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Cyclic Development of Axial Parts of Slow-Spreading Ridges: Evidence from Sierra Leone Area, the Mid-Atlantic Ridge, 5-7°N

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1. Introduction

Slow- and ultraslow-spreading mid-ocean ridges became come to attention of researchers in recent years again because identification of so-called oceanic core complexes (OCCs). These complexes are characterized by tectonized and heterogeneous lithosphere, large yields of altered gabbros and serpentinized mantle at the oceanic bottom and presence of large deep-sea hydrothermal fields and mineralization (Conference..., 2010). For example, OCCs are quite common in the slow-spreading Mid-Atlantic Ridge (MAR) where they make up ~30% of its length (Escartín et al., 2008; Smith et al., 2008; MacLeod et al., 2009 and references therein). OCC form about 50% of ultra-slow South-West Indian Ridge length (Cannat, 2010); the most studied site here is Atlantis Bank (Thy, 2003; Schwartz et al., 2009). OCCs are known in back-arc seas too, for example in the Philippine Sea (Ohara et al., 2001).

The largest of the OCC is the Godzilla Mullion in the Philippine Sea. The second in the world and the largest in the MAR is the St. Peter and St. Paul complex about 90 km long and up to 4000 m in height, located near the axial zone of MAR in the equatorial region, south of the Sierra Leone area. A feature of this OCC is a dissected topography, with its most elevated blocks even reach the ocean surface to form the St. Peter and St. Paul Rocks. They are composed mainly serpentinized often sheared mantle hornblende (metasomatized) peridotites, containing hornblendite schlierens and veins (Roden et al., 1984; Hékinian et al., 2000). Such peridotites are commonly found as xenoliths in intraplate (plume-related) basalts of oceans and continents, representing fragments of the cooled upper parts of mantle plume heads above its melting zone (Magmatic ..., 1988); so, that is tectonic block of the upper edge of a mantle plume moved out to the surface here.

The name for OCCs was given by analogy to metamorphic core complexes (metamorphic cores), located in core (inner) parts of orogens on continents. In essence, such complexes are represented by exposed metamorphosed deep-crustal rocks, which underwent by viscous-plastic and brittle deformation. The same situation is typical for OCCs, which are outcrops of tectonized and altered deep-seated crustal and mantle rocks in the axial parts of mid-oceanic ridges. Because of characteristic striated surface (mullion structure), such complexes often referred as megamullions (Tucholke, 1998).

According to the commonly accepted (Penrose) model of plate tectonics, the occurrence of mid-ocean ridge (MOR) is associated with uprising of hot deep mantle material, which, reaching shallow depths, begins to melt due to adiabatic decompression. It is assumed that formation of new oceanic crust occurs here, which symmetrical spreads to both sides of the ridge due to convection currents in underlying mantle. Resulted excess of the crust is absorbed in subduction zones beneath island arcs and active continental margins. The axial part of the MORs, where crust is generated (constructive plate boundaries), considered as centers or zones of oceanic spreading.

From such positions, outcrops of plutonic rocks in the spreading zones do not fit in the traditional model of plate tectonics. According to numerous studies of OCCs, axial parts of ridges are uplifted relative to their average height, and often have asymmetrical structure, where outcrops of plutonic rocks are disposed outside of axial valleys, where neovolcanic hills are located (Ildefonse et al., 2007; Smith et al., 2008; MacLeod et al., 2009, etc.). Modern volcanism is practically absent, however, numerous hydrothermal vents occurred.

In this regard, it was suggested that *oceanic core complex* results from activity of an *oceanic detachment fault* (Conference..., 2010). This fault is a large-offset normal fault formed at or in the vicinity of a mid-ocean ridge axes that accommodates a significant fraction of the plate separation (Fig. 1); offsets range from kilometers to tens kilometers or more. According to this model, oceanic detachment faults may initiate as steep normal faults at depth, and turn into shallow low angle extensional faults through rotation of the footwall. It is suggested that this type of spreading should be recognized as a fundamentally distinct mode of seafloor spreading that does not result in a classical Penrose model of oceanic crustal structure. However, many elements and details of this hypothesis of “one-side spreading” are poorly justified (i.e., unknown fault geometry at depth, structure of magmatic systems, route of hydrothermal currents, etc.), as well as motives of appearance of such detachment faults, which absent in fast-spreading ridges.

Identification of the OCCs set to geologists a number of problems which solution is possible only using the complex of geological, petrological and geochemical studies. Such work was done on example of Sierra Leone area, located in axis of the MAR (5-7°N). It was based on materials dredged during the cruises of R/V "Akademik Ioffe" (10th cruise, 2001-2002) and "Professor Logachev" (22th cruise, 2003) (Sharkov et al., 2005, 2007, 2008; Savelieva et al., 2006; Simonov et al., 2009; Aranovich et al., 2010). Judging on presence here of serpentinites upon mantle peridotites and altered tectonized lower-crustal gabbros, as well as widespread

development of extensional structures, including normal faults, the Sierra Leone area can be determined as OCC. However, unlike of typical OCCs, the altered deep-seated rocks were found mainly in the bottom and slopes of deep graben-like depressions, whereas surface of the ridge is covered by the flows of fresh pillow lavas with chilled glassy crusts; i.e. a kind of structural discordance occurred in the area. Marked asymmetry in structure of the ridge is not found here as well as clear evidence of oceanic detachment fault existence. In this context, studied area is of great interest as a possible example of the transition from the typical OCCs to regions of the ridge between them where only basalts developed and spreading is symmetrical.

