, called stage 2, are commonly found; stage 2 continues until the lowest temperature point on the cotectic curve is reached. Some samples from Cabo Frio Island, Itatiaína, Itatiaia and Rio Bonito indicate that the magma composition arrived at the point closest to the lowest temperature. During stage 2, the assimilation of the continental crust country rocks can occur. Then, the magma composition is pulled up from the cotectic curve to the granite composition, thereby crossing over the thermal divide (Fig. 10a, b). This process, called stage 3, forms felsic alkaline rocks without nepheline; examples of this are found at Mendanha, Soarinho, Morro dos Gatos and Cabo Frio Island.

The pyroclastic rocks present at Mendanha and Itatiaína were considered to be constituent rocks of the surface volcanic deposits. Based on this idea, they were interpreted to be extinct volcanic edifices. The contact planes between the pyroclastic bodies and their host rocks are subvertical without an intercalation of palaeosoil and organic materials. Therefore, the outcrops are considered to be intrusive contacts. Some of the pyroclastic bodies are very small (less than 4 m wide: Motoki et al. 2007c) and are described as pyroclastic dykes. A pyroclastic dyke of the Morro dos Gatos is composed of densely welded vitric tuff.

According to the fission track dating for apatite (Hackspacher et al. 2004; Motoki et al. 2007b), the present exposure is considered to be a subvolcanic structure from 3 km below the surface at the time of eruption (Fig. 11). The volcanic edifices and surface eruptive materials of that time have been completely eliminated by 3 km of regional uplift that occurred until 40 Ma (Riccomini et al. 2004). Motoki et al. (2008c) proposed the following eruption model: (1) trachyte dyke intrusion and its arrival at the Earth’s surface, called the intrusion stage (Fig. 11a); (2) fluidization of the trachyte
magma and pyroclastic flow occurrence, termed
the fluidization stage (Fig. 11b); and (3) volcanic
conduit implosion, and successive welding and
secondary flowage of the vent-filling pyroclastic
materials, defined as the implosion stage (Fig. 11c).

Representative examples of the alkaline intru-
sions are described in more detail below.

**Cananeia.** The Cananeia Massif, in the so-called
Ribeira Valley (State of São Paulo, SE Brazil),
is represented by two small bodies of alkaline
rocks (Morro de São João, 1.8 km², and Morrete,
0.4 km²). The rocks are syenitic in composition,
dominantly intrusive, covered by recent sediments
and emplaced into the Precambrian basement of
the Mesoproterozoic Açungui Group. From the tec-
tonic point of view, they are associated with the
Guapiara Lineament at the northern limit of the
Ponta Grossa Arch and intruded into the homon-
yous province, which includes a great number of
alkaline centres and mafic dykes along a NW
trend. Ar/Ar radiometric determinations in biotite
indicate an average age of 83.6 Ma for the syenites,
which is not very different from that given by a
Rb–Sr reference isochron on whole rock for differ-
ent lithologies that yielded an age of $85.6 \pm 2.7$ Ma
and an initial $^{87}$Sr/$^{86}$Sr ratio of $0.70667 \pm 0.00014$
(mean square weighted deviation (MSWD) = 1.14).
The data confirm the inclusion of the Cana-
eia Massif within the age group of the Late Cretac-
eous alkaline occurrences.

**Ponte Nova.** The Ponte Nova alkaline mafic–
ultramafic massif lies in the northern sector of the
Serra do Mar Province, close to the eastern part
of the Mantiqueira mountain range, SE Brazil.
Fig. 10. Geochemical evolution of nepheline syenite magma for the alkaline rocks of the Poços de Caldas–Cabo Frio magmatic alignment: (a) data plotted on the SiO$_2$–NaAlSi$_3$O$_8$–KAlSi$_3$O$_8$ diagram without H$_2$O and with 1 kb of H$_2$O; and (b) its interpretation proposing three stages of magmatic evolution.

Modified from Motoki et al., 2010.

Fig. 11. Schematic illustrations for the formation processes of the pyroclastic rocks of the Mendanha, Itaita, Morro dos Gatos and Cabo Frio Island: (a) forceful intrusion of trachyte dyke and lava dome formation on the surface; (b) magma fluidization and pyroclastic flow emission; and (c) conduit implosion by vent collapse, and welding and secondary flowage of vent-filling pyroclastic materials.

Modified from Motoki et al., 2008.
The massif is exposed in two different areas separated by basement rocks: the larger (c. 5.5 km²) is elliptical in shape and has a wide variety of rock types; the smaller (c. 1 km²) is irregular, petrographically less complex and occurs south of the former. It is primarily composed of an alkaline gabbro association generated by successive magmatic pulses. The more abundant rocks are metababbros and ultramafic cumulates (e.g. olivine clinopyroxenites and olivine-bearing metababbros) found in the lower parts of the massif, together with porphyritic, equigranular and banded gabbros, and monzogabbros in the upper portions. A magmatic breccia and a suite of dykes (lamprophyres–tephriphonolites) cut the intrusion. K–Ar geochronological data for the different rock types yielded an average Late Cretaceous age of 87.6 Ma (see Supplementary material), which is comparable to the age of other alkaline intrusions present in the northern sector of the province.

São Sebastião. São Sebastião Island is located on the SE coast of the State of São Paulo (Fig. 2). It is composed of Precambrian granitic rocks that were modified by the Brasiliano Cycle, and it was intruded by Early Cretaceous subalkaline basic–acid dykes, and by Late Cretaceous alkaline stocks and dykes. The Early Cretaceous dykes have a NE trend, and are of a variable thickness (2–50 m) and limited extent (2–15 km). These dykes are cut by alkaline stocks (syenites). Chlorite and epidote were observed in most of the basic and acid dykes, indicating that the rocks suffered high-temperature alteration processes. The Early Cretaceous basic dykes can be considered as an easterly extension of the Santos–Rio de Janeiro swarm located inland. A whole-rock K–Ar age determination of the Santos–Rio de Janeiro swarm located between Rio de Janeiro and Cabo Frio was modified by the Brasiliano Cycle, and it was intruded during the break-up of Gondwana. The alkaline complex is composed of syenites, foyaites, pulaskites, quartz syenites, magmatic breccias and alkaline granite. The mean Ar/Ar age obtained from 10 biotite samples from the Itatiaia rocks is 70.5 ± 3.3 Ma.

