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Tectonics of the Southern Ocean Passive Margins in the Africa–East Antarctica Region

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Abstract—Based on geological and geophysical data for the conjugate Africa–East Antarctica margins, the peculiarities of preparation of the breakup of central Gondwana are discussed. When using the historical approach, a significant inheritance of the Middle-Upper Jurassic tectono-magmatic development from the preceding time is shown. The first location of tectono-magmatic activity in zones of weakness on the proximal margin, its subsequent migration to distal margins, and further opening of the ocean is established. The geochemical features of magmas of the region and their sources are discussed. Evidence is presented for the decisive influence of the Karoo–Maud plume on the development of magmatism. A significant feature of plume manifestation is considered: the presence of high-magnesian ferruginous picrites, formed by melting of a pyroxenite source with specific composition, coinciding with the central part of the plume and corresponding to the earliest eruptions. We determined the source of magmatism at the initial stage could have been the substance of a rising plume, and magmas reached the surface through existing fractures without interacting with the lithosphere. In the course of evolution, the admixture of pyroxenites in the source decreased and the melts acquired the features of melting lithospheric mantle, which was reflected in the isotopic characteristics of melts with a predominant enriched EM2 component. The structure and magmatism of the Southern Ocean and South Atlantic are compared. Also discussed the locations of the Mesozoic Karoo–Maud and Tristan plumes, as well as the zones of subsequent breakup of Gondwana, above the margins of the African superplume, indicating a relationship between surface and deep-seated events.

Keywords: rifting, breakup, opening of the ocean, magmatism, magmatic source, plume, superplume

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INTRODUCTION

Consideration of the system of Mesozoic oceanic structures of the Atlantic and Southern oceans has revealed their sequential foundation in regions of Gondwana's ancient continental lithosphere. It was proved that the areas of foundation are confined to the periphery of the African superplume—the Tuzo large, low-velocity province at the core–mantle boundary [7, 79, 80]. Such lower mantle provinces with low-velocity transverse waves have recently been termed "superswells" [8]. Initiation of continental breakup (middle of the Triassic) was localized in the near-equatorial region, at the northwestern margin of the future African continent. Northern progradation of the breakup and sublatitudinal opening of the ocean are traced from this starting point beginning with the Iberia–Newfoundland region (end of the Triassic–beginning of the Jurassic). Later (middle of the Jurassic), breakup events were localized in the Southern Hemisphere with the development of meridional extensions and opening of the Southern Ocean, later followed by renewed sublatitudinal opening of the ocean in the South Atlantic (Early Cretaceous).

Preparation of continental breakup began ubiquitously with the formation and development of conjugate passive margins. Therefore, analysis of the margins' history is crucial for understanding the geodynamics of rifting and initial seafloor spreading, as demonstrated in [6]. The present article continues the authors' cycle of works on the tectonics of the Mesozoic passive margins of the Atlantic Ocean and examines the features of the conjugate Africa–East Antarctica margins. Both published geological–geophysical and geochemical data were used in the discussion. We have formulated the problem of determining the conditions for rifting, magmatism, and preparation of continental breakup in the opening of the Southern Ocean.

PROXIMAL MARGINS OF THE SOUTHERN OCEAN

Southern African Margin

The continental basement of southern Africa is composed of the rocks from Gondwanan fragment. These are the Archean Zimbabwe and Kaapvaal cratons, the Proterozoic Limpopo belt dividing them,

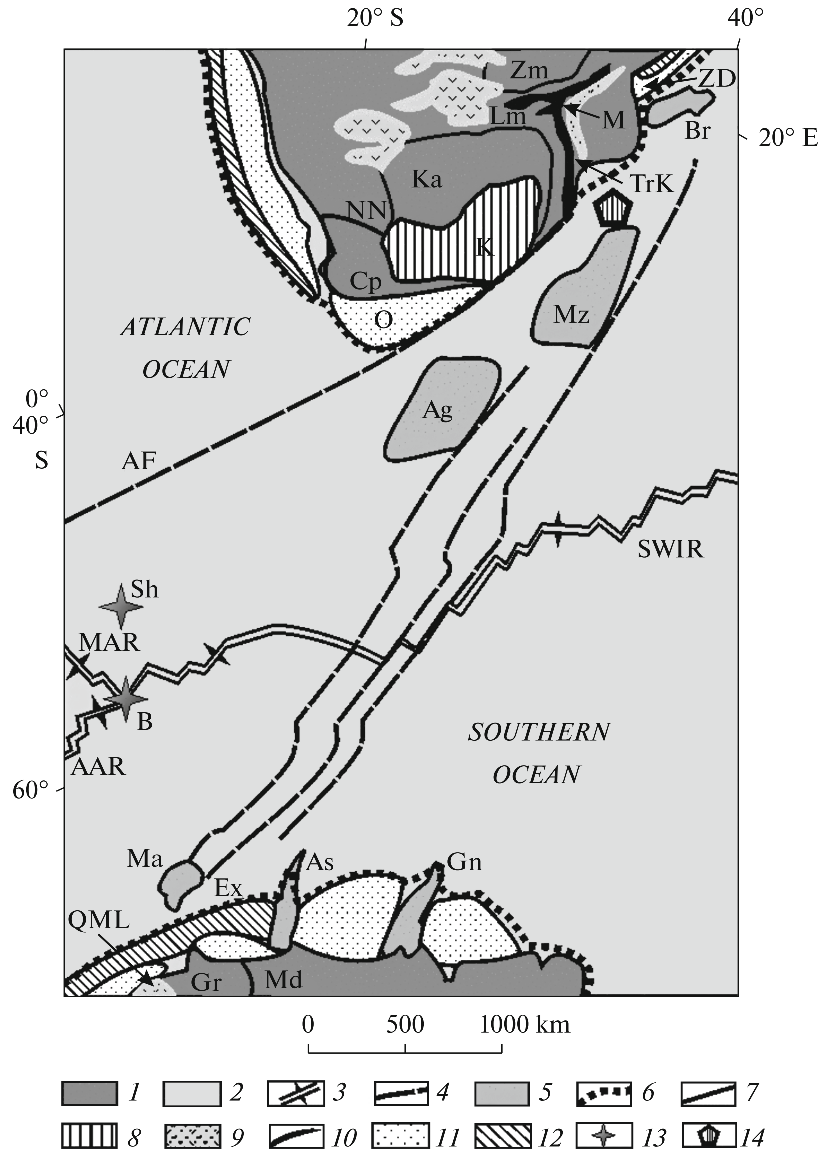

Fig. 1. Tectonic pattern of Southern Ocean margin using data of [49, 55, 56, 66]. Notation: Queen Maud Land, QML; Mwenezi, M. Notation on continents and proximal margins: Zimbabwe Craton, Zm; Kaapvaal Craton, Ka; Grunehogna Craton, Gr; Limpopo belt, Lm; Namaqua and Natal belts, NN; Cape belt, Cp; Maud belt, Md; Karoo Basin, K; Karoo triple junction, TrK. Notation on distal margins: Outeniqua Basin, O; Zambezi Delta Basin, ZD; Explora Wedge, Ex; Gunnerus Uplift, Gn; Astrid Uplift, As. Notation within ocean: Beira Uplift, Br; Mozambique Uplift, Mz; Alguhas Uplift, Ag; Maud Uplift, Ma; Agulhas–Falkland transform fault, AF; Bouvet hotspot, B; Shona hotspot, Sh; South Eastern Indian Ridge, SWIR; Mid Atlantic Ridge, Mar; American Antarctic Ridge, AAR. Arbitrary notes: (*1*) Fragments of Gondwana supercontinent with Precambrian and Palaeozoic crust; (*2*–*6*) oceanic crust region: (*2*) ocean floor; (*3*) axial zones of spreading ridges; (*4*) major faults; (*5*) oceanic uplifts and microcontinents; (*6*) continent–ocean boundary; (*7*–*10*) proximal zones of Mesozoic passive margins: (*7*) boundaries of of structural elements; (*8*) platform basin (C_2–J_2), including numerous sills (J_{1-2}); (*9*) distribution of lavas (J_{1-2}); (*10*) dikes of Karoo triple junction (Pcm and J_{1-2}); (*11, 12*) distal zones of Mesozoic passive margins: (*11*) basins filled with synrifting and postbreakup sediments (K–CZ?); (*12*) thick volcanic series (J_2–K?) forming SDRs; (*13*) hotspots; (*14*) position of center of Karoo–Maud plume.

and other fold belts (Fig. 1). Successive replacement of ancient elements by younger ones is traced to the south: from the Kaapvaal Craton to the Proterozoic Namakwa and Natal belts, and ultimately to the Late Paleozoic Cape fold belt in the far south. Seismic data confirm the heterogeneity of the African basement, which includes a mosaic of blocks of varying thickness, structure, and composition [81]. The features of the ancient continental crust reflect more than 3.5 Ga of history, with alternating continental accretion and breakup periods, as well as episodes of basalt magmatism, in particular, in the Natal region. Recurring kimberlite emplacement has been established, which was particularly significant in the Mesozoic and Early Cenozoic. Voluminous Mesozoic flood basalts and intrusive rocks, widespread within the conjugate margins of southern Africa and East Antarctica, make up the Karoo Large Igneous Province (LIP) [22].