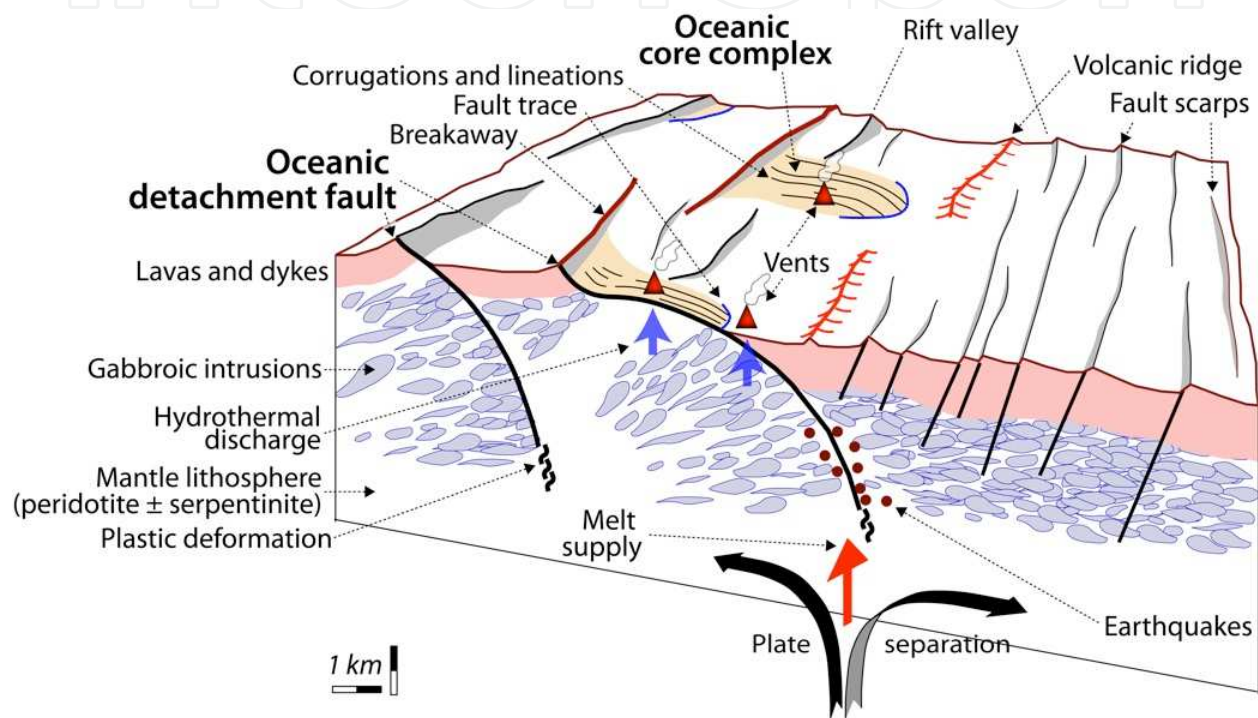
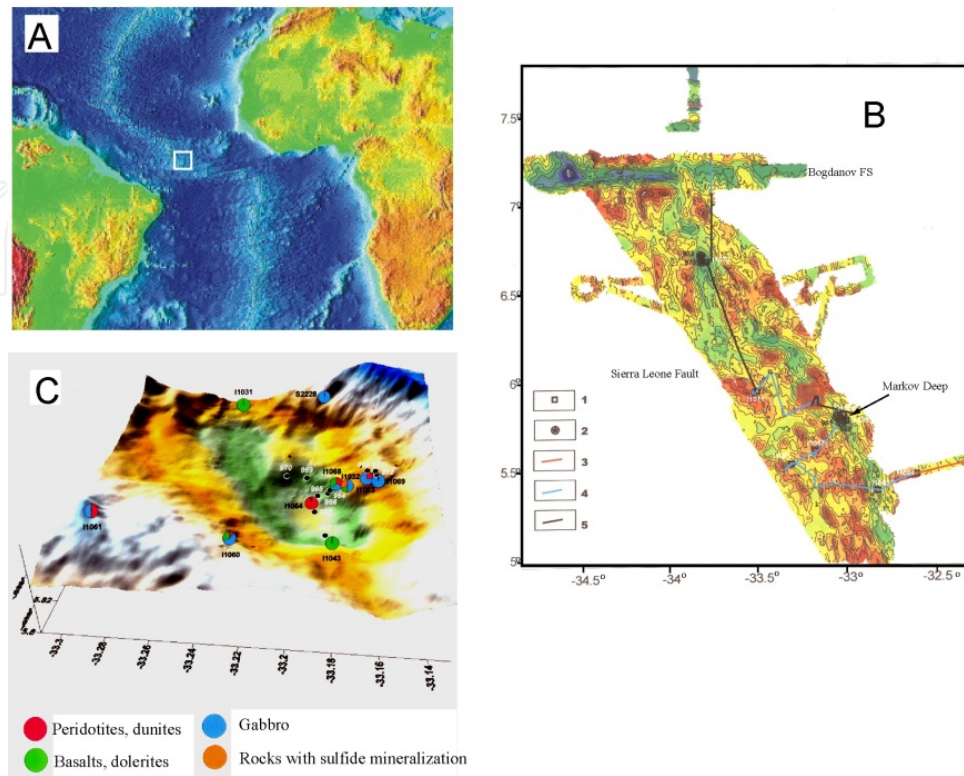


Figure 1. Scheme of oceanic core complex with oceanic detachment fault. After: Conference ..., 2010.

The aim of this paper, based on our data from the Sierra Leone area and published information, to discuss diverse processes, occurred in axes of the modern slow-spreading MORs, and give a new way to interpret of geological, petrological and geodynamical data both in their spreading zones and in underlying mantle.

2. Brief description of geological background

The studied segment of the MAR with strongly dissected relief is located in the vicinity of non-transformed Sierra Leone Fault, between Bogdanov Fracture Zone (7°10' N) and 5°00' N (Fig. 2). South to area, from 5°00' N and to the Strakhov FZ, the MAR represents leveled basaltic plateau, crossed by narrow meridionally-oriented axial rift valley. Geological structure of the area is showed in (Pushcharovsky et al, 2004).

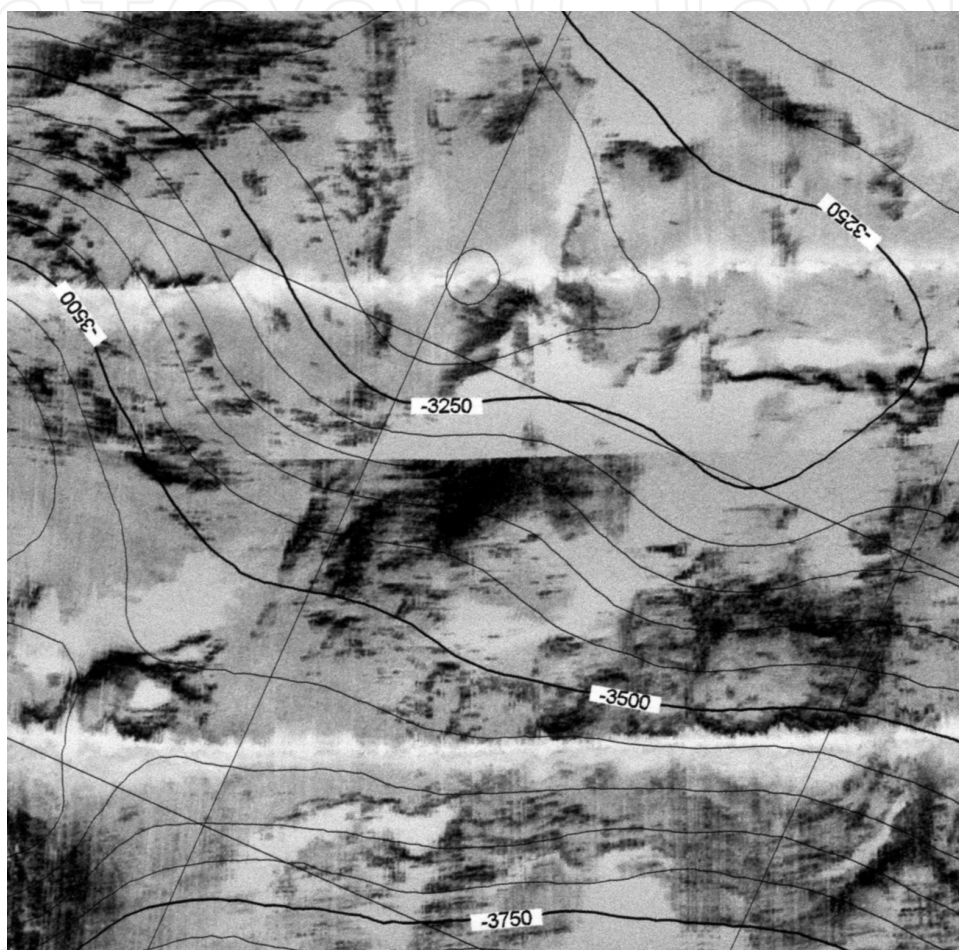


A - location of the Sierra Leone area in the Atlantic; B – Bathymetric map of the Sierra Leone area: 1- sites of dredgings; 2 – sites of Rosetta module; 3-6 – profiles; C – Markov Deep

Figure 2. Sierra Leone area, the Central Atlantic

Feature of morphostructural image of the area is lack of transform faults and the spreading zone is represented here by an echelon system of graben-like depressions (valleys) of 4-5 km depth from ocean surface. As it mentioned above, altered deep-seated rocks found mainly in the sides of rift valleys and on their floor, at that outcrops of plutonic rocks are traced for about 60 km along the MAR axis. Flows of fresh pillow lavas cover top of the ridge and partly fill bottom of some rift valleys. Thickness of these flows is small because within the area of their distribution are found outcrops of altered plutonic rocks. Despite the uneven sampling, we can say with confidence that both sides of the rift valleys formed by the same complex of rocks that characterize the entire section of oceanic crust.