Passa Quatro. The Passa Quatro Alkaline Complex (148 km²) is close to the Itatiaia complex. It was emplaced into the Precambrian metamorphic complexes of Juiz de Fora, Paraiba do Sul and the Açungui Group. The main lithological types are alkali plutonic rocks (nepheline syenites) with minor phonolitic dykes. The K–Ar age obtained from only one sample of amphibole separated from a nepheline syenite is 67 ± 3 Ma. The Rb–Sr whole-rock age calculated by Brotzu et al. (1979) is 77 ± 3 Ma (Rᵣ = 0.705051, with a MSWD = 6). This MSWD value indicates a perturbation of the Rb–Sr system. The Rb–Sr age (whole rock) is 70.4 ± 0.5 Ma (Rᵣ = 0.70540). The initial Sr isotopic ratio in both determinations suggests that significant crustal contamination is not evident in these rocks.

Mendonha. The Mendonha Massif is a young alkaline complex (80–53 Ma, K–Ar; 64 Ma Ar/Ar) inserted into a NW–SE magmatic alignment in Rio de Janeiro (Fig. 8). It is distinguished by the inclusion of subvolcanic and volcanic types, which are rarely identified in other plutonic provinces in this alignment. The Mendonha Massif comprises a non-saturated suite predominantly composed of foyaites, tinguaytes and nepheline syenites. It presents a mineralogical and textural variation showing syenite, trachitic lavas and breccia intercalation. The plutonic suite and trachitic lavas are associated with two main volcanic structures. The first one is a 2 km conduit structure, originally described as the Nova Iguacu Volcano by Lamego (1954), which consists of a central agglomerate with bombs and abundant tuff and lapilli. The second one is a smaller conduit composed of trachytic welded tuffs and volcanic breccias. The record of these volcanic structures may suggest rapid explosive magmatic processes possibly controlled by ascendant hot gases with suspended fragments (fluidization) that accumulated in flat magmatic chambers (Fig. 12).

Tanguá. Tanguá Hill is the western most intrusion associated with the Rio Bonito Massif, which is located between Rio de Janeiro and Cabo Frio (Fig. 8). The alkaline massif yields an isochronic Rb–Sr age of approximately 72 Ma, and includes several rock types such as nepheline syenite, alkali syenite, breccias and phonolites (Fig. 13) (Motoki et al. 2010).
Paranaíba Arch igneous intrusions. The Paranaíba Arch is located along a NW lineament that extends from the Cabo Frio region, between the Campos and Santos basins, towards the central Brazilian region, west of Belo Horizonte (Fig. 2). It separates the Palaeozoic Paranaí Basin from the Precambrian São Francisco Basin. Several igneous intrusions are registered along this trend, which is mainly marked by linear magnetic anomalies (Fig. 14). The Catalão, Serra Negra, Araxá and Tapira intrusions are a few of the many igneous bodies that occur along the lineament, which is also marked by many kimberlite pipes, carbonatite and kamafugite intrusive and extrusive rocks. The origin of the lineament has been questionably ascribed to the Trindade plume, whereas other authors suggest a genetic link to the Tristão da Cunha hot spot (Van-Decar et al. 1995).

The Serra Negra intrusions lie near the city of Patrocínio in Minas Gerais, and the basement rocks correspond to the metasediments of the São Francisco Basin (Fig. 15). The Palaeozoic sediments of the Paraná lie to the SW of the lineament, indicating a major uplift during the Late Cretaceous emplacement of the intrusive rocks. NW–SE magnetic lineaments, similar to those that are observed in the Ponta Grossa Arch of the Paranaí Basin, are associated with linear dykes that are associated with the intrusive bodies (Fig. 16).

Morro de São João. The Morro de São João Alkaline Complex is located in the NE part of Rio de Janeiro State, near the border fault of the Campos Basin, and shows a pronounced topography near the coastline (Fig. 17). It is characterized by the following lithologies: coarse-grained felsic syenites (K-feldspar, nepheline, hornblende, titanite and pseudoleucite) and mafic syenites (with K-feldspar, hornblende and pyroxene). Petrography and lithogeochemistry data suggest a bimodal suite. Felsic
and mafic magma mixing and mingling textures are locally observed, indicating the presence of coeval magmas. Nd and Sr isotope compositions correspond to EMI (Enriched Mantle I) mantle reservoir signatures, suggesting an asthenospheric-enriched mantle source with low $^{87}\text{Sr}/^{86}\text{Sr}$ values (from 0.7049 to 0.7061) and low $^{143}\text{Nd}/^{144}\text{Nd}$ values (from 0.512361 to 0.512428). The $\epsilon_{\text{Nd}}$ values range from $-4.03$ to $-5.54$, indicating an anomalous enriched mantle reservoir, confirmed by the high TDM (depleted mantle age) values (between 730–830 Ma), which are very different from the 72–56 Ma Ar/Ar cooling ages. The comparison of Sr and Nd signatures with related hot-spot traces (Trindade, St Helena and Tristan da Cunha) indicates that they are similar to those of Tristan da Cunha, but somewhat different from those of Trindade and St Helena.

Cabo Frio Volcanic Province in the offshore basins

The Cabo Frio Volcanic Province is located between the Santos and the Campos basins (Figs 2 & 8). Several intrusive and extrusive igneous bodies are identified in the seismic profiles (Fig. 18) that are associated with sediments from the Late Cretaceous to the Eocene age (Mohriak 2003; Oreiro 2006). A number of oil fields have been discovered in turbidite sands adjacent to and underlying some of these volcanic structures.

### Continental platform and deep ocean magmatism

Brazil has several volcanic complexes in the continental margin that are located near the continent–ocean boundary, such as the seamounts in the Cumuruxatiba and Jequitinhonha basins. There are several oceanic archipelagos, some emerging from the continental shelf and some occurring in the deep sea: Abrolhos, Vitória-Trindade, Martin Vaz, Fernando de Noronha and the Rio Grande Rise (Fig. 1). On the African side, the Cameroon Line is the only record of magmatic activity during the Tertiary, but the Walvis Ridge (Namibia) and the Angola Seamount Lineament (Sumbe Lineament) in southern Angola are most probably related to the break-up and early drift phases. In the northern Brazilian margin, the small islands of São Pedro and São Paulo, located near the Romanche Fracture Zone, are the only known occurrences of

Fig. 13. Photomicrography in crossed nics for the samples of the Tanguá alkaline intrusive body: (a) nepheline syenite; (b) alkaline syenite; (c) subvolcanic vent breccia; and (d) phonolite. Af, alkaline feldspar; Ne, nepheline; Amp, amphibole; Tn, titanite; Tr, trachyte (phonolite?) clast.
serpenitized mantle rocks that bear continental crust affinities but were exhumed in the oceanic crust basement.

