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Tectono-Magmatic Evolution of the South Atlantic Continental Margins with Respect to Opening of the Ocean

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Abstract—The history of the opening of the South Atlantic in Early Cretaceous time is considered. It is shown that the determining role for continental breakup preparation has been played by tectono-magmatic events within the limits of the distal margins that developed above the plume head. The formation of the Rio Grande Rise–Walvis Ridge volcanic system along the trace of the hot spot is considered. The magmatism in the South Atlantic margins, its sources, and changes in composition during the evolution are described. On the basis of petrogeochemical data, the peculiarities of rocks with a continental signature are shown. Based on Pb–Sr–Nd isotopic studies, it is found that the manifestations of magmatism in the proximal margins had features of enriched components related to the EM I and EM II sources, sometimes with certain participation of the HIMU source. Within the limits of the Walvis Ridge, as magmatism expanded to the newly formed oceanic crust, the participation of depleted asthenospheric mantle became larger in the composition of magmas. The role played by the Tristan plume in magma generation is discussed: it is the most considered as the heat source that determined the melting of the ancient enriched lithosphere. The specifics of the tectono-magmatic evolution of the South Atlantic is pointed out: the origination during spreading of a number of hot spots above the periphery of the African superplume. The diachronous character of the opening of the ocean is considered in the context of northward progradation of the breakup line and its connection with the northern branch of the Atlantic Ocean in the Mid-Cretaceous.

Keywords: rifting, breakup, opening of the ocean, proximal and distal margins, hot spots, magmatism, isotopic composition

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INTRODUCTION

The northward expansion of the opening of the ocean has been quite reliably reconstructed in the Mesozoic history of the South Atlantic beginning from the Early Jurassic in the Karoo and until the end of the Early Cretaceous [85]. To understand the geodynamics of rifting and early spreading in the South Atlantic, it is crucial to study tectono-magmatic peculiarities of the conjugated margins on both sides of the ocean. The Mesozoic margins of South America and Africa have all the characteristic features of passive volcanic margins. Their structure is characterized by the presence of proximal and distal zones (Fig. 1). The former are located within land and have an ancient continental basement belonging to the South American and African Platforms. The latter are located off the coast and are characterized by the presence of newly formed magmatic crust that includes thick volcanic/volcanoclastic complexes, which form the characteristic seismic images of wedges with seaward dipping reflectors (SDRs). Igneous rocks of oceanic margins which pertain to the Paraná–Etendeka Province are considerable in volume, although they are arranged asymmetrically on both sides of the ocean [66, 85].

The main aims of the present article are (a) to determine the tectonic settings under which rifting, magmatism, and continental breakup preparation occurred in the margins of South Atlantic, (b) to reveal how these continental margins were related to the subsequent evolution of hot spots, and (c) to consider the northward propagation of newly formed oceanic structures and continental margins and their connection with the Central Atlantic system. The paper is based on published geological, geophysical, and geochemical data.

SOUTH AMERICAN MARGIN

Tectonics of the Proximal Zone

The tectono-magmatic peculiarities of margins are best preserved on the South American side. Complexes of continental crust in the proximal margin of South America include large blocks of Archean and Paleoproterozoic platform basement, which are sur-

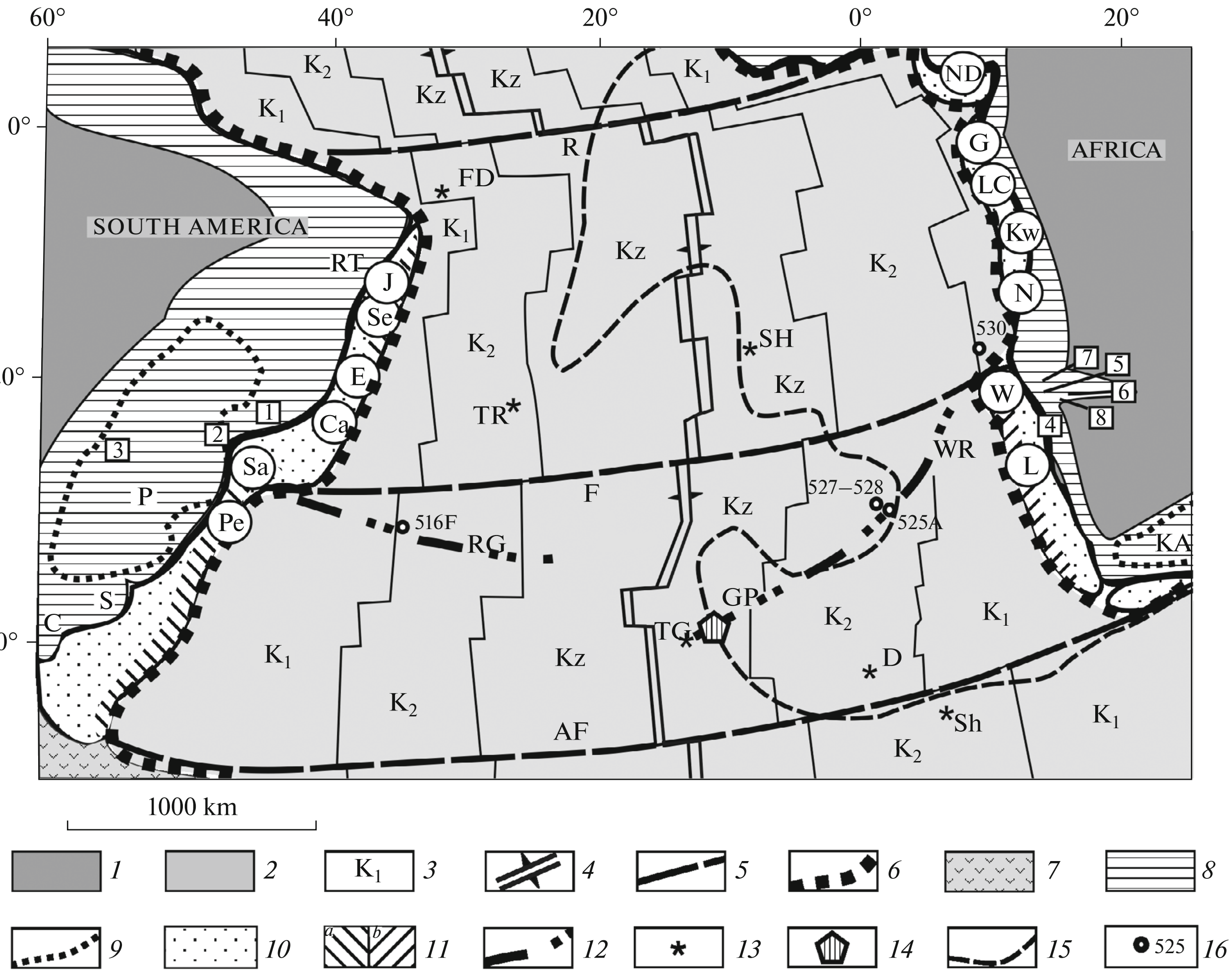

Fig. 1. Scheme of locations of tectonic elements in South Atlantic (with data from [37, 85]). Notation: continental basins: P, Paraná; RT, Recôncavo–Tucano–Jatobá; S, Salado; C, Colorado; KA, Karoo. Elements of Rio Grande Rise–Walvis Ridge volcanic system: RG, Rio Grande Rise; WR, Walvis Ridge; GP, Guyot Province. Main transform faults: R, Romanche; F, Florianopolis; AF, Agulhas–Falkland. Hot spots: TG, Tristan–Gough; SH, St. Helena; FD, Fernando de Noronha; TR, Trindade; D, Discovery, Sh, Shona. Squared numerals denote dike series: 1, Pan Paulo–Rio de Janeiro; 2, Ponta Grossa; 3, Asunción-Sapucai; 4, Horingbaai; intrusive massifs of Damaraland complex: 5, Messum, 6, Erongo, 7, Doros, 8, Spitzkoppe. Encircled letters denote Jurassic–Cretaceous basins in distal zone: J, Jacuipe; Se, Serguipe; E, Espirito Santo; Ca, Campos; Sa, Santos; Pe, Pelotas; ND, Niger Delta; G, Gabon; LC, Lower Congo; Kw, Kwanza; N, Namib; W, Walvis; L, Luderitz. Notes: (*1*) fragments of Gondwana supercontinent with Precambrian and Paleozoic crust; (*2*–*6*) area of oceanic crust: (*2*) ocean floor, (*3*) age of oceanic crust, (*4*) axial zones of spreading ridge, (*5*) main transform faults, (*6*) continent–ocean boundary; (*7*) South Sandwich active margin; (*8*–*11*) passive volcanic margins: (*8*) proximal zones, (*9*) boundaries of large platform basins in proximal zones; (*10*) extent of syn-rift deposits in distal zones; (*11*) thick volcanic sequences in distal zones forming SDRs in South American (*a*) and African (*b*) margins; (*12*) Rio Grande Rise–Walvis Ridge volcanic system; (*13*) hot spots; (*14*) Tristan plume; (*15*) approximate location of western boundary of African superplume (at depth of 2750 km); (*16*) numbers of deep sea drilling boreholes.

rounded by Neoproterozoic fold belts (as established from both geological and seismic data [55, 72, 79, 85]). The most important structure within the margin, in the area extending from Brazil to Uruguay, is the Paraná longitudinal platform trough (syneclise), more than 2000 km in extent, which had been evolving since the end of the Ordovician until the Late Cretaceous, reaching a total subsidence depth of about 7–8 km [55, 85] (Fig. 1). In the platform sequence of the Paraná trough which was studied on the basis of boreholes there are a number of significant hiatuses, but all horizons occurred conformably. Repeat manifestations of basaltic magmatism were characteristic of this region, in particular, in the Devonian and, especially, in the Cretaceous time. Synrift Upper Jurassic–Lower Cretaceous formations (2 km thick), as well as the Upper Cretaceous sediments overlapping them, are represented in subaerial facies.

The basement rocks and the Paraná trough sediments are locally disturbed by longitudinal faults and small NE-trending grabens related to Mesozoic rifting. These are, e.g., the Reconcavo–Tucano–Jatoba trough and faults and dikes of the San Paulo– Rio de Janeiro series, which range parallel to the coastline. The younger fault and dike systems to the west of the Paraná trough, in particular, the Asuncion–Sapucai dike system, and those located east of it, near the coast, are of oblique trend towards to continental margin zone, as well as the earliest Mesozoic grabenlike troughs (Salado, Colorado, and San Jorge) in the territory of Argentina.