The structure of bedrocks on the eastern slope of the deepest (~5 km) Markov Deep can be seen on Fig. 3, which were finding by marine acoustic complex (sidescan sonar) GBO MAK-1M during the 22th cruise of R/V "Professor Logachev". The crust has a well-defined subhorizontal layered structure, partially masked by sediments, and looks like structure of the Kane OCC (23°30' N) (Dick et al., 2008). Numerous steep-dipping normal faults are clearly visible here; one of them (at the left), apparently filled with dolerite dike which, probably, represents a lava flow's feeder.



Clearly visible layering of the lithosphere, partially overlapped by sediments (gray). Numerous steeply dipping normal faults are visible; one of them (on the left side of the figure) seems to be filled with dolerite dikes and, probably, was a feeder of lava flow.

Figure 3. Structure of the eastern slope of the Markov Deep by data of remote sensing obtained using marine acoustic complex (sidescan sonar) GBO MAK-1M from board of R/V "Professor Logachev" (22th cruise, 2003).

3. Dredged rocks from the Sierra Leone area

The spectrum of dredged rocks at the area is typical for slow-spreading ridges (Sharkov et al., 2005, 2008; Savelieva et al., 2006):

1. strongly serpentinized ultrabasites (depleted lherzolite and harzburgite, rare dunite); most of them are mantle restites, but in some samples relics of cumulate structures preserved, attesting their intrusive origin;
2. two types of altered tectonized gabbros of lower oceanic crust: (i) primitive magnesian gabbros (troctolite, olivine gabbro, and gabbro), which related to MORB and (ii) ferrogabbros (Fe-Ti-oxides-bearing gabbro, hornblende-bearing gabbro and gabbro-diorite), related to specific siliceous Fe-Ti-oxide series (see Section 2.3);
3. small veins and nests of plagiogranites (trondhjemite);
4. dolerite dike and/or sill complexes, including ilmenite- and hornblende-bearing varieties also;
5. basalts – fragments of pillow and massive lavas; very fresh varieties with chilled glassy crusts predominate among them.

Most of the rocks were undergone to secondary alterations. Magmatic minerals (olivine, pyroxene, and plagioclase) often display deformation textures resulted from early high-temperature cataclasis, associated with plastic flow of solidified, but still hot rocks. Judging by the Ti-zircon thermometry, it occurred within a temperature range from 815°C to 710°C (Zinger et al, 2010). During pervasive low-temperature alterations, peridotites underwent strong serpentinization, while gabbros and some basalts – amphibolization with appearance of fibrous actinolite upon pyroxenes and thin veins of prehnite, carbonate and chlorite along the fractures. In some cases rocks were schistozed and brecciated, and underwent by metasomatic processes; the thickest metasomatic zone bear veinlet-disseminated sulfide mineralization (see Section 3).

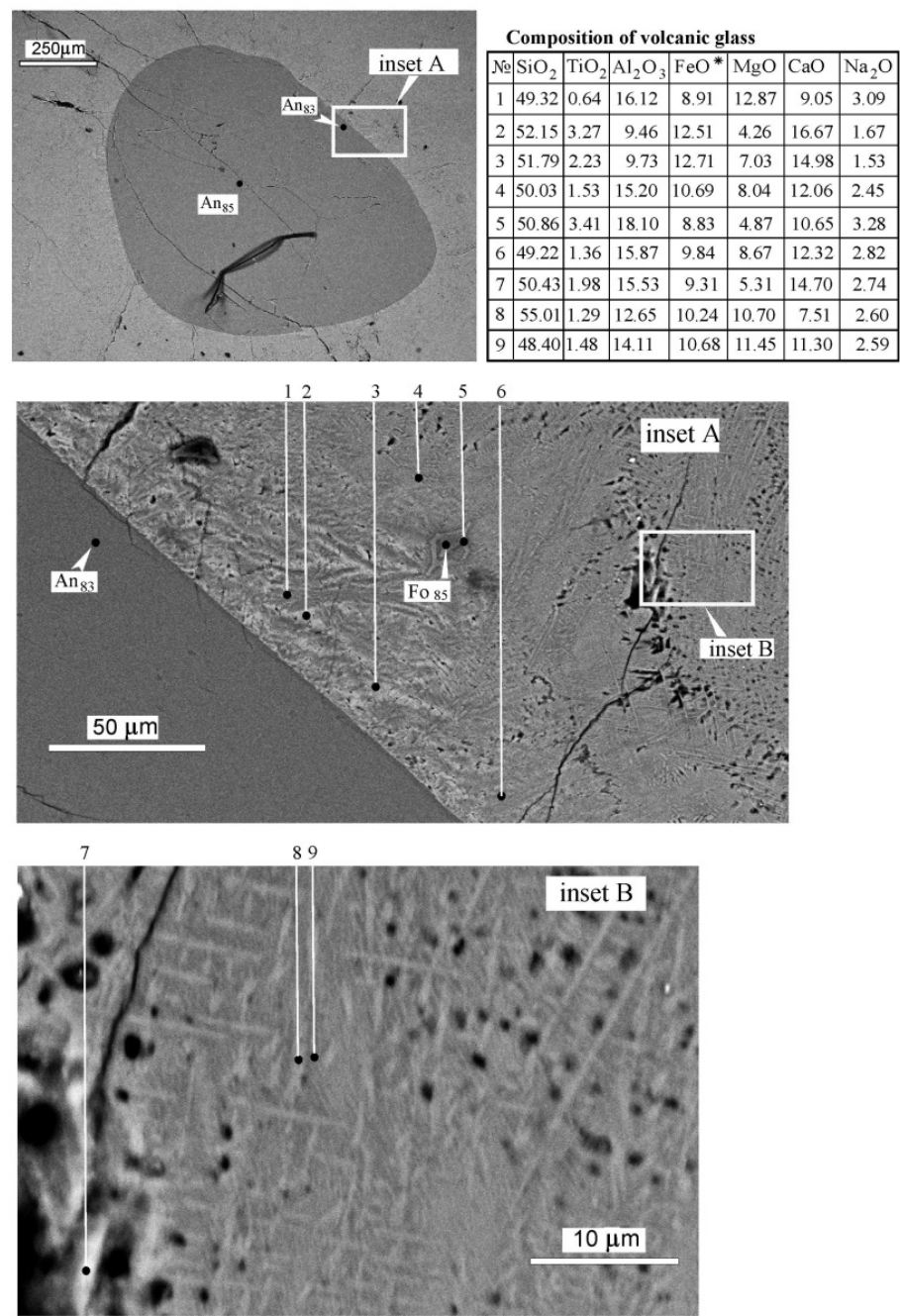
3.1. Features of the fresh basalts

Most of studied fresh basalts with chilled glassy crusts often have porphyritic structure with phenocrysts of three major types: Ol±Chr, Ol+Pl±Chr and Pl+Cpx, which is typical for MORB (Langmuir et al., 1992). Equilibrium cumulates in transitional magma chambers have to correspond with dunite, troctolite, olivine gabbro and gabbro, typical for many layered mafic-ultramafic intrusions on continents (Sharkov, 2006).