The Abrolhos Bank is the largest expression of the continental platform offshore of Brazil. It is marked by very shallow bathymetry (the carbonates overlying the basaltic rocks are within 100 m of sea level) and is surrounded by an abrupt passage to a deeper water setting (approximately 1500–2000 m) on all but the western (landward) side (Fig. 19). The magmatic succession observed in the Abrolhos Archipelago comprises three units: olivine–plagioclase basalt, pyroxene–plagioclase–olivine basalt and pyroxene–plagioclase basalt. These volcanic units are stratigraphically stacked from the base to the top in units separated by marked differences in terms of texture, structure and mineralogy. The Abrolhos basalts that have been sampled by exploratory boreholes comprise a transitional series of alkaline affinity, and the rocks were classified as: basalts; trachy-basalts; basanites and tephrites; and basalts and trachy-basalts. A regional seismic profile across the Abrolhos Volcanic Complex and extending through the Besnard Bank (Figs 20 & 21) indicates that the magmatism was accompanied by compressional tectonics affecting the Late Cretaceous–Tertiary sedimentary sequences (Mohriak 2003).

Vitória–Trindade. The Vitória–Trindade Chain is an east–west lineament of seamounts that passes to the south of the Abrolhos Bank (Fig. 20). It extends for approximately 1300 km and is composed of 13 large volcanic edifices. Half of them correspond to guyots; therefore, these volcanic edifices are higher than 3500 m from their oceanic basements. The seamounts are covered by biogenic carbonate sediments with thicknesses greater than 200 m. The pillow-lava basalts outcrop adjacent to the volcanoes, and occasionally occur at the heads of landslides and valley bottoms. At the east end of this volcanic chain, wave-cut erosion exposes the small islands of Trindade and Martin Vaz, which correspond to a horizontal section through these volcanoes. The present-day island surfaces rise a few tens to a few hundreds of metres above sea level, and are the only places in which fresh rock samples can be obtained for geochronology.

It has been suggested that there is a relationship between these seamounts and the flood basalts of the Abrolhos Banks. The analysis of the geophysical data, however, indicates no clear evidence that the oceanic extension of the Vitória–Trindade Chain produced the basement under the Besnard Bank (Fig. 21). The basement can be modelled as a homogeneous igneous layer with a good fit to the geophysical data, particularly in the area between Besnard

Fig. 14. Regional topographical map of the Paranaíba Arch in Minas Gerais State, west of Belo Horizonte. The arch is marked by NW lineaments based on magnetic anomalies and Upper Cretaceous igneous rock intrusions, identified on the map by red circles (Catalão in the NW, Serra Negra in the centre, and Araxá and Tapira to the south, near 20° S).
Bank and the rest of Abrolhos Bank, so both are interpreted as Precambrian crust overlain by basalts and sediments. The Abrolhos Bank flood basalts occur within a sedimentary sequence interpreted as Late Cretaceous–Early Tertiary.

The K–Ar and Ar/Ar ages for the rocks from the islands in the Abrolhos Archipelago yielded values from 40 to 60 Ma. The younger ages are related to (top) basaltic rocks from the Santa Bárbara Island, and the older ages suggest that several magmatic episodes piled up different volcanic formations that are presently observed in the archipelago and in offshore seismic data in the Espírito Santo Basin (Mohriak 2003).

The oceanic extension of the Vitoúria–Trindade Chain is composed of many seamounts and guyots that rise up to 4–5 km above the sea floor, and extend for more than 1000 km along the 20°30′S parallel. There are three main banks that are referred to as the Vitoúria, Davis and Columbia seamounts. A seismic profile illustrating the seamounts in the Vitoúria–Trindade Chain (Fig. 22) indicates that the top of the volcanic edifice was near sea level in Tertiary times.

VanDecar et al. (1995) have suggested that there is no evidence of a mantle plume, and that the magmatism forming the Trindade, Martin Vaz and Vitoúria seamount chains between Trindade and the Brazilian mainland is the result of a ‘leaky transform fault’. This suggestion may be considered as an end-member case of a leaky transform fault, which is a spreading centre. However, a spreading centre generates an oceanic crust of normal (c. 7 km) thickness over the convecting mantle with a global ambient potential temperature of approximately 1300 °C; it does not generate a seamount chain.

With the exception of Trindade and Martins Vaz Island, the basalt outcrop areas along this volcanic seamount chain are virtually unknown. There are no available Ar/Ar datings, and only one sample of the Columbia Seamount has had a geochemical study. The analytical results indicate that the rock is a clinopyroxene-rich alkaline basalt (anakaramite), and the isotopic ratios of the clinopyroxene crystals resemble those of the Trindade Island (Fodor & Hanan 2000). Vintage K–Ar ages for the Vitoúria–Trindade Chain range from the Middle Pliocene to the Holocene (2.3 and 2.9 Ma: according to Cordani 1970 and Valencio & Mendía 1974). The oldest Ar/Ar age obtained from a basanite dyke sample from this chain is 4 ± 01 Ma, and the youngest age is 0.17 Ma.

Fig. 15. Geological map of the Paraiba Arch in Minas Gerais State, between the Paraná and the São Francisco basins. Selected large alkaline igneous intrusions along the NW–SE lineament, between Catalão and Serra Negra, are marked by yellow dotted lines. The simplified lithostratigraphy is from CPRM (Geological Survey of Brazil) geological maps.
Trindade and Martin Vaz are built on an oceanic crust greater than 70 Ma in age; the oceanic lithosphere of this age is around 120 km thick, with an approximately 90 km-thick mechanical boundary layer. Trindade and Martin Vaz rise from a broad topographical swell beneath water that is 5 km deep. Trindade Island reaches about 600 m above sea level, and its total height is, thus, approximately 5.5 km. Trindade is therefore a volcanic edifice that is similar in height to those of the Hawaiian Islands and the Canary Islands in NW Africa, although it has steeper sides and is therefore less voluminous. It is built on a lithosphere that is probably somewhat thicker than the Hawaiian oceanic crust and drifting at a similar velocity to the plate beneath Hawaii.

A seismic profile of the oceanic extension of the Vitória–Trindade Chain, basinwards of the Besnard Seamount (Fig. 22), bears several similarities with the seamount chains in the NW African margin, such as the islands and seamounts along the Camer-oon Volcanic Line or the Canary Islands in NW Africa. The model for these post-break-up structures includes an igneous cone, subaerial volcanics and volcaniclastic rocks forming the flanks of the volcanic edifice (Fig. 23).

The small Trindade Island (8 km$^2$) is a volcanic edifice in the western South Atlantic Ocean, located approximately 1100 km from the Brazilian mainland and 1200 km north of the Rio Grande Rise. Its main constituent rock is a highly silica-undersaturated Na-rich alkaline basalt, and pyroclastic rocks are also common (Weave 1990). There are 16 large phonolite necks, up to 400 m in diameter, which intrude into the basalt (Almeida 1961). The trace elements’ behaviour and isotopic compositions suggest that the alkaline rocks may have originated from a mantle plume (Siebel et al. 2000).

