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Development of Passive Volcanic Margins of the Central Atlantic and Initial Opening of Ocean

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Abstract—Geological and geophysical data on the Central Atlantic are discussed in order to elucidate the tectonic setting of the initial magmatic activity, rifting, and breakup resulting in the origination of Mesozoic ocean. The structural, magmatic, and historical aspects of the problem are considered. It has been established that the initial dispersed rifting and low-capacity magmatism at proximal margins was followed by the migration of the process toward the central part of region with the formation of distal zones and the development of vigorous magmmatism, further breakup of the lithosphere and ocean opening. Magmatism, its sources, and the features of newly formed magmatic crust at both the rifting and breakup stages of margin development are discussed and compared with subsequent spreading magmatism. Sr, Nd, and Pb isotopic compositions show that the magmatic evolution of the Central Atlantic proximal margins bears the features of two enriched components, one of which is related to the EM-1 source, developing only at the North American margin. Another enriched component typical of the province as a whole is related to the EM-2 source. To a lesser extent, this component is expressed in igneous rocks of Guyana, which also bear the signature of the MORB-type depleted source typical of spreading tholeiites in the Atlantic Ocean. Similar conditions are assumed for subsequent magmatism at the distal margins and for the early spreading basalts in the adjacent Atlantic belt, which also contain a small admixture of enriched material. A comparison of the magmatism at the margins of Central and North Atlantic reveals their specificity distinctly expressed in isotopic compositions of igneous rocks. In contrast to the typical region of the North Atlantic, the immediate melting of the enriched lithospheric source without the participation of plume-related melts is reconstructed for the proximal margins of the Central Atlantic. At the same time, decompression and melting in the lithosphere could have been determined by the thermal effect of the Central Atlantic hot plume. This is testified by the intense melting in a short time interval over a vast area; the generation of rather homogeneous melts and creation of the thick magmatic crust; the radial arrangement of the dikes intruded in the course of plume ascent; as well as by the data of seismic tomography indicating the occurrence of the hot upper mantle material, which has kept the "memory" of the action of a shallow-seated Mesozoic plume. The formation of the Central Atlantic plume can be presumably regarded as a result of upwelling remobilisation adove the ancient African superplume and the rearrangement of the deep structure in Triassic and Jurassic times.

Keywords: rifting, breakup, ocean opening, proximal margin, distal margin, magmatism, isotopic composition, magma source

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INTRODUCTION

The study of Mesozoic volcanic and nonvolcanic passive margins is crucial for the reconstruction of the initial extension in Atlantic. It is known that the opening of the Atlantic Ocean and the creation of a common tectonomagmatic system was controlled by prograde extension and magmatism that spread northward and partly southward from the central part of the future ocean with a consecutive attachment of oceanic segments and their margins and a further coordinated development. In the Central Atlantic, the initiation of this process with the following separation of North America from Africa is dated back to the end of Triassic or the begining of Jurassic. To the north, the breakup of Newfoundland and Iberia started in the Early Cretaceous; in the Labrador Sea the breakup took place in the Late Cretaceous or Paleocene; and between Greenland and Norway in the early Eocene. The latter region, pertaining to the North Atlantic Igneous Province (NAIP), is considered to be a tectonotype of volcanic passive margins [1, 2].

Its preliminary comparison with the margins of the Central Atlantic Magmatic Province (CAMP) shows a similarity in the large expansion area, crustal structure and thickness and the character of magmatic activity, synchronous to rifting and breakup, as well as a short time interval of these phenomena. At the same time, it is necessary to discuss geological and geophysical data on the Central Atlantic to provide insights into the tectonic setting of initial magmatism, rifting, and breakup resulting in the origin of the future ocean. For this purpose, we consider in this paper Mesozoic magmatism at the margins of the Central Atlantic, including the composition and thickness of igneous rocks, character of their sources, and features of the newly formed crust. We used for discussion the published data on magmatism at the pre-breakup (rifting) and breakup stages of margin evolution and compared it with the following spreading magmatism.

ATLANTIC MARGIN OF THE UNITED STATES AND SOUTHEASTERN CANADA

Igneous rocks of the CAMP occur along eastern America for 5000 km. The most representative data are related to the eastern margin of the United States and southeastern Canada. At this margin, like in the North Atlantic, the proximal zone, with a thick Paleozoic continental basement, and the eastern distal zone, transitional to the ocean, with a newly formed magmatic crust, may be distinguished (Fig. 1).

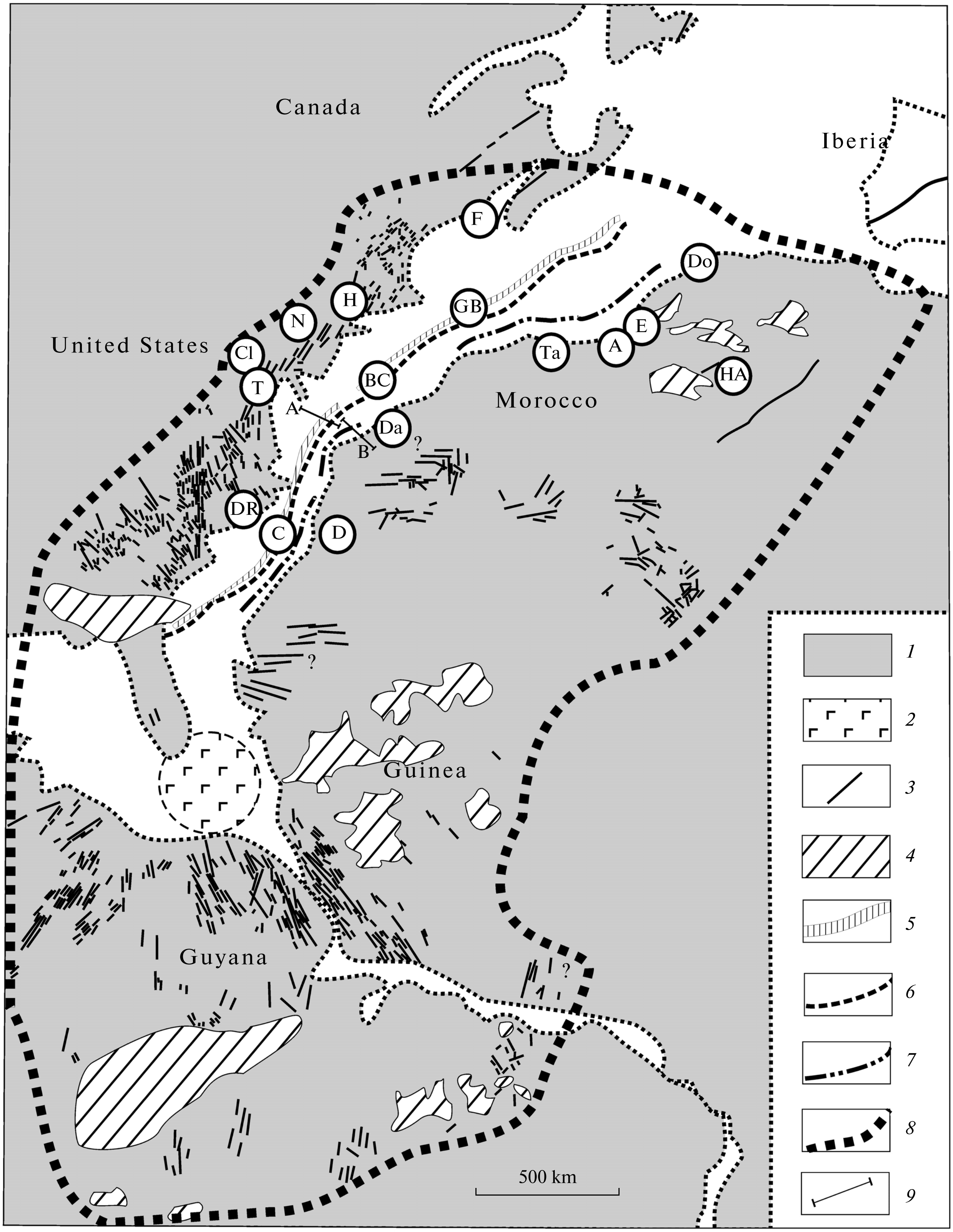
In the proximal zone up to 400 km wide in the land and inner shelf of North America, the Mesozoic pattern is controlled by a system of rift basins which escaped from erosion and extend with slight bends in the northeastern direction parallel to the Atlantic coast [44, 45, 58]. The basins rest on the Hercynian basement. *Synrift sedimentarty basin fill* of Ladinian to Sinemurian age comprise a continental clastic sequence up to 7–8 km thick, red beds and evaporites, occasional coal seams in the south, as well as lavas and sills pertaining to the CAMP. In the southern margin part, in the Taylorsville, Deep River, and other basins, the synrift sedimentary fill is completed with Triassic deposits, whereas in the north, in particular, in the Culpeper, Newark, Hartford, and Fundy basins, the section also involves the Lower Jurassic beds. Based on this difference, the southern and the northern segments of the margin divided by a diffuse boundary are recognized [45, 58, 64]. The asynchronous completion of the rifting is noted. In the southeastern United States, the completion predated magmatism. The following change of stresses resulted in the formation of dikes crosscutting the basins. In the northeastern United States and Canada, rifting continued during and after magmatic activity.

Igneous rocks in the proximal zone occur from the Fundy Basin in Nova Scotia to Florida and, after a gap in the Caribbean region, farther to Venezuela, French Guyana, and Brazil. Because of long-term erosion, lavas have been retained almost exclusively within the sedimentary basins of the northern segment. Numerous dolerite dikes intruded into the Neoproterozoic–Lower Paleozoic rocks between the basins or in the Lower Mesozoic sedimentary deposits within the basins were partly the feeding conduits for lavas initially covering wider areas [44–46]. It cannot be ruled out, however, that prevalence of dikes over the much less abundant lavas is a distinguishing feature of the CAMP [12]. The orientation of early dikes varies from the NW in Guyana and in the southeast of the United States to near-meridional in North Carolina and NE in Quebec and New England [11, 47, 58]. Occasionally, in particular, in the margin north, between the Hartford and Fundy basins, giant dikes more than 150 km in extent have been mapped.