Peculiarities of magmatism

Igneous rocks of the Paraná region (Cerra Jeral Series and its analogs) are distributed over a vast area, reaching Uruguay in the south. All volcanic rocks are represented by subaerial units. The thickest (1.5–1.7 km) lava sequences are found in the northern Paraná trough, in its deepest part. The volcanic complex and dikes are characterized by a bimodal composition of rocks (plateau basalts and rhyolites), with the sharp predominance of tholeiitic basalts, and, in part, andesite basalts (>90%) [34, 51, 66]. The final phase of volcanism was accompanied by eruptions of rhyodacites and rhyolites. The sills studied by boreholes in the eastern part of the region are mostly comagmatic with respect to the lavas and demonstrate similar geochemical characteristics [34, 50].

In terms of radiologic dating (^{40}Ar–^{39}Ar, partially U–Pb), the plateau basalts of Paraná trough yield ages in the range between 137 and 127 Ma [66, 88]. Owing to the technical improvement of ^{40}Ar–^{39}Ar age determinations, a number of earlier dates have recently been revised, so this interval for the absolute majority of rocks has been narrowed to 134–132 Ma [70, 82]. The ^{40}Ar–^{39}Ar age determinations have also been verified by data of recent U–Pb determinations [42, 69]. Thus, the total duration of basaltic magmatism in the Paraná trough can be estimated to be as long as 2–3 Ma. The approximately synchronous deep heating and onset of magmatism in a large area could be related to the determining role played by a deep plume in magma generation at the South Atlantic margins.

The yield of several more ancient ^{40}Ar–^{39}Ar ages (138–135 Ma), which were obtained for volcanic rocks occupying a small volume and for dikes in the western part of the lava field [66, 80, 88], to the mentioned dates in the Paraná trough, and also the young ages (126–121 Ma) obtained in the coastal dike band [70] can indicate the successive migration of magmatism towards the distal zone.

The majority of Paraná lavas are aphyric, characterizing by a low MgO content (3.0–6.6 wt %). Lavas having MgO of 6.5–9.0 wt % make up less than 2% of the total volume, reflecting the intensive crystal fractionation with the sequence of crystallization phases being as follows: ol–cpx–pl and Fe-Ti oxides [12, 66]. The characteristic peculiarity of the discussed lavas and dikes is the presence of two rock types, high-Ti and low-Ti (with TiO_2 contents >2 and <2 wt %, respectively) [13, 51, 66]. The rocks of these groups are mostly spatially separated from each other, however sometimes they appear as interbedding flows. Tholeiites of high-Ti group (Urubici, Ribeira, Pitanga, and Paranápanema formations) dominate in the northern Paraná trough, while low-Ti rocks (Gramado and Esmeralda formations) are predominant south of ~26° S. The spatial distribution of high- and low-Ti rock complexes may reflect either lateral changes in the composition of the magmatic source or analogous changes in the degree of melting, which depends on the relationship with plume [26]: it is high for low-Ti melts generated above the plume axis and low for high-Ti melts formed closer to the periphery of the plume. However, rocks in both the northern and southern Paraná trough, as well as those of the same type, demonstrate quite broad ranges of TiO_2 contents [51, 66]. This peculiarity has been reported by many researchers who carried out geochemical studies of lavas in particular areas. For example, lavas of the Urubici Formation demonstrated interbedding of dominant low-Ti rocks with high-Ti ones close to those of the Gramado Formation [66].

The distribution of incoherent elements for both low- and high-Ti basalts of the Paraná trough shows a close specific character, with well-expressed negative Ta–Nb anomalies and positive Pb, Ba, and partially Rb anomalies (see [66, 67, 73] and others). Such a composition characterizes the specifics of the enriched component with a continental signature. The features of high-Ti magmas are higher concentrations of all lithophile elements, a higher degree of enrichment in incompatible elements compared to compatible ones, and higher La/Yb and Gd/Yb ratios reflecting the presence of garnet in the melted source [66].

The differences between the two groups of rocks are also determined from Pb–Sr–Nd isotopic composition data. The main trend of variations for high-Ti rocks (Pitanga and Paranápanema formations) is quite limited for the ^{206}Pb/^{204}Pb (17.8–18.2), ^{207}Pb/^{204}Pb (15.48–15.54), and ^{208}Pb/^{204}Pb (37.8–38.4) ratios, as well as for the ^{143}Nd/^{144}Nd (0.5123–0.5125) and ^{87}Sr/^{86}Sr (0.7055–0.707) ratios (Fig. 2). The lavas of the Urubici Formation, which demonstrate a broader range of compositions, represent an obvious trend with lower ^{206}Pb/^{204}Pb ratios (down to 17.4) and lower ^{143}Nd/^{144}Nd ratios for the given ^{87}Sr/^{86}Sr ratio. In general, Pb isotopic ratios suggest that high-Ti magmas from the Paraná region are characterized by an admixture of model-enriched EM I component. The same group also includes several samples of low-Ti basalts from the northern Paraná region [51] (Fig. 2).

Low-Ti basalts, compared to high-Ti basalts, are typical of higher isotopic ratios, attaining the following values in the most enriched units: 15.65–15.68 for ^{207}Pb/^{204}Pb, 38.8–38.4 for ^{208}Pb/^{204}Pb, 0.5126–0.5128 for ^{143}Nd/^{144}Nd; for such values, the mentioned rocks

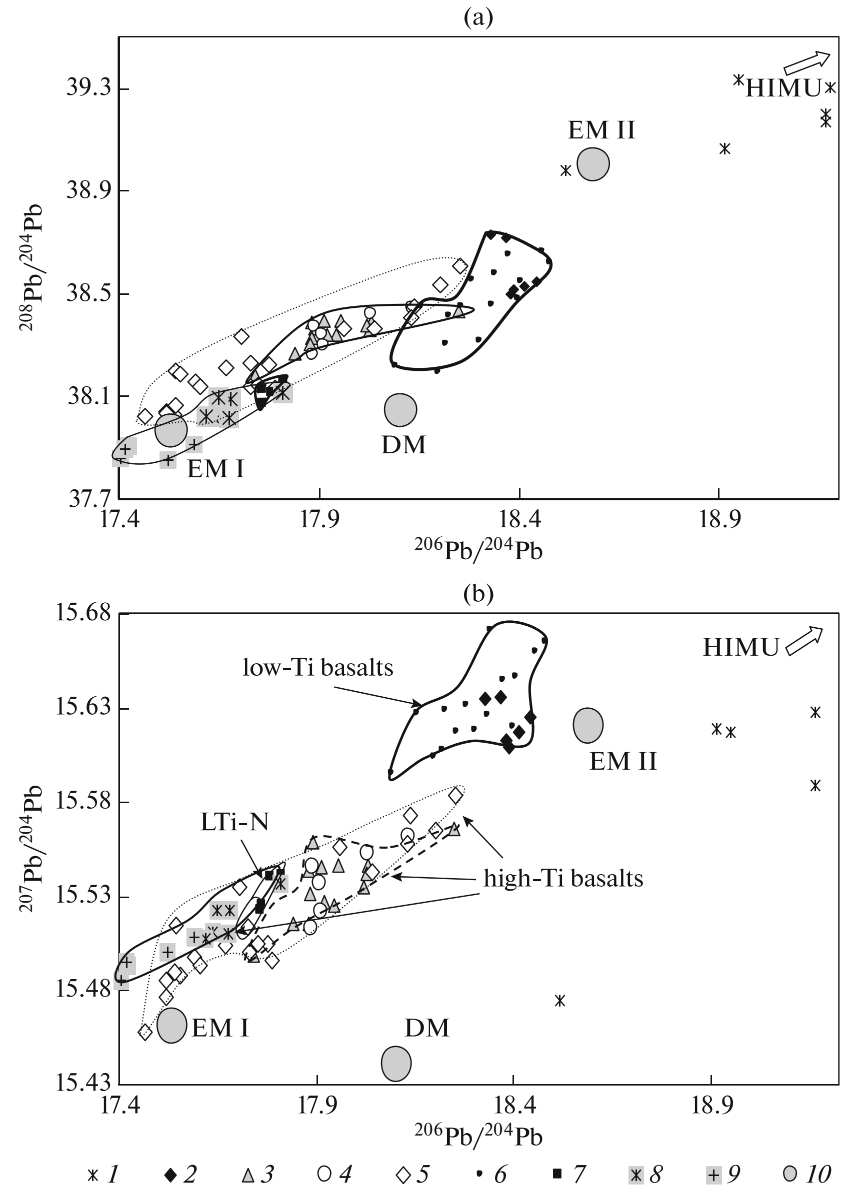

Fig. 2. Isotopic characteristics of Mesozoic traps of Paraná region (with data from [8, 25, 27, 28, 51, 66, 73, 74]). LTi–N, field of low-Ti basalts in northern Paraná region. Notes: (*1*) alkaline basalts of northeastern Brazil; (*2*) traps of Paraná, undifferentiated; (*3–5*) high-Ti basalts of Paraná: (*3*) Pitanga, (*4*) Paranápanema, (*5*) Urubici; (*6, 7*) low-Ti basalts of (*6*) southern and (*7*) northern Paraná region; (*8*, *9*) high-Ti basalts of (*8*) northern and (*9*) southern Paraná region; (*10*) model enriched sources.

are close to the EM II enriched component (Fig. 2) [44, 66, 73, 74]. Alkaline magmas represent a particular trend in the plots: they have higher contents of radiogenic lead and probably an admixture of the HIMU enriched component. Judging by the data on isotope classifications and ratios of lithophile elements (La/Th, Nb/La, Zr/Ta, and Ce/Pb), basalts do not contain an admixture of material from the depleted source. The obtained results indicate that magmatism of the Paraná region is related to melting of the subcontinental lithosphere, which was enriched during earlier metasomatic events at different depths [17, 38, 51, 66].

Rhyolites are common predominantly in the southeastern Paraná region and form the upper part of the lava sequence about 132–129 Ma in age [14, 66, 88]. In terms of petrogeochemical data characteristics, they can be subdivided into high-Ti and low-Ti rhyolites. Remarkably, basalts and rhyolites with different titanium contents spatially correspond to each other: high-Ti rocks can be found predominantly in the north, whereas low-Ti ones are common mostly in the south. High-Ti rhyolites (Chapeco Formation) were shown to have high contents of incompatible elements and higher $^{87}Sr/^{86}Sr$ ratios (0.705–0.708), similar to those in high-Ti basalts. Low-Ti rhyolites (Palmas Formation) which dominate in volume over the entire area from Brazil to Uruguay have low contents of incompatible elements and high $^{87}Sr/^{86}Sr$ ratios (0.714–0.727) [32, 44].