The ages of the Trindade rocks by K–Ar dating are between 2.90 and 2.30 Ma. The rocks from the Desejado Sequence were formed between 2.30 and 1.50 Ma, and the Morro Vermelho Formation rocks formed earlier than 0.17 Ma. According to Sr–Nd isotopic systematics, mixing between the predominant depleted mantle and the subordinate EMI components may explain the isotopic variations. The magmatic activity at Trindade was essentially
bimodal, generating various ultrabasic rocks and mesocratic–leucocratic phonolites. The older episodes comprised the pyroclastic rocks of the Trindade Complex. The youngest volcanic events were composed exclusively of ultrabasic rocks (clinopyroxenites, ijolites and malignites). The very small Martin Vaz Island (1 km²), which is located approximately 70 km east of Trindade, ascends nearly 5175 m from the ocean floor and 175 m above sea level. Both islands form the easternmost part of the largest seamount chain (Trindade–Columbia or Trindade–Vitória seamounts) that extends offshore of the eastern coast of Brazil.

Discussions involving the origin of the Vitória–Trindade oceanic chain often point to a geotectonic correlation with the onshore Poços de Caldas–Cabo Frio alkaline rock alignment. Herz (1977) observed that the radiometric ages of the onshore alkaline rocks tend to become younger from the west to the east, and attributed the magmatic alignment to a hot-spot track. The well-defined Rb–Sr age for the Poços de Caldas Intrusive Complex, the west-end alkaline body, is approximately 85 Ma, and the radiometric age for Cabo Frio Island, located at the east end, is 51 Ma.

Thomáz-Filho & Rodrigues (1999) and Thomáz-Filho et al. (2005) attempted to link the Poços de Caldas–Cabo Frio alignment to the Vitória–Trindade volcanic chains, interpreting them as a continuous single hot-spot track. These chains are subparallel, but the offshore chain is situated approximately 280 km to the north of the onshore trend (Fig. 2). The above-mentioned works have proposed two sharp inflections for the South America plate motion to resolve the large offset controversy between these two chains. According to the model, the inflections in the plate movement should have occurred at 35 Ma (counterclockwise rotation) and at 55 Ma (clockwise rotation).

The above-mentioned hot-spot track model for the Poços de Caldas–Cabo Frio and Vitória–Trindade alignments contains some still unresolved problems (Gibson et al. 1997). Although the felsic alkaline bodies of the Poços de Caldas–Cabo Frio alignment have a general tendency to become younger from the west to the east, the ages are not quantitatively proportional to the position. Recent Ar/Ar dating has revealed that there are age inversions. The eruption ages of the seamounts are largely unknown, but the islands at the easternmost extremity of the chain are younger.
Fig. 19. Three-dimensional image of the topobathymetry along the eastern Brazilian margin, showing the Abrolhos platform, the Vitória–Trindade seamount chain and the seamounts on oceanic crust.

Fig. 20. Predicted bathymetry relief map for the Vitória–Trindade seamount chain (based on the TOPO database version 12.1). Approximate locations of seismic profiles SS1 (across the Abrolhos Bank) and SS2 (along the Vitória–Trindade Chain) are shown as white lines.
However, the main problem is related to the kinetics of the South American Plate’s movement. The present plate’s motion direction, relative to the hot spots measured by satellite, is to the NNW, and that from the Gondwana break-up is NW to NNW. This direction is parallel to the Macau–Cabugi Cenozoic magmatic chain of alkaline basalts of the Rio Grande do Norte State, which includes the Ferraz, Stocks, Fleming and Paraiba ridges, and two segments of the North Brazilian Ridge. The Cruzeiro do Sul Lineament extends from the Rio Grande Rise towards the Cabo Frio region along the limit between the Santos and Campos Basin, and includes several seamounts in this direction (Mohriak 2003). Accordingly, these NW-trending directions are considered to be hot-spot tracks, oblique to the east–west trend of the present-day fracture zones. However, there are volcanic chains trending in an east–west direction, such as the Vitória–Trindade Chain, the Fernando de Noronha–Atoll das Rocas Chain and at least two other segments of the North Brazilian Ridge in the Equatorial Margin (Fig. 1). Although their direction is subparallel to the relative motion between the South American and African plates, it is widely different from the absolute plate motion; that is, the motion relative to hot spots. Therefore, it is difficult to accept the hot-spot track model for the chains along an east–west direction. In this sense, the directions of the Vitória–Trindade Chain and the Poços de Caldas–Cabo Frio alignment are still open to debate, as is the process of magma generation for the massifs along this trend.

Ferrari & Riccomini (1999) and Alves et al. (2006) proposed a different mechanism to explain the Vitória–Trindade seamounts by associating

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**Fig. 21.** Seismic profile extending from the Abrolhos Volcanic Complex towards the Besnard Seamount (a possible continental fragment in the platform) and the oceanic crust locally affected by compressional structures (profile SS1, Fig. 20). The approximate distribution of the volcanic rocks in the Abrolhos region and the location of the seismic profile are shown on the inset map in the bottom left part of the seismic section.

**Fig. 22.** Seismic profile showing a guyot in the Vitória–Trindade Lineament (profile SS2, Fig. 20). The flat top of the Besnard Seamount suggests a carbonate cover or wave erosion, indicating that the volcanic edifice was above or close to sea level in Tertiary times. The northern projections of the Champlain, Montagne and Jaseur seamounts are characterized by submarine volcanic edifices with tops at around 1200–1600 m below sea level along the profile.
volcanic features with magma ascension along the abyssal fracture zones. This hypothesis attributes the volcanic chain to a weak zone in the lithosphere and therefore avoids the problem of the plate’s motion direction. However, abyssal fracture zones are deep and cold, and thus the generation of large amounts of magma for rapid seamount building by volcanism is another topic for debate.

The Rio Grande Rise. The Rio Grande Rise corresponds to a major positive structural feature in the South Atlantic between the Argentine and Brazil oceanic basins; it rises above the 1000 m isobath, and the surrounding sea floor has a mean depth of 4000 m (Fig. 2). It has generally been interpreted as an aseismic ridge formed on oceanic crust and dated as Late Cretaceous. However, Deep Sea Drilling Project (DSDP) boreholes in the structural apex recovered only Eocene basalts dated to approximately 40 Ma. The DSDP-516 borehole drilled in the northern flank of the structure penetrated basalts dated around the Santonian–Coniacian, and had chemical similarities to mid-ocean ridge basalts that occur in Iceland (Baker et al. 1981).