As follows from the determination of $^{40}Ar/^{39}Ar$ and partly the U–Pb ages, the begining of magmatic activity is established to be almost synchronous in all basins and dikes of the proximal zone. This is also corroborated by bio-, chemo-, and magnetostratigraphic datings [10, 35, 42, 48] (Fig. 2). In general, the age of igneous rocks at the proximal margin is estimated mainly from 201.0 ± 1 to 198.6 ± 1, however, in each district the main volcanic event was short-term, approximately 1 Ma long. A peak of volcanic activity everywhere fell on the Triassic–Jurassic boundary. A younger date (190.6 ± 1 Ma) in Nova Scotia gives evidence for a low-capacity tail of waning magmatism [35].

The volcanic series at the proximal margin, which reach 450 m in thickness and are composed of lava flows intercalating with sediments, make up three subdivisions somewhat variable in composition (Fig. 2). The large sills, like Rapidan and Palisade, 350 m and more in thickness, are apparently comagmatic with the entire body of volcanic rocks [11, 42]. As follows from major element contents, all rocks are identified as basalts and basaltic andesites varying from quartz-normative to olivine–hypersthene-normative compositions. The rocks are olivine and pigeonit-porfiric containing also augite, plagioclase, Cr-spinel, titanomagnetite, and ilmenite phenocrysts.

Fig. 1. Tectonic scheme of Central Atlantic: reconstruction for 195 Ma. Modified after [1, 2, 12, 18, 25, 35, 40, 44, 45, 57, 58]. (*1*) Fragments of Pangea supercontinent in Africa, North and South America; (*2*) Central Atlantic plume; (*3–7*) passive volcanic margins: (*3*, *4*) igneous rocks at proximal margins: (*3*) dikes, (*4*) sills and lava flows; (*5–7*) elements of distal margins: (*5*) igneous rocks of SDRs; (*6*, *7*) magnetic anomalies: (*6*) ECMA, (*7*) WACMA; (*8*) boundary of CAMP; (*9*) location of seismic sections. Triassic–Jurassic rift basins mentioned in text (letters in circles): T, Taylorsville; DR, Deep River; Cl, Culpeper; N, Newark; H, Hartford; F, Fundy; GB, Georges Bank; BC, Baltimore Canyon; C, Carolina Trough; A, Al Jida Agadir; Do, Doukkala; E, Essaouira; Ta, Tarfaya; Da, Dakhla; HA, basins of High Atlas.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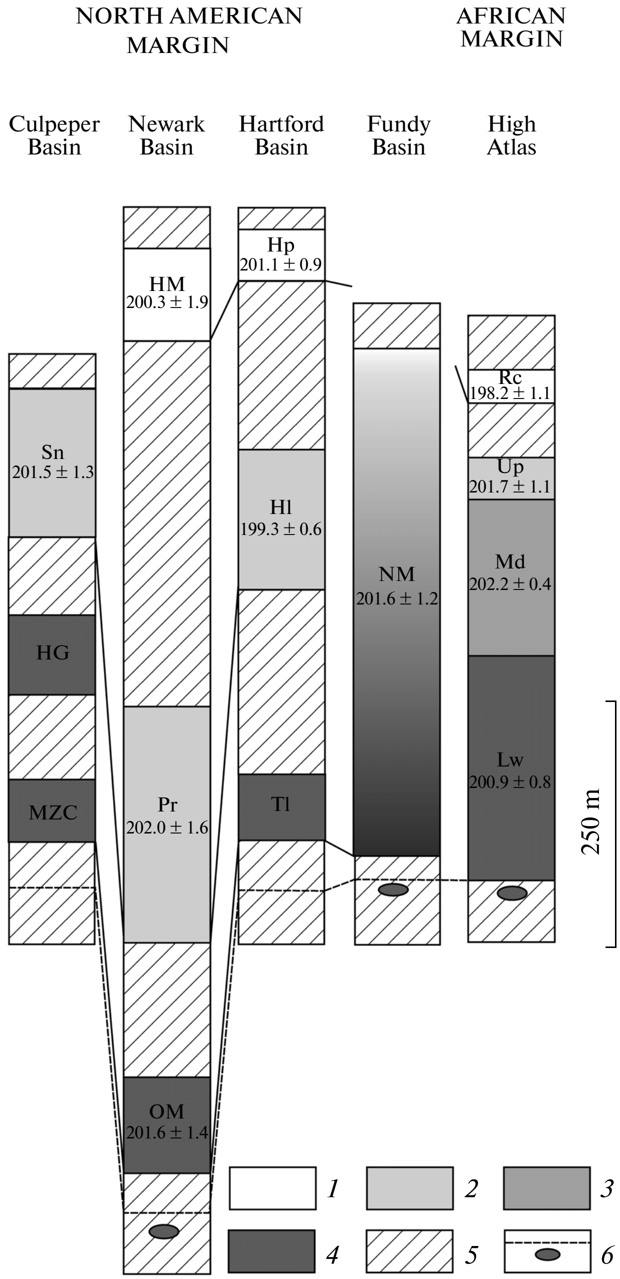

Fig. 2. Early Mesozoic volcanic sections of conjugate margins of Central Atlantic. Modified after [14, 18, 42, 58]. (*1*) Basalts moderately enriched in lithophile elements and radioactive isotopes; (*2–4*) enriched basalts with upsection decrease in degree of enrichment; (*5*) nonmarine sediments; (*6*) boundary drawn by last finding of *Patinasporites densus* in uppermost Triassic spore–pollen complexes, after [14]. Numerals are $^{40}Ar/^{39}Ar$ age, Ma. Abbreviations: Sn, Sander basalt; HG, Hickory Grove basalt; MZC, Mount Zion Church basalt; HM, Hook Mountain basalt; Pr, Preakness basalt; OM, Orange Mountain basalt; Hp, Hampden basalt; Hl, Holyoke basalt; Tl, Talcott basalt; NM, North Mountain basalt; Rc, Reccurent basalt; Up, Upper basalt; Md, Middle basalt; Lw, Lower basalt.

Rocks varying in compositions from almost primary to markedly evolved varieties (14.8–4.7 wt % MgO) with a predominance of moderately enriched low-Ti tholeiites (0.40–1.35 wt % TiO_2) are characteristic of volcanic complex and dikes in the proximal zone. In addition to Ti, all rocks are depleted in Nb and Ta and enriched in Rb, Ba, and Pb, i.e., they bear an obvious continental signature [11, 42, 51] (Figs. 3a, 3b). The stratigraphically correlated lava flows are close in composition in several basins. The early lavas and sills corresponding to the stage of evolved rifting, in particular, the lower Orange Mountain, Mount Zion Church, Talcott, and North Mountain basalts in the Newark, Culpeper, Hartford, and Fundy basins, respectively make up a group of tholeiites enriched in lithophile elements and radiogenic isotopes. For instance, the enrichment of rocks from the Newark Basin in LREE reaches $(La/Yb)_n = 5$. The compositions of rocks systematically changes upsection, so that the upper lavas corresponding to the stage of the late rifting—Hook Mountain basalts in the Newark Basin and Hampden basalts in the Hartford Basin—make up a group of only slightly enriched tholeiites with $(La/Yb)_n = 2.1–2.2$ in rocks from the Newark Basin with a relatively flat REE pattern and much higher Nb contents as compared with other lavas at the margin [42].

The isotopic compositions of 62 samples from dikes located from Georgia in the south to Virginia in the north [11, 51] make up an extended field with variable values: $^{87}Sr/^{86}Sr = 0.7042–0.7075$, $^{143}Nd/^{144}Nd = 0.5127–0.5120$, $^{206}Pb/^{204}Pb = 17.41–19.0$; $^{207}Pb/^{204}Pb = 15.54–15.70$, and $^{208}Pb/^{204}Pb = 37.2–39.0$ (Fig. 4). The compositions inherent to the rocks from the Palisade Sill [24] fall into the same field. As follows from the scanty data, similar $^{87}Sr/^{86}Sr$ values are noted for rocks of the Canadian margin [26].

At the southern end of CAMP in the slightly enriched tholeiites of Guyana, which are close in age (200–195 Ma), variations in isotopic compositions are much less than in basalts from the eastern United States (Fig. 4). The complex of dolerite and gabbroic dikes that cut through rocks of the Guyana Shield is a separate group with low SiO_2 and high TiO_2 (2.5–3.5 wt %) contents and variable $(La/Yb)_n = 1.5–5.1$ [19]. This slightly enriched complex is characterized by the following isotope ratios: $(^{87}Sr/^{86}Sr)_i = 0.703175–0.705082$, $(^{143}Nd/^{144}Nd)_i = 0.512600–0.512669$, $(^{206}Pb/^{204}Pb)_I$ – 17.48–18.473, $(^{207}Pb/^{204}Pb)_I = 15.460–15.647$, and $(^{208}Pb/^{204}Pb)_I = 37.647–38.0$.

Intrusions of alkaline rocks both saturated and undersaturated with silica, including predominant gabbro, syenite, and lamprophyre dikes especially numerous in the northern districts, occur among post-breakup rocks at the margin along with kimberlites and related ultramafic rocks [34, 44, 47, 52]. Post-breakup magmatic phases are synchronous to the main tectonic events in this large region, including the initial rifting between Labrador and Greenland (140 Ma), the separation of the Iberia and Newfoundland continental plates (115 Ma) and the Labrador as well as Greenland plates (83–92 Ma) [34].