There also are a number of fine alkali intrusions in the periphery of the Paraná trough; they have been mainly studied in the territory of Paraguay [17, 18, 36]. There are reported manifestations of small-volume sodium magmatism along the western margin of the Paraná trough: they took place both 100 Ma before eruption of tholeiites and at the final stage of magmatism (61–56 Ma ago). Pre- and posttholeiitic Lower Cretaceous rocks are represented by almost exclusively potassic alkali rockd [17, 18, 36]. Their manifestation demonstrates the tendency of younger events (~109–88 Ma ago) shifting eastward, towards the future ocean.

Potassic rocks cover a broad range of compositions, from basanites to phonolites and from alkali basalts to trachytes, including associated carbonatites, syenites, and, rarely, granites. Sodium alkali rocks are represented by ankaramites, nephelinites, and phonolites. Potassic rocks, as revealed by the studies in Paraguay, are characterized by highly fractionated REE spectra, negative Ta–Nb–Ti anomalies, and high Sr contents, whereas sodium rocks are typical of small positive Ta–Nb anomalies and negative Ti and Sr ones [17, 18, 36]. Geochemical and isotopic characteristics of potassic rocks demonstrate a similarity to the associated tholeiites and also indicate the important role played by the lithospheric source in their genesis. Pb–Sr–Nd isotope studies reveal two enriched components responsible for generation of alkali magmatism: EM I, which was predominant during the Cretaceous K-alkali event, and HIMU, which played a more important role during Late Cretaceous and Paleocene Na-magmatism [17, 36] (Fig. 2). The peripheral position of areas of both K and Na alkali magmatism relative to the erupted tholeiites supposedly reflects the relationship with the margins of the plume system [17].

Deep structure

Seismic investigations in the proximal zone of Brazil yielded high seismic velocities (V_p = 6.9–7.0 km/s) for a number of lower crustal complexes; this probably corresponds to the local predominance of Archean basic granulite gneisses and amphibolites [43]. The total thickness of ancient continental crust is more than 40 km, but it reduces to 10–15 km at the flexure bench near the eastern limit of the proximal zone [81].

Several recent seismotomographic studies [72, 79] also revealed high velocities of P and S waves at lithospheric depths beneath the Paraná Basin which correspond to the deep (down to 200–250 km) structures of the San Francisco ancient shield preserved within the basement of the basin. In contrast, the surrounding fold belts were characterized by mantle velocities that were less than average at these depths. At greater depths in the upper mantle, down to 500 km or more, there is a cylindrical low-velocity anomaly (about 260 km in diameter) supposedly corresponding to an ancient plume conduit that transported heat upwards to form plateau basalts in the Paraná region [72, 79].

A bright feature of the lower mantle beneath the Paraná Basin is the partially expressed continuation of the subducting Nazca Plate [79]. The subducting plate is expressed by two eastward-dipping high-velocity reflectors imaged by both P and S waves: one reflector is located in the west, at a depth of about 500–700 km, while the other occurs at a depth of more than 1200 km in the central part of the region [72, 79]. The peculiarities of the crust and mantle in the proximal zone reflect the character of ancient continental structures altered first by the collision and assembly of Gondwana, then by the subsequent effect of plume, Mesozoic magmatism, and breakup of Gondwana, and finally during the subsequent transformations related to Cenozoic subduction and origination of the Andean orogen. Additionally, the subducting Nazca Plate apparently cut the buried conduit that determined the formation of the Mesozoic complex in the Paraná–Etendeka igneous province.

Tectonics of the Distal Zone

In the distal margin, within the limits of the Brazilian shelf and continental slope, there are large salt basins—the Jacuipe, Sergipe, Espirito Santo, Campos, and Santos troughs (Fig. 1); south of here, there are saltless basins, like the Pelotas and others. Synrift formations of basins (ranging in age from Neocomian to Aptian, up to 5 km thick or more) are represented by shallow marine carbonates and Aptian evaporates [1, 19, 81]. Marine postbreakup carbonate systems of the distal margin overlap the Aptian salt sequences with an angular unconformity [59]. Broadly represented Mesozoic volcanogenic complexes determine the presence of elongated wedges of seaward dipping reflectors (SDRs), similar to those known in other Atlantic margins (Fig. 3) [81].

Peculiarities of magmatism

Based on multichannel seismic profiling and drilling data, the volcanic complex occurs below salt deposits and their stratigraphic analogs [10, 29, 58, 81]. The age of this complex of the distal zone can be dated between Barremian and beginning of Aptian, so it appears to be a little younger than the volcanic rocks from the proximal zone [58, 85]. For example, the absolute age of magmatism in the Pelotas Basin is estimated at 133–113 Ma, whereas dating of volcanic rocks in the near part of the Paraná Basin yielded 134–132 Ma [81]. These data allow us to consider erupted basalts in the distal margin as an episode of lateral expansion of vol-

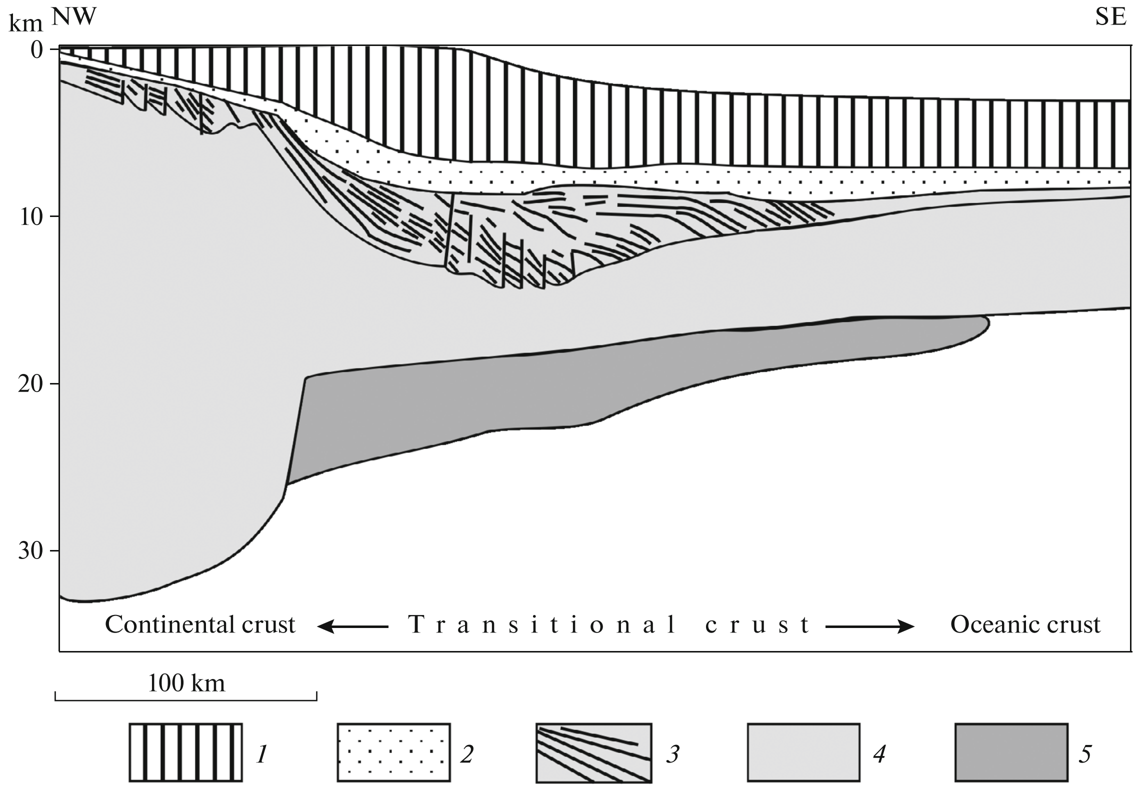

Fig. 3. Geological and geophysical cross section of Pelotas Basin (with data from [15]). Notes: (*1*) postbreakup deposits (K_2–Kz); (*2*) synrift deposits, upper layer (K_1ap); (*3*) volcanic/volcanoclastic complex (SDRs; K_1br–ap); (*4*) rocks of consolidated crust transiting from thinned continental to oceanic; (*5*) high-velocity lower crust (HVLC).

canism from the Paraná Basin towards the future ocean at a time close to that of the breakup [58].

Magmatism in the distal zone is characterized by a broad distribution of Lower Cretaceous plateau basalts and an insignificant presence of Upper Cretaceous–Lower Tertiary basalt flows and intrusives. Drilling in the Pelotas Basin covered the uppermost 800 m of the basaltic sequence; additionally, the uppermost 600 m of plateau basalts and tuffs with interbeds of subaerial and lagoonal sediments were probed by drilling in the Campos Basin [29, 58, 66]. Similar basalts in small volumes were also sampled in the Santos and Espirito Santo basins [29, 41].

The basalts recovered from boreholes can be referred to enriched tholeiites, although their identification is complicated because of considerable alteration. The rocks are aphyric, more often porphyric, with the phenocrusts of cpx and pl (rarely Fe–Ti oxides and ol). Based on the studies of basalts from the Campos Basin (60 samples from 19 boreholes), it was found that magmatism in general had been of low-Ti type and in many aspects similar to the one in the southern Paraná region [58]. However, the studied samples often demonstrated significant variations in composition at close distances. For example, basalts in 31 samples from 12 boreholes, drilled within the Espirito Santo, Campos, and Santos basins, were determined as both enriched rocks and less-enriched units; one sample of basalt was also found with characteristics comparable to N-MORB [29]. The isotopic characteristics of recovered basalts are scarce and pertain to Sr–Nd classification at that. The provided data show a broad range of compositions (Fig. 4) [58]. It can also be sen that earlier basalts (124–122 Ma in age) are more enriched in radiogenic Sr, while younger ones (80–50 Ma in age) fall within the domain of enriched magmas of the Paraná region.