The Rio Grande Rise is also characterized by a prominent rift structure over its crest, as evidenced by a major regional NW–SE lineament extending from the oceanic crust towards the continental crust. The Southern Cross Lineament extends from the Rio Grande Rise towards the Cabo Frio High, which divides Brazil’s two most prolific petroleum provinces, the Campos and Santos basins, which are marked by distinct salt tectonics styles. Between the Pelotas and Santos basins, the outstanding Abimael Ridge, located south of the Avedis Chain and west of a major volcanic belt north of the Florianópolis Fracture Zone, corresponds to an aborted proto-oceanic ridge marked by igneous intrusions or possibly by a local mantle exhumation.

The Rio Grande Rise Ar/Ar age was obtained in two basaltic samples. The first yielded $88.7 \pm 0.5$ Ma and an isochron age of $87.2 \pm 8.9$ Ma. The second sample yielded $95.5 \pm 0.5$ Ma. An apparent age of 88 Ma was chosen as the best available time constraint for the crystallization of this site. Baker et al. (1981) also investigated the rocks of the Rio Grande Rise using the Ar/Ar technique and concluded that $86.0 \pm 4.0$ Ma was the best estimate of the age of the crystallization.

The Cameroon Line. The Cameroon Volcanic Line is a major structural feature oriented N30°E, forming a bathymetric extension of the St Helena Chain into the Gulf of Guinea and extending from the oceanic crust towards Central Africa (Fig. 24). The continuation of the lineament towards the continent is known as the Central African Shear Zone (CASZ), which includes segments of other
lineaments, such as the Fomban Shear Zone and several linear rifts formed as strike-slip basins, such as the Muglad Basin. The shear zone was formed in the Precambrian (and continues into Brazil as the Pernambuco Lineament) and was repeatedly reactivated during the Mesozoic break-up and also in the Cenozoic. It is associated with a chain of Early Cretaceous–Recent volcanoes stretching from the Atlantic island of Pagalu to the interior of the African continent in Sudan. The onshore Cameroonian magmatic province is also related to a major uplifted area in Central Africa, the Adamawa Uplift (Fig. 24), which is most probably related to a mantle plume.

The Cameroon Lineament is characterized by the alignment of oceanic volcanic islands (Pagalu, São Tomé, Príncipe and Bioko) towards the continental volcanoes and plutons. This province includes approximately 140 strombolian cones scattered on the flanks of huge stratovolcanoes (Fig. 25). Approximately 100 of them are located on the south, SE and SW flanks of the Cameroon volcano, which extends towards the coastline of the Atlantic Ocean. Although the Cameroon volcanic line does not have a graben structure, its origin is closely linked to that of the nearby Benue Trough and other rifts in the CASZ. Several volcanic episodes along this lineament have been reported in the past century (the major ones were in 1909, 1922, 1954, 1959 and 1982).

The Cameroon volcanic line in the offshore region formed as a consequence of a series of NE-trending parallel fissures and of some transversal events associated with transform faults (Meyers et al. 1998). This lineament is composed of 12 main volcanic centres with radiometric ages ranging from 51.8 Ma to the Present that extend from the oceanic crust (Pagalu Island) towards Lake Chad. However, the Cameroon Lineament does not show any age progression and, therefore, cannot be directly linked to a hot-spot origin.

Geochemical and isotopic data show no significant differences between the basaltic rocks in the continental and oceanic sectors. However, the more evolved rocks in the two sectors are quite distinct. The continental magmas evolve towards peralkaline rhyolite, whereas those in the oceanic sector evolve towards phonolite. Progressive crustal contamination of the continental magmas accompanied by crystal fractionation is required to explain this distinction. The seismic interpretation of regional deep seismic profiles in the Cameroon volcanic

Fig. 24. Simplified geological map of the NW African margin overlain on topobathymetric map.
line suggests an origin related to the Late Tertiary uplift of an Aptian–Late Cretaceous oceanic crust by magmatic and tectonic events (Meyers et al. 1998).

**Fernando de Noronha.** The oceanic islands along the Fernando de Noronha transform zone occur in the equatorial margin of Brazil (Fig. 26), and comprise a diverse magmatic series, ranging from nephelinites and basanites to trachytes. All rock types are highly undersaturated in silica (with the exception of trachytes). They correspond to the sub-volcanic bodies of ultrabasic–intermediate alkaline rocks and pyroclastic deposits belonging to different volcanic events. The older volcanic event (12 Ma) produced phonolite domes and a variety of rock types, including lamprophyre dykes. The younger volcanic events (1.5 Ma) are primarily composed of melanephelinite flows and pyroclastic rocks (the Quixaba Formation).

The Holocene sedimentary deposits represent a small parcel of the stratigraphic units in these islands. The aeolian (dunes) and alluvial fan deposits, algal reefs and beaches are distinguishable on the surface of this famous tourist resort in NE Brazil. This island does not have perennial aquifers, which is a natural limitation to the human population, including the yearly number of tourists it can accommodate. Despite this fact, Fernando de Noronha has been inhabited permanently since the sixteenth century, and has been receiving growing numbers of national and international tourists attracted mainly to its marine biota and exquisite geology.

**Ascension.** Ascension Island is one of a number of hot-spot oceanic islands in the South Atlantic. Ascension lies close to the Mid-Atlantic Ridge (80 km to the east) and just south of the Ascension Fracture Zone (50 km to the north). Atypically, Ascension Island is not hot-spot-centred; geophysical and geochemical data indicate that the Ascension hot spot lies to the east of the Mid-Atlantic Ridge at approximately 10°S, approximately 250–300 km from the island.

The volcanic edifice tipped by Ascension Island is constructed on a 5–6 Ma oceanic crust of the South American Plate, with its base at a depth of 3200 m below sea level. The basal diameter of the volcanic edifice is approximately 60 km, and

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**Fig. 25.** Three-dimensional digital elevation model (DEM) of the Cameroon Volcanic Line in NW Africa.
only the topmost and youngest portions of the volcanic structure are exposed above sea level. Nothing is known about the submerged part of the volcano.

Descriptions of the geology of Ascension can be found in Nielson & Sibbett (1996). A detailed geological map of the island, including the most important geographical features, was reported by Nielson & Sibbett (1996). The central and eastern parts of the island predominantly comprise pyroclastic deposits, trachyte and rhyolite lava flows and flow domes, and mafic lava flows. K–Ar age dates suggest that trachyte flows and flow domes on and around Green Mountain are 0.65–1.0 Ma old, and that all of the exposed trachyte bodies on the island have ages between approximately 0.6 and 1.0 Ma. The southern, western and northern parts of the island have a less pronounced topographical relief, and are composed of mafic lava flow plains punctuated by scoria cones. Based on outcrop considerations, the lava flows appear to be younger than those in the eastern part of the island, but few radiometric age dates are available. At least one of the igneous centres (the Sisters Complex) was active very recently, perhaps within the past few hundred years. The volcanic rocks of Ascension Island are a transitional to mildly alkaline basalt–hawaiite–mugearite–benmoreite–trachyte–rhyolite suite.