In the distal zone, 80–100 km wide, at the margin of the United States and southern Canada, several rift basins with thick sedimentary fill are also known. In the Scotian and Baltimore Canyon basins the total thickness of sedimentary fill reaches 15 km. Two wedges of seaward-dipping reflectors (SDRs) similar to the well-known SDRs at the Norwegian and Greenland margins have been studied in the near-shore zone along seismic reflection lines. These SDRs correspond to layers of volcanic and/or volcaniclastic rocks [8, 28–30, 49, 61] (Figs. 1, 5). A thick (~10 km) wedge, with a dip angle of reflectors up to 30° in the outer shelf beneath the Georges Bank, Baltimore Canyon, and Black Plateau basins and the Carolina Trough, is overlapped by Middle Jurassic postrift sedimentary deposits [29, 30, 49, 64]. This allows us to refer the wedge formation to the Early Jurassic, apparently followed volcanic eruptions in the proximal zone. The less-extended outer SDRs wedge, 3–4 km thick and with a reflector dip angle of ~15°, is located to the east of the Carolina Trough in the zone of continental slope and probably corresponds to younger volcanics.

Thus, the development of magmatism related to the North American margin formation resulted in the occurrence of low-capacity igneous rocks in its proximal zone and thick plateau basalt complexes in the distal zone with the formation of a specific seismic image of SDRs in the upper crust. So the Mesozoic fragmentation and magmatism in the proximal zone led only to an insignificant reduction of the ancient continental crust thickness (36 km with a seaward decrease), whereas the thick (25 rm) magmatic crust was newly formed in the distal zone. The formation of magmatic crust at the stage of continental breakup is a distinguishing feature of this margin and the Central Atlantic Province as a whole.

The velocity model of the proximal zone based on data from wide-angle seismic profiling displays a subdivision of the continental crust into three layers with velocities varying from 5.5 to 6.8 km/s (Fig. 5) [8, 29, 30, 49, 65]. As follows from this seismic image, Appalachian crustal rocks (Meguma Terrane) are presumably traced here. The upper and middle crust is interpreted as Paleozoic metasedimentary rocks (Vp = 5.5–5.9 km/s), as well as felsic and intermediate igneous or metamorphic rocks (Vp = 6.2–6.3 km/s). The underlying crust, with Vp = 6.4–6.8 km/s, is interpreted as the lower crust of the Appalachians.

The physical properties of the crust abruptly change at the boundary with the distal zone. According to the results of wide-angle seismic profiling, the upper crust of the distal zone with SDRs wedges is characterized by Vp = 6.3–6.5 km/s and the middle crust, by 6.6–6.8 km/s (Fig. 5) [8, 28–30, 49]. The crust is almost completely composed of volcanic rocks

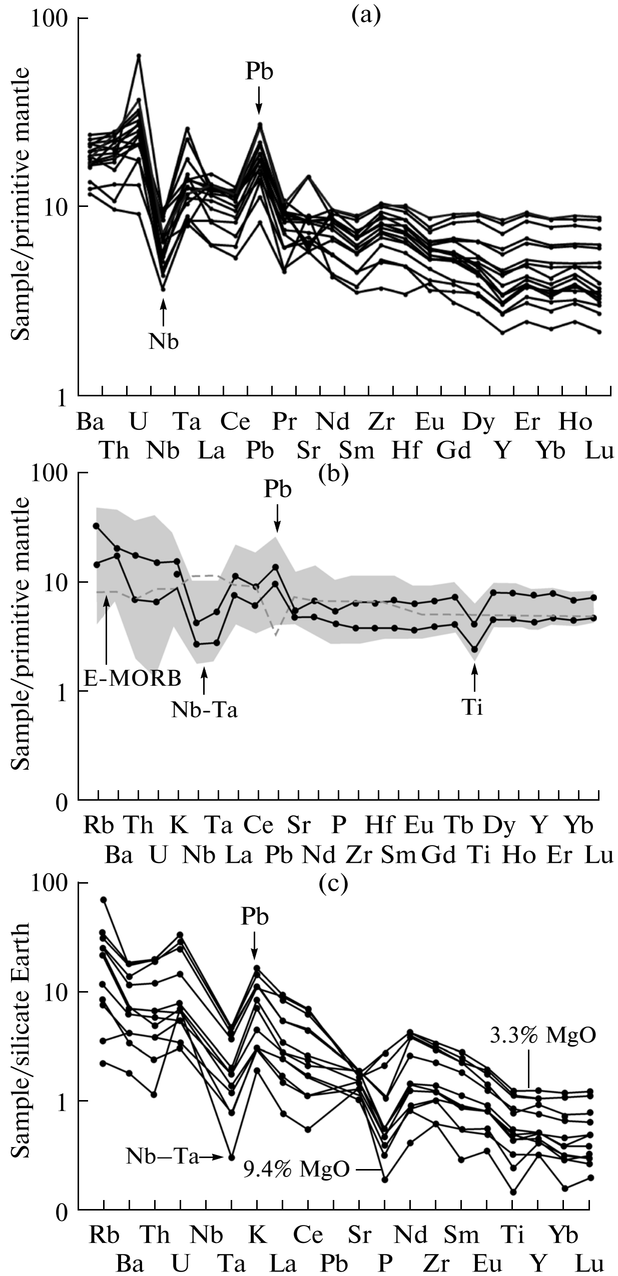

Fig. 3. Spidergrams of lithophile elements in rocks at conjugate margins of Central Atlantic related to melting of lithosphere under thermal impact of Central Atlantic plume. Chemical compositions of rocks are normalized to (a, b) primitive mantle [60] and (c) silicate Earth [43]. (a) Basaltic lavas from Newark and Culpeper basins, after [42]; (b) dolerite dikes at United States margin, modified after [11]. Field of composition is shown in gray. Spidergrams of two high-Mg samples are shown by solid lines. It is clearly seen that above spidergram differs from that of enriched oceanic basalts (dashed line). (c) Dolerite from giant Messejana–Plasencia dike in Iberia, after [12]. Graph displays regular enrichment in incompatible elements with degree of fractionation (decrease in MgO content from 9.3 to 3.3 wt %). Distributions of lithophile elements in rocks from North American and African margins are similar with Nb, Ta, and Ti minimums and Pb maximum.

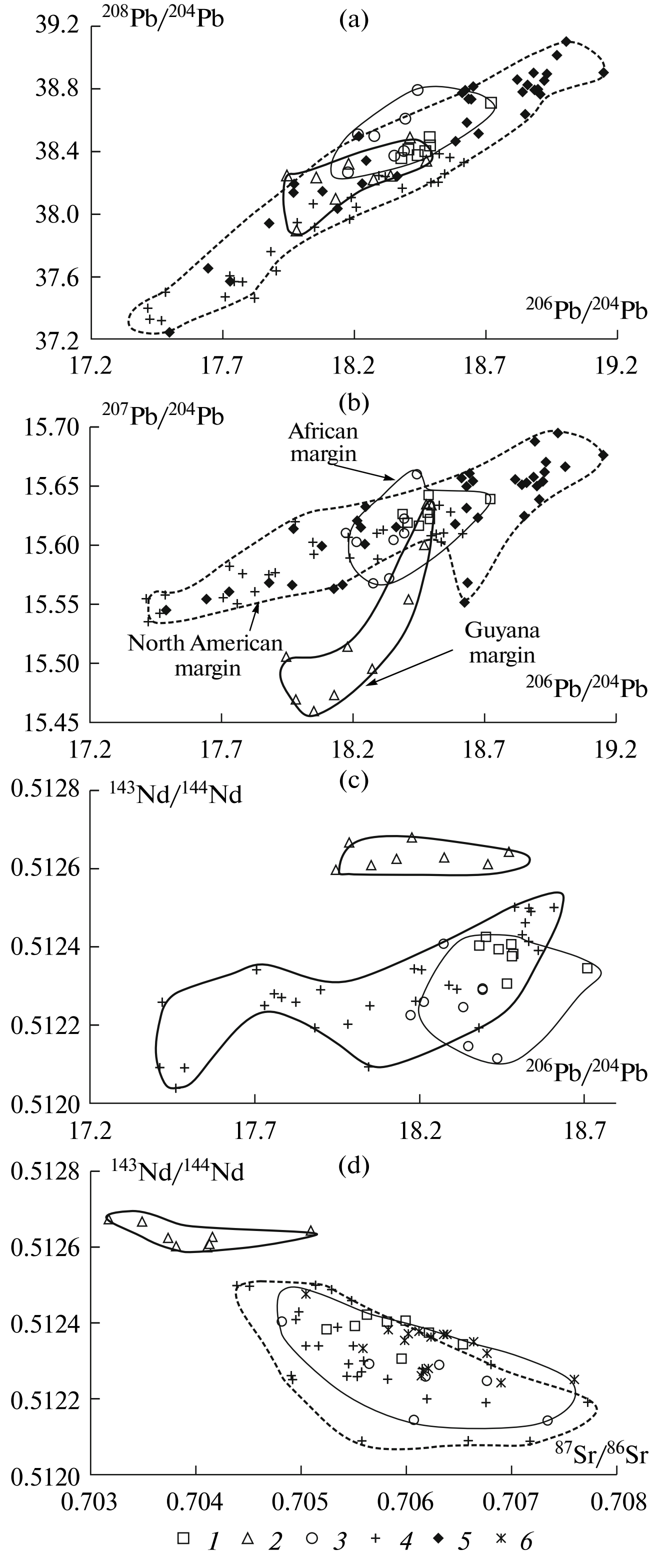

Fig. 4. Variations of isotopic characteristics in rocks from margins of Central Atlantic, after [11, 12, 18, 19, 51]: (a) $^{208}Pb/^{204}Pb-^{206}Pb/^{204}Pb$, (b) $^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb$, (c) $^{143}Nd/^{144}Nd-^{206}Pb/^{204}Pb$, (d) $^{143}Nd/^{144}Nd-^{87}Sr/^{86}Sr$. Initial data are recalculated to 200 Ma. (*1*) Rocks from Messejana–Plasencia dike in Iberia; (*2*) rocks from Guyana; (*3*) rocks from Guinea; (*4*, *5*) rocks from eastern United States: (*4*) after [11] and (*5*) after [51]; (*6*) rocks from Morocco. Compositional fields are shown. Compositional field of Guyana rocks is highlighted in gray.

probably with very insignificant participation of ancient crustal material. The high-velocity (Vp = 7.1–7.2 to 7.5 km/s) lower crustal complex, 6–13 km thick, which occurs at depth, is comparable to those identified at other volcanic margins. This complex is traced across the strike for 30–40 km beneath the inner and outer SDRs wedges. This combination of volcanic rocks with a high-velocity lower crustal complex makes it possible to explain the genesis of the latter by magmatic underplating. The high seismic velocities indicates that the lower crustal complex is enriched in ultramafic rocks. The positive East Coast magnetic anomaly (ECMA), up to 350 nT in amplitude, corresponds to the boundary with oceanic beds and a belt of basic volcanic rocks and the lower crustal intrusions [8, 30, 41, 49, 61].