The largest structure of the Mesozoic margin is the Karoo longitudinal platform basin (syneclise), with a length of some 1400 km which has been studied on the basis of drilling and seismic data [21, 72]. The basin foundation within the Gondwana supercontinent happened as result of subsidence displacement from the Cape Basin to the north. It developed over a span of ~150 Ma, with subsidence compensated by accumulating sediments of the Karoo Supergroup (C_2–J_2). These are predominantly subaerial rocks (up to 6 km thick) that change upsection from glacial to aeolian, with a thick basalt horizon in the roof. The tectonomagmatic features of the Karoo Basin are comparable to those of the Paraná Basin in Brazil, considered in [7]. At the same time, the initiation of subsidence in the Karoo Basin is attributed to a later time; its extent, just like its depth, is smaller compared to the Paraná Basin.

Specific Features of Magmatism

The magmatic complexes in the region are represented by flood basalts, dikes, sills, and gigantic dike series, which sprawl over the vast area of southern Africa [39, 49, 51, 65]. The flood basalts (up to 1600 m or more) were protected from erosion in the inner part of the Karoo Basin, in the restricted territory of Lesoto. However, initially, they covered a much larger area [51]. Flood basalts with the same age and composition are also widely encountered to the north: a vast field in Botswana and Zimbabwe [23]. Ubiquitous sills are a feature of widespread magmatism in the Karoo Basin, which predominate in volume over volcanics. The Okavango, Save–Limpopo, Olifants River, and Lebombo gigantic dike series in Mozambique and Botswana, at the northeastern end of the Karoo Basin, are important elements in the marginal structure [51]. This is the so-called Karoo triple junction, consisting of numerous subvertical dikes. Its radial geometry, in addition to other magmatic features, were used earlier as evidence for plume impact and the initiation of plume magmatism [28, 83].

The main manifestations of Mesozoic magmatism in the Karoo Province have been $^{40}Ar/^{39}Ar$ dated as ~184–178 Ma, with age concentrations ranging from 184 to 181 Ma, which corresponds to a total main event duration of ~3 Ma [49, 52]. In addition, U–Pb zircon dating of dolerite sills and dikes along the entire Karoo Basin yielded ages of 183–182 Ma, corresponding to a time interval of ~1.0 Ma [77]. In eastern Mozambique, in the Rooi Rand dikes cross-cutting the Karoo basalts, the latest datings were obtained, up to 174–172 Ma [52]. In eastern areas, the young, compositionally similar Movene basalts are also well known, which crown the volcanic sequence in the Lebombo monocline and are covered by Cretaceous deposits [49, 62].

For dikes of the triple junction system, $^{40}Ar/^{39}Ar$ determinations yield ages close to those for the flood basalts [49, 50]. However, in-depth studies also revealed a significant number of Precambrian dikes in the system's composition [50, 51]. For dolerites of the Olifants River series, Archean and Proterozoic datings were obtained almost exclusively, and the majority of the dikes that cut through the basement are not observed in the Jurassic horizons. These data showed that the peculiarities of Jurassic dike series correspond to their inherited formation, which was governed by basement structures [51]. Therefore, the geometry of the Karoo triple junction most likely reflects the position of zones of weakness for magma to penetrate and cannot be used as a Mesozoic plume marker.

Within the Karoo Basin, flood basalts and the associated dolerite dikes and sills have a weakly enriched tholeiitic composition. The lower volcanic sequence also hosts a small amount of nephelinite and picrite. Rocks of the Rooi Rand dike series and Movene basalts in the Lebombo monocline, corresponding to the final magmatic stage, have a depleted composition close to MORB [49, 62]. The upper sequence also include ignimbrite, dacitic and rhyolitic tuffs and lavas, both underlying and interlayered with the Movene basalts [52, 62]. All of the volcanics are represented by subaerial rocks.

Based on petrogeochemical data, high- and low-Ti types with TiO_2 contents greater and less than 2 wt %, respectively, have been identified among the flood basalts, dolerites, and picrites. Usually, these types of rocks are spatially unrelated, but the dike series of the triple junction host both high- and low-Ti varieties. A sharp replacement of low-Ti varieties by high-Ti ones has been noted for the uppermost parts of some basalt sequences in Lebombo and Botswana [49]. High-Ti basalts are characterized by higher concentrations of all lithophile elements, as well as a higher degree of enrichment in the most incompatible elements compared to the most compatible [49]. Low-Ti basalts have less differentiated compositions. Negative Nb and positive Pb anomalies are observed in spider plots for both types of rocks [49, 65].

Judging from the available literature data [23, 43, 49], the isotopic characteristics of high- and low-Ti basalts differ strongly, forming fields that hardly overlap at all in the Pb–Sr–Nd isotope coordinates (Fig. 2). The presented diagrams of Pb isotope variations clearly show the specifics of two types of magma in the Karoo province: low-Ti basalts are characterized by relatively high $^{206}Pb/^{204}Pb$ ratios ranging from 17.6 to 18.0, in contrast to high-Ti rocks (with $^{206}Pb/^{204}Pb_i$ = 16.5–17.6). Elevated $^{87}Sr/^{86}Sr$ ratios reaching 0.707 have also been noted for these. Comparison of the traps of the Karoo and Paraná–Etendeka LIPs has established for the latter a more typical manifestation of enriched component, related to melting of the subcontinental lithosphere [7].