Deep structure

In the seismic profiles across the Pelotas and other basins, volcanic and volcanoclastic rocks are expressed in a series of SDRs traced with small breaks for about 3000 km along the distal zone [15, 19, 81] (Figs. 1, 3). Near the Brazilian coast, SDRs form voluminous crustal bodies up to 5 km (or even more) in total thickness, which considerably exceeds the thickness of lava sequences of the proximal margin [35, 41]. The abundance of volcanics yielding the SDR pattern significantly varies over the area, peaking in the Pelotas Basin. The SDRs complex is traced into the adjacent part of the Santos Basin, whereas it is weakly expressed north of it [81]. Probably, the volume of volcanic products in the north was insufficient for SDRs

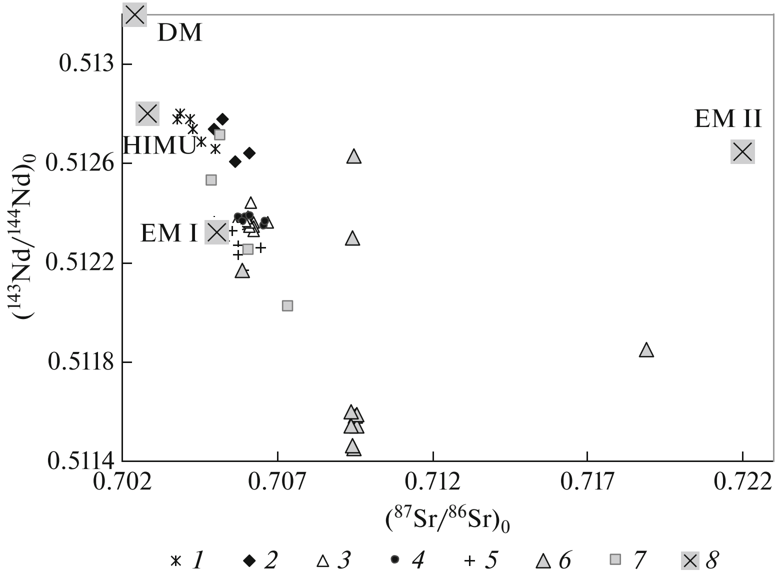

Fig. 4. Correlation between Sr–Nd ratios for rocks of Campos Basin and Paraná region (with data from [8, 27, 28, 51, 58, 66, 73, 74]). Analyses are recalculated to eruption age. Notes: (*1*) alkaline basalts of northeastern Brazil; (*2*) traps of Paraná; (*3–5*) high-Ti basalts of Paraná: (*3*) Pitanga, (*4*) Paranápanema, (*5*) Urubici; (*6, 7*) basalts of Campos Basin of different age: (*6*) 124–122 Ma, (*7*) 82–50 Ma; (*8*) model enriched sources.

to form, or their images on seismic profiles are hidden by salt deposits. Further north, in the Jacuipe and Sergipe basins, where the thickness of the salt sequence significantly reduces, the SDRs wedge reappear in profiles [41, 59]. The presence of thick SDRs has also been reported in some profiles crossing the southern part of the discussed region, off the coast of Argentina [30, 61]. Here, in a section more than 10 km thick, three series of SDRs can be seen, which overlap each other and are divided by unconformities.

The evolution of the basin system and subsequent manifestation of the breakup show diachronity with northward migration. In the Pelotas Basin, on the basis of detailed seismic and magnetometric data, the successive northward movement of rifting was traced, with its simultaneous eastward migration and breakup [81]. The eastward migration of rifting was accompanied by lateral eastward accretion of series of SDRs, which was traced from the results of multichannel seismic profiling, as shown in [81, Fig. 10]. Near the oceanic end of the SDRs wedge, other volcanic complexes appear and often form a seismic pattern with chaotic reflectors which may correspond to a lateral change of subaerial volcanism to submarine.

A peculiarity of the distal margin is the specific character of the crust. Gravimetric and seismic data on a number of sites in the distal margin of Brazil indicate that SDRs occur below by high-velocity lower crust deeper by the high-velocity body (HVLC) with V_p = 7.1–7.3 km/s, which comprises a considerable volume of the entire crust [11, 61, 62, 81] (Fig. 3). The presence of high-velocity bodies of smaller volume has also been reported in profiles without SDRs. A characteristic seismic image combining thick complexes of SDRs and HVLC in the crust, as well as the respective magnetic anomalies, has also reported offshore of Argentine [30].

The most realistic explanation for how such crust could form along the South American coast is underplating and basic magma intrusion [11]. Variations in spatial relationships between HVLC and SDRs, with absent SDRs or HVLC shifted oceanwards in places, indicate the possible formation of HVLC during both the rifting and breakup stages. According to [45] think that the specifics of the crust in the distal margin characterizes it as proto-oceanic, analogous to that which formed in slow spreading ridges. The peculiarities of this crust were also pointed out by other authors, who considered it transitional, initial oceanic, or extended continental, etc. [15, 35, 41].

SOUTH AFRICAN MARGIN

Tectonics of the Proximal Zone

Analogous to the American side of the Atlantic, the continental crust complexes in the proximal margin of South Africa are composed mainly of rocks of the Precambrian platform basement representing a fragment of Gondwana. The continental crust in general includes ancient shields, fold belts (Neoproterozoic, or Late Paleozoic on the very south), and sites of Meso-Cenozoic reactivation [35]. Basement rocks are frequently intruded by kimberlite pipes of Paleozoic, Mesozoic, and Early Cenozoic age (they are not considered in the present article). To the south of the Kameroon Line, at certain distance of the coast, the series of syneclises extends (Congo–Okavango–Kalahari); these syneclises originated in the Neoproterozoic and evolved with breaks and deformations up until the end of the Mesozoic–Paleogene. Although there is an undoubted similarity between the characters of Upper Jurassic–Cretaceous sedimentation in the Paraná and Congo Gondwanan syneclises [49], the latter syneclise does not demonstrate the occurrence of plateau basalts, as well as an uplifted basement band along the Atlantic coast.

Peculiarities of Magmatism

Igneous rocks synchronous to basalts from the Paraná region are represented in the South African proximal margin by (a) volcanics of the Etendeka complex, which can be found in the coastal parts of Angola and Namibia south of 17° S, and (b) fine intrusions of Damaraland, which are known in the Damara Belt south of 19.5° S [23, 24, 48, 53, 56, 65, 86, 90]. The distribution zone of igneous rocks appears to be much narrower than the one on the American side of the ocean (Fig. 1).

The absolute ^{40}Ar–^{39}Ar ages of lavas and dikes predominantly correspond to the interval of 133–131 Ma [48, 57, 70, 82, 90]. In the west, in the near-shore dike zone, as well as in the terminal eastern part of the discussed area, the ages of dikes are estimated at a few million years younger, until 126–124 Ma. Lava eruptions preserved in the Etendeka complex generally preceded the formation of intrusive bodies. The age of the most ancient oceanic magnetic anomaly (M4, off the coast of Namibia) is ~127 Ma, indicating the formation of near-shore dikes during the continental breakup and immediately before it.

The Etendeka region volcanics (of up to 1000 m thick) comprise the bimodal complex with plateau basalts interbedded with acid lavas and ignimbrite layers, which play a significant role in the sequence. Basic lavas are subdivided into two series differing in geochemical and isotopic compositions, as well as in mineralogical characteristics [24]. In the northern Etendeka region, there also are rocks with both high Ti and Zr contents ($TiO_2 > 2.5\%$, Zr > 250 g/t; Khumib type, or HTZ) and low ones (Tafelberg type, or LTZ). In the south, high-Ti basalts are absent, making this area similar to the Paraná region on the conjugated margin. Khumib type rocks vary from mid-alkaline to tholeiitic and contain ol + pl ± cpx phenocrysts. Tafelberg-type rocks vary from high-Mg basalts to icelandites containing phenocrysts (± ol + pl + cpx ± Fe–Ti oxides). The majority of samples typically demonstrate low MgO contents rarely exceeding 7 wt %. However, thin flows of olivine tholeiites (Tafelberg type basalts), which are known at the base of the northern sequence, enriched in FeO* and MgO, and close to primary melts in composition [24, 53, 65], are of fundamental interest. Comparison of the manifestation of magmatism in Etendeka and Paraná has shown that rocks like those of the Tafelberg Series in Etendeka are equivalent to the Gramado low-Ti type in the Paraná region, while the Khumib type corresponds to the Urubici high-Ti type [24].

In southern Etendeka, more than 20 intrusions and dike series that penetrated the Neoproterozoic Damara orogenic belt were studied in a number of massifs (Erongo, Mesum, Okenenya, Doros, and others). The established variety of rocks in them includes both Si-rich rocks (tholeiitic gabbros, granodiorites, granites, and their volcanic equivalents) and ones with a relatively low Si content (carbonatites, basic alkaline rocks, syenites, and foyalites). In particular, in the igneous complex of the Mesum massif (up to 800 m thick), there are alternation of basaltic and quartz latite layers which cut by gabbro dikes and sills [24]. In the Erongo sublovanic center (the largest in Namibia), a composite bimodal rock complex (more than 1000 m thick) was described: it contains a sequence of lava flows from predominant basalts to rhyolites, with subsequent intrusions of granodiorites and granites, and, finally, dikes of basic alkaline rocks [86, 90]. Tholeiite basalt flows occurring at the base of the Erongo rock complex are comparable to Tafelberg type basalts. Among the Horingbaai dikes, which are abundant on the western coast of Namibia, the absolute majority contains subalkaline tholeiite basalts and andesite basalts possessing predominantly high-Ti units and high Mg content (often more than 10 wt % MgO) [83, 87].

Regarding the geochemical characteristics of basic rocks of the Etendeka region, we should note the presence of typical negative Nb and Ta anomalies and positive Pb ones in spidergrams of lithophile elements: these features reflect the presence of enriched crustal component in the source [83, 87]. The plots constructed from the data available in literature [23, 24, 48, 65, 83, 84, 87] (Fig. 5) show variations in isotopic ratios of Pb and Nd in different types of basalts of the North and Southern Etendeka. Both regions demonstrate the trend of isotopic ratios from less to more radiogenic, with the extreme values ranging from 17–17.2 to 19–19.5 for $^{208}Pb/^{204}Pb$; from 15.45 to 15.72 for $^{207}Pb/^{204}Pb$; and from 37.5–37.6 to 39.2 for $^{208}Pb/^{204}Pb$.