The SDRs complexes typical of the volcanic margin, the high-velocity lower crust, and the ECMA are traced to the northeast, reaching the southern Nova Scotia Peninsula (Figs. 1, 5). These features are distinktly expressed along BA6, 801, 89-3, and 89-4 seismic profiles [28, 30, 65]. To the north, the absence of SDR wedges in the upper crust and the decreased ECMA along the 88-1, 88-1a, and 89-11 seismic profiles probably correspond to limited magma generation. The disappearance of all above-mentioned crustal features on the 89-1 seismic profile (near 45° N) imply a gradual transition to the nonvolcanic margin of Canada [36, 37, 65].

The transition from SDRs to the oceanic crust is marked by marginal uplift similar to the Vøring Plateau at the Norwegian margin. The section of the initial oceanic crust to the east of volcanic margin is not ordinary. Near the Carolina Trough, the crust is distinguished by higher velocities (6.2–6.9 km/s) than those of the normal oceanic crust; the thickness of 8 km is maximal for the oceanic crust [30]. Near the Baltimore Canyon Basin crustal thickness increases up to 15–20 km primarily due to the lower crustal high-velocity body extending seaward [61].

THE CONJUGATE MARGIN OF NORTHWESTERN AFRICA

As in the west, the proximal zone and the distal zone transitional to the ocean are recognized at the eastern margin of the Central Atlantic (Fig. 1). **The proximal zone** with a thick continental Precambrian and Hercynian basement occupies a wide (up to 500 km) area in Morocco and adjacent Algeria, including the High and Middle Atlas and Western and Eastern Meseta. Its structure is complicated by the combination of the Atlantic margin in the west and the

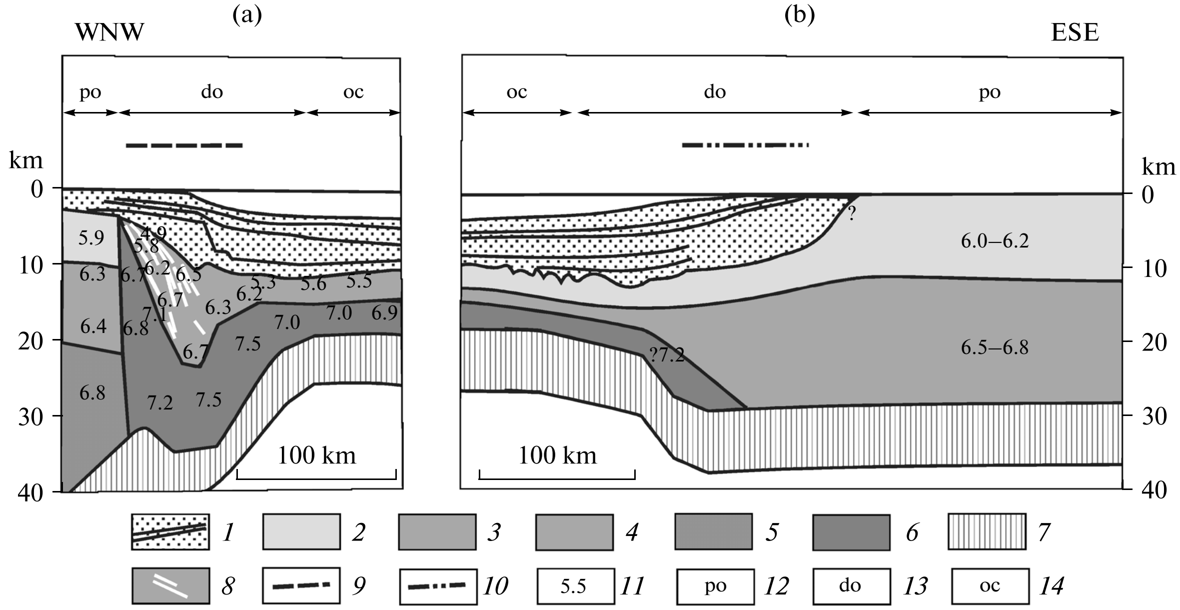

Fig. 5. Deep structure of conjugate margins of Central Atlantic from data of reflection wide-angle seismic profiling and and magnetic data: (a) section across North American margin along profile 801 at 37° N, modified after [28, 29]; (b) section across African margin along profile DAKHLA at 24° N, modified after [38, 40]. (*1*) Sedimentary deposits; (*2–6*) crustal section: (*2*) upper crust, (*3*) middle crust, (*4*) upper and middle crust, unspecified, (*5*) lower crust, (*6*) lower crustal high-velocity rocks; (*7*) mantle rocks; (*8*) seaward-dipping reflectors (SDRs); (*9*, *10*) magnetic anomalies: (*9*) ECMA and (*10*) WACMA; (*11*) P wave velocity, km/s; (*12*) proximal margins with ancient continental basement; (*13*) distal margins with newly formed magmatic crust; (*14*) oceanic crust.

Tethian margin in the north along the boundary with the Mediterranean. The proximal zone extends southward up to Guinea and Côte d'Ivoire. In Morocco, the system of sedimentary basins inherits, by a significant measure, the strike of the Late Hercynian basement structures with subsequent modification by Alpine folding-thrusting deformations. This has predetermined the formation of the system of ENE-trending narrow basins in the High Atlas, as well as NE-trending basins in the Middle Atlas and the coastal zone. The numerous dikes have the same orientation.

The synrift fill of the basins—Ladian–Carnian in the south and Norian–Sinemurian in the north—reaches 5–6 km in total thickness and consists of fluvial–deltaic and lagoonal clastic rocks with local limestone interlayers and red beds; and evaporites at the Triassic–Jurassic boundary covered by Lower Jurassic carbonate rocks [9, 18, 25, 67]. Initiation of rifting in this region took place in Triassic, as has been established in Al Jida Agadir and most other basins. In the High Atlas, local rifting occurred at the very end of Permian [9, 67].

The igneous rocks of the African margin are represented by basaltic and andesite basaltic lavas corresponding to the Central Atlantic Igneous Province. They are close in age and composition to the rock complexes of the Atlantic margin of North America [9, 18, 35, 42, 48]. The lava series occur primarily in Morocco and Algeria, whereas only dikes, commonly near-latitudinal, are exposed at the present-day denudation surface in the vast area of Mauritania and Senegal (Fig. 1). Large sills, laccoliths, and lava flows in combination with numerous NW-trending dikes appear in the extreme south (in the coastal zone of Mali and Guinea). The predominance of intrusive bodies probably was the primary feature of the proximal African margin, whereas the volcanic rocks was subordinate in volume.

Judging by the $^{40}Ar/^{39}Ar$ and U–Pb isotopic ages, the duration of magmatic activity in each district of the African margin was about a million years, and the total duration covered the time interval of 202.5 ± 3 to 194.3 ± 2 Ma [10, 39, 42, 48] (Fig. 2). The palynological data on subaerial deposits indicate that volcanic activity began in Morocco somewhat earlier than at the American margin [14]. The uppermost lavas (so-called Recurrent basalts) in the High Atlas are dated back to 198.2 ± 1 Ma [42]. Younger dolerites and basalts known in southwestern Algeria [13] and Guinea [19], dating back to 192.7 ± 3 and 195 Ma respectively, suggest the occurrence of a young "tail" of magmatism or a longer time interval of volcanic activity than that in the main part of the CAMP.

One or several flows, frequently with sedimentary interbeds, are observed in the lava series of Morocco and adjacent Algeria [9, 13, 18, 42]. The subaerial pahoehoe lavas dominate; red beds and plaeosoils are observed. The thickness of the volcanic series reaches 100–200 m (occasionally up to 350 m). The most complete and the thickest sections are retained in the

High Atlas (Fig. 2). The Lower, Middle, Upper and Recurrent lava units are composed of basalts close to plateau basalts and basaltic andesites reveal a certain variation upsection, the same as was noted for the North American margin.

The rocks are quartz-normative tholeiitic basalts and basaltic andesites, which are distinguished from volcanic rocks at the margin of the United States by their higher SiO_2 and K_2O contents. The widespread pigeonite occurence in most flows probably reflects intense degassing in the course of magma ascent and almost dry crystallization conditions with a low CaO activity in melt. Fractionation proceeded with consecutive crystallization of olivine, olivine + augite, augite (±pigeonite) + plagioclase and Fe–Ti oxides at the late stage [18].

Like in North America, basalts in Morocco are subdivided into two groups differing in degree of enrichment [18, 42]. The early volcanic rocks (Lower and Middle basalts) occupy more than 90% of the total section and are represented by low-Ti tholeiites enriched in incompatible elements including LREE with $(La/Yb)_n$ = 5–6. The geochemistry of the rocks is close to that of basalts from Orange Mountain and their counterparts at the margin of the United States. The second-group of Recurrent basalts are more enriched. They are also low-Ti, $(La/Yb)_n \sim 2$, and similar in composition to the Hook Mountain and Hamden basalts in the United States. In general, basalts from coeval level of sections at margins of North America and Morocco are close to one another in composition [42].

In Guinea, within the West African Platform, the Fouta Dyalon sills, the Kakoulima laccolith (which is more than 1000 m thick) and, to a lesser extent, dikes, consist of gabbro, dolerite, dunite, and wehrlite, which represent tholeiites and mafic and ultramafic cumulates [19]. The high SiO_2 content (51–58 wt %), low TiO_2 (0.7–1.2 wt %) and FeO contents are characteristic of tholeiites from Guinea.