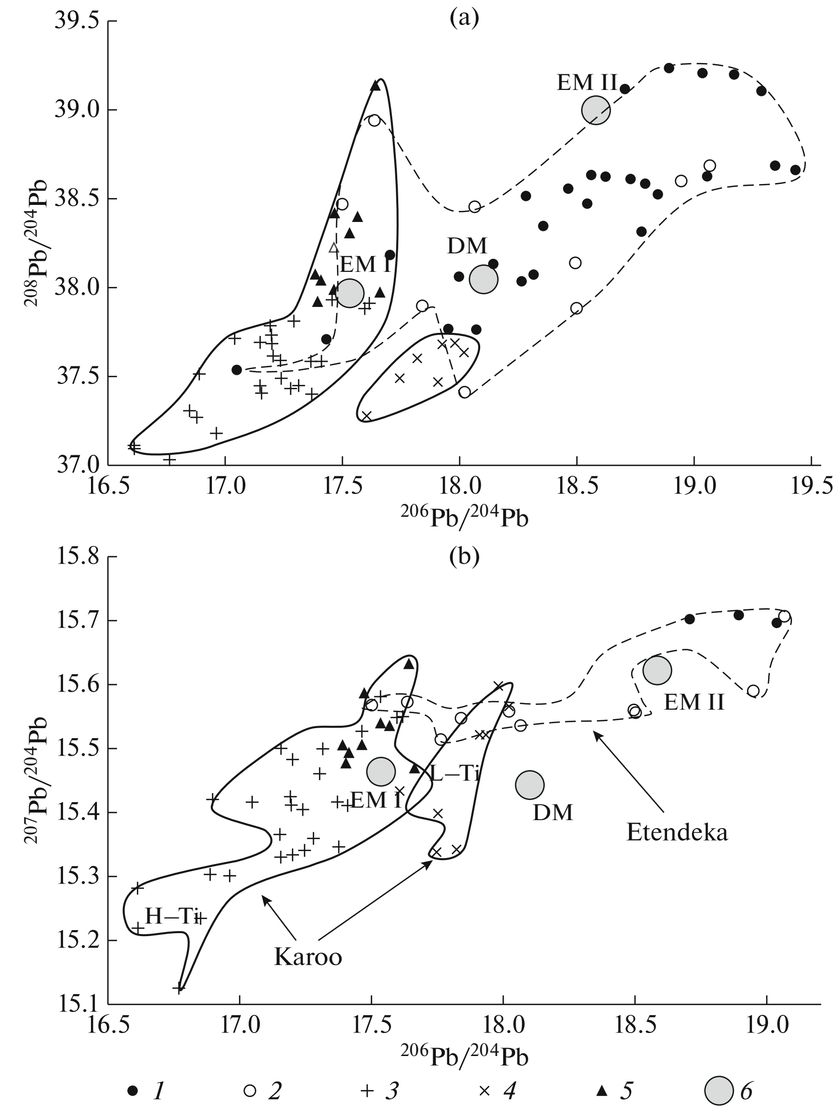

Fig. 2. Comparative characteristic of Pb isotope ratios in igneous provinces of Africa related to Karoo–Maud (180 Ma) and Tristan (130 Ma) plumes: for Karoo province (based on data of [23, 43, 49, 53]) and southern Etendeka region (based on data of [7]). Data are recalculated to primary age of lava flows. Notation: LTi, low-Ti basalts; HTi, high-Ti basalts. Arbitrary notes: (*1*, *2*) basalts of Southern Etendeka region: (*1*) low-Ti and low-Zr; (*2*) alkali; (*3–5*) Karoo basalts: (*3*) high-Ti; (*4*) low-Ti; (*5*) high-Fe picrites of Nuanetsi region; (*6*) model isotope sources, after [12].

The fundamental separation of magma in the Karoo Province into two types—high- and low-Ti—entails a difference in their mantle sources [27, 49, 68]. However, this does not yield an unambiguous answer about the origin of the magmas. The spatial dissociation of the magma types may be due to the heterogeneity of the feeder plume with different magma compositions in its central part and on its periphery, as well as to the existence of inhomogeneities in the melting lithosphere, the composition of which remains insufficiently studied. As was shown for the region of Nuanetsi and northern Lebombo [24], strongly enriched high-Ti magmas could have formed from plume melts contaminated during passage through lithosphere containing veinlets of earlier alkali melts. Low-Ti magmas in southern Lebombo may reflect melting in peripheral areas of the plume head. Study of widespread olivine–porphyritic high-titanium bearing basalts in Nuanetsi established high temperature melting (1500–1600°C) [20, 42]. Based on a study of high-magnesian olivine and the geochemical features of these basalts, V.S. Kamenetsky et al. [53] hypothesized the presence in their source of pyroxenitic mantle with EM1 characteristics, included as recycled components into the composition of the ascending plume.

On the other hand, according to [49], the indicated peculiarities of the basalts, in particular, the presence of negative Nb and positive Pb anomalies, may correspond to melting of heterogeneous subcontinental lithosphere with differing depths and a varying amount of garnet in the source. For high-Ti basalts and picrites, deeper melting (more than 80 km) with the presence of garnet in the source is assumed, in contrast to the shallow spinel-containing source that formed low-Ti magmas.

A special study of Precambrian rocks found in dikes of the Karoo triple junction showed a general similarity of their geochemical characteristics, as well as their magma sources, with those obtained for the Jurassic basalts and dolerites of southern Africa [48]. This makes it possible to relate the formation of igneous complexes separated by 900 Ma to a single source in the enriched lithosphere making up the African Platform.

Deep Structure

The velocity structure of the proximal zone is mainly determined by the features of its ancient basement. The mantle structure in southern Africa generally corresponds to the surface geology, just like that established for the São Francisco Craton in South America [73]. The presence of thick lithospheric roots (to a depth of 200–300 km) beneath the Kaapvaal and Zimbabwe cratons has been suggested based on recent seismotomographic P and S wave data [30]. Significant variations in thickness and seismic velocities in the crust have been noted, which resulted from preceding episodes of compression and mafic intrusions [81].

In the Karoo and Cape regions, the crustal thickness is mainly estimated based on seismic refraction profiles at 40–42 km with a decrease to the south [67, 72, 74]. The seismic velocities in the upper crust (V_p = 4.5–5.5 km/s) correspond to deformed sedimentary and metamorphic rocks of the Cape and Karoo supergroups. When intrusives and lavas are present, the velocities in the upper crust increases to 6.3–6.4 km/s. Lower-crustal velocities of V_p = 6.2–6.9 km/s are common here for unstretched continental crust and likely correspond to underlying Precambrian complexes. However, an explanation is required for the presence of a lenticular lower-crustal horizon up to 7 km thick near the southern coast, with elevated velocities of V_p = 7.0–7.4 km/s. Its formation is assumed to be related to either the presence of ancient mafic intrusive rocks in the basement metamorphic complex or more likely to the emplacement of Jurassic gabbroid intrusions in the lower crust [74].

East Antarctic Margin

Just like in Africa, on the conjugate Antarctic margin in Queen Maud Land, Precambrian complexes within the basement represent a fragment of Gondwana. These are Archean and Proterozoic complexes of the East Antarctic Platform comparable to the African complexes [37]. The Archean Grunehogna Craton is part of a single structure with the African Kaapvaal Craton and is bounded in the southeast by the Mesoproterozoic Maud belt, which is a continuation of the Natal belt (see Fig. 1) [58]. The position of the boundary of Archean–Proterozoic lithosphere, based on aeromagnetic and gravimetric data, has been reconstructed close to the northern part of the Vestfjell Mountains [59].

Specific Features of Magmatism

In western Queen Maud Land, flood basalts and dolerite dikes are well known, comparable in composition and $^{40}Ar/^{39}Ar$ ages to complexes of the southern African margin [39, 41, 49, 60, 69]. Earlier low-volume igneous manifestations in the regions of Almannriggen and Utulror have also been noted, with $^{40}Ar/^{39}Ar$ ages of ~190 and ~205 Ma, respectively [39, 60]. Flood basalts (up to 900 m thick) are exposed in the Vestfjell, Kirvanveggen, and Hemifrontfjell mountains in the west of the area, while their intrusive counterparts (dolerite dikes) are exposed primarily in the Vestfjell Mountains [1]. Rocks close in age and composition are also represented in dikes of the Ferrar zone in the Transantarctic Mountains [26]. The youngest basalts (173 Ma) are found in central Queen Maud Land, in the Schirmacher Oasis [76].

Analysis of the magma composition of southern Africa and Queen Maud Land carried out based on database compiled by A.V. Luttinen [58] revealed for rocks of these regions almost complete coincidence of variations in rock-forming elements and Sr–Nd isotope ratios (Fig. 3). The main compositional group consists of differentiated basalt varieties with a MgO content ranging from 9 to 2 wt % (7% on average). However, in both regions, a high-magnesian basalt group exists, which may include, in addition to cumulative varieties, magmas close to the primary melts. Among these, the presence of rocks with elevated TiO_2 (and K_2O) contents is noteworthy for southern Africa; they are hardly represented at all in the territory of Queen Maud Land (see Fig. 3a).

Similar to southern African magmas, Queen Maud Land basalts are distinguished by high- (TiO_2 = 3.8–5.2 wt %) and low-Ti (TiO_2 < 2.2 wt %) types, which differ in the degree of geochemical enrichment, although varieties both enriched and depleted in lithophile elements are encountered in the composition of each type [58]. Within the low-Ti complex in the Vestfjell Mountains, interbedding of three basalt subtypes was established based on detailed sampling of two sections: CT1, CT2, and CT3, which differ in the relationship of lithophile elements [59]. Their comparison with rocks that developed in the Lebombo region in Africa determine the similarity of CT1 basalt to the low-Ti tholeiites of southern Lebombo, and of the CT2 basalts to the Rooi Rand dolerites and their extrusive counterparts. The CT3 subtype, which has