The Walvis and St Helena ridges

The Walvis Ridge is a non-continuous aseismic feature in the SE Atlantic Ocean with a general WSW–ENE trend that extends approximately 2800 km from the SW African continental margin towards the Mid-Atlantic Ridge (Fig. 1). Close to the principal interruptions of the ridge is a north–south topographical lineament. The ridge appears to be attached at its NE end to the continental shelf of Angola and Namibia. Towards its SW end, it connects with the eastern flank of the Mid-Atlantic Ridge through two volcanic islands, Tristan da Cunha and Gough. These two islands are composed of recent alkali–basalt–trachyte suites. The geology of the Walvis Ridge has remained relatively unknown, and a clear association with the Rio Grande Rise in the conjugate Brazilian margin is often indicated in palinspastic reconstructions.

Based on morphological and structural characteristics, the Walvis Ridge Chain displays different tectonic settings at the time of volcanic emplacement and loading on the oceanic basement. The NE part (east of 3°E) has a ridge-like, elongated morphology rising 2–3 km above the surrounding sea floor. Large-scale block faulting in this area is prominent, as inferred from the gravity, bathymetry and seismic data. Further SW, the ridge splits into
two branches, one trending north–south and a second one trending NE–SW; both are composed of individual seamounts and guyots.

The north–south-trending branch terminates near 34°S, whereas the oblique branch continues WSW towards the present-day hot-spot location on the eastern flank of the Mid-Atlantic Ridge. The initial manifestation of the Walvis hot spot occurred at the opening of the South Atlantic approximately 130 Ma ago, when it contributed to the emplacement of the Paraná (SE Brazil) and Etendeka (SW Africa) flood basalts, with radiometric ages ranging from 127.5 to 139 Ma. The hot spot was initially located on the American Plate, affecting the Pelotas and Santos basins in Brazil and the Namibian margin in Africa. It crossed the spreading ridge axis 80–70 Ma ago and progressively separated from it, moving towards its present-day location on 7 Ma oceanic crust at the African Plate.

The St Helena Chain is less well defined, and is characterized by a broad and ill-defined band of scattered seamounts and volcanic ridges with a shorter history than that of Walvis but with a similar progressive separation of the hot spot from the spreading centre axis. The oldest dated sample along the St Helena Chain is 81 Ma (O’Connor & Le Roex 1992) and is dredged on a seamount situated at the NE extremity of the chain.

The Walvis and St Helena chains may have recorded the decrease in velocity of the African Plate that occurred between 30 and 19 Ma BP, when migration rates changed from 30 to 20 mm year\(^{-1}\). This change is recorded at 30 Ma along the Walvis Chain, with a reduction from 31 to 22 mm year\(^{-1}\). However, the plate velocity slowdown has been estimated solely on the two younger ages available for each chain and is, therefore, poorly constrained. Moreover, it assumes that the chain follows a continuous NW direction without taking into account the hot-spot tracks deduced from the rotation poles.

St Helena Island. St Helena Island is composed of two coalescent shield volcanoes. The smaller volcano was mostly buried beneath the flanks of the main SW shield edifice after a subaerial lifetime of approximately 3 Ma (between 14.6 and 11.4 Ma). After volcanic activity shifted to the SW (approximately 12 km away), the new centre continued to erupt for another 3 Ma (between 11.3 and 8.5 Ma). In the later stages, highly alkaline dykes intruded the centre and upper flanks of the SW shield at approximately 7.5 Ma. The total subaerial life cycle was approximately 7 Ma.

The shallower depth anomalies observed on the eastern side of the ridge axis between the Ascension and St Helena islands is evidence of an off-ridge axis hot spot located on the African Plate. This hot spot may actually represent a topographical swell due to a deep-mantle anomalous source that extends to the south towards St Helena Island and to the east towards the African margin. Rocks collected at the ridge axis between the Ascension and St Helena islands indicate an origin associated with a mantle plume. Accordingly, the origin of the St Helena Chain on the African Plate might be associated with the emplacement of the conjugate margin Brazilian seamounts on the American Plate (O’Connor & Le Roex 1992). Geochemical (Schilling et al. 1995) and seismological studies indicate a present-day migration of the St Helena plume towards the spreading axis.

Tristão da Cunha. The archipelago of Tristão da Cunha in the South Atlantic Ocean is located approximately 2778 km west of Cape Town, South Africa. There are five islands in the Tristan archipelago: Tristan, Inaccessible, Nightingale, Middle and Stoltenhoff. Radiometric data, although still very sparse, suggest that each island has a ‘life cycle’ consisting of a brief constructional volcanic phase that lasts less than 1 Ma followed by an erosional and thermal subsidence phase of approximately 20 Ma that results in the drowning of the volcanic edifice. Tristan da Cunha Island is purely volcanic and appears to have formed around 1 Ma BP; the Nightingale Island is the oldest in the archipelago and was formed around 18 Ma BP.

Tristan da Cunha is the tip of an ancient volcano, projecting from waters 615 m deep on the Mid-Atlantic Ridge. Marine erosion has formed the high, steep cliffs near the coastline (the Main Cliffs) that surround most of the island. Above the Main Cliffs is a more gently sloping region at elevations of between 600 and 1000 m (the Base). The base of the volcanic edifice is located 3700 m below sea level, and the summit is at almost 2100 m above sea level. The peak, which is predominantly composed of pyroclastic deposits erupted from the central vent, cinders and other volcanic rocks, rises to approximately 2060 m, and is usually covered by orographic clouds. The Base and Main Cliffs are predominantly composed of thin basaltic lava flows commonly separated by thin pyroclastic layers. There are over 30 cinder cones on the flanks of the main volcano, many of which have produced small lava flows. The sea-floor spreading rate in this region is approximately 5–9 cm year\(^{-1}\), and there is some evidence that this rate is regular. Distance measuring shows that the nearby Nightingale Island is approximately 43 km from the Mid-Atlantic Ridge, which means that it would have been above the mid-ocean ridge approximately 18 Ma ago. As Tristan and Inaccessible are both substantially younger than this, a hot spot or mantle plume must exist below the islands because they are still active.
Gough Island. Gough Island, one of the most southerly islands on the Mid-Atlantic Ridge, is located 350 km SE of Tristan da Cunha. It is uninhabited, and the volcanic edifice that rises to approximately 1000 m above sea level extends for a length of 12 km and a width of 6 km. Most of the coastline consists of cliffs ranging from 150 to 300 m high.