At the northern end of the Central Atlantic margins, some large dolerite dikes extend farther to the northeast into the adjacent nonvolcanic margins. In particular, the giant Messejana–Placensia dike, 204.7 ± 2.5 to 198.8 ± 2.7 Ma in age, extends for 530 km into the Iberian Peninsula, where it crosscuts the Hercynian basement [12]. Over its entire extent, this dike consists of rather homogeneous tholeiites with plagioclase and clinopyroxene as the main phases in combination with olivine and titanomagnetite as subordinate minerals. The rocks are relatively enriched in SiO_2, Al_2O_3, and CaO and depleted in P_2O_5 and TiO_2.

Basalts from all three studied provinces: Morocco, Guinea, and Iberia are distinguished by enrichment in lithophile elements with negative Nb–Ta anomalies and a positive Pb anomaly (Fig. 3c). This feature is also characteristic of rocks in the east of the United States and can be explained by the influence of the subcontinental lithospheric mantle previously enriched by older metasomatism related to subduction [12, 51]. The plot of lithophile elements contained in the Messejana–Placensia dike and normalized to chemical composition of the silicate Earth (Fig. 3c) displays persistent distribution for both slightly fractionated (~9 wt % MgO) and evolved rocks, indicating that crystallization was not accompanied by assimilation.

The isotopic characteristics obtained for rocks from three African regions partly coincide with those for dikes at United States margin, making up a more compact field (Fig. 4). Sr–Nd isotope systematics of volcanic rocks from the High Atlas shows variations similar to the upsection trend for the United States [18]. In the oldest basalts from the Lower and Intermediate units, a certain enrichment is established ($^{87}Sr/^{86}Sr$ = 0.70595–0.70761; $^{143}Nd/^{144}Nd$ = 0.512240–0.512383). Judging by a single sample, the rock of the Upper unit is depleted in radiogenic Sr ($^{87}Sr/^{86}Sr$ = 0.70587) and has an almost chondritic Nd isotopic composition ($^{143}Nd/^{144}Nd$ = 0.512333–0.512350). The analyses of rocks from the youngest series of Recurrent basalts are distinguished by the lowest $^{87}Sr/^{86}Sr$ = 0.70504–0.70506 and the highest $^{143}Nd/^{144}Nd$ = 0.51245–0.51248.

The rocks of Guinea and Iberia [12, 19] are close in Sr and Nd isotope ratios to the enriched rocks of the High Atlas (Fig. 4b). The occurence of large magmatic reservoirs in the continental crust, forming thick sills, laccoliths and giant dike, could have facilitated the interaction of mantle-derived magma with crustal material and its contamination. In particular, the $^{87}Sr/^{86}Sr$ = 0.7078 and $^{143}Nd/^{144}Nd$ = 0.5123 values in the Messejana–Placensia dike assume a certain contamination with material of the enriched crust, most likely with felsic granulites known from xenoliths [12]. This is confirmed by $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios indicating an enrichment in radiogenic lead (Figs. 4a–4d). Isotopic compositions of basalts and dolerites from Guinea and the aforementioned dike from Iberia make up a single field. Data on gabbroic rocks and ultramafic cumulates [19] fall into the same intervals of values.

Post-breakup rocks related to the evolution of the African margin are represented by minor volumes of alkaline rocks that occur in the northern frame of CAMP up to the Bohemian Massif and the Pannonian Basin in the north [50].

In the distal zone of the African margin, up to 130 km wide, a number of features noted for the margin of North America are repeated. Thick (up to 12 km) synrift sedimentary sequences and Cretaceous postrift fill are known near the continental slope, in the Doukkala, Eassouira, and Tarfaya basins and farther to the south.

The crustal section in the proximal zone of Morocco has a three-layer structure with velocities from 5.2 to 6.8–7.0 km/s (Fig. 5) [16, 32, 38]. Its continental nature is confirmed by basement gneisses penetrated by Site 544 DSDP and by a salt diapir drilled by Site 546, as well as by characteristic rotated faulted blocks. Crustal thickness reaches 35 km in the Middle Atlas and 39 km in the northern High Atlas. The thickness decreases to 27 km southward along the strike of the proximal zone.

According to the results of the DAKHLA wide-angle seismic profiling experiment, the high-velocity lower crust (Vp = 7.0–7.5 km/s), more than 10 km thick [38], probably related to underplating was established (Fig. 5). The high-magnetic lower crustal rocks and their boundary with the oceanic crust is marked by the West African Coastal Magnetic Anomaly (WACMA), which in plan view mimics the ECMA anomaly in eastern North America [38, 41, 57] (Fig. 1). The upper crustal SDRs wedge is mentioned in some publications [16, 32]. Its occurrence, however, remains ambiguous, because the interpretation of the reflector pattern is complicated by salt diapirs and a great thickness of the carbonate platform. Klingelhoefer et al. [38] do not consider this wedge in the DAKHLA profile.

The structure of the distal zone changes along its strike. Slackening of the WACMA anomaly in central Morocco is probably caused by a moderate manifestation of magmatic underplating. However, the lower crustal high-velocity zone definitely revealed to the west in the oceanic crust [16, 31] presumably occurs here as well. According to the SISMAR-04 profile [16, 32], the high-velocity zone disappears in North Morocco at 33° N indicating a transition to the nonvolcanic margin similar to that noted in the Nova Scotia.

The boundary with the normal oceanic crust in the west of African margin is characterized by a variation of velocity structure, pinch-out of the salt-bearing unit, and a modification of the basement surface from smooth to rough, which is common for the oceanic crust in line with the features of the magnetic field. In the two-layer oceanic crust to the west of M25 magnetic anomaly, the velocity range (5.5 to 6.6–6.9 km/s) and the seismic image are close to those of the slow-spreading Atlantic-type crust [38]. In the south, near the volcanic segment of the margin, the thickness of oceanic crust reaches 8 km and velocities in the lower crust are maximal for oceanic sections.

COMPARATIVE CHARACTERIZATION OF MAGMATISM AT CENTRAL ATLANTIC MARGINS AND GEOCHEMICAL ENRICHMENT OF MAGMAS

Comparison of the magmatism in the proximal zones of southeastern North America and northwestern Africa close to each other in time interval (202–195 Ma) reveals many common features. Both lavas and dikes formed in the course of fragmentation and rifting are composed of moderately evolved tholeiites enriched in lithophile elements and radiogenic isotopes. Negative Ti and Nb–Ta anomalies, as well as a positive Pb anomaly, are noted everywhere and characterize the specificity of the enriched component bearing a continental signature (Fig. 3). It should be emphasized that a depleted source similar to contemporary MORB with $^{87}Sr/^{86}Sr$ close to 0.7022 is not identified in magmas from the main part of CAMP. This is evident from both the distribution of lithophile elements and isotope geochemistry.

The isotopic data (not very abundant) on rock complexes from various districts of CAMP show that basalts from Morocco, Guinea, Iberia, and North America make up a single extended field in the Sr–Nd systematics ($^{87}Sr/^{86}Sr$ = 0.705–0.708; $^{143}Nd/^{144}Nd$ = 0.5125–0.5121 (Fig. 4d). This field corresponds to a small degree of enrichment, which is corroborated by the isotopic composition of Os ($^{187}Os/^{188}Os$ = 0.128–0.144) [11]. The relatively higher $^{143}Nd/^{144}Nd$ values published in [51] as compared with the data from [11] should be noted; however, this difference does not obscure the general trend of enrichment expressed in dikes from the northern and southern parts of the eastern coastal zone in the United States. Basalts from Guyana are distinguished from the rocks of other CAMP districts by their more depleted source, with $^{87}Sr/^{86}Sr$ = 0.7032 and $^{143}Nd/^{144}Nd$ = 0.5127 in the most depleted varieties.

The data on Pb isotopes (which are not available for basalts from Morocco), reveal a certain difference between the rocks from the North American and African margins. As follows from Figs. 4a and 4b, the range of Pb isotopic compositions of basalts from the eastern United States ($^{206}Pb/^{204}Pb$ = 17.40–18.85, $^{207}Pb/^{204}Pb$ = 15.54–15.65, and $^{208}Pb/^{204}Pb$ = 37.47–38.76) is much wider than of their counterparts from the African margin. The tendency to lowering $^{206}Pb/^{204}Pb$ is typical only of the American basalts, which are characterized by two trends of enrichment: (1) with low $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ and (2) with an increase in contribution of radiogenic leads. The latter trend is commonly related to the enriched isotope component EM-2 typical of the majority of enriched lavas on continents, although the character of enrichment varies on local and regional scales. The same trend is noted for basalts from Iberia and Guinea somewhat enriched in ^{208}Pb as compared with the rocks of North America. They make up a rather compact field despite the sampled dikes being distant from one another for many hundreds of kilometers. On both margins the consecutive variation of elemental and isotopic compositions is traced, beginning from the relatively enriched varieties pertaining to the stage of evolved rifting, to the less enriched rocks at the final rifting stage.

The separate field of depleted basalts from Guyana stands out in all plots [19]. They are characterized by higher $^{208}Pb/^{204}Pb$ values than the basalts of North American margin but lower values than those of African rocks with the same $^{206}Pb/^{204}Pb$ ratios. They also make up their own trend in $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ coordinates, which are distinguished from basalts in other parts of the CAMP.