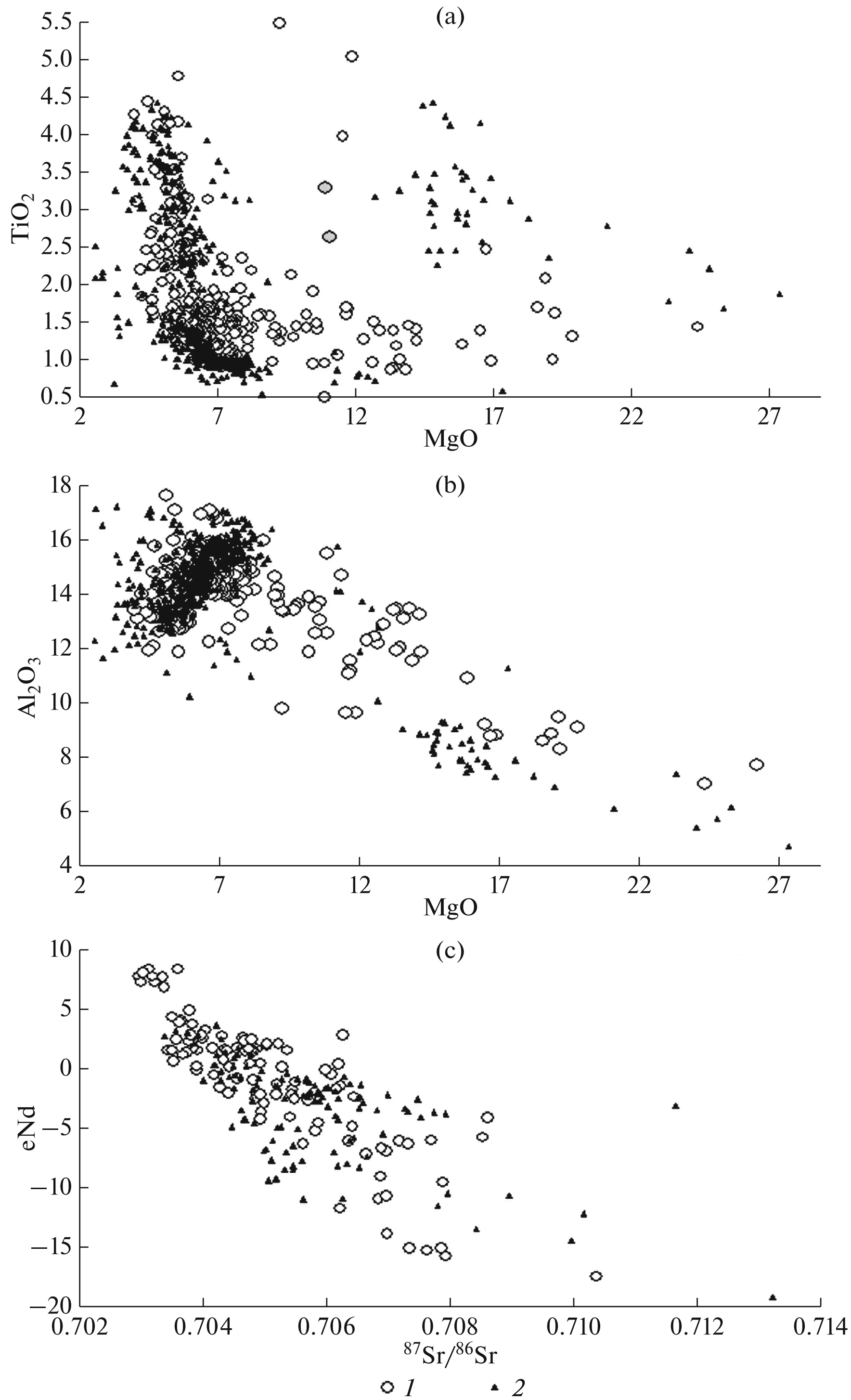

Fig. 3. Correlation diagrams of magma compositions formed under influence of Karoo Maud plume (based on data of [58]). Arbitrary notes: (*1*) rocks of Queen Maud Land (Antarctica); (*2*) rocks of southern Africa.

no direct counterparts in Africa, is close in composition to MORB, with high eNd_i and nonradiogenic $^{87}Sr/^{86}Sr_i$ values. It was hypothesized in [59] that the CT1, CT2, and CT3 basalt subtypes reflect the lateral heterogeneity of the melting lithosphere generated during ancient subduction.

Of particular interest are the high-magnesian and high-ferruginous basalts with elevated TiO_2 content from the Almannriggen (Vestfjell) region, which are combined into the CT4 subtype [41, 59, 60]. They are similar to the high-Ti rocks of the Mwenezi region in the north of the Lebombo monocline. Rocks of the

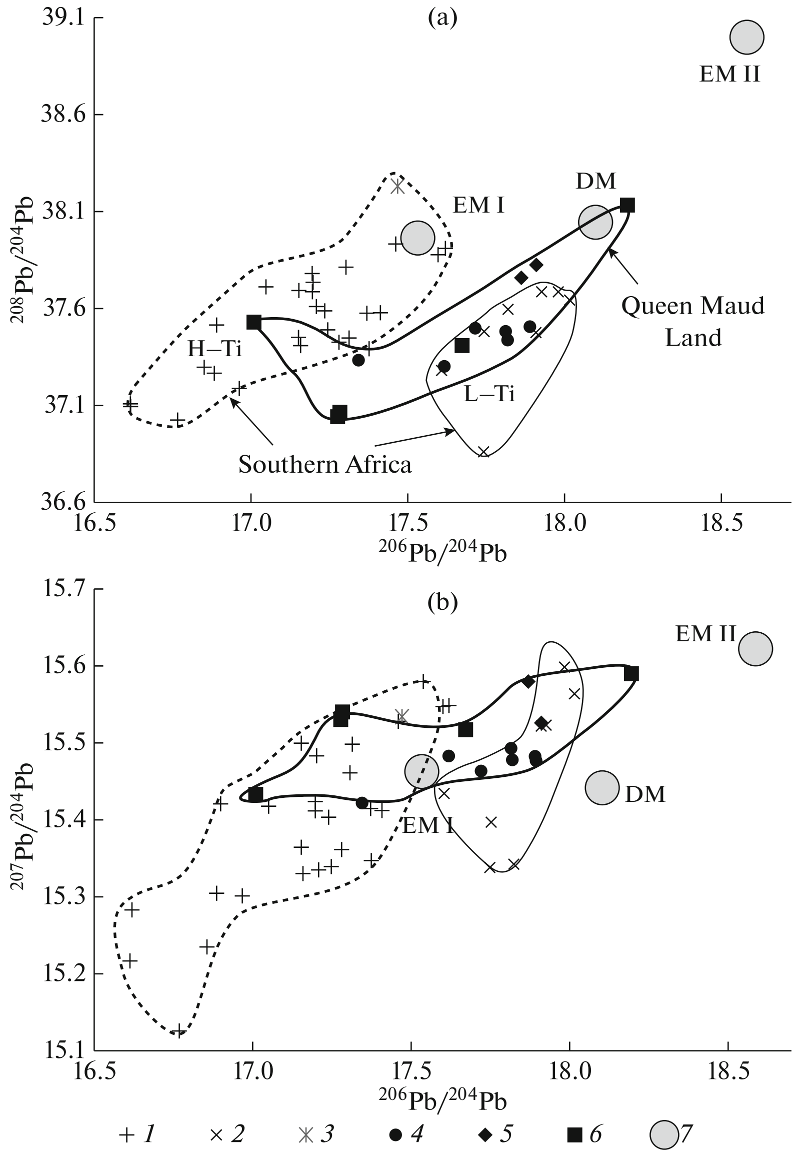

Fig. 4. Variations in Pb isotope ratios in Queen Maud Land magmas (based on data of [41, 53, 58, 60]) and southern Africa (based on data of [24, 43, 49]). Notation: LTi, low-Ti basalts; HTi, high-Ti basalts. Arbitrary notes: (*1–3*) basalts of southern Africa: (*1*) high-Ti; (*2*) low-Ti, (*3*) high Ti, high-Fe basalt from Nuanetsi region, after [53]; (*4–6*) basalts and dolerites of Queen Maud Land, based on classification [59]: (*4*) depleted ferropicrites; (*5*) enriched ferropicrites (CT4 subtype); (*6*) low-Ti basalts (CT1, CT3 subtypes); (*7*) enriched model sources, after [12].

CT4 subtype are the least differentiated and least contaminated by crustal material and differ both in the primitive distribution spectrum of lithophile elements and high $\varepsilon Nd_i = 9$ at low $^{87}S/^{86}Sr_i = 0.703$ values. This subtype also differs from the others by the content of inert gases and volatiles. They have elevated $^{40}Ar/^{36}Ar$ ratios (640), a high He concentration, and an elevated volatile component [1], which may indicate their plume origin. This magma subtype, pertaining to ferropicrites, is frequently considered as specific melts occurring in the upper parts of a plume head at the earliest evolutionary stages of plume magmatism [32, 69].