The composition dispersion for southern Etendeka rocks appears to be greater (partially because of the abundance of alkaline units), so magmas form a large field in the plots, with insignificant differences between rocks at some sites (Fig. 5). Alkaline rocks in Spitzkoppe dikes in the south represent an independent trend which differs in higher values of radiogenic lead isotopes [84]. It is seen in the $^{208}Pb/^{204}Pb$–$^{143}Nd/^{144}Nd$ plot that compositions of the majority of rocks from southern Etendeka fall within the domain of higher $^{143}Nd/^{144}Nd$ values compared to the majority of samples from northern Etendeka. For example, Horingbaai high-Mg basaltic dikes have $^{143}Nd/^{144}Nd$ values up to 0.5028 at $^{87}Sr/^{88}Sr$ = 0.7028, which is

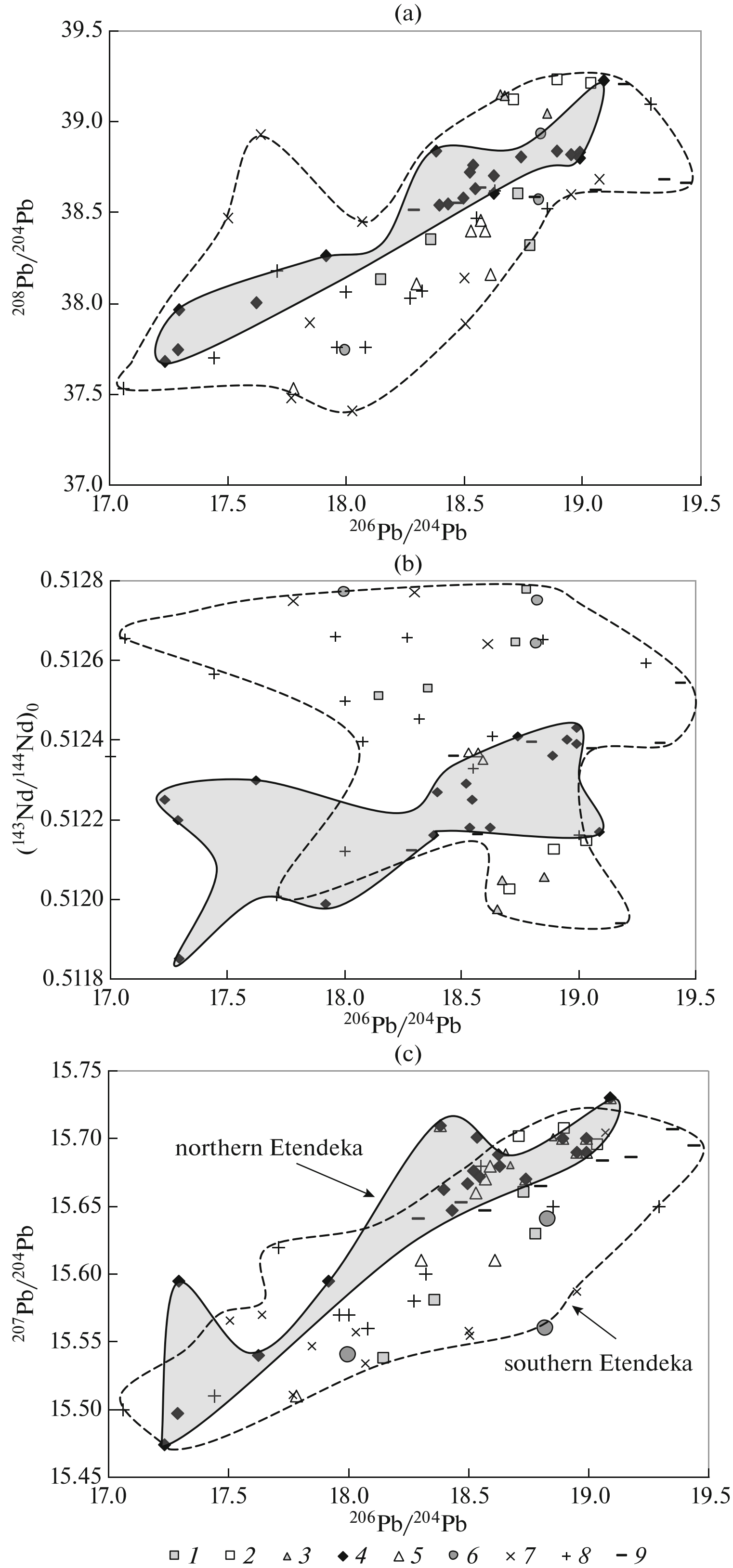

Fig. 5. Variations in Pb and Nd isotopic ratios for magmas of Etendeka region (with data from [23, 24, 48, 65, 83, 84, 87]). Notes: (*1*–*3*) southern Etendeka basalts: (*1*) low-Ti–high-Zr, (*2*) low-Ti–low-Zr, (*3*) rocks of Copper–Mezan region; (*4*) northern Etendeka basalts; (*5*–*9*) rocks of different areas of southern Etendeka: (*5*) Fals, (*6*) Horingbaai, (*7*) Okorusu alkaline basalts, (*8*) dolerites of various areas, (*9*) dolerites of Spitzkoppe dikes.

close to the known ones for enriched MORB. This allowed some authors to assume that the mentioned dikes formed from plume magmas with certain participation of depleted asthenospheric mantle in melting [23, 65, 83].

The comparison shows a great similarity between the compositions of basalts from the entire Paraná–Etendeka Province. Nevertheless, an important point is that high-Mg and high-Fe rocks were revealed in southern Etendeka, but they have no equivalents reported in the Paraná region. These are gabbroids of the small Doros lopolith and Tafelkoppe basalts occurring at its base [24, 34, 53, 65, 83]. The contents of MgO and FeO* in these rocks are up to 5–16 and 10–16 wt %, respectively, which makes them similar to Tafelberg type lavas. These basalts contain high-Mg liquidus olivines with Mg* > 92. Characteristic features are that the rocks are weakly enriched in lithophile elements and have high and variable values of Ti/Y, Ti/Zr, and Zr/Y, as well as relatively low REE contents.

Based on petrogeochemical data, the origin of Tafelkoppe basalts and their intrusive analogs is related to uncontaminated plume melts in which depleted mantle material plays a considerable role [23, 34, 65]. Their formation can be explained by melting (~10%) of the upper part of a heterogeneous plume at a high pressure (43–35 kbar) and temperature (1550° C) [34]. These rocks supposedly correspond to the earliest phase of magmatism in the Paraná–Etendeka Province which occurred before the lithosphere was significantly thinned and underwent conductive heating, and magma was not "infected" by lithospheric material [23, 34, 65]. Local penetration plume melts through the thick lithosphere is supposedly linked to the presence of weakened zones in the ancient basement [86].

Later volcanic and intrusive complexes of Paraná–Etendeka Province, possessing signatures of metasomatozed lithosphere, were melted during the main event that formed plateau basalts under conditions of a heated lithosphere (however, the lithosphere was quite thick and prevented significant supply of melts from the plume). The greatest amount of the lithospheric component was revealed in early Tafelberg and Esmeralda lavas [23]. The final stage of magmatism is represented by intrusion of alkaline magmas at the time when the lithosphere had already been significantly thinned [86]. Local manifestations of alkaline magmatism have also been reported for the post-breakup time (Late Cretaceous and Paleogene).

Summing up all the main geochemical peculiarities of magmatism in Etendeka region compared to syngenetic magmatism in Paraná region, we can point out the undoubted similarity between them, although rocks that common in African margin have broader ranges of compositions. Based on isotopic ratios, the presence of both types of enriched magmas (EM I and EM II) is found. In the American side magmas are slightly shifted towards the EM I component, with higher values of radiogenic lead at the given $^{206}Pb/^{204}Pb$ ratios. Additionally, basalts of the Paraná and Etendeka regions in some cases demonstrate a certain influence of a HIMU-type enriched source having high Pb and Nd isotopic ratios and lower Sr ones. In general, the origin of basic magmas in the Paraná–Etendeka Province undoubtedly reflects the properties of the lithospheric mantle, which was metasomatozed at different stages of Gondwana formation, and partially crustal contamination of mantle melts in Cretaceous time [24, 38, 66].

Deep structure

According to the seismic data, the thickness of the ancient continental crust in the proximal margin within the limits of Namibia is estimated from 40 to 30 km [39]. The thickest (40 km) crust is characteristic of the Congo ancient shield in the north; it decreases to 35 km within the limits of the Damara fold belt (Neoproterozoic) and to 30 km in the Mesozoic reactivation zone near the Atlantic coast. Along the boundary with the distal zone, an abrupt decrease in crustal thickness is observed.

Tectonics of the Distal Zone

In the distal margin of South Africa several large synrift troughs: Niger Delta, Gabon, Lower Congo, Kwanza, and Namib rivers are conjugate structures to the Jacuipe, Serguipe, Espirito Santo, Campos, and Santos troughs (Fig. 1). All these trughs are predominantly salt basins. The Walvis and Luderitz salt-free basins are located to the south. Similar to the South American margin, the synrift formations of the basins (from the Berriasian to Aptian, or more ancient in the south) demonstrate a change in sediments upsection from subaerial facies to shallow marine carbonates and Aptian evaporates, which preceded accumulation of postrift marine sediments [2, 3].

Peculiarities of magmatism

The volcanics studied by drilling and multichannel seismic profiling form the elongated SDRs wedges (Fig. 6), which are like mirror image of the same objects in Brazilian distal zone [15, 61]. They occur below the salt deposits and their stratigraphic analogs. So the age of magmatism can be referred between Barremian and Aptian, which is slightly younger than the dates obtained for proximal margin rocks.

The basaltic complex traced from the SDR wedges has been reported predominantly to the south of the Florianopolis Fault, in the Walvis and Luderitz basins and south of them [10, 35, 46, 61]. The composition of this complex is represented mainly by basalts, as drilling data has shown [35, 54]. For example, in the Kwanza Basin, Angola, despite the absence of SDRs, the borehole drilled at 11° S recovered a volcanic

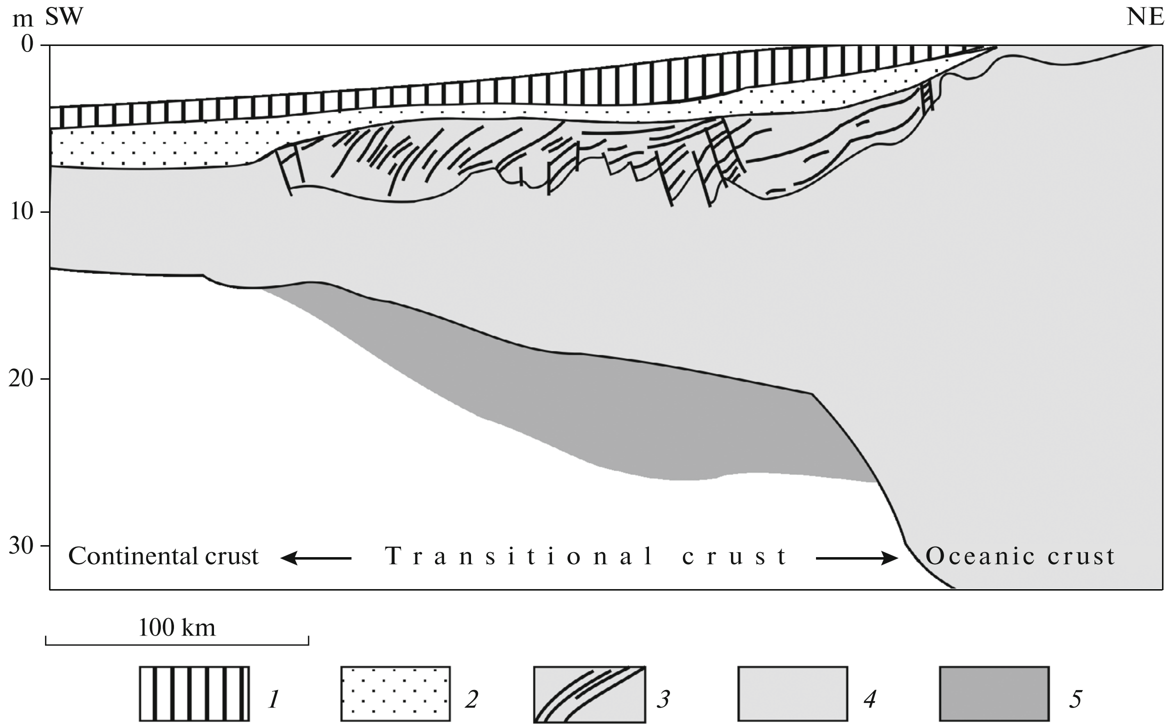

Fig. 6. Geological and geophysical cross section of Walvis Basin (with data from [15]). Notes: (*1*) postbreakup deposits (K_2–Kz); (*2*) syn-rift deposits, upper horizon (K_1ap); (*3*) volcanic/volcanoclastic complex (SDRs; K_1br–ap); (*4*) rocks of consolidated crust with transition from thinned continental to oceanic; (*5*) HVLC.