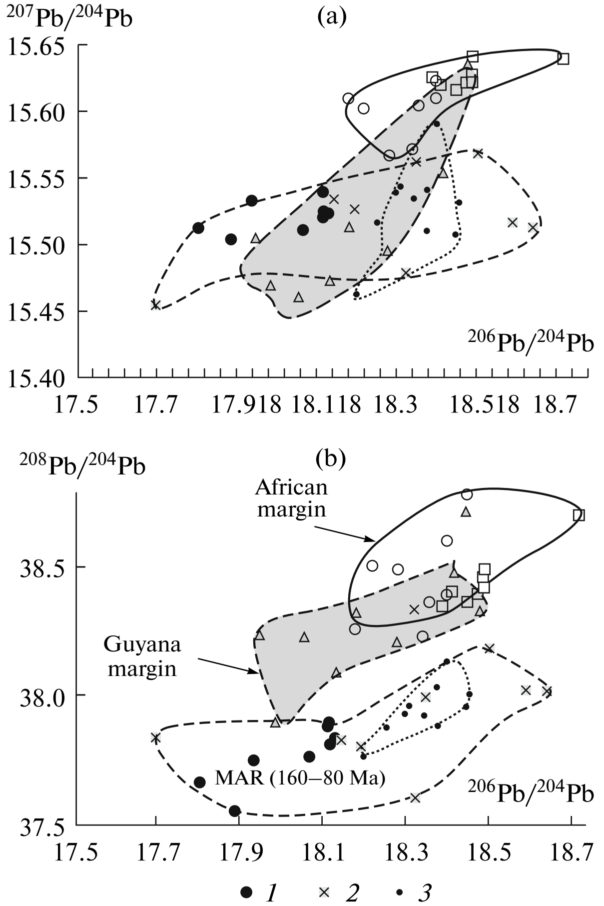

Fig. 6. Comparative characterization of Pb isotopic ratios in rocks of Central Atlantic margins and adjacent oceans: (a) ^{207}Pb/^{204}Pb–^{206}Pb/^{204}Pb and (b) ^{208}Pb/^{204}Pb–^{206}Pb/^{204}Pb, modified after [33]. (*1*) Basalts of intial stages of MAR formation dated at 160–140 Ma; (*2*) basalts from MAR dated at 140–80 Ma; (*3*) basalts from MAR rift zone at 22°–28° N (unpublished data of Sushchevskaya). See above for other sources and Fig. 4 for other symbols.

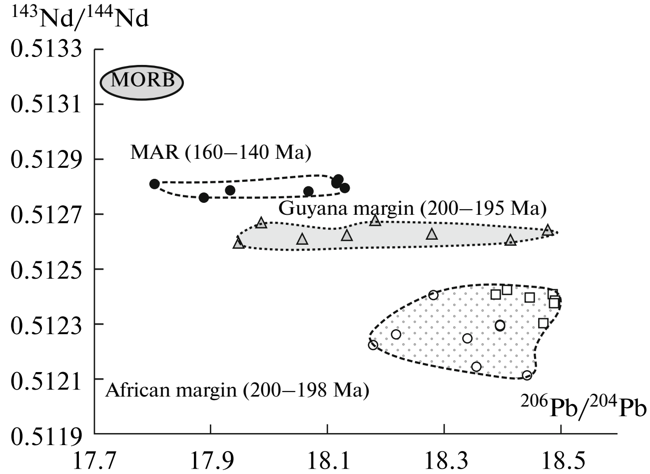

Fig. 7. Variation of degree and character of enrichment of Central Atlantic rocks from 200 Ma to present time. See above for sources and Figs. 4 and 6 for symbols.

Rocks from Guyana are intermediate in Pb isotopic composition between CAMP basalts at the North American margin and the younger oceanic crust rocks in the adjacent part of Atlantic ocean.

Figure 6 shows variations in isotopic compositions of rocks from the considered margins and of spreading tholeiites near the eastern coast of America are discussed in [33]. The comparison of tholeiites from sites 534 (160 Ma), 105 (158 Ma), 100 (155 Ma), and 387 (140 Ma) corresponding to the initial stage of spreading with younger tholeiites sampled in sites 384 (123 Ma), 417 (118 Ma), 386 (110 Ma), and 355 (80 Ma) shows that the degree of magma enrichment decreases with the opening of the Atlantic. As a result, the young spreading basalts are more depleted in incompatible elements than the products of early eruptions [33]. Further increases in ^{143}Nd/^{144}Nd and ^{206}Pb/^{204}Pb, decreases in ^{87}Sr/^{86}Sr and, occasionally, in ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb make the analyzed samples indistinguishable from the strongly depleted MORB in the rift valley of the Mid-Atlantic Ridge at 20°–26° N (Fig. 6).

The time-dependent variation of the degree of enrichment for igneous complexes of the Central Atlantic is traced in the ^{143}Nd/^{144}Nd–^{206}Pb/^{204}Pb plot (Fig. 7), which displays the trend that connects the depleted asthenospheric source of MORB with the enriched source typical of the African margin. The African enriched source of the (2) type is also identified in dolerites from Guyana, however, to an insignificant degree and still weaker in the early spreading tholeiites of Central Atlantic. A certain enrichment of early oceanic tholeiites testifies in favor of the thermal effect of a plume that spreads over vast areas of the sublithospheric mantle. Heating and melting of the lithosphere result in the local appearance of tholeiitic lavas with lithospheric signatures, including the newly formed oceanic domains. The enriched magmatism rapidly disappears with development of spreading and decompression melting of the asthenospheric mantle, and beginning from ~120 Ma, magmatic activity is characterized by the eruption of depleted MORB-type basalts formed in the Mid-Atlantic Ridge.

Thus, based on variations of Nd, Sr, and Pb isotopic compositions, it is assumed that the development of magmatism at the margins of the Central Atlantic bore attributes of two enriched reservoirs. The derivatives of the EM-1 reservoir marked by low ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb ratios occur only at the North American margin. The EM-2 reservoir characterized by elevated Pb isotope ratios and a high ^{87}Sr/^{86}Sr ratio is typical of the entire CAMP. To a lesser extent, the influence of this reservoir is documented in igneous rocks from Guyana, which also bear the signature of a source producing depleted MORB-type spreading tholeiites of the Atlantic. The weak post-breakup magmatic activity mainly developing at the periphery of the CAMP is represented by Cretaceous alkaline igneous rocks.

SPECIFIC FEATURES OF PASSIVE MARGINS OF THE CENTRAL ATLANTIC

The widespread magmatism at the margins of the CAMP provides evidence for an anomalously hot mantle and its melting over a vast area. The trigger mechanism for the partial melting related to the formation of large igneous provinces (LIPs), e.g., CAMP, is a matter of debate. The following hypotheses are being discussed: (1) heating of the mantle beneath the Pangea supercontinent [3, 7, 13, 15, 19, 48, 54, 52]; (2) adiabatic melting at the plate margin in the process of lithosphere extension and ocean opening [7, 64]; (3) the activity of an anomalous thermal plume beneath the West African Craton, which controlled magmatism and breakup of the continent [12, 17, 33, 42, 50, 63]. This plum was defined as the Central Atlantic plume [12, 50].

The data on the Central Atlantic discussed above give evidence for the activity of this plume. Primarily, this is approximately coeval deep heating, which induced a synchronous onset of magmatic activity over the entire CAMP and the large thickness of magmatic crust in the distal zone determined by the scope of melting.

Preliminary conclusion about initial prevalence of intrusive bodies over volcanic rocks in proximal zones is assumed to be a substantial attribute of the Central Atlantic. This feature could have been caused by weak initial magmatism and its short-term duration in proximal zones (about a million years in each district). The uniform composition of igneous rocks (see above) and the character of their geochemical enrichment probably matches moderate magmatic activity.

The radial arrangement of the Late Triassic–Early Jurassic tholeiitic dikes established by prerift reconstructions and accepted as evidence for plume appearance is considered to be one of the important features of the Central Atlantic [12, 33, 59, 63]. The not strictly radial orientation of dikes in the CAMP provokes objections from some authors [3, 45, 54, 62]. A certain distortion of dike-system geometry in the northern parts of the proximal margins can be explained by the influence of the structural pattern of underlying Hercynian complexes. In the south, where the Precambrian basement occurs on both sides of the ocean, the radial arrangement of dikes is expressed quite distinctly (Fig. 1), so that the suggested relations of dikes to the lateral propagation of magmas away from the Central Atlantic plume are thought to be valid.

To explain the specific structure of Central Atlantic, the proposed reconstructions considered (a) movement of the plume head along the detachment surface in the sublithospheric mantle with its tearing off from the feeding plume stem [12] or (b) action of a shallow-seated plume devoid of root at a greater depth [33]. Indeed, it is acceptably to think that such a plume was formed above the western margin of the African superplume, which is fixed in the lower mantle from the results of seismic tomography.[1] Several models of the lower mantle in West Africa display the occurance of low-velocity (hot) material with a deviation of the P wave velocity from a mean value by 0.5–0.7% at the given depth in contrast to an insignificant deviation in the middle mantle [23]. In the upper mantle, at a depth of 630–300 km, the seismic velocities also decreases by ~0.5–1.0% in the lateral direction at margins of Central Atlantic [23, 66]. The pattern shown in Fig. 8 is presumably interpreted as a separation of asthenolens in the upper part of the African superplume, its tearing off from an ancient root with vertical redistribution of hot material, which rises to a shallow depth and is transformed into an independent plume with subsequent protracted preservation of the “memory” about Mesozoic events and the existence of the Central Atlantic plume in the deep structure.

GEODYNAMICS OF OCEAN OPENING AND THE ROLE OF CENTRAL ATLANTIC PLUME

The evolution of Central Atlantic margins began with dispersed rifting and low-capacity magmatism and was followed by a subsequent migration toward the future ocean with the formation of distal zones, vigorous magmatic activity, further breakup of the lithosphere, and opening of the Mesozoic ocean.

The initial fragmentation of the continent and preparation of the breakup of Pangea involved vast areas that spread far beyond the margins of the future ocean. The localization of early eruptions (~202–198 Ma) in the already existing basins of the proximal zone allows us to suggest an arching and initial extension related to the action of the plume before the onset of magmatic activity. The oldest synrift sedimentary sequences resting on the Paleozoic basement are the Upper Permian in the Argan district (Morocco) and probably in the Fundy Basin (Canada). In small grabens of the High Atlas and some basins in the eastern United States, the oldest sequences are the Middle Triassic (Anisian–Ladinian, ~240 Ma) [58, 67]. The evolved rifting at the both margins started in the Late Triassic (Carnian Age, ~228 Ma) and migrated northward up to the Norian. Sporadic eruptions of alkali basalts dated at 225–230 Ma could have been related to the Late Triassic fragmentation [21, 53]. The origination of rift basins under conditions of initial

[1] Global seismotomographic models are capable of really outlining these deep-seated heterogeneities, and the relative conservatism of the internal Earth’s structure allows an assumption of their significant antiquity [66].