Just like other magmas, the ferropicrite group is geochemically heterogeneous [41, 44, 58]. However, all rocks, both enriched and depleted in lithophile elements, are characterized to a particular degree by a negative Nb anomaly, which is presumably related to an admixture of subduction component in the source, which is also confirmed by oxygen and osmium isotopy data [41, 44]. These features may be evidence of fluid enrichment in the most incompatible lithophile elements.

In Nd–Sr isotope coordinates, all magmas of East Antarctica, just like Southern Africa, are characterized by quite similar extensive trends, from the least radiogenic (depleted) to enriched compositions (Fig. 4). In addition, the observed wide dispersion of isotopic compositions within each type may reflect either the heterogeneity of the melt source (with lithospheric admixture) or contamination with crustal material during the ascent of the primary plume magmas [59].

Deep Structure

The basement of the East Antarctic margin has seismic characteristics typical of unstretched continental crust and generally similar to those obtained for southern Africa. According to wide-angle seismic profiling data, V_p = 5.5–6.0 km/s in the upper crust and V_p = 6.3–6.9 km/s in the lower crust have been simulated; the thickness of the crust is estimated at 45 km with localized swelling and pinching of up to 40 km toward the coast [14].

The similarity and former unity of the continental basement within its proximal margins can be clearly seen from the above description of the Southern Ocean's frame. The features of Mesozoic magmatism on both margins are also quite similar. Meanwhile, based on the isotopic characteristics, it can be observed that the most depleted compositions are more often encountered in Queen Maud Land. Variations in the isotopic ratios in basalts here are more limited compared to the margin of southern Africa and are close to the field of the southern Etendeka traps (see Fig. 4). These features of the Antarctic basalts were probably governed by a more rapid melt supply to the surface.

DISTAL MARGINS OF THE SOUTHERN OCEAN

Southern African Margin

Despite the overall similarity of the conjugate proximal margins of the Southern Ocean, differences are observed in the present-day structure of its distal zones, which are complicated by multiple faulting. The Southern African Margin can be considered a transform margin related to the Agulhas–Falkland fracture zone, ultimately forming at the beginning of the Early Cretaceous [67]. Elements of the transform margin overlay an earlier distal structure—the Outeniqua Basin.

The Outeniqua Basin is situated almost completely on the shelf and is separated from the Karoo syneclise by an extensive uplift formed by fold complexes of the Cape Belt. Based on palinspastic reconstructions [67, 68], the Outeniqua Basin and more western Falkland Basin are considered elements of a single Late Mesozoic structure that were separated during displacement along the Agulhas–Falkland transform. Within the basins, the age of lower sedimentary strata covering the continental basement has been estimated as the middle of the Jurassic, as has been established by boreholes DSDP 237A, 330, and 511 on the Maurice Ewing Bank [13, 78]. The rifting sequence consists of shallow marine sediments with lignite interlayers; overlying drift sediments are pelagic in nature. The total thickness of sediments from the Upper Jurassic to the Cenozoic in the Outeniqua Basin reaches 6 km or more [67].

The internal structure of the Outeniqua Basin, studied based on seismic profiling of refracted and reflected waves [67, 74], includes a series of small grabens and semigrabens (subbasins) striking northwest, obliquely opening to the south into the extended southern Outeniqua subbasin. This subbasin, like the basin as a whole, has an asymmetrical structure with a steeper southeastern wall and is bounded by the Diaz marginal ridge, uplifted along the Agulhas–Falkland transform. The orientation of the subbasins corresponds to left-lateral shear established along the transform. In the modern structure, a ridge–ridge displacement value of ~290 km has been established, but a significantly larger amplitude has been reconstructed for the Cretaceous [16, 74].

Going from the proximal margin toward the Outeniqua Basin, the thickness of the continental crust decreases sharply: up to 26–29 km in the northern subbasins, established by two refracted-wave profiles [74]. In the southern subbasin and the Diaz marginal ridge, further thinning of the crust up to 21–22 km occurs, which is comparable to that calculated for the Falkland Basin. In terms of its parameters, this is considered to be stretched continental crust, with V_p in the upper crust of ~5.5–6.5 and 6.6–7.1 km/s in the lower crust; velocities gradually increase to the south [67, 74]. The continental nature of the basement of the distal margin is also confirmed by geological data. In the Falkland Basin, gneiss was recovered in borehole 330; on the northern ridges of the Outeniqua Basin, samples similar to Paleozoic rocks of the Cape Belt were obtained. The continent–ocean boundary zone is marked by the Agulhas–Falkland transform, where the character of the crustal sequence changes and its thickness decreases up to 7 km [67, 74].

Neither drilling nor seismic data have revealed any volcanics on the distal Southern African Margin. Although Jurassic manifestations of magmatism may be indicated by the high-velocity lower-crustal body near the southern coast. To the north, near the coast of Mozambique, such structures appear in the distal zone as a high-velocity crustal body (V_p = 7.2–7.4 km/s, thickness of 3 km or more) and a wedge of seaward dipping reflectors (SDRs) [63] (see Fig. 1), which is typical of volcanic margins. The wedge of SDRs is covered by sediments of the deep Zambezi Delta Basin with a thickness of up to 11 km. The marginal structures are complicated by deformations related to postbreakup transform displacements.

Antarctic Margin in the Region of the Weddell, Lazarev, and Riiser–Larsen Seas

Along the Antarctic coast, on the shelf, and on the continental slope, the acoustic pattern and magnetic data have established the characteristic features of the volcanic margin [4, 47, 55]. In Queen Maud Land, the results of multichannel seismic profiling and magnetometry studies revealed the presence of a wedge of SDRs beneath the ice and sediment cover. This is the Explora Wedge, with a thickness of up to 4–4.5 km, extending sublatitudinally ~1700 km [47, 55] (see Fig. 1). The wedge spreads from the coast to a width of more than 180 km, leveling out significantly to the north. In the eastern part of the wedge, near the Astrid Ridge, the successive occurrence of two groups of SDRs was observed, also differing in their seismic expression and age, with a change in magnetic polarity [47]. Within the Explora Wedge, in the upper crust, V_p estimates from 4.2–4.5 km/s upsection to 5.6–6.0 km/s downsection were obtained. In the lower crust, the velocities increase up to 6.4–6.8 km/s. In the lower part of the crustal profile, the presence of a thick (up to 7 km) high-velocity horizon with V_p = 7.2–7.4 km/s has been noted.

To the east, near the coast of the Riiser–Larsen Sea, no SDRs have been discovered. However, based on magnetic and gravimetric data, blocks have been modeled in the upper crust, which correspond to mafic intrusives emplaced in the thinned continental crust, which has also been confirmed by seismic profiles [4, 56]. Based on this, the authors hypothesize a specific type of margin, where plutonism predominates, probably with small eruptive component.

On the whole, the distal margin has a dissected tectonic relief. In addition to the wedge of SDRs, along the margin, a broken band of deep sedimentary depocenters is traced based on multichannel seismic profiling data. In terms of acoustic features, rifting and drifting deposits are distinguished in their sequence (from Late Mesozoic to Cenozoic). Their overall thickness reaches up to 10 km, as has been demonstrated for the Riiser–Larsen Sea [56].

In the area passing from the proximal margin to the Gunnerus and Astrid ridges, reduction in crustal thickness to 25 km or less has been noted [47], which is characteristic of stretched continental crust. Apparently, the zone of stretched continental crust extends continuously along the entire coast of the Riiser–Larsen, Lazarev, and Weddell seas [33]. A magnetic anomaly parallel to the coast identified above the wedge of SDRs forms the boundary between the subaerial low-amplitude and marine linear anomalies; farther to the northwest, distribution of the oceanic crust with a somewhat increased thickness (up to 10 km) has been documented, with a thickened third layer and high seismic velocities.

In palinspastic reconstructions, it is assumed that the Explora Wedge (or lower group of SDRs) correspond to conjugate structures of the volcanic margin within the Lebombo monocline and narrow coastal zone near Mozambique, where the presence of both a wedge of SDRs and a high-velocity lower-crustal body was established, as mentioned above [47]. At the base of the continental slope, in the continent–ocean transition zone, unusual basement deformation zones were discovered based on multichannel seismic profiling data; the displacement that separated them is hypothesized to have occurred in the Middle Jurassic [54, 63].