Sometimes partly-melted xenocrysts were found in basalts and volcanic glass: olivine F_{088-89} , similar in composition to the olivine of mantle restite, and plagioclase An_{83-86} (Fig. 4), similar in composition to the plagioclases of lower-crustal primitive gabbro. This is evidence that the basaltic melts crossed rocks of the shallow lithosphere on their way to surface.

All studied fresh lavas are commonly oceanic plateau basalts (T-MORB) and more rare close to E-MORB in composition. They are characterized by the same level of REE with typical for MORB flat character of distribution; the Ce/Yb ratio ranging from 0.95 to 1.69. Judging on #mg (56-63) and mineral compositions, they are not primary mantle-derived melts and

underwent by crystallizing differentiation in transitional (intrusive) magma chambers. It is in a good agreement with small negative *Eu*-anomaly which reflects the fractionation of plagioclase in intermediate magma chamber (Sharkov et al., 2005).



Diamonds denote basalts and their glasses (glasses are shown in the inset by open symbols), boxes denote gabbros, and circles are trondhjemites. Dashed lines indicate the position of the data point of metasomatite replacing gabbro. Hypothetical sources: (1) HIMU, (2) EM2. Continuous line outlines the field of the MAR basalts between 3° and 46°S (Fontingie and Schilling, 1996), dashed line denotes MAR basalts between 30° and 50°N (Yu et al., 1997), dotted line outlines basalts of Sao Miguel Island, Azores (Widom et al., 1997).

Figure 4. Dissolution of plagioclase xenocrysts and textural–compositional heterogeneity of the chilled glass Sample I1052/38. Image in back-scattered electrons.

Fresh basalts of the Sierra Leone area in terms of Sr-Nd isotopic characteristics fall into central part of the field of modern MORB for the southern hemisphere and occupy an intermediate position between the most depleted basalts of the MAR ($^{87}\text{Sr}/^{86}\text{Sr} < 0.7025$, $\epsilon\text{Nd} > 12$) and enriched basalts of high latitudes both the northern and southern hemisphere ($^{87}\text{Sr}/^{86}\text{Sr} > 0.7030$, $\epsilon\text{Nd} < 8$) (Fig. 5). Variations of the isotopic characteristics within a relatively small (less than 300 km in the meridional direction) studied area is comparable in scale with variations along the 15-20 times more extended segments of the MAR (Sharkov et al., 2008). The points form an elongated box on the diagram which suggests the presence here of two finite member (depleted and enriched) mixing in different proportions.

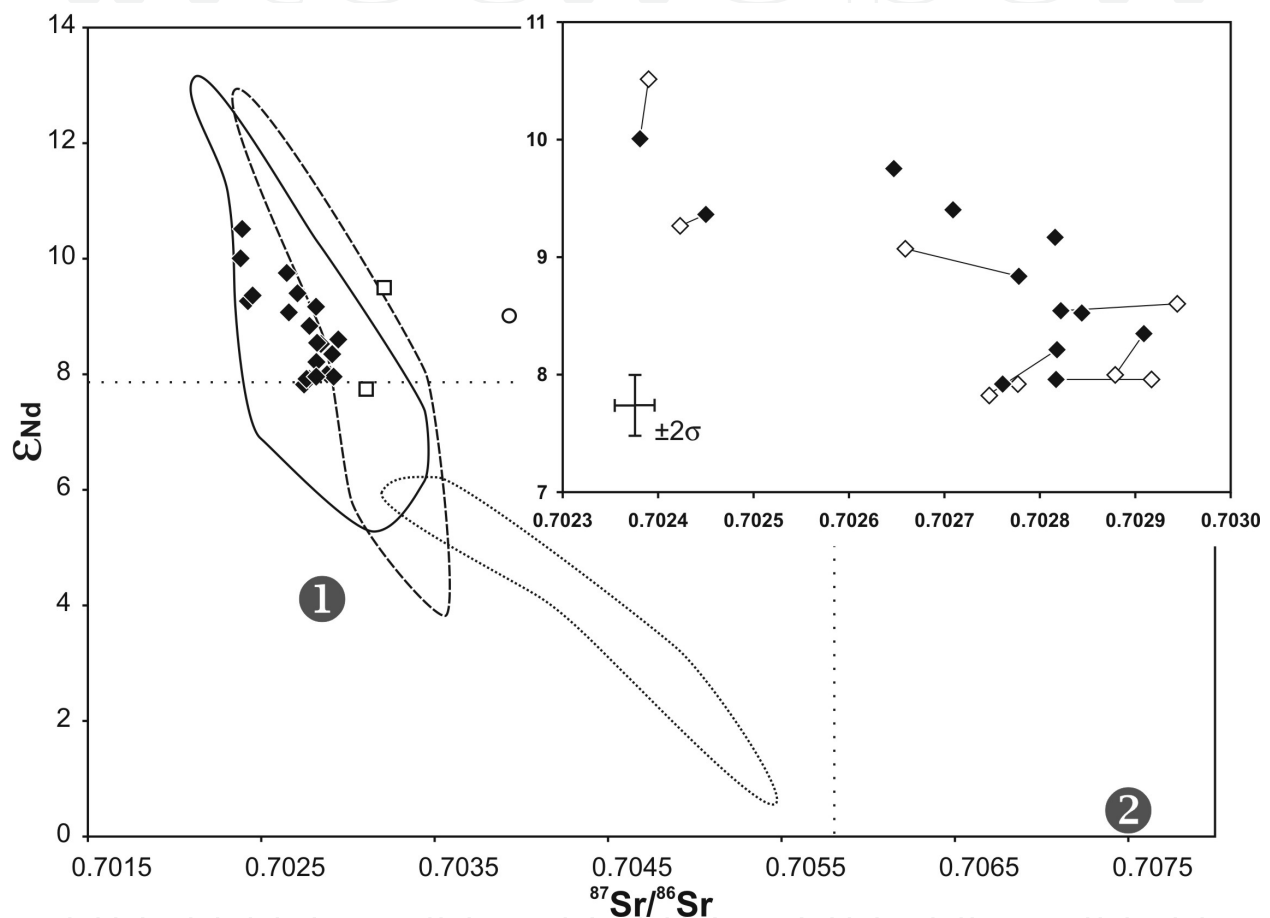


Figure 5. Sr–Nd isotope diagram for the studied basalts and their glasses dredged at the Sierra Leone area, Mid-Atlantic ridge, 5°–7°N.