sequence of abouth 1000 m thick beneath the salt horizon, which is coeval and close in composition to plateau basalts from the Campos Basin and southern Paraná region [54]. The sequence is composed of differentiated basalts and andesite basalts with low TiO_2 contents (<2 wt %) and incompatible elements, and with a Sr isotopic ratio of 0.7045–0.7075. The youngest dikes in the Kwanza Basin (126 Ma) are similar in composition to those located in coastal Brazil and Namibia. The Late Cretaceous magmatic episode is represented by small volumes of Na-alkaline volcanics interbedded with marine sediments.

Deep structure

The total thickness of SDRs is up to 7 km, probably even more. Their internal structure is formed by wedges of dipping reflectors (from three to four), delimited by significant unconformities [10, 61, 62]. Overlapped sections of several wedges suggest intermittent manifestations of volcanism, alternated with periods of erosion and sedimentation. SDRs in these wedges differ in both the features of reflection and velocity characteristics. In particular, different wedges with V_p from 5.6 to 6.2 km/s have been reported [61]. Based on magnetometric data, diachronicity of SDRs wedges was found, with younger units located in the north. The SDRs wedges in the territory of Namibia are underlain by a high-velocity lower crust (V_p = 7.1–7.3 km/s) and then by an anomalous HVLC (V_p is up to 7.5 km/s), as revealed by wide-angle seismic profiling [10, 11] (Fig. 6). The total crustal thickness in distal margin can be up to 20 km or more, with HVLC thickness of up to 8–10 km. It is characteristic that high-velocity units in the African margin make up a considerably larger volume everywhere than in the South American margin, as was shown in [11]. Their presence was reported for a number of profiles where SDRs were absent. For example, in the northern profiles where SDRs wedges were not present [60], wide-angle seismic profiling using bottom seismographs also revealed the presence of the anomalous HVLC (V_p = 7.2–7.8 km/s) [20]. The comparison of the Angola margin to the typical margins—both volcanic (Namibia) and nonvolcanic (Iberia)—for the features of the velocity structure and crustal thickness does not solve the problem of whether the Angola margin pertains to either of them [20]. Nevertheless, the ubiquitous presence of the anomalous HVLC at the crustal base, the above-mentioned presence of thick volcanic sequences recovered from the borehole in the Kwanza Basin, and the existence of SDRs in the coupled Brazilian margin are indicators that the Angola margin has certain features of a volcanic margin.

RIO GRANDE RISE–WALVIS RIDGE VOLCANIC SYSTEM

The elements of the Rio Grande Rise–Walvis Ridge volcanic system are linked along their trend to both conjugated margins considered above and active volcanoes of Tristan da Cunha and Gough islands in South Atlantic central part (Fig. 1). Palinspastic reconstructions for C34 chron (84 Ma) show the joint locations of the Rio Grande Rise and Walvis Ridge within the ocean and their belonging to a single system which later came apart during jumps in the spreading axis [40, 64, 75, 89]. The present-day structure of the region from the Etendeka margin to the volcanic islands can be considered a unified volcanic zone diverging into two parallel branches on its southwestern side.

Peculiarities of Magmatism

The borehole-recovered basalts from Rio Grande Rise and Walvis Ridge date predominantly to the Coniacian through the Maastrichtian. Dredged samples from both structures also indicate local manifestations of anomalously young Eocene volcanism. On the basis of $^{40}Ar/^{39}Ar$ determinations, the age progression of magma formation along the course of the Walvis Ridge [40, 64, 75] was established. Successive changes were traced from 114 Ma ago at the northeastern end of the ridge to 72 Ma ago or greater (boreholes 525A, 527, and 528) in the southwest. Further southwest, along the Guyot volcanic province, the age progression continues to 49–27 Ma ago, reaching the contemporary eruptions on Tristan da Cunha and Gough islands. In general, the authors of the mentioned works determined the volcanism movement rate from the Etendeka region (133–126 Ma ago) along the Walvis Ridge volcanic zone to be about 30 mm/yr. The intermittent distribution and decreasing size of volcanoes in the Guyot Province suggest a gradual reduction of volcanic activity in Cenozoic time.

Basalts of the Rio Grande Rise and Walvis Ridge contain both high-Ti and low-Ti units (the TiO_2 content ranges from 1.1 to 3.5 wt %). A MgO content of less than 7 wt % indicates significant differentiation of the basaltic melt during crystallization. In terms of geochemical peculiarities and isotopic composition, basalts can be subdivided into two groups of close ages [34, 40, 71, 78]. The first group is comprised of rocks recovered from borehole 516F at the Rio Grande Rise, those from the borehole 525A, and the samples dredged from the axial part of the Walvis Ridge; the second group is represented by rocks recovered from boreholes 527 and 528 on the northwestern slope of the Walvis Ridge. The differences between these two groups are in the ratios of both lithophile elements (La/Sm, La/Nb, U/Pb, Nb/U, Ce/Pb, and Zr/Nb) and isotopes.

Isotopic variations in magmas of the Rio Grande Rise–Walvis Ridge system, with both dredged samples and samples obtained from deep-sea drilling taken into account, primarily determine the positions of the majority of basalts in terms of $^{206}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, and $^{207}Pb/^{204}Pb$ values in the field of isotope variations of Paraná–Etendeka Province (Fig. 7). The differences between the isotopic ratios for basalts from borehole 525A and those from boreholes 527 and 528, which are close in age, emphasize the melting sources heterogeneity within the limits of the Walvis Ridge. The compositions of rocks from borehole 525 fall within the domain of isotopic variations mentioned above for basalts of the Paraná region, with moderate values of $^{87}Sr/^{86}Sr$ isotopic ratio and low ones of $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$. This indicates an admixture of material corresponding to the model EM I enriched component, similar to the high-Ti traps of the Paraná region [34, 40, 71, 78]. The compositions of basalts from the Rio Grande Rise also have close isotopic ratios.

Basalts recovered from boreholes 527 and 528 have higher Pb isotopic ratios, reaching 15.65–15.68 for $^{207}Pb/^{204}Pb$, 38.8–38.4 for $^{208}Pb/^{204}Pb$, and $^{143}Nd/^{144}Nd$ = 0.5126–0.5128 in the most enriched samples. Based on these values, we can identify admixtures of the EM II enriched component and probably the HIMU one, which are also seen in alkaline basalts of northeastern Brazil (Fig. 7). The higher $^{143}Nd/^{144}Nd$ ratios in basalts recovered from boreholes 527 and 528 compared to the Paraná traps probably reflect the influence of the depleted asthenospheric mantle (DM). The same features are identified in some low-Ti basalts of the Paraná region.

The rocks dredged along the Walvis Ridge form a longer trend compared to basalts from the boreholes. This indicates a predominant admixture of either EM I or HIMU component in different basalts, without any regular age pattern observed in basalt compositions. Enriched basalts from the Gough Island, Tristan da Cunha Islands, and a certain part of the Walvis Ridge with high $^{206}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, and $^{207}Pb/^{204}Pb$ ratios show their own insignificantly differing trends (Fig. 7). In the plots in $^{206}Pb/^{204}Pb$–$^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$–$^{143}Nd/^{144}Nd$ coordinates, these trends are located between the fields of basalts from boreholes 527 and 528 and basalts dredged at the Walvis Ridge. Their enriched component is close to alkaline lavas of Brazil, indicating the probable presence of an admixture of continental source material in the primary plume magmas. At the same time, many contemporary lavas of the Tristan da Cunha Islands, similarly to basalts from boreholes 527 and 528, form the trend of lower values of $^{207}Pb/^{204}Pb$ at the given $^{206}Pb/^{204}Pb$ values, indicating the peculiarities of the ancient lithospheric melting source distinct in lower initial U/Pb ratios.