MICROCONTINENTAL FRAGMENTS AND HOTSPOTS IN THE SOUTHERN OCEAN

The presence of microcontinental fragments within submarine uplifts is an essential feature of the Southern Ocean, as demonstrated in [17]. However, ideas about the tectonic nature of a number of uplifts, including the largest Agulhas and Mozambique uplifts, remain debatable: their increased crustal thickness can be explained by the presence of either thickened oceanic crust [34, 35, 66] or stretched and thinned continental crust [2, 17]. Apparently, the interpretation of the crustal profile cannot always be considered unambiguous. At the same time, collections of dredged rocks, although small, obtained from submarine uplifts, are definite evidence of the presence of continental complexes. During dredging, researchers sorted out samples in order to exclude the possible influence of ice rafting.

According to [38], in the south of the Mozambique Ridge, apopelitic rocks of granulite facies metamorphism were obtained, similar to known rocks in ancient crustal complexes in southern Africa. On the Agulhas plateau, in addition to fresh basalts, gneiss samples were recovered with a K–Ar age of 1074 ± 36 and 478 ± 17 Ma, corresponding in petrography and ages to features of continental rocks from areas of Africa and Antarctica [11]. Indeed, deep seismic data on the Agulhas plateau revealed areas with smaller lower-crustal velocities compared to the surrounding oceanic crust, which makes it possible to assume inclusion of continental outliers, albeit small ones, into the crust [66].

Models of crustal sequences obtained from the results of wide-angle seismic refraction and reflection data turned out to be similar for the Agulhas and Mozambique uplifts [34, 35, 66]. Both structures are characterized by thickened (up to 20–22 km) seismically homogeneous crust. In the upper crust, V_p = 5.3–6.7 km/s; in the lower crust, which makes up more than half of the crustal thickness, V_p = 6.7–7.4, with an increase in velocities up to of 7.5–7.6 km/s toward the base. Based on data on the velocity structure and large crustal thicknesses, a conclusion was drawn about the oceanic nature of the Agulhas and Mozambique uplifts —similar to oceanic igneous provinces like the Ontong–Java [34, 35, 66]. This hypothesis is also confirmed by thick manifestations of Cretaceous magmatism. Within the Agulhas uplift, numerous extrusion centers have been identified based on reflected wave profiles, while reflectors in the upper crust are interpreted as thick lava flows [66]. The age of the flows, judging from the overlying sediments, corresponds to the Cretaceous. Lower Cretaceous basalts and tuffaceous rocks were also obtained in borehole 249 DSDP on the Mozambique uplift [82]. In borehole 690 ODP on the Maud uplift, alkali basalts of Campanian age were recovered, similar in composition to oceanic island basalts—of the island of Gough, in particular [71].

However, the nature of the considered ridges is still a matter of debate. Apparently, it is quite difficult to distinquish the structure of thinned continental and thickened oceanic crust based on geophysical characteristics. In particular, it is necessary to explain the similarity of crustal peculiarities on the uplifts with those known for the Explora Wedge on the distal southern margin. In both cases, the crustal thicknesses and velocity parameters turned out to be comparable, particularly the presence of a high-velocity lower crustal horizon. In addition, multichannel seismic profiling data have also revealed stratified wedges in the upper crust of the Alguhas and Mozambique uplifts, reminiscent of the structure of the SDRs in the Explora Wedge [34, 66]. The known Cretaceous and Late Cenozoic igneous formations on the uplifts are probably comparable to the rocks of hotspots. As was mentioned earlier [17], the presence of such uplifts as the Agulhas and Mozambique may have triggered tectonic activation due to stretching along their boundaries. So neotectonic block faulting and basalt magma generation may have been possible if a thermal anomaly existed at depth.

The small Beira uplift near the coast of Mozambique is undoubtedly microcontinental in nature. It is characterized by a sharp increase in crustal thickness (up to 20–23 km) compared to adjacent oceanic areas. The velocity sequence of the uplift corresponds to stretched and intruded continental crust, as shown by wide-angle seismic profiling and gravimetric modeling data in [64]. The sequence includes the upper (V_p = 5.4–5.8 km/s), middle (V_p = 6.3–6.7 km/s), and lower crust (V_p = 6.8–7.0 km/s), with small velocity gradients that sharply differ from those known for oceanic crust. Near the northwestern boundary of the uplift, the presence of a small high-velocity (V_p = 7.1–7.4 km/s) lens has been established at the base of the crust. Based on seismic and magnetometric data, within the uplift, signatures of magmatism have been noted in the upper crust: two thick sills and lava flows in Lower Cretaceous layers. The Gunnerus Ridge is also close to microcontinents, where dredging recovered samples of Precambrian gneisses and granitoids [56]. The character of the sequence (V_p = 5.8–6.1 in its upper part) and crustal thickness (25–27 km) on the Gunnerus Ridge correspond to stretched continental crust with incomplete detachment of continental complexes from the mainland.

Both Late Cretaceous and modern hotspots are known among those south of the Agulhas–Falkland fault. The Bouvet hotspot (2 Ma) is the most studied. It formed above an area of the triple junction with a thinner and more plastic lithosphere [3]. Based on seismic tomography data, the presence of a vertical column of deconsolidated (hot) material at depth has been modeled [36]. For the Shona system, the foundation at the end of the Cretaceous and subsequent fragmentation with displacements along the Agulhas–Falkland fault is hypothesized [46]. Low-volume manifestations of young magmatism are also known based on data from dredging and drilling on the Agulhas and Mozambique uplifts. The location of magma manifestations of different scale in the complex structural setting has determined their heterogeneity of their magmatism [3, 46]. Their localization on the whole corresponds to the periphery of the African superplume.

THE ROLE OF A MANTLE PLUME IN MAGMA GENERATION

The extremely important role of the Karoo–Maud plume in the evolution of Mesozoic magmatism in the Karoo province has been reconstructed [5]. The broad heterogeneity of rock compositions probed within the province reflects the entire complexity of processes influenced by the plume. Melt generation has been revealed, which occurred both in the plume itself as it ascended and in the overlying heated subcontinental lithosphere. Moreover, A.V. Luttinen [58] demonstrated that despite the separation of coeval magma sources (frequently with specific geochemical characteristics), lava flows during eruptions could have spread out and mixed, forming single structures.

Some of the data discussed above can undoubtedly serve as evidence for the determining influence of the mantle plume on magma formation in the Karoo province, as demonstrated for a number of Atlantic regions [6]. These are:

(1) synchronous deep heating, which triggered the onset of magmatism in the entire region of southern Africa–East Antarctica;

(2) a vast amount of volcanic and intrusive complexes and signatures of significant melt fractionation as magma reservoirs evolved;

(3) the ubiquitous formation of high-temperature flood basalts;

(4) the presence of ferropicrites within the complex, which correspond to primary plume melts;

(5) the high hypsometric position of the region during eruptions;

(6) localization of igneous activity of the Southern Ocean's frame immediately above the margin of the African superplume [36, 79]—the stable position of this thermochemical reservoir over no less than 300 Ma was substantiated in [8, 79, 80];

(7) the presence of low-velocity anomalously hot material higher in the mantle, which has been established by seismic tomography data [14, 70], as well as the location of a significant positive geoid anomaly corresponding to the presence of low-velocity gravitating masses at depth [61].