Significant nonsystematic differences in $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and less significant differences in ϵNd value between basalts and their chilled glassy crusts were firstly found in some samples (Sharkov et al., 2008). Higher Sr isotopic ratios can be observed both in the glasses and the basalts at the same lava fragments (Fig. 5, inset), at that isotope and geochemical characteristics of the samples show no essential correlation. So, seawater did not affect to the Sr and Nd isotope system in the chilled crusts of the studied pillow lavas. It is suggested that such isotopic differences are related to a small-scale heterogeneity of the melts which had no time to homogenized during their rapid ascent to the surface. The heterogeneity was

presumably related to the partial contamination of basaltic melts by older plutonic rocks material (especially, lower-crustal gabbros) (Fig. 3).

3.2. Primitive gabbro

The magnesian primitive gabbros are represented by troctolite, olivine gabbro and gabbro, which dominated among lower-crustal rocks of the area. The same gabbros are widespread in rocks of the lower oceanic crust and traditionally viewed as intrusive equivalents of MORB (Pearce, 2002; Ildefonce et al., 2007; Dick et al., 2008, etc.). Absence of reactionary subsolidus pyroxene-spinel rims between Mg-olivine and Ca-plagioclase, typical for deep-seated gabbros of continents evidence, that crystallization of parental melts occurred under pressure, essential low 5 kbar (Sharkov, 2006).

According to our geochemical data, these gabbros have lower contents of REE, Th, Nb, Ta, Zr and Hf as compared to the fresh basalts of the area (Sharkov et al., 2005). From this follows that the fresh basalts and older primitive gabbros were formed from some different mantle sources.

3.3. Ferrogabbro

Different ferrogabbros play essential role among lower-crustal rocks (about 1/3 of the gabbros' samples). They are represented by melanocratic troctolite, norite, gabbro-norite, and gabbro-norite-diorite, enriched in Fe-Ti oxides (ilmenite and magnetite) and often by brown primary-magmatic hornblende (kaersutite) (Sharkov et al., 2005). Subvolcanic analogues of ferrogabbro are represented by hornblende Fe-Ti-oxide dolerites, and very rare basaltic flows with essential amount of Fe-Ti oxides, mainly ilmenite.

Ferrogabbros, like primitive gabbros, are characterized by low concentrations of light REE; however, they are enriched in ore components – Zn, Sn and Mo, have elevated contents of Cu and Pb, and low – Ni and Cr. In contrast to the primitive gabbro, ferrogabbros have positive anomalies of Nb and Ta. Study of melt inclusions in chromites from rocks of this series showed that their composition vary from Fe-Ti basalt to andesite (icelandite) and dacite (Simonov et al., 2009). The ion-microprobe study of the melt inclusions yielded direct evidence for elevated water content (up to 1.24–1.77 wt %) in the melts that produced ferrogabbros; small globules of Fe-Ni sulfides were found in them also. So, these rocks from one hand are saturated and supersaturated by SiO₂ and have increased H₂O content, which typical for subduction-related magmas, and on the other hand have high contents of Ti, Fe, Nb, Ta and P, typical for magmas of plume origin.

Ferrogabbros are obligatory component of the lower-crustal sections of rocks in OCCs, where they play essential role. Many people thought that the ferrogabbros were produced by fractional crystallization of the MORB-type melts (Dick et al., 1992; Thy, 2002 and references therein). However, they often intruded primitive gabbros (Thy, 2002) and their quantity usually exceed possibility of the MORB crystallizing differentiation.

We believe that these rocks belong to magmatic siliceous Fe-Ti-oxide series, specific for the oceanic environment, which origin related to melting of hydrated oceanic lithosphere by action of a new mantle plume (Sharkov et al., 2005). Newly formed mantle-derived melts passed through the upper cooled part of the plume head, accumulated at the mantle-crust boundary and produced a magma chamber, which started to ascend according to the zone refinement mechanism, i.e. by melting the roof and crystallizing at the bottom (Fig. 6). The melt was continuously enriched in components not only melted rocks of the chamber's roof but also from the partly melted rocks at the heated peripheries of the melting zone, where processes of anatexis occurred (see Section 2.4), as well as fluid material from the heated rocks on the distant periphery. Obviously, unusual characteristics of these melts, like their enrichment in SiO_2 , H_2O , and some ore components, typical for hydrothermal activity (Pb, Cu, Zn, etc.), can be explained by such features of melting process.

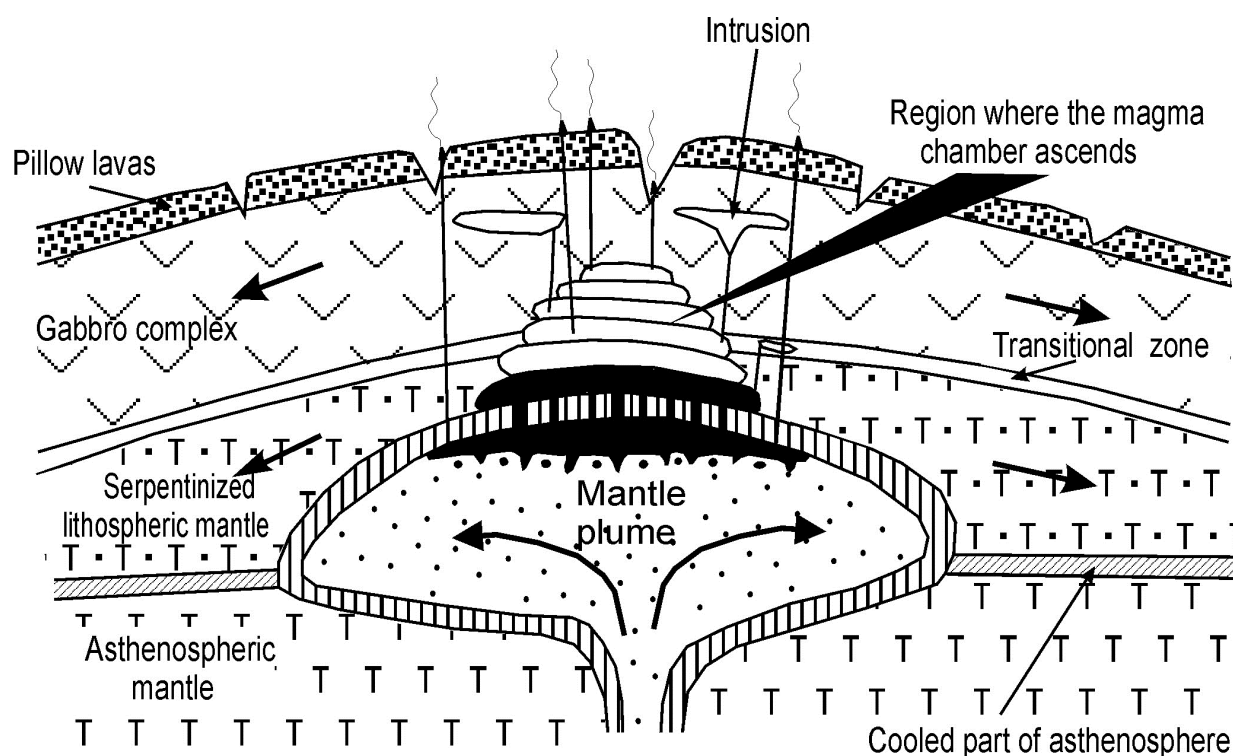


Figure 6. Hypothetical scheme of the melts of the siliceous Fe-Ti-oxide series genesis

D. Pearce (2002) drawn attention to the fact that, unlike the fast-spreading ridges, in the slow-spreading ridges volcanic equivalents ferrogabbros very rare. Truly, there are only two small fragments of hornblende basalt with ilmenite, as well as a sample of variolite (Krassivskaya et al., 2010) in our collection. Apparently, the main cause of the limited vertical mobility of such melts is their water saturation, which decreases sharply at a pressure about 1 kbar (Fluids..., 1991). This leads to separation and removal of water, following increase of the solidus temperature and, as a result, to rapid solidification of melts at depth; therefore, the volcanic eruption of such magmas are rare, how it is clearly seen in the most OCCs and, particularly, in studied area.