Despite the difference between the proposed explanations for the heterogeneities in magmas that formed the structures of the Rio Grande Rise and Walvis Ridge, the relationship of these magmas to the Tristan plume is undoubted, judging from the geochemical and, primarily, isotopic data. However, the

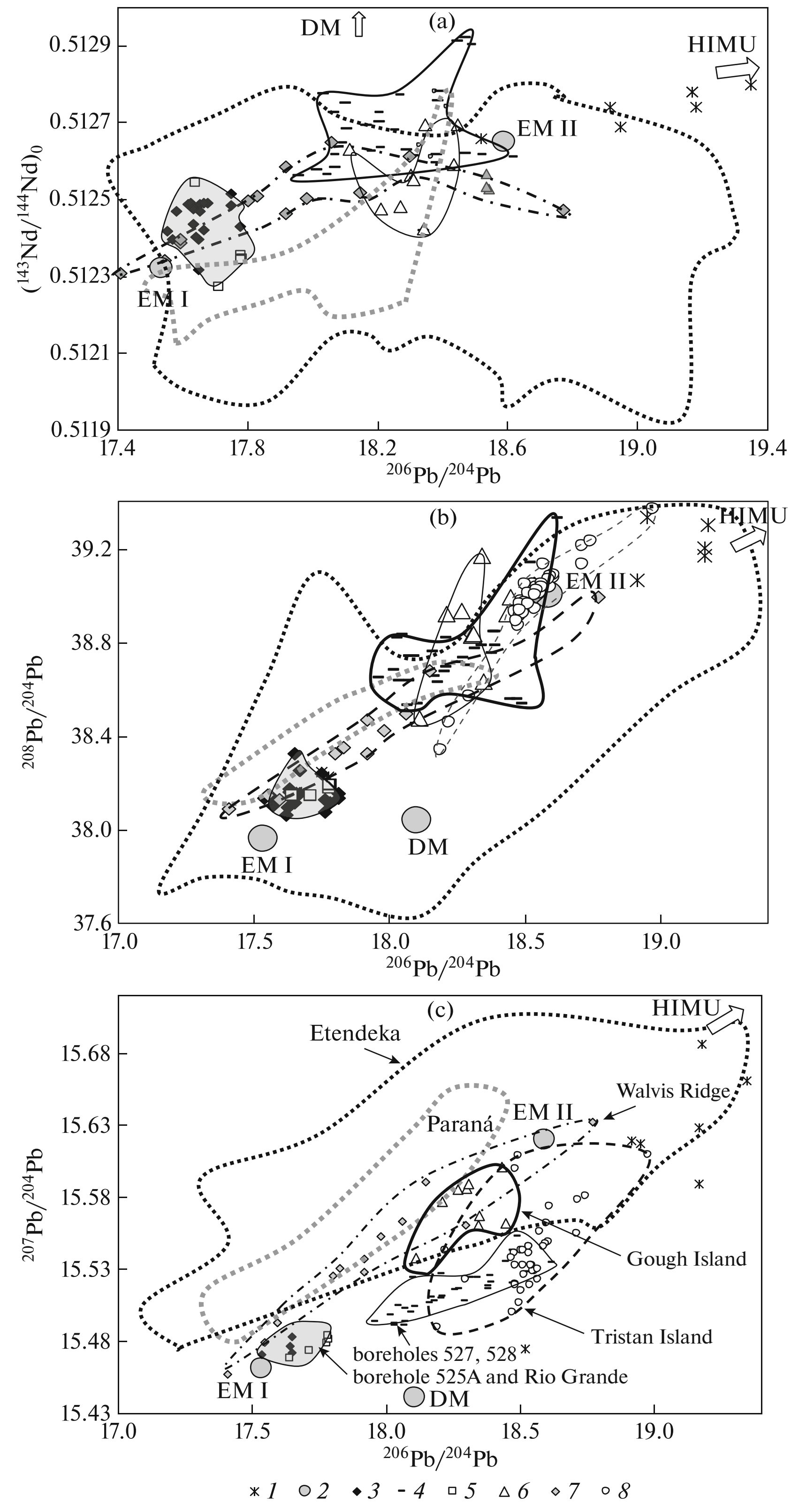

Fig. 7. Comparison of variations in isotopic ratios for magmas of Paraná and Etendeka regions and submarine rises of South Atlantic related to Tristan plume (with data from [8, 33, 40, 71, 78]). Notes: (*1*) alkaline basalts of Southeast Paraná region; (*2*) model enriched sources; (*3–5*) basalts of submarine rises recovered by boreholes (nos.): (*3*) 525A, (*4*) 527 and 528, (*5*) 516F; (*6*) rocks of Gough Island; (*7*) basalts dredged along Walvis Ridge; (*8*) rocks of Tristan da Cunha Islands.

presented data on the magmatism in the Rio Grande Rise–Walvis Ridge system and in land parts of the Paraná–Etendeka Province revealed the peculiarities reflecting the properties of the lithospheric mantle source. Within the entire province, magmas contain different amounts of EM I and EM II enriched admixture components.

The change in the composition of magmatism during its evolution was traced. In contrast to the early magmatism, seamounts were formed with certain participation of the depleted asthenospheric mantle in melting; this mantle did not differ much in terms of the Pb isotopic composition from the depleted oceanic mantle, but it had lower $^{143}Nd/^{144}Nd$ ratios. The continued supply of a limited volume of lithospheric material into the melt, determined from the plots in Fig. 7, could be caused by preservation of continental crust fragments in the oceanic crust, as was reported for the Rio Grande Rise.

Deep Structure

Seismic studies show a heterogeneity of crustal structure in the Rio Grande Rise–Walvis Ridge system. Wide-angle seismic profiling using bottom stations in Rio Grande Rise revealed crustal peculiarities characteristic of thinned continental crust [22, 45]. These are, in particular, subdivision of the crustal section into two layers based on velocity (V_p = 5.2–6.4 and 6.6–6.9 km/s), with a low velocity gradient and total thickness of up to 18 km. The presence of a layer with V_p = 4.5 km/s within sediments probably reflects the presence of igneous rocks. Upper mantle velocities of 8.0–8.2 km/s characterize peridotites and exclude serpentinization of the mantle, which had been assumed before the mentioned studies appeared. The presence of a continental crust fragment on the Rio Grande Rise is apparently supported by obtaining of granites and gneisses dredged from its slope during the Brazilian–Japanese expedition in 2013 [77]. The crustal structure becomes complicated in the northeastern part of the Rio Grande Rise, where a thin layer with V_p = 6.0–6.5 km/s is underlain by one with anomalous velocities (7.0–7.8 km/s) and the Moho is not traced in seismic profiles. Such a structure is interpreted as atypical oceanic crust, exhumed lower crust, or continental crust intruded by mafic material [22].

Based on deep seismic sounding data, the crust within the limits of Walvis Ridge is thought to be oceanic, but thickened (18–22 km, increasing up to 30 km near the coast) [31]. The upper crust (down to 6 km depth) includes layers with V_p ranging from 4.2–4.8 to 6.1–6.5 km/s, which are quite close to the velocities identified in the Rio Grande Rise. Along with this, the thick lower crustal layer beneath the Walvis Ridge has a velocity more than 7.3 km/s, similar to the one identified in profiles of the distal margin.

The relationship of the Rio Grande Rise–Walvis Ridge system and elements of the Paraná–Etendeka igneous province, ubiquitous thick series of high-temperature plateau basalts, a relatively high hypsometric position of the eruption zone (probably caused by uplift of the hot material), and directed migration of volcanism toward the younger part of the system indicate a long-term evolution of eruption over a plume head [34, 40].

TECTONO-MAGMATIC EVOLUTION OF THE SOUTH ATLANTIC MARGINS

The overview of Mesozoic margins of South Atlantic presented above reflects an evolution in many aspects similar to that revealed for the North and Central Atlantic [4]. The prehistory of the South Atlantic margins also shows extension in the continental lithosphere in the Neoproterozoic and partially in the Paleozoic. Repeated renewal of extension episodes and basaltic magmatism might be determined by dynamic support at depth, related to reactivation of upwelling system and appearance of plumes over the ancient African superplume. The Mesozoic events in the Paraná–Etendeka Province related to the Tristan plume effect, after a certain pause followed an episode of tectono-magmatic activity (also determined by plume effect) in the Karoo region.

The onset of activity in the Paraná–Etendeka Province was characterized by origination of future proximal zones on the basement of ancient Gondwana crust. Early events began with arching and crustal fragmentation, which preceded magmatic manifestation of the plume effect. Rifts often inherited the directions of ancient structures (in particular, it is assumed in eastern Argentina). The specifics of the regional evolution was established on the American side of the province. Here, along with the formation of Late Mesozoic troughs, the inherited evolution of the Paraná syneclise continued, similar to the known example of the Karoo syneclise in South Africa. It is these syneclises where magmatic activity was the most intensive and determined the foundation of Large Igneous Provinces.

In the South Atlantic, hot and fast rifting conditions dominated, with large areas covered in the proximal margin and volumetric melting of lithosphere. The sequential migration of magmatism towards the future ocean ended with magmatism confined in distal zones. The most recent episode of magmatism within the limits of proximal zones was intrusion of dike series currently known along the coasts of Brazil and Namibia. The total manifestation interval of intrusive and effusive magmatism in the proximal margins is estimated between 134 and 131 Ma. The rocks are represented by tholeiites enriched in lithophile elements and radiogenic isotopes. The younger magmatism, manifested predominantly in the province periphery, is characterized by alkaline eruptions of small volume.

We can assume that the ascent and accumulation of large masses of low-density plume material having a positive buoyancy near the lithosphere base led to its breakthrough, considerable extension of the continental lithosphere, and the foundation of distal zones here. In contrast to the Central and North Atlantic, these events occurred in the eastern, not the central, parts of the province.

The time immediately before the ocean opening was marked by crucial structural transformation. Active magmatism that formed sequences with volcanic rocks (SDRs) and a high-velocity igneous complex at depth (HVLC) determined the new growth of thick igneous crust, similar to the other Atlantic margins. Studies of SDRs wedges revealed a certain inhomogeneity and intermittence of magmatic supply [30, 81], but the total volume of volcanics and HVLC that made up the igneous crust was much larger than that in the proximal zone. Although the character and thickness of SDRs are similar in both considered margins, HVLCs on the African side cover larger areas and are often much thicker than those in South America [11].

Thinning of the lithosphere and thermal erosion of its base under the action of a plume might led to further weakening of resistance against extension forces, and the appearance of continental breakup over the plume head [6]. The breakup of Gondwana and opening of the Atlantic were localized in the axial part of distal structures, i.e., asymmetric relatively to the igneous province as a whole.

The structural evolution of the margins, events lithosphere breakup, and South Atlantic opening clearly show the northward moving diachroneity. The diachroneity is also seen in foundation of troughs in the distal margin [3, 85] and formation of volcanic and/or volcanoclastic complexes SDRs on both ocean sides [61, 81]. The northward movement of continental breakup and ocean opening ranges from 135–134 Ma in the south to 127 Ma and later in the Angola Basin in the north [46]. The coupling between the South Atlantic system of the ocean and continental margins and Central and North Atlantic structures has been reconstructed as occurring in the mid-Cretaceous [9]. The manifestation of this process in the zones of transform margins of Africa and Brazil needs to be considered in particular.

After opening of the South Atlantic, with ongoing plume activity, the formation of Rio Grande Rise–Walvis Ridge volcanic system began on the area of newly formed oceanic crust and continental fragments. The volcanic system corresponds to the trace of hot spot and is linked with the elements of the Paraná–Etendeka Province on both ocean sides. The position of the hot spot between ~89 and ~78 Ma ago is assumed to have been near the initial spreading ridge axis [34, 40, 64]. Resulting from spreading axis jumps in the period of 70–50 Ma, the separation of volcanic system elements has been reconstructed [40, 64, 75, 89]. As the volcanic system moved into the ocean, the role of lithospheric material in magma generation decreased and depleted asthenospheric mantle became involved in melting. Hot spot activity weakened (the hot spot itself became intraplate), and the Guyot Province of individual volcanoes formed along its trace. Simultaneously with a reduction in magmatic supply in Cenozoic time, the magmatic source supposedly split into two small plumes, which produced volcanic chains corresponding to Tristan da Cunha and Gough island groups [40].