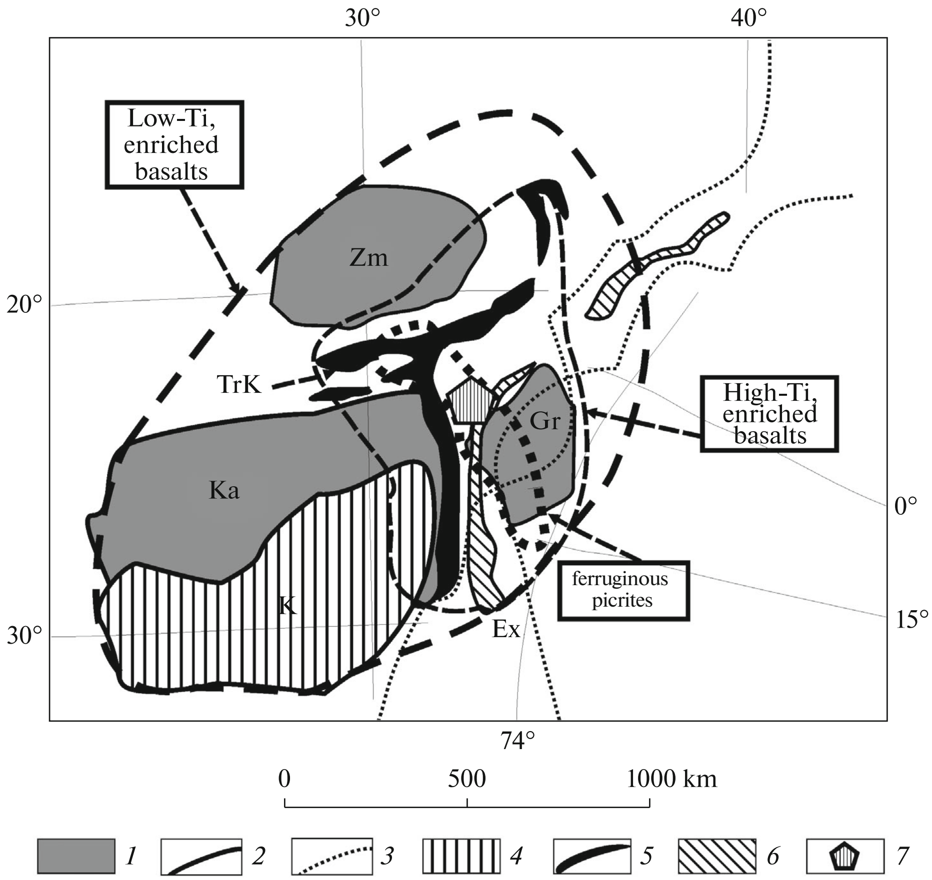

Fig. 5. Surface expression of Karoo–Maud plume with reconstruction for time of preparation of Gondwana breakup (180 Ma). The distribution of different geochemical types of rocks in the Karoo LIP is shown (field), reflecting the zoning of the plume, after [24, 29, 42, 58]. Notation: Zimbabwe Craton, Zm; Kaapvaal Craton, Ka; Grunehogna Craton, Gr; Karoo Basin, K; Karoo triple junction, TrK; Explora Wedge, Ex. Arbitrary notes: (*1*) Fragments of Gondwana supercontinent; (*2*) boundaries of structural elements; (*3*) coastline; (*4–6*) elements of Karoo LIP: (*4*) platform basin, including numerous sills; (*5*) dikes of Karoo triple junction; (*6*) thick volcanic series forming SDRs; (*7*) position of center of Karoo–Maud plume.

The leading role of a mantle plume in magma generation in the Karoo province has been acknowledged by most researchers. However, based on structural and geochemical data, the position of the plume center has been reconstructed differently by different authors [39]. Proposed localizations have consistently been revised: at the center of the Karoo triple junction or to its east [19], near the southeastern coast of Africa [83], near the Falkland Islands (at the Karoo, Ferrar, and Chong Aik junction) [75], and in the Weddell Sea [24]. The idea of a relationship between the Mesozoic dikes of the Karoo triple junction and the plume center was quite popular. However, the lithospheric control established for the dikes shows that the geometry of the triple junction is a structural feature of the ancient basement and cannot be used as an indicator of the stress pattern for the initiation of Mesozoic magmatism.

Geochemical zoning seems quite important when discussing the position of the plume center, in particular, the distribution of low- and high-Ti flood basalts [58]. The latter, especially the group of ferropicrites, can apparently serve as a marker for the central part of the plume that fed the magmatism of the proximal Africa–East Antarctica margin in the areas of Mwenezi and Almannriggen (Fig. 5). Subsequent igneous manifestations within the distal margin that formed the SDRs complexes in the upper crust and high-velocity bodies at depth are confined precisely to this area. These facts can be crucial in reconstructing the position of the plume center. It was shown above that surface igneous manifestations were structurally inherited and could have thus been displaced from the center of the Mesozoic plume toward zones of weakness. Numerical modeling has also confirmed the possibility of similar displacement of surface expression of the plume that occurred during the migration of plume material beneath the base of the lithosphere [18].

TECTONIC EVOLUTION OF THE SOUTHERN OCEAN MARGINS

The Mesozoic history of the Southern Ocean margins characterizes the geodynamics of the central part of Gondwana at the initial breakup stage. Triggering of activity at the Africa–East Antarctica margins and preparation of continental breakup are attributed to the end of the Early Jurassic. However, the foundation of the margins on a basement of ancient continental crust in many aspects was prepared by the preceding evolution of Gondwanan crustal structures. Multiple episodes of both continental accretion (with the elements of different rheological properties playing a part) and stretching in their early history led to the formation of zones of weakness, and significant inheritance of strike from structures that had already existed in the Precambrian–Early Paleozoic. Thus, the Sabi monocline follows the Archean Limpopo belt, the Lebombo monocline parallels the Proterozoic Mozambique belt, and the Okavango dike series inherited the pan-African trend that formed at the end of the Proterozoic–Early Paleozoic. The Karoo triple junction on the whole has a polygenetic character, with undoubted lithospheric control both in terms of the location and composition of Mesozoic dike magmas.

The existence of the inherited Karoo Basin is well known, beginning from the Late Carboniferous. Its foundation occurred after subsidence displacement to the north of the Cape Basin [72]. The total subsidence in these structures has been fixed at an extent of ~320 Ma with filling by terrigenous sediments of the Cape (O_1–C_1) and Karoo (C_2–J_2) supergroups. In terms of total duration of subsidence, the basins are comparable with the South American Paraná Basin [7] but differ by a hiatus in sedimentation lasting 30 Ma and migration of the sedimentary depocenter.

The subsidence development terminated at the end of the Early–beginning of the Middle Jurassic with a powerful flare in igneous activity, which created the Karoo LIP. The area of magmatism encompassed previously existing zones of weakness, both the Karoo Basin and the Karoo triple junction system. Despite the brevity of the main event (~3 Ma), a vast amount of igneous material accumulated on the proximal margins of the Southern Ocean, similarly to the Paraná–Etendeka LIP in the South Atlantic. The scale of magmatism at the Southern Ocean margins characterizes the definitive influence of the plume on igneous process.

Rocks of the Karoo LIP usually bear the signature of melting from heated subcontinental lithosphere with the participation of plume melts. At the onset of eruptions, input of a small amount of highly heated plume material is observed, marked by the formation of high-magnesian and high-ferruginous basalts close to the primary plume melts. Weakly depleted final-stage magmas (in the Rooi Rand dikes) could have formed during the ascent and melting of asthenospheric mantle. Their generation is close in time to continental breakup events.

In the Middle Jurassic, the large masses of low-density plume material with positive buoyancy that accumulated at the foot of the lithosphere should have resulted in a significant decrease in thickness, a reduction in strength, and ultimately, stretching of the lithosphere. On the thinned continental basement, distal zones formed with the occurrence here of a number of longitudinal basins, in particular, the Outeniqua. A volcanic eruption band migrated into the newly formed distal zones. Intense magmatism and creation of thick magmatic crust have been revealed only on the conjugate margins of East Africa and part of East Antarctica, which are now separated. In the remaining area of the distal margins, only intrusive magmatism is evident, as noted above for regions near the southern African coast and along Antarctica east of the Astrid Ridge.

The tectono-magmatic events on the proximal and distal margins that developed in the area impacted by the Karoo–Maud plume provided the preparation of the breakup of Gondwana. It seems that thermal erosion influenced by the plume and thinning of the lithosphere led to further weakening of the overall structure and continental breakup in the distal zones above the plume head. The preparation of continental breakup lasted ~30 Ma. Using magnetic chron data, different researchers performed dating in different ways. The most developed reconstructions are based in [54, 63]. The authors hypothesize that the breakup and formation of the conjugate Mozambique, Weddell, and Riiser Larson ocean basins occurred in the middle of the Jurassic. This time includes the ultimate separation of East Antarctica and Africa and the formation of the Southern Ocean. At the end of the Middle Jurassic, following brief spreading to the northwest, meridional opening of the Southern Ocean took place [54].

The postbreakup events at the end of the Jurassic–beginning of the Cretaceous involved multiple complication of the overall structure of the ocean, the creation of the Bouvet triple junction and its restructuring [3], the onset of dextral-shear displacement of the structures of Madagascar and Antarctica in relation to the structures of Africa, and the formation of transform margins along the Davey and Gunnerus ridges [54, 63]. The significant increase in tectonic compartmentalization of the Southern Ocean in the Cretaceous was determined by the formation of oceanic uplifts or microcontinents with partial or complete detachment of small blocks from the mainland. According to reconstructions [34, 66], the existence of the Agulhas, Maud, and Northeast Georgia structures is assumed for the Early Cretaceous, in the form of a single uplift superposed on an earlier system of spreading magnetic anomalies. Fragmentation of the uplift under the action of prolonged spreading has been reconstructed at the beginning of Late Cretaceous.