3.4. Oceanic plagiogranites

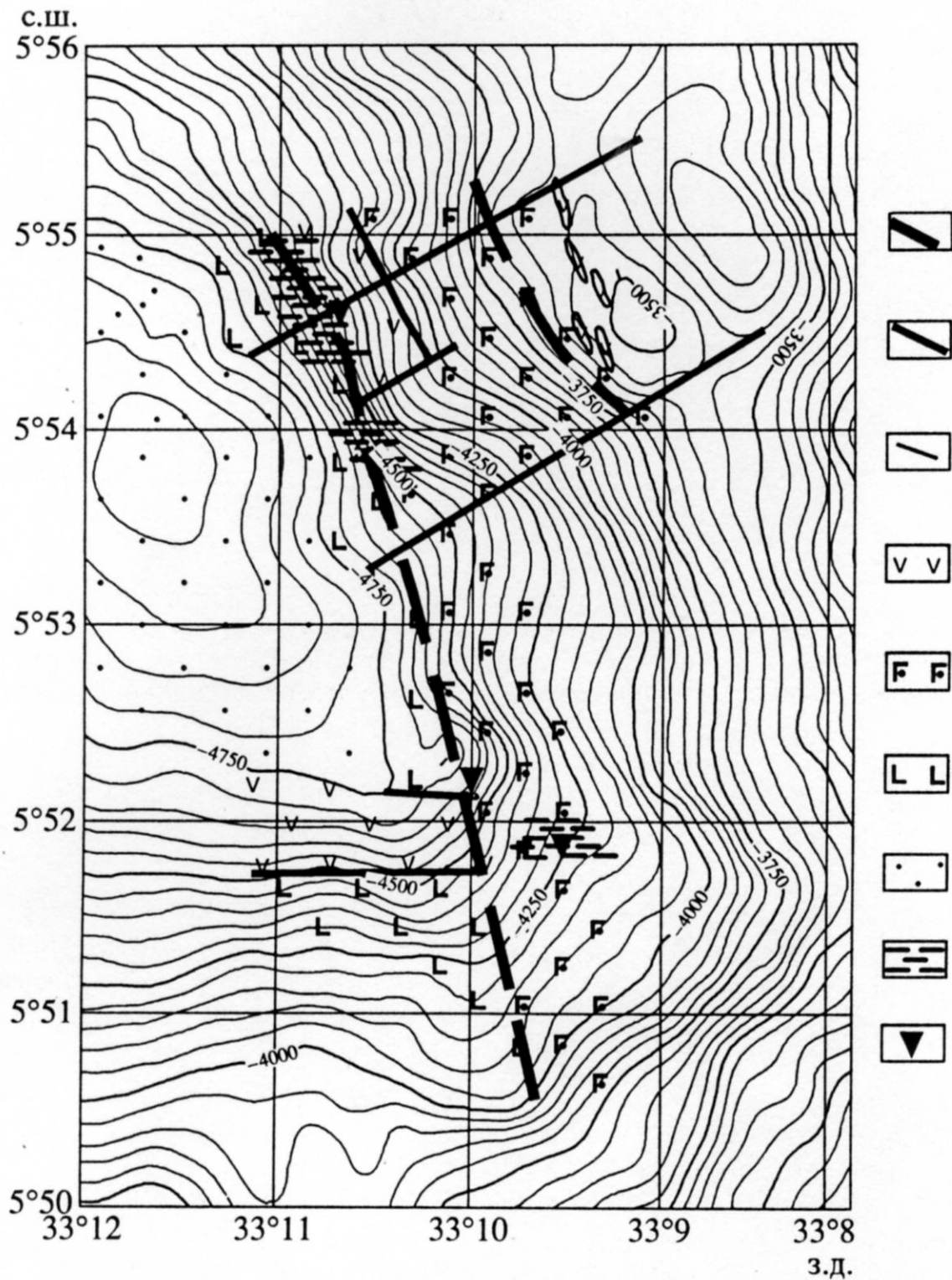
As in all OCCs, small quantities of plagiogranites (tonalites and trondhjemite) are found on the area. Their origin is usually attributed to later stages of magmatic crystallization. However, according to our data, formation of such melts can be explained by anatexis of hydrated lithospheric rocks near intrusive contacts (Aranovich et al, 2010). Special role in this process belongs to "metamorphosed" sea-water from subfloor hydrosphere, enriched in NaCl due to absorption of pure part of sea-water during formation of the secondary hydrous minerals (serpentine, chlorite, actinolite, etc.) in the bedrocks.

4. Metasomatism and ore mineralization

Hydrothermal metasomatic zone with rich sulphide mineralization was found in the Markov Deep (Sharkov et al., 2007 and references herein). According to results of dredging, at least two zones of intense tectonic deformation and metasomatism (at depth 4400-4600 and 3700 m) occur here, extending in NW direction with gentle angles (30°- 40°) dip to east (Fig. 7). These zones are formed by brecciated and schistosed ferrogabbros to thin-foliated cataclasites upon them of chlorite-amphibole-epidote-clinozoisite composition. The presence of chaotic plication, striation, grooves, slickensides and slip-scratches on the surface of the clasts as well as fragments of small folds with distinct axis, which are oriented along lineation, point to the fact that tectonic movements have evolved under shear conditions.

Sulfide mineralization represented by quartz-sulfide and prehnite-sulfide veins, sulfide dissemination and massive ore deposits. Mineral composition of ores is represented by pyrite, chalcopyrite, sphalerite, pyrrhotite, bornite, and atacomite as well as native Cu, Pb, Zn, Au and Sn and intermetallides (isoferroplatinum, tetraferroplatinum, and brass).