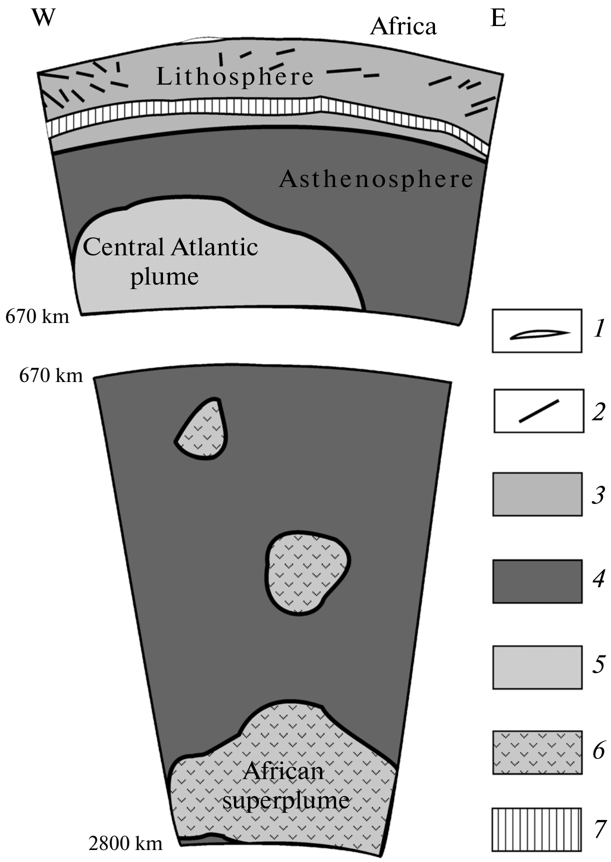

Fig. 8. Magma generation at proximal margins of Central Atlantic: a scheme. Data from [12, 23, 56] are used. (*1*) Basaltic lavas; (*2*) dolerite sills, (*3*) lithosphere, (*4*) sublithospheric mantle; (*5*) shallow-seated plume; (*6*) superplume; (*7*) zone of heating and melting in lithosphere.

arching and extension of the lithosphere frequently followed the strike of the preceding Paleozoic structures.

At the Triassic–Jurassic boundary, the stage of evolved rifting has been interrupted as a result of inversion and change of stress fields in the south of the North American margin [58]. In time and space, these events correspond to the onset of magmatic activity in the southern CAMP, so that possible causal links between them cannot be ruled out. The asynchronous termination of rifting characteristic of the American structures took place in the Late Triassic (southeastern United States), the Early Jurassic (northeastern United States and southeastern Canada), and finally in the Early Cretaceous at the Grand Banks of Newfoundland [58].

The Early Jurassic magmatism in the northern segment of the North American margin as well as in Morocco is represented by lava series, dikes, and sills related to ongoing rifting. In the southern segment and in the African margin south, magmatism is expressed in numerous dikes probably formed after the termination of rifting. In general, the formation of radial dike systems at conjugate margins makes it possible to establish that the plume ascended near the junction of North America, Africa, and South America within the Pangea supercontinent [12, 50] (Fig. 1). This localization of plume is supported by diachronity of extensions spreading from here northward, as is outlined from datings of rift basins in the coastal districts of Africa and from the time of termination of rifting in the United States and Canada.

The outburst of magmatism at both Atlantic margins confirms the influence of the Central Atlantic plume on the development of magmatic activity. The relationship of synchronous magmatic events to deep heating over the vast area of the future CAMP is thought to be without doubt. At the same time, the effect of plume and mechanism of magma generation have so far remained ambiguous. The formation of enriched rocks with continental signatures could have been a result of the contamination of ascending plume-related magma with lithospheric material or the thermal effect of a plume with heating and partial melting of the overlying lithosphere.

As has been shown in this paper, magmas with isotopic signatures corresponding to the melting of the lithosphere are predominant in CAMP. The absence of depleted varieties in the main part of CAMP is indirect evidence in favor of the involvement of the continental lithosphere in melting. The viewpoint of Pegram [51] and other authors [11, 12, 42] who connect magmas enrichment with melting of the ancient subcontinental lithospheric mantle under thermal effect of plume is the best-grounded for the comprehension of the source of tholeiite dikes in the eastern United States and their analogs at the African margin.[2] The enrichment of the mantle source is presumably explained by suprasubduction metasomatism during creation of the Rodinia [51] or, more likely, Pangea [11] supercontinents. The model of Callegaro et al. [11] suppose that the subducting upper continental upper crustal material and oceanic sediments, as well as portions of the obducted lower continental crust could have been incorporated into the lithosphere and underlying mantle wedge due to the Paleozoic continental collision. It is noted that the high mantle temperature (1430–1480°C) deduced from the chemical composition of liquidus olivine testifies to the thermal influence of plume on the generation of Triassic and Jurassic basaltic magmas in the eastern United States. No evidence for the melting of the plume's material itself has been adduced in any publications mentioned above.

The petrogenetic modelling data shows that the plume only occasionally could have been an immediate magma source in CAMP [12]. More likely the melt was formed in the lithosphere due to its conductive heating above the mantle plume under conditions of decompression and partial melting of the metasomatically enriched and readily fusible ancient rock com-

[2] In [54], this melt is explained by the heating of the mantle beneath the Pangea supercontinent.

plexes at the stage of evolved rifting. The formation of enriched tholeiitic melts with continental signature explains why geochemical indicators of a deep-seated mantle magma sources are not established for these basalts [3, 7, 20, 45, 54].

A certain depletion of melts at the final stage of rifting established at both margins could have been related to the involvement of the asthenospheric mantle into magma generation. Indeed, an active rise of the asthenosphere is assumed for that time [33, 58]. The most depleted basalts probably have been almost completely derived from the asthenosphere or the depleted material of the plume proper with only a minor contribution of continental contamination as is assumed for the Guyana margin. Similar conditions of magma generation and the supply of plume material are also suggested for the basalt generation at the newly formed distal margins (in SDRS) and then in the zone of initial ocean spreading. Spreading magmatism almost immediately bore attributes of the depleted MORB source with an insignificant admixture of the enriched material, the contribution of which decreased with time. It is evident that the Jurassic–Early Cretaceous basalts of the Atlantic crust were derived from the mantle sources differing in isotopic composition from those of Late Cretaceous–recent basalts of the Mid-Atlantic Ridge [33].

The total duration of intrusive and volcanic magmatic activity at the proximal margins is estimated at a time interval of 202–198 Ma. The younger “tail” of magmatism (195–190 Ma) at the periphery of CAMP was less significant [35, 48]. Its northernmost manifestation is the Keyforn dike in the Armorican Massif, France (193.4 ± 3.7 to 174.3 ± 3 Ma) [18, 35].

It may be assumed that the extremely short duration and relatively low productivity of magmatism at proximal margins have been related to the low intensity of initial plume action as well as fast migration of this process to the internal part of the province. The accumulation of large masses near the lithosphere bottom increased their positive buoyancy and could have led to the upward breakthrough of this material with the thinning and breakup of the lithosphere. In the Early–Middle Jurassic, the breakthrough area was a place of origination of distal zones and the formation of volcanic or volcaniclastic complexes of SDRs wedges, especially significant on the American side. These events were accompanied by compression and inversion in the proximal zones [58].

As was shown above, Mesozoic events in proximal zones have led only to the insignificant reduction of the thickness of the ancient continental crust, whereas in the course of subsequent magmatic activity in the distal zones the thick magmatic crust has been formed as a specific attribute of the Central Atlantic Province. The outburst of magmatism and formation of a new magmatic crust in the distal zones at the stage of continental breakup[3] gave rise to the eventual formation of the Atlantic margins of America and Africa.

The breakup of the Central Atlantic followed the sutures of the Alleghenian–Hercynian Orogen created during the amalgamation of Pangea supercontinent in the Carboniferous and Permian. The initial opening of Central Atlantic and breakup of Pangea marked by conjugate ECMA and WACMA anomalies were earlier dated at 175 Ma. New gravity and seismic data, magnetic anomalies, and transform faults on both sides of Atlantic, as well as the position of fragments of the Triassic salt basin along the ocean–continent boundary made it possible to date the first oceanic crust as early as the Sinemurian (190 Ma) [41, 57], i.e., older by 15–20 Ma than previous datings. For this time interval immediately following the breakup, the extremely low half velocities of initial spreading (~8 mm/yr) are estimated. After the structural rearrangement in the Bajocian (170 Ma), half velocities increased up to 17 mm/yr and then (~154 Ma ago, chron M25) to 28 mm/yr with subsequent transition to the slow-spreading regime in the Tithonian (~150 Ma, Chron M22) [41].

Comparison of CAMP magmatism with that developing at volcanic margins of the NAIP 60–53 Ma ago under the effect of the younger Iceland plume makes it possible to reveal the specificity of the CAMP rocks. No less than two enriched sources for the lower parts of volcanic complex and the depleted or slightly enriched source close to MORB for the upper parts were determined in the NAIP based on isotopic data [1, 2]. In general, this is similar to the features of CAMP. At the same time, a wide heterogeneity in type and character of enrichment, especially in terms of isotopic data, as well as significant variations of enrichment degree in the course of evolution were established for rocks from NAIP in contrast to CAMP.