The onset of sublatitudinal opening of the South Atlantic in the Early Cretaceous and the foundation of the Agulhas–Falkland transform had served as a turning point in the evolution of the Southern Ocean margins. The amplitude of dextral-shear Cretaceous displacements along the transform was ~1200 km [16]. It is assumed that in the Palaeocene time with recurring jumps of the spreading ridge, transform movements weakened, so that in the present-day structural pattern, the ridge–ridge displacement amplitude is ~290 km.

The evidences for multiple shearing of the crust, the formation of microcontinental fragments, and their inclusion into the structure of large uplifts, as well as episodes of magmatism of different scale and age, seems quite essential for describing the opening of the Southern Ocean. This evidence supplements the conclusions of jumps of the ridge during spreading, shear displacements, and rotation of blocks, which resulted in the complicated crustal structure of the ocean and its margins [3, 31].

DISCUSSION

Contemporary knowledge of the Africa–East Antarctica region makes it possible to judge its structural and magmatic peculiarities. The evidence of stretching of the lithosphere, rifting, and magmatism can be considered preparation of continental breakup and opening of the ocean in the Southern Hemisphere. A historical approach reveals that development of these processes was significantly inherited from the preceding time. A relationship is traced between tectonomagmatic activity and, first of all, ancient zones of weakness, followed by its migration and localization on the distal margins (at the place of the future ocean). The combination of typical passive margin elements and subsequent strike-slip faults determined the specifics of the overall structure in the Southern Ocean's frame. There is an undoubted relationship between the formation of dextral strike-slip faults and the action of sublatitudinal stretching during the opening of the South Atlantic at the beginning of the Cretaceous. Shear displacements and the formation of small uplifts and hotspots led to significant tectonic dismembering of the region, which is characteristic feature of the Southern Ocean.

In seems that multiply recurring episodes of stretching and basalt magmatism in the region's long history may have been governed by geodynamic events at depth along the margin of the ancient African superplume. Namely, the activation of upwelling above the superplume can explain the ascent of the Mesozoic Karoo–Maud plume and the outburst in magmatism in the Karoo LIP.

The main question when discussing magmatism related to the Karoo–Maud plume is: was the action of the plume only thermal, similar to the Tristan plume [7], or did the magmas derive directly from the plume. The broad discussion in the literature on the geochemical features of the two types of basalts (high- and low-Ti) [40, 49, 58] demonstrated the large heterogeneity of magmatism, both regional and localized. Within the distinguished types, individual subtypes are frequently separated: either with different distributions of lithophile elements or different isotope characteristics. Thus, A.V. Lutinnen [58], based on a study of more than 800 basalt compositions of southern Africa and Queen Maud Land, established a bimodal distribution in an area of geochemically relatively Nb-rich and Nb-depleted magma subtypes. Just like the role of Ti, the concentration of Nb with respect to other incompatible elements can be considered a key moment for describing a mantle reservoir.

In the central part of the Karoo LIP, high-Ti rocks are predominantly distinguished, with localization of ferropicrites at the center (see Fig. 5). Along the periphery of the province, low-Ti basalts predominate, which are characterized by higher Nb/Y values for given Zr/Y values in comparison to basalts of the central area. A similar territorial separation of different magmas may reflect a certain control of their compositions by melting from different parts of the plume [58].

Isotope data established that the majority of Karoo magmas, similar to rocks of the Paraná–Etendeka LIP, have an EM2 admixture typical of continental lithosphere. Meanwhile, within the Karoo LIP, the presence of ferropicrites has been noted, the primary compositions of which are related to a source containing pyroxenites. Pyroxenites could have formed in an ascending deep plume during the transformation of eclogites, i.e., recycled ancient oceanic crustal material [9, 10]. Also encountered are basalts strongly depleted in incoherent elements derived from melting of mantle peridotites.

Thus, it has been established that some of the melts—pyroxenitic, high-ferruginous, high-magnesian, and higher-temperature melts—that formed at the early stages of magmatism may have corresponded to the composition of the plume and were brought to the surface along existing fractures without interacting with lithosphere material. Such magmas are widespread in Queen Maud Land and the conjugate African margin. They reached the surface near the marginal parts of the thick Kaapvaal–Grunehogna shield near the boundary with the Maud fold belt. In the plume's evolution, the pyroxenite admixture in the source decreased and the melts assumed the features of the submelting lithospheric mantle, which is reflected in the isotope characteristics of EM2 melts, similar to rocks forming trap provinces along the frame of the North, Central, and South Atlantic [6, 7]. These relatively low-Ti rocks, which developed mainly along the periphery of the Karoo LIP (see Fig. 5) and are related to melting of the metasomatized lithospheric mantle, constitute the main part of the igneous complex.

In summary, it can be said that the magmatism that occurred under the influence of the Karoo–Maud plume proceeded in the initial melting of plume material, accompanied by mixing of the primary magmas and material entrained in the melting of Gondwana's lithosphere. The subsequent stages were characterized by melting of the heterogeneous lithosphere, ancient and metasomatically enriched, without any input of melts from the plume [49].

CONCLUSIONS

An examination of the Southern Ocean margins in the structural, magmatic, and historical aspects makes it possible to discuss the features of continental breakup in the central part of the Gondwana supercontinent.

(1) Comparison of the Southern Ocean and the South Atlantic reveals the significant similarity of their continental margins in terms of overall zoning, the specifics of structural elements, and their history. As noted above, the basement structures are similar, representing fragments of Gondwana in both regions. The tectono-magmatic features of the Paraná and Karoo basins at the proximal margins are also comparable. In particular, study [57] demonstrated the close similarity of the Upper Paleozoic–Lower Mesozoic sequences of these basins. The features of preparation of continental breakup were also similar for both regions, with a powerful outburst in magmatism and the formation of igneous crust.

(2) During preparation of the breakup of Gondwana, it is distinctly clear that the structures were inherited from ancient Gondwanan zones. As well, subsidence in the Karoo Basin continued unceasingly from the Late Paleozoic. For the dikes of the Karoo triple junction, not only the utilization of zones of weakness, but also the inheritance of magma sources has been noted.

(3) Two powerful plumes within Gondwana—The Karoo–Maud and Tristan, with a close duration of magmatism—led to the formation of large trap provinces: the Karoo (190–178 Ma) and the Paraná–Etendeka (135–131 Ma). The formation of most traps in both regions is related to enriched generation EMII source, which is explained by melting of Gondwana's heated continental lithosphere. The admixture of material from less-expressed EM1 mantle sources related either to an ancient subducted component or to an admixture of older lithosphere in the source has been established in the central part of the Karoo LIP, fragmentarily in the Paraná–Etendeka LIP, and within the Walvis Ridge.

(4) When discussing magma sources, it was noted above that for the Karoo LIP, one of the most important features of manifestation of the Karoo–Maud plume is the presence of high-magnesian, high-ferruginous, incompatible-element-depleted magmas against a wide variety of geochemical types of magmatism. The genesis of similar high-magnesian ferropicrites, which are rarely encountered in other igneous plume provinces, can be related to melting of mantle pyroxenitic source with a specific composition. The uniqueness of such melts revealed in the Karoo LIP is determined by their confinement precisely to the central part of the plume, as well as the probable correspondence to earliest effusions.

(5) Interaction between plumes and the ancient lithosphere; erosion at the lithospheric base; its thinning; and a decrease in resistance to tensional forces led to discontinuity of the lithosphere, which determined the breakup of Gondwana.

(6) Multiple thick replenishment of igneous material with the formation of volcanic margins and recurring episodes of compression and extension should have been supported by renewed deep plume activity. The specific location of the Mesozoic plumes, as well as zones of the subsequent breakup of Gondwana above marginal areas of African superplume, indicates a relationship between surface and deep-seated events. Such a relationship is also expressed in the occurrence of hotspots, as well as the long tectono-magmatic development of the Karoo and Paraná syneclises, which extended along the southern and western periphery of the African superplume. We believe that one of the key tasks in the immediate future is to unveil geological evidence on the dynamics of the African superplume, the time sequence thereof, and features of the relationships between the superplume and development of surface structures.

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