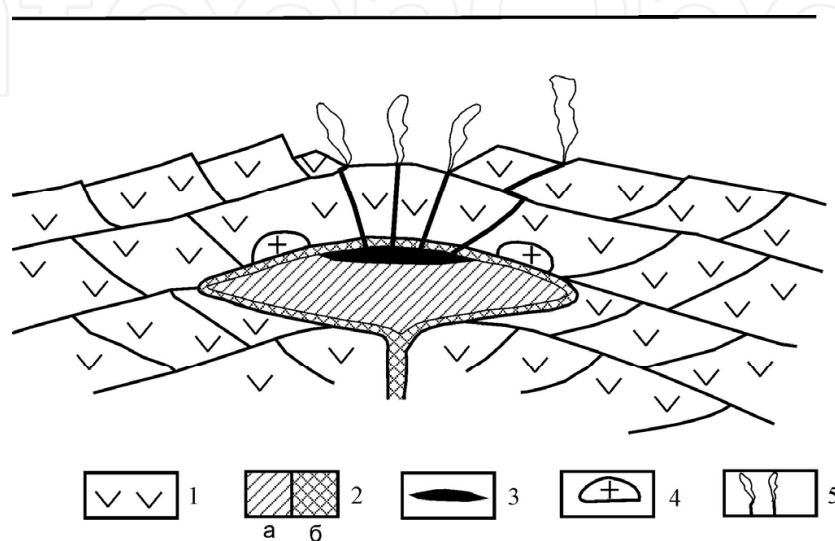
According to our data, hydrothermal-metasomatic processes occurred under low pressure (0.5-1 kbar) and started at temperature ~750°C; however, the major ore-forming metasomatic processes occurred in range 400-160°C. Sm-Nd isotopic data and $\delta^{34}\text{S}$ value evidence that ore-bearing fluid initially had magmatic origin and then were progressively diluted with sea-water of oceanic subfloor hydrosphere.



1 - zones of tectonic deformation and metasomatism, 2 - faults, 3 - geological boundaries; 4-7 – fields of preferential distribution: 4 - basalts, 5 - gabbro, 6 - ultrabasic, 7 - sedimentary cover; 8 - zone of hydrothermally altered rocks; 9 - sulfide mineralization in the bedrock.

Figure 7. Scheme of the geological structure of the eastern edge of the Markov depression. According to Beltenev et al. (2004).

The main source of ore-bearing fluids could be an intrusion (Fig. 8), formed by water-saturated melt of siliceous Fe-Ti-oxide series, which contains sulfur and ore components (see Section 2.3). Addition of the ore material can be leached from the host gabbros on the way up, and part of the sulfur been introduced by sea water. Separation of fluids from such magmas commonly occurs at a pressure of about 1 kbar, when the solubility of water in them decreases sharply (see Section 2.3), i.e. at the depth of 3-4 km below the seabed, where, apparently, was located solidifying intrusion.



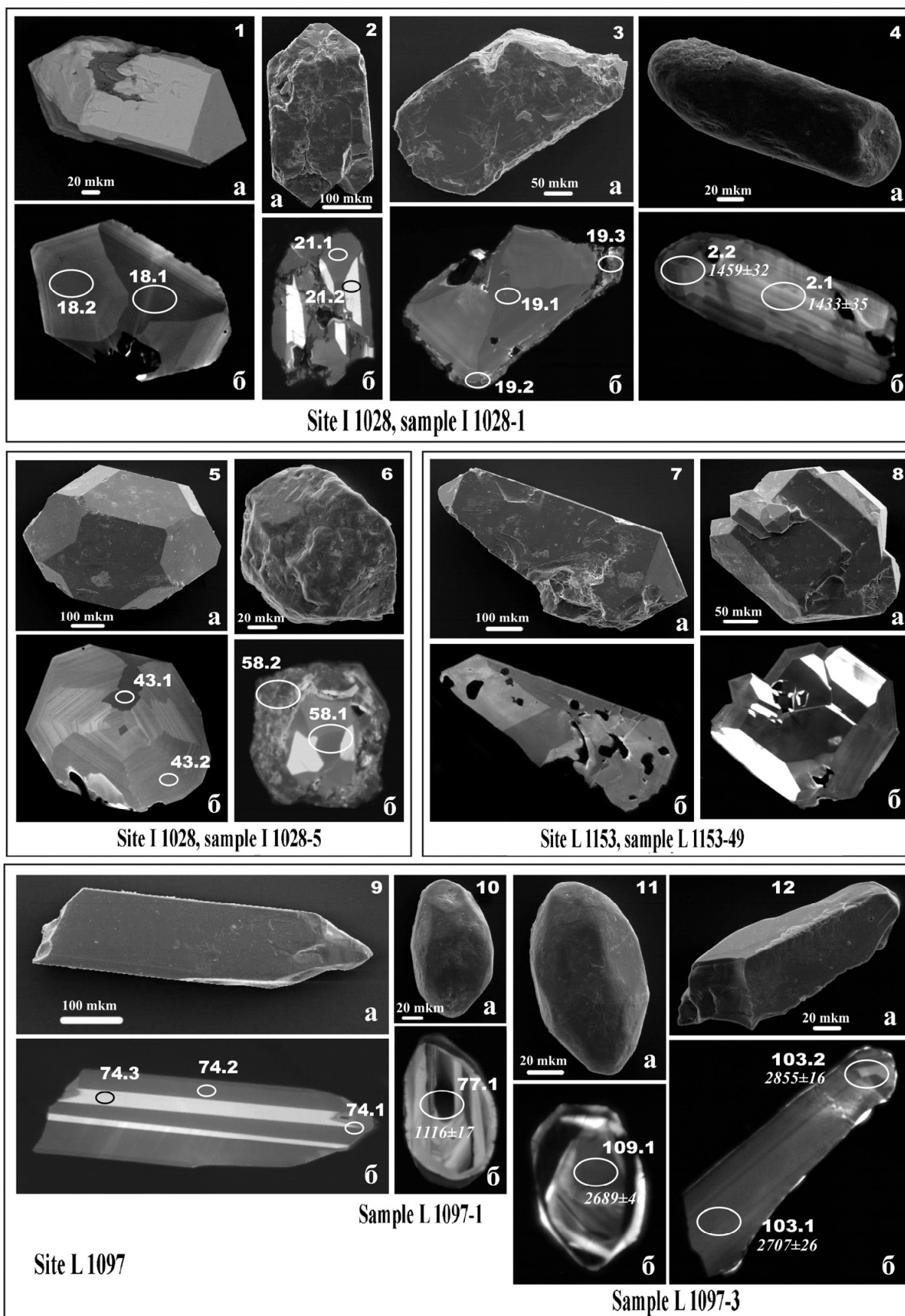
1 – vents of hydrothermal systems at the ocean bottom o ("black smokers"), 2 – solidifying intrusion of siliceous Fe-Ti-oxide series with lenses of the residual melt; 3 – place of formation of plagiogranite melts; 4 – chilled zone of the intrusion, 5 - fractured rocks of hydrated oceanic lithosphere.