Gough Island consists of rocks of the alkali basalt–trachyte association, and is represented by several rock types, including picrite basalt, olivine basalt, trachybasalt, trachyandesite and trachyte. Four main periods of volcanic activity on the island are recognized. These comprise the eruption of the Older Basalt Group, which ranges in age from 2.5 to 0.52 Ma, and corresponds to pillow basalts and hyaloclastites formed when the island emerged from below sea level. This was followed by the intrusion of aegerine–augite trachyte plugs (0.8–0.47 Ma), then voluminous trachyte extrusion (0.30–0.12 Ma) and, finally, the eruption of the Edinburgh Basalt (0.20–0.13 Ma), which erupted in the vicinity of the Edinburgh Peak and represents the youngest volcanic activity on the island.

Abyssal mantle exposure at the Saint Peter and Saint Paul Islets

Oceanic islands generally correspond to the tops of submarine volcanoes and expose volcanic rocks represented by basalt. However, in the Equatorial Atlantic Ocean, there is an oceanic archipelago with islets constituted by abyssal mantle ultramafic rocks. These islets, called the Saint Peter and Saint Paul Rocks (Arquipélago das Rochas de São Pedro e São Paulo), are situated at the NW border of the Saint Peter transform fault zone at the co-ordinates N00°55.1′, W29°20.7′, approximately 1000 km to the NE of the city of Natal, State of Rio Grande do Norte, Brazil (Fig. 26).

They are located on Mioene oceanic crust that is offset by the São Paulo transform faults north of the large Romanche Fracture Zone (Fig. 27). The islets are present at the top of a large submarine topographical elevation (namely the Saint Peter and Saint Paul Peridotite Ridge), which is 100 km long, 20 km wide and 3800 m high above the ocean bottom (Fig. 28).

The exposed rocks are highly fractured mylonitic peridotite. The majority of them are highly serpentinitized (Fig. 29b, c), with the remainder unserpentinitized (Fig. 29d). Basaltic lava and gabbroic dykes are not present. They were considered to be the ultramafic rocks of a transform fault (Fig. 29a) (Tilley 1947; Melson et al. 1967; Hekinian et al. 2000; Campos et al. 2003) and they are the only abyssal mantle exposure above sea level known in the Atlantic Ocean (Sichel et al. 2008; Motoki et al. 2009a; Campos et al. 2010). In the central part of Belmont Island there is non-serpentinitized mylonitic peridotite (Fig. 29d). The exposed rock is fresh and contains pyrite crystals up to 400 μm in diameter.

The serpentinitized peridotite contains semi-rounded porphyroclasts composed primarily of olivine with secondary occurrences of pyroxenes and amphibole (with special attention to the presence of kaersutite) (Fig. 29f). The matrix is constituted by small crystals of olivine, pyroxenes, serpentine and chrome spinel. A strong plastic deformation, such as the augen-like shape of the porphyroclasts, is not observed on either the porphyroclasts or the matrix. This texture indicates that the mylonitic deformation is not typically ductile but brittle–ductile, which would occur at a relatively shallow depth. The parallel fractures in three directions are developed at an interval of 10 cm.

At Sudeste Island (Challenger Island), deformed kaersutite-rich ultramafic rock layers are present. The rock could correspond to the melt generated by a low-degree partial melting of the host peridotite. All rocks are cut by numerous carbonate veins of 1–3 cm in width (Fig. 29b, c, f). They are generally straight but sometimes show curvatures (Fig. 29b, f). There are also wide carbonate veins containing angular fragments of rocks and shells. They are considered to be fractures filled by surface-origin materials (Campos et al. 2003). However, the narrow veins, especially the curved ones, are not clarified in their origin, so isotopic studies of oxygen and carbon are desirable. On these ultramafic rocks, a recent sedimentary cover of carbonates and conglomerate is present.

Transform faults and abyssal fracture zones generally form linear morphological depressions without magma production (Schilling et al. 1995; Thibaud et al. 1998). The oceanic crust is thin and, in some localities, the abyssal mantle peridotite is exposed directly on the sea floor without an igneous crust cover. In the areas near the mid-ocean ridge, abyssal mantle peridotite is exposed not only along the transform fault but also on the zones between the transform faults and the abyssal fracture zone, forming carapace-like elliptic hills, called megamullions (Fig. 30) (e.g. Blackman et al. 1998; Tucholke et al. 1998, 2001; Ohara et al. 2001). On the surface of the megamullions, there are small linear morphological depressions parallel to the adjacent transform faults, called corrugations.

Megamullions occur where a low-rate ocean plate spreading and/or low-temperature abyssal mantle takes place (Cann et al. 1997; Whitmarsh et al. 2001; Ritzwoller et al. 2003; Canales et al. 2004). The equatorial Atlantic region around the Saint Peter and Saint Paul Islets has such conditions
Fig. 27. Locality map for the Saint Peter and Saint Paul Rocks, located near the Saint Paul Fracture Zone. The bathymetry map is based on the TOPO 12.1 with a maximum resolution of 1.85 km.

Fig. 28. Submarine morphology of the Saint Peter and Saint Paul Peridotite Ridge based on the TOPO database of version 12.1 with a maximum resolution of 1.85 km. The exhumed mantle rocks are located near the boundary between the African and South American plates, adjacent to abyssal fracture zones.
However, the submarine morphology around the Saint Peter and Saint Paul Islets is quite different from that of typical megamullions. The mantle rock ridge is 3800 high (Fig. 31) (Sichel et al. 2008; Motoki et al. 2009a), and this peculiar morphology suggests the existence of an intense tectonic uplift. The morphological analyses of the Flandrian wave-cut bench and $^{14}$C dating for coral fossils collected from the island revealed the tectonic uplift rate relative to sea level to be 1.5 mm year$^{-1}$ over the past 6000 years (Motoki et al. 2009a; Campos et al. 2010). This suggests that the Saint Peter and Saint Paul Peridotite Ridge is a megamullion deformed by active tectonism.