A specific feature of the South Atlantic is areal expansion of magmatic activity in the postbreakup time, which resulted in the formation of a number of small plumes that produced hot spot structures above the periphery of African superplume.

DISCUSSION

Under the conditions of passive margins, the general crustal structure can be preserved for a long time without significant changes. In this respect, study of its structure can help in revealing the geodynamics of ocean opening. The given characteristics of the South Atlantic margins affected by the Tristan plume show their similarity to the margins of the North and Central Atlantic in both structural–magmatic peculiarities and preceding history [4]. In the proximal zones of South Atlantic margins, peculiarities of basement characterize the distribution of distrubed ancient continental crust. A historical approach to their study makes it possible to reveal constant alternation of convergence and breakup events that determined the early pre-Atlantic history of the region.

Mesozoic rifting and magmatism in the proximal margins of South Atlantic lasted about 3 Ma. The very short-term manifestation interval and relatively low productivity of magmatism in the proximal margins may be related to rapid migration of magmatism toward the internal part of the province. Here, in distal zones, an intensive episode of magmatism and crust formation was revealed: it formed volcanic and/or volcanoclastic SDRs wedges on crustal top and an HVLC complex at the base. As a result, Mesozoic fragmentation and magmatism caused only insignificant thinning of the ancient continental crust in the proximal zone, whereas in the distal zone, thick newly formed igneous crust originated. This was the event that had played the determining role in preparation of the continental breakup. During the subsequent spreading and formation of the Rio Grande Rise–Walvis Ridge system, reduction in volcanic activity was traced. It was especially significant in the Guyot Province and on Tristan da Cunha and Gough islands. Such damping of magmatic process in the Cenozoic was pointed out in many publications, e.g., in [5, 63].

Judging from the data of Pb–Sr–Nd isotopic studies, the origin of enriched plateau basalts that formed within the margins was related to the presence of enriched EM I and EM II model components in the source, as well as a minor part of HIMU. The specifics of enriched components with continental signatures indicates a relationship between the main plateau basalt event in the Paraná–Etendeka Province and melting of subcontinental mantle enriched during early metasomatic events. In light of this, the role of the Tristan plume in magma generation should be predominantly defined as the heat source that caused melting of the ancient lithosphere. The change in magma compositions that are found on seamounts can be explained by the reduction of the role played by lithospheric material and the increase in the participation of asthenospheric mantle in their melting which was a result of propagation of the volcanic system within the newly formed oceanic crust).

In discussing the available geochemical data, a number of researchers proposed different models of magma melting for the South Atlantic margins. For example, J. Hoernle et al. [40], noting the heterogeneity of compositions of magmas from the Rio Grande Rise and Walvis Ridge, distinguished two parallel trends in the $^{206}Pb/^{204}Pb$–$^{207}Pb/^{204}Pb$ plots: one is the Gough Island–Rio Grande Rise–borehole 525A–Guyot Province trend, and the other is the Tristan da Cunha Islands–boreholes 527 and 528 trend; the latter falls within the domain of Atlantic tholeiites. This pattern can be explained, according to [40], by the heterogeneity and zonality of the feeding plume, which existed since the earliest stages of the plume's development.

The authors of [78] believe that the features of both mentioned trends are caused by the presence of the EM I component in magmas, and its fraction is larger in basalts of borehole 525A. Basalts of the boreholes 527 and 528 have the EM I component mixed with the FOZO-like material. The same authors also suppose that the EM I component is quite ancient (about 3.5 Ga) and was formed by addition of plume melts into the mantle which had a composition close to that of the united Earth (4 Ga). The lower melting degrees (5–10%) of the obtained heterogeneous mantle calculated for the Cretaceous yielded melts typical of borehole 525A, whereas relatively high degrees (10–15%) yielded the more depleted magmas typical of boreholes 527 and 528. In all cases, melting took place under conditions of stable garnet peridotite.

Many researchers [16, 34, 38, 66] believe that melting of the material of the ancient subcontinental lithosphere played an important role in the formation of magmas of both the Paraná–Etendeka Province and Walvis Ridge. For example, C. Class and A.P. le Roex [16] found that the elongated isotopic anomaly in the South Atlantic (DUPAL), which is observed in the majority of magmas from seamounts, was formed owing to involvement of upper and lower crust fragments from the Proterozoic Namaqua-Natal fold belt. S.A. Gibson et al. [34] showed that metasozmatozed lithospheric mantle similar to that beneath the Congo Craton and Damara collision zone was involved in melting since the early formation stages of the Walvis Ridge structure.

Numerical simulation in [34] allowed the authors to reconstruct magma generation conditions for the key sites of the region. The model of formation of basalts from borehole 530A (Angola Basin, near the Walvis Ridge, 100 Ma) implies that their source was material of similar magma with a degree of melting of about 13%. Tholeiitic basalts from borehole 516F (Rio Grande Rise, 89 Ma) formed at depths of 30–80 km and at 24% decompression melting of heterogeneous mantle with 10% content of enriched source material [34]. Close melting conditions were revealed for tholeiites from borehole 525A at the Walvis Ridge: they also formed with a high degree of melting (up to 24%) and at depths of 20–70 km, with 15% addition of enriched melts from delaminated subcontinental mantle, whose composition was similar to that of the mantle source of alkaline magmas from Brazil and Paraguay. For the most depleted magmas from boreholes 527 and 528 have been reconstructed as forming with melting (up to 22.5%) of waterless peridotite at depths of 100–20 km with the addition of about 10% of melt from enriched mantle similar to that of southeast Brazil. Finally, alkaline magmatism of islands younger than 3 Ma in age (Tristan da Cunha, Ascension, and Gough) is assumed to form magmas under decompression melting of plume at about 7–10% and at a depth of ~85 km with the addition of enriched melts from recycled metasomatized sublithospheric mantle [34]. Some other authors with different melting models attribute an important role to the Tristan Plume and lithospheric source of magmas which is supported by the present work, as well as the large depth of magma generation.

The determining influence of the Tristan Plume during magma melting in the South Atlantic margins is also supported by shear wave seismic tomography data for southwest Africa and Tristan da Cunha Islands [37, 76]. Here, directly over the marginal part of the ancient African superplume, they model the presence of a vertical column of decompacted (hot) material ascending from the lower mantle and diverging to form branches, one running to the west toward the Tristan da Cunha Islands.

Thus, there are strong reasons why many researchers (e.g., the authors of [21]) consider the volcanic chain of the Walvis Ridge–Tristan da Cunha Islands to be the trace of one of the largest hot spots on Earth, linked to the lowermost mantle and having originated from a primary plume. It seems that the opinion of these researchers that the traces of many other hot spots in the South Atlantic, shorter in extent and having a shorter-term evolution, are related to secondary plumes that formed at smaller depths is also true. These are, e.g., the volcanic systems of St. Helena

Island, the Discovery and Shona ridges, etc. Indeed, these structures could have formed under the action of small shallow plumes. Nevertheless, they could also coincide with the margins of African superplume, as is seen in some well-known seismotomographic models [37] (Fig. 1). Such an arrangement of hot spots suggests that these small plumes could have diverged from the ancient superplume and ascended to the upper mantle by the Late Cretaceous–Early Cenozoic time.

The St. Helena volcanic system and certain others are comparable to the Rio Grande Rise– Walvis Ridge volcanic system in their evolutionary peculiarities, general character of volcanism, and its sources [47, 63]. However, the participation of the HIMU enriched component with high $^{206}Pb/^{204}Pb$ ratios, a low $^{87}Sr/^{86}Sr$ ratio, and higher $^{143}Nd/^{144}Nd$ ratios appears to play a greater role in their genesis. The compositions of products of postbreakup magmatism demonstrate considerable heterogeneity. The role played by the HIMU component is often predominant, as was shown, e.g., for the Trindad hot spot [7].

CONCLUSIONS

The evolution of volcanic passive margins and opening of the South Atlantic are described. Formation of young voluminous igneous crust during preparation of the breakup of Gondwana is shown to be the most important peculiarity of the distal margins. Continental breakup propagated north, favored by polefugal forces caused by Earth's axial rotation.

In the Atlantic southern margins there is a clearly expressed asymmetry of the surface structure, which is more significant with respect to the North Central Atlantic. The formation and subsequent breakup of distal margins shifted to the eastern parts of the region, probably due to the peculiarities of horizontal asymmetric stresses in the upper envelopes of the solid Earth. Formation of the HVLC layer in the distal zones crust in the ocean east was more extensive than in the west.

The determining influence of the Tristan plume on magma generation is shown: this plume is considered predominantly as a heat source that caused melting of the lithosphere. The evidence for plume participation in magma generation are, e.g., the formation of thick series of high-temperature plateau basalts, the relatively high hypsometric position of the eruption zone, and migration of volcanism toward the younger part of the system. Characterization of plumes usually involves data on the geochemistry of ocean island basalts. However, such problems as the composition of plume material, ratios between the enriched and depleted components in it, and the character of the plume's zonality remain insufficiently solved.

The considered composition of rocks from the Paraná–Etendeka Province and enriched magma sources (EM I and EM II) are close in terms of their isotopic characteristics to rocks from the Central and North Atlantic margins, which were also founded on the ancient continental basement. We think that the most probable cause of geochemical enrichment of melts was the supply of enriched EM I and EM II components (as well as a small part of the HIMU one) in the case of in situ melting of continental lithosphere material, which was especially significant at the early stages of magma generation. As the process expanded to the domain of newly formed oceanic crust, the depleted mantle (DM) component played a larger role in the composition of melts.

A peculiarity of the South Atlantic is the formation of the large Rio Grande Rise–Walvis Ridge volcanic system, which was supposedly related to the influence of primary plume [21]. An essential difference of the South Atlantic branch from the northern and central parts of the Atlantic is a broad distribution of igneous manifestation in the Late Cretaceous–Cenozoic due to the formation of a large number of hot spots. Such an episode of magmatism can be an important event determined by activation of ancient African superplume.

The distribution of young hot spots in the South Atlantic and long-term tectono-magmatic evolution of Paraná and Karoo syneclises along the western and southern periphery of the African superplume can characterize the dynamics of this plume. In addition, the genesis of kimberlites of various ages in Africa and South America may be related to the dynamics of the African superplume also.

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