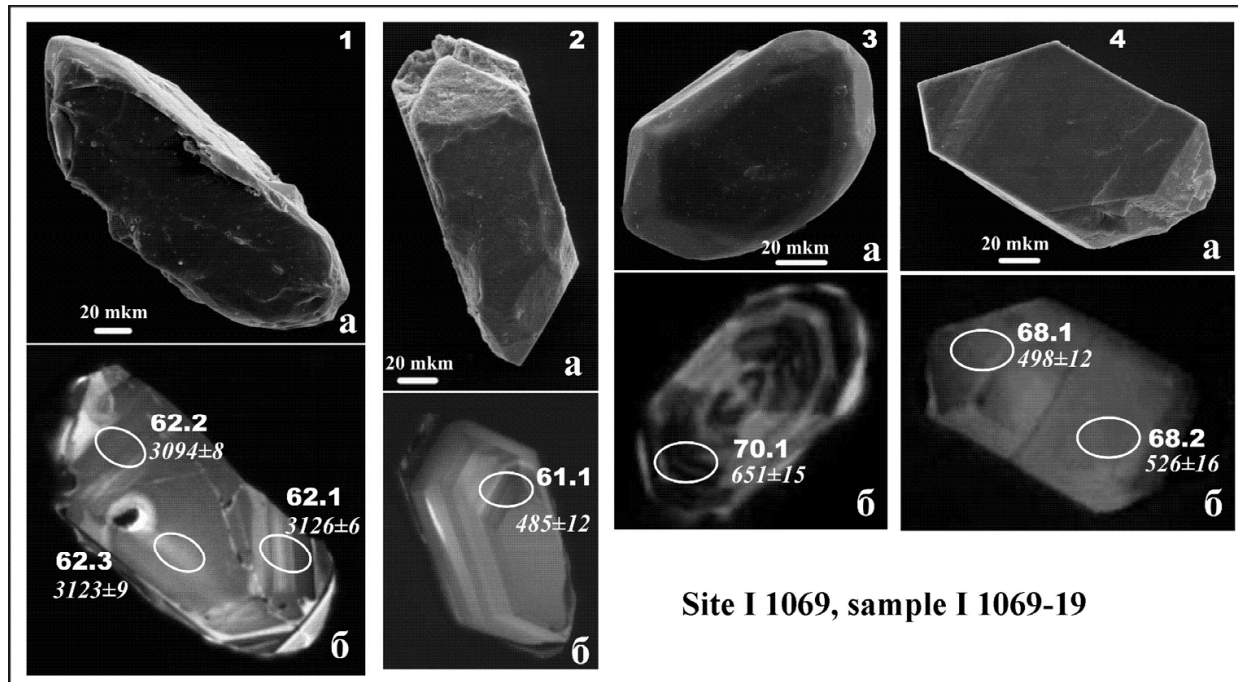
Figure 8. Scheme of the ore-bearing hydrothermal system structure

The appearance of relatively high-temperature metasomatites on the oceanic floor indicates that these rocks were moved to the surface after their formation at the depth. Judging by presence of atakamite and weak oxidation of sulfides, it happened very recently, apparently in the process of ongoing formation of the present Markov Deep. We suggest that this ore-bearing zone is fragment of feeding system of an extinct black smoker.

5. Results of U-Pb dating of zircon from gabbros by SHRIMP-II

The U-Pb SHRIMP-II dating of zircons from the gabbros of the area showed that these rocks, which are in the present-day oceanic spreading axis of the MAR, were formed earlier, in the Holocene-Pleistocene, 0.7-2.3 Ma; above, presence of zircon grains with age up to Mesozoic (older than ~ 87 Ma up to 3117 Ma) were established (Bortnikov et al., 2008) (Fig. 9). The magmatic nature of young zircon with thin oscillatory zoning and sectorial structure suggests that its age defines the crystallization age of the host magmatic rocks; "old" zircon are defined as xenocrysts. Later the presence of uneven-aged zircon grains were found not only in the gabbros of the Sierra-Leone area, but in gabbros as well as ultramafics, plagiogranites, diorites, and even basalts of other parts of the MAR, i.e., presence of ancient xenogenic zircon grains in oceanic bedrocks is widespread (Skolotnev et al, 2010 and references herein)





A. Microimages of zircons from gabbro-norites of the Markov Deep (dredge sites I1028, L1153, and L1097). Hereinafter: (a) natural appearance, (b) cathodoluminescence image (CL); index of dredge site: (I) R/V *Akademik Ioffe* and (L) R/V *Professor Logatchev*. Spot numbers of U-Pb age determination are as in Tables 1 and 2. Age is shown for xenogenic zircons. (1) Euhedral zircon with weakly corroded prism surface and diopside inclusion (dark); sectorial and oscillatory zonings are seen; (2) bipyramidal zircon with corroded prism face; oriented light fragments of bands (reflection of high-temperature cataclasis) are seen in the CL images; (3) zircon with corroded prism and pyramid faces; the CL images demonstrate sectorial zoning, resorption of prism and pyramid faces, and formation of colloform shell; (4) prismatic zircon with weakly corroded surface; the CL image shows coarse zoning, weak resorption of prism and pyramid faces, and thin shell; (5) euhedral grain with well-expressed oscillatory zoning; (6) zircon with corroded surface; the CL image shows core with fragments of light bands (reflection of high-temperature cataclasis) and colloform shell; (7) subhedral zircon with corroded prism surface; the CL image demonstrates fragments of sectorial zoning and small inclusions of plagioclase (dark) of irregular shape (poikilitic structure); (8) growth of secondary small pyramidal zircons due to redeposition of matter on the other side of the crystal; oriented light bands produced by high temperature cataclasis are seen clearly in the CL; (9) fragment of long-prismatic zircon with corroded pyramidal termination; deformation-related light bands are observed in the CL image; (10) rounded zircon with coarse zoning in the core and thin shell; (11) analogue of zircon 10, but with a wider shell; (12) fragment of prismatic zircon lacking internal structure in the CL.

B. Microimages of zircons from troctolite, Site I1069-19. (1) Prismatic grain with corroded surface; fragments of coarse zoning and shell are seen in the CL; (2) analogue of 1, with wider shell; (3) subhedral zircon with coarse concentric zoning, elements of sectorial zoning, and fragments of thin shell; (4) subhedral grain with weak corrosion of one pyramid; no internal structure was identified in the CL.

Figure 9. Zircons from gabbros of the Markov Deep. After N.S. Bortnikov et al. (2008).

We believe that such xenogenic zircon could initially belong to fragments of material from the "slab graveyards" in the deep mantle, captured by mantle plume, which moved from the core-mantle boundary (Bortnikov et al, 2008). Such "graveyards" may contain rocks of different ages and backgrounds, including the Precambrian gneisses and sedimentary rocks involved in subduction zones. A detailed study of exhumed slabs presented by ultrahigh-pressure complexes of Kazakhstan, China, Norway and others, which were formed at $P > 2.8-4$ GPa (and possibly up to 8.5 GPa) and $T = 600-900^{\circ}\text{C}$, showed that zircon could persist even under these conditions (Ernst, 2001 and references herein). Apparently, these PT -

conditions preserved in rocks "graveyard slabs" also, because, according to seismic tomography (Karason, van der Hilst, 2000), they form a great bodies of hundreds kilometers thick; billions years are required to warm up them by conductive heat.

Possibility of existence of buried subducted material beneath the Central Atlantic also evidence from results of study of lithium isotopy in basaltic glasses at 12-16°N (Casey et al., 2010). Like in Sierra Leone area, these basalts in composition are intermediate between E- and T-MORB and are characterized by positive Ta - and Nb -, as well as Ti -, Sr - and Eu -anomalies. They set the lowest of recorded value of δ^7Li , indicating presence in magma components of refractory rutile-bearing eclogite.

According to geophysical data, asthenosphere beneath the MAR is represented by lens-like body about 200-300 km thick (Fig. 10) (Anderson et al., 1992; Ritsema, Allen, 2003). So, our finding of ancient zircons in gabbros and Li-isotopic data support the idea about existence of colder mantle beneath the axial part of the MAR, which has penetrated by mantle plumes.