The basalts of the Greenland margin are related to the enriched source close to EM-1 with a lower $^{206}Pb/^{204}Pb$ value and a higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios. As was noted above, a similar source is identified for certain CAMP rocks at the North American margin, however, the EM-1 source in CAMP is more enriched in radiogenic leads as compared with Greenland basalts, for which $^{206}Pb/^{204}Pb$ extend to 13.5 (Fig. 9a). This may be a result of later formation of the lithospheric source in CAMP related to the amalgamation of Pangea. The distribution of lithophile elements are also different. The negative Nb and Ta anomalies are not so pronounced in NAIP as in CAMP and disappear in the post-breakup series of basalts [27]. At the same time, the enriched source for Norwegian margin and Hold-with-Hope rocks close to EM-2, with a higher $^{206}Pb/^{204}Pb$ value combined with lower $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios [2], is comparable in a number of parameters with source

[3] Some authors, e.g., [22], refer SDRs formation in distal zones to initial spreading.

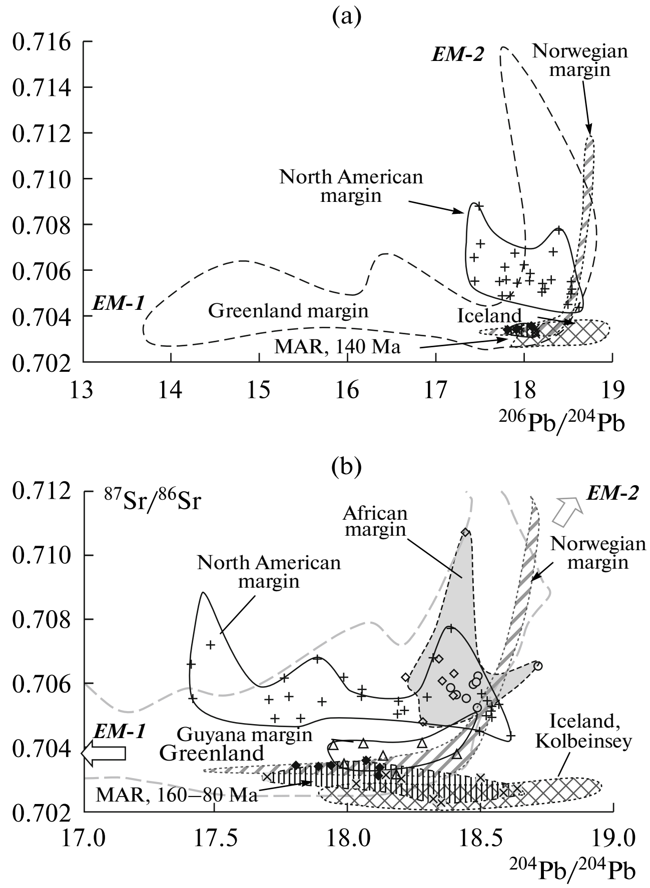

Fig. 9. Comparative characterization of magmatism in CAMP and NAIP related to deep-seated plumes, modified after [1, 2]: (a) general pattern of $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isotope ratios for magmatism related to Iceland plume (within NAIP) and Central Atlantic plume (within CAMP). Range of isotope ratios in CAMP is narrower than in NAIP; (b) more detailed pattern of $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isotope ratios in igneous rocks from particular CAMP regions against the background of isotope ratio fields at Greenland and Norwegian margins, present-day Iceland, Jan Majen Island, and Kolbeinsey Spreading Ridge. Similarity in $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isotope ratios for tholeiites of Guyana margin and early stages of Atlantic opening is pointed out. See above for other sources and Figs. 4 and 6 for symbols.

EM-2 established for all CAMP districts (Fig. 9). However $^{206}Pb/^{204}Pb$ value in CAMP rocks is commonly much lower than this value in Norway (not greater18.5).

The depleted asthenospheric mantle source was also developed to a higher or lower degree at all stages of magma formation in NAIP in contrast to the main CAMP area, where it is assumed only at the final stage of evolution. At the Guyana margin, this source is close to that existing in NAIP. The subsequent eruptions of spreading basalts in the Central Atlantic are distinguished by a higher degree of depletion as compared to the studied rocks of northern part of the ocean. Particularly depleted basalts devoid of enriched component have erupted here since 120–80 Ma, reflecting the same depleted source as in the adjacent part of the MAR (Fig. 9b) [5, 6].

The isotopic discrepancy between two igneous Atlantic provinces characterizes the special features of their evolution. As shown in this paper, the composition of CAMP magmas is determined by the melting of the continental lithosphere. In the NAIP, heating and melting of both the lithosphere and asthenosphere took place above the plume head already at the initial stage of magmatic activity. The participation of the plume itself is suggested later [2], and its influence on oceanic magmatism has continued up to present time. The role of enriched sources related to the lower crustal material at the Greenland margin and probably to the upper crustal material at the Norwegian margin is reflected in the isotopic characteristics of igneous rocks (Fig. 9a). The material of the ancient continental lithosphere in the NAIP could have been incorporated into the plume during its ascent, whereas in the main area of CAMP, magmas are devoid of asthenospheric admixture, providing evidence for only an ancient lithospheric source.

The ascent of the Central Atlantic plume, rifting, and magmatic evolution determined the starting point of the northward progradation magmatic process. The occurrence of the collision zone of the Alleghenian–Hercynian Orogenic Belt in this region with mechanically weakened areas with crust contrasting in thickness probably facilitated the large-scale sublithospheric propagation of the plume and breakup zone in the north-northeastern direction [12, 50, 63] which was sustained by the constant action of rotation forces. The laterally flowing of material, thinning of shallow-seated plume, and conductive lose of heat to the surrounding cold mantle resulted in a fast cooling and an exhaustion of the plume. This style of development and rapid northward shift of the process apparently can explain the absence of hot spots in the Central Atlantic.

The activity of prograding breakup rupture in the lithosphere, which is filled with relatively high-temperature and low-viscosity material, gave rise to the propagation of the extension into the cold lithospheric domain and initiation of cold rifting in the Iberian–Newfoundland segments and northerly districts [2, 17, 55].

CONCLUSIONS

Geological and geophysical data on the conjugate margins of CAMP allow us to consider the structural, magmatic, and historical aspects of the initial opening of the ocean. As was shown above, the breakup of Pangea and opening of the Mesozoic ocean were predated by arching in the future proximal margins with the development of dispersed rifting and low-capacity magmatism, subsiquent migration of these processes with the origination of distal margins, vigorous magmatism, and subsequent breakup.

The outburst of magmatic activity in the Central Atlantic Province testify to almost synchronous deep heating and melting over a vast area. For an obvious reason, a wide thermal anomaly arising in the Early Mesozoic initiated widespread extension, fragmentation, and magmatic activity. Controversies appear concerning the source of heat, which could have accumulated in the sublithospheric mantle of the Pangea supercontinent or been related to the plume ascent. The idea of the leading role of plume in activation of magmatism and destruction of continental masses stated by W.J. Morgan in 1971 is currently shared by many researchers. One of the objections to the plume hypothesis[4] is the absence of Jurassic–Cretaceous hot spots in the CAMP, which are inherent to the LIPs. This discrepancy can be explained by fast exhaustion of shallow-seated Central Atlantic plume and its propagation to the north-northeast from the place of initial origin.

However, "plume skepticism" [3, 7, 19, 20, 21, 44, 54] is primarily brought about by the composition of igneous rocks, which do not bear geochemical and isotopic signs of their derivation from the deep mantle. Indeed, the nature of magmatism in CAMP does not fit simplified plume models and requires special discussion. As was shown above, rift-related basalts at the Central Atlantic proximal margins are enriched in lithophile elements with a distinct continental signature: negative Ti and Nb–Ta anomalies and a positive Pb anomaly inherent to the island-arc sources. According to isotopic data, two enriched components have been established for basalts. One of them, determined at the North American margin, is related to the EM-1 source with lower $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios, and the second component, typical of the entire CAMP, is related to the EM-2 source with elevated contents of the radiogenic Pb isotopes and high $^{87}Sr/^{86}Sr$ ratio. The EM-2 source parcipitated to a lesser extent in the generation of basaltic rocks from Guyana which are also related to a depleted MORB-type source. Similar conditions are assumed for magmatism of distal zones as well as the early spreading basalts containing a small admixture of enriched components.

In contrast to the type NAIP region, the direct melting of the enriched lithospheric source without the participation of plume-related melts is suggested for the igneous rocks from the main CAMP area devoid of MORB admixture. At the same time, decompression and partial melting of the lithosphere could have been maintained by the rise of an anomalously hot plume. This is indicated by a large-scale melting in a short time interval over a vast area, as well as by the generation of melts rather constant in composition, creation of thick magmatic crust, and radial arrangement of dikes injected synchronously with plume ascent. In addition, data from seismic tomography, though remaining limited, are evidence for existence of the hot upper mantle material in the region, which has kept a "memory" of Mesozoic events.

The considered geodynamic concept of the initial opening of the Atlantic Ocean undoubtedly needs additional argumentation. A deep insight into the long history of the region with alternating convergence and breakup at the place of the future Mesozoic ocean is a promising approach. It may be assumed that the abrupt resumption of extension and large-scale melting should have a dynamic support at a depth, probably, owing to the activation of the older upwelling zone in the system of mantle convection. The formation of the shallow-seated Central Atlantic plume can presumably be regarded as a result of upwelling activation above the African superplume and the rearrangement of the deep structure in Triassic and Jurassic times.

When magmatic and tectonic events at that time are considered, the global character of the rearrangement should be taken into account, including not only the onset of the Atlantic opening but also the renewal of the Pacific oceanic pattern and confinement of the events to the quiet Jurassic magnetic epoch.

To characterize the Atlantic opening further, it is necessary to find out the causes which determined the localization of the primordial magmatic activity, rifts, and the breakup that gave birth to the Mesozoic Ocean. A special discussion on the prehistory of the Central Atlantic, the additional isotopic timing of Mesozoic basalts, and the specification of seismic tomographic data will facilitate the solution of this problem. In general, the complex history of the Atlantic comprises both plume activity giving rise to extension and hot rifting and cold rifting that stimulated action of the inherited Iceland plume, vigorous magmatism, and hot rifting.

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