Fig. 29. Abyssal mantle peridotite of the Saint Peter and Saint Paul Rocks, Equatorial Atlantic Ocean: (a) serpentinitized mylonitic peridotite (Sp); (b) serpentinitized peridotite (Sp) cut by carbonate veins (Cc); (c) weathered surface of serpen tinized peridotite; (d) Fresh non-serpentinitized peridotite with pyrite; (e) curved carbonate vein; and (f) photomicrography of serpentinitized mylonitic peridotite. The field photographs are credited to K. Motoki and R. Soares, and the photomicrography to T. Campos.
(a) Transform fault and abyssal fracture zone

(b) Conventional expansion with magmatism

(c) Tectonic expansion without magmatism

**Fig. 30.** Schematic illustration for megamullion and its formation process after Sichel et al. (2009): (a) relationship between the mid-ocean ridge segment, the transform fault and the abyssal fracture zone; (b) normal spreading of oceanic plates with magmatism and consequent new oceanic crust generation; and (c) tectonic spreading without magmatism and oceanic crust generation. The vertical scale is exaggerated about 10 times.

**Fig. 31.** North–south geological cross-section of the Saint Peter and Saint Paul Peridotite Ridge, with deformed mantle rocks rising from bathymetries of around 4000 m.
Summary and conclusions

The K–Ar and Ar/Ar data summarized in this work allow new insights into the geological evolution of the South Atlantic opening. The magmatic events show a geographical distribution pattern that indicates an extensional environment initially linked to continental rifting, and subsequently linked to oceanic crust formation and plate divergence. In addition, plume magmatism and leaking fracture zones are observed, cutting previous continental and oceanic crust at several epochs. In this way, the following main episodes may be envisaged (Table 1).

The Serra Geral–Etendeka magmatism, composed of tholeiitic basaltic rocks, records the continental crust break-up in the Early Cretaceous. This magmatism is interpreted as a pre- and syn-rift response to a temperature increase below the South American–African landmass, with a radiometric age of approximately 133–120 Ma (Ar/Ar). A NW-trending mafic dyke swarm is observed in the Ponta Grossa Arch in the Paraná Basin and extends into the Santos Basin. Other NE-trending dykes also occur along the coastline from the Santos Basin towards the Campos and Espírito Santo basins. These dykes fed the flood basalts observed in the Paraná Basin and in the lower sequence of the rift basins along the continental margin.

The frequency of radiometric ages for post-break-up rock samples from the South Atlantic can be divided into four main classes. The largest, with more than 40 radiometric ages for the intervals 60–80 Ma, is related to an Upper Cretaceous event and may represent magmatism along deep fissures or a plume trace. It also follows a NW-trending mafic dyke swarm with igneous and kimberlite intrusions.

The Cabo de Santo Agostinho is composed of granitic and basaltic rocks whose Ar/Ar analysis yielded 102 ± 1 Ma. It is interpreted as a hot-spot trace related to the conjugate margin (Nigeria and Cameroon) in Africa. The Cabo Granite presents an acidic, alkaline, volcano-plutonic association generated by the partial melting of the continental crust (S-type granite). Concomitant with the emplacement of the Cabo Granite, an important basic–acidic (basaltic–rhyolitic) volcanism is observed in the region, characterizing a bi-modal magmatic event.

The Poços de Caldas–Cabo Frio east–west lineament records the post-break-up alkaline magmatism that occurred during the drifting of the South American and African plates from the Mid-Cretaceous to the Late Tertiary, culminating with platform uplifting phenomena and the formation of small sedimentary basins onshore of SE Brazil in the Late Tertiary. The observed alkaline

| Age (Ma) | South American side Description/interpretation | Age (Ma) | African side Description/interpretation |
|----------|-----------------------------------------------|----------|----------------------------------------|
| ?        |                                               | 2.0–0.0  | Ascension Island                        |
| 2.9–2.3  | Trindade–Martin Vaz island                    | 2.5–0.5  | Ocean ridge                            |
| 12–1.5   | Fernando de Noronha                          | 14–11    | St Helena island Hot spot               |
| ?        |                                               | 18–5     | Tristão da Cunha                       |
| 60–45    | Abrolhos Plume                               | 52–0.0   | Cameroon Line Parallel fissure (N30°)  |
| 85–55    | East–west Poços de Caldas–Cabo Frio alkaline lineament, NW-trend along Paraíba Arch |          |                                       |
| 86       | Rio Grande ridge Aborted oceanic ridge        | 81       | Walvis and St Helena ridges Aborted oceanic ridge |
| 102      | Santo Agostinho Cape Granite Plume           |          |                                        |
| 133–120  | Serra Geral Formation and dykes Pangea break-up | 133–120  | Etendeka and dykes Pangea break up     |
| 560      | St Peter and St Paul Islets Mantle exhumation in post-Miocene oceanic crust |          |                                        |
magma with respect to the coasts of Africa and South America.

The Vitória–Trindade Chain is composed of several seamounts and guyots, and the main bank to the NE of the chain corresponds to the Abrolhos Volcanic Complex, which is a major volcanic province with Late Cretaceous–Early Tertiary basalts overlying the continental crust. The seamounts (Vitória, Davis, Columbia, Trindade and Martin Vaz) yielded radiometric ages up to the Pleistocene in Trindade and are built on an oceanic crust older than 70 Ma. The plume-track model presents some still-unresolved problems. The eruption ages of most of the seamounts are unknown.

Recent Ar/Ar datings have revealed that there are age inversions (Mota unpublished data 2011). Ferrari & Riccomini (1999) and Alves et al. (2006) proposed a model based on the magma’s ascension along the abyssal fracture zones. However, oceanic fracture zones are deep and cold; therefore, it is difficult to generate large amounts of magma for seamount-building volcanism.

Volcanic islands, such as Ascencion (1.0–0.65 Ma), Tristão da Cunha (2.5–0.1 Ma) and St Helena (12 Ma), most probably correspond to mantle plumes or hot spots. Recent, but limited, radiometric age data suggest that each island in the Tristan da Cunha Archipelago has a ‘life cycle’ of approximately 20 Ma, consisting of a brief constructional volcanic phase lasting less than 1 Ma, followed by an erosional phase and thermal subsidence. Rocks collected at the ridge axis between the Ascension and St Helena islands indicate a genetic link with a plume-type mantle. The origin of the St Helena Chain on the African Plate is associated with the emplacement of the Brazilian seamounts on the American Plate.

The thermal structure of the lithosphere underneath the African Plate is distinct from the South American Plate around the Ascension and St Helena islands. The shallower depth anomalies observed on the east side of the ridge axis between the Ascension and St Helena islands is evidence of an off-ridge axis hot spot located on the African Plate. This hot spot may actually represent a topographical swell due to a deep mantle anomalous source, which extends to the south to St Helena and to the east to the African margin.

The SW–NE trend of the volcanic islands and the igneous massifs along the western side of the African margin (Cameroon, Walvis Ridge) are most probably related to the hot lines that were formed as convection in the mantle reached the weak zones inherited from the Precambrian shear zones, which were reactivated during the Mesozoic break-up and locally up to the Recent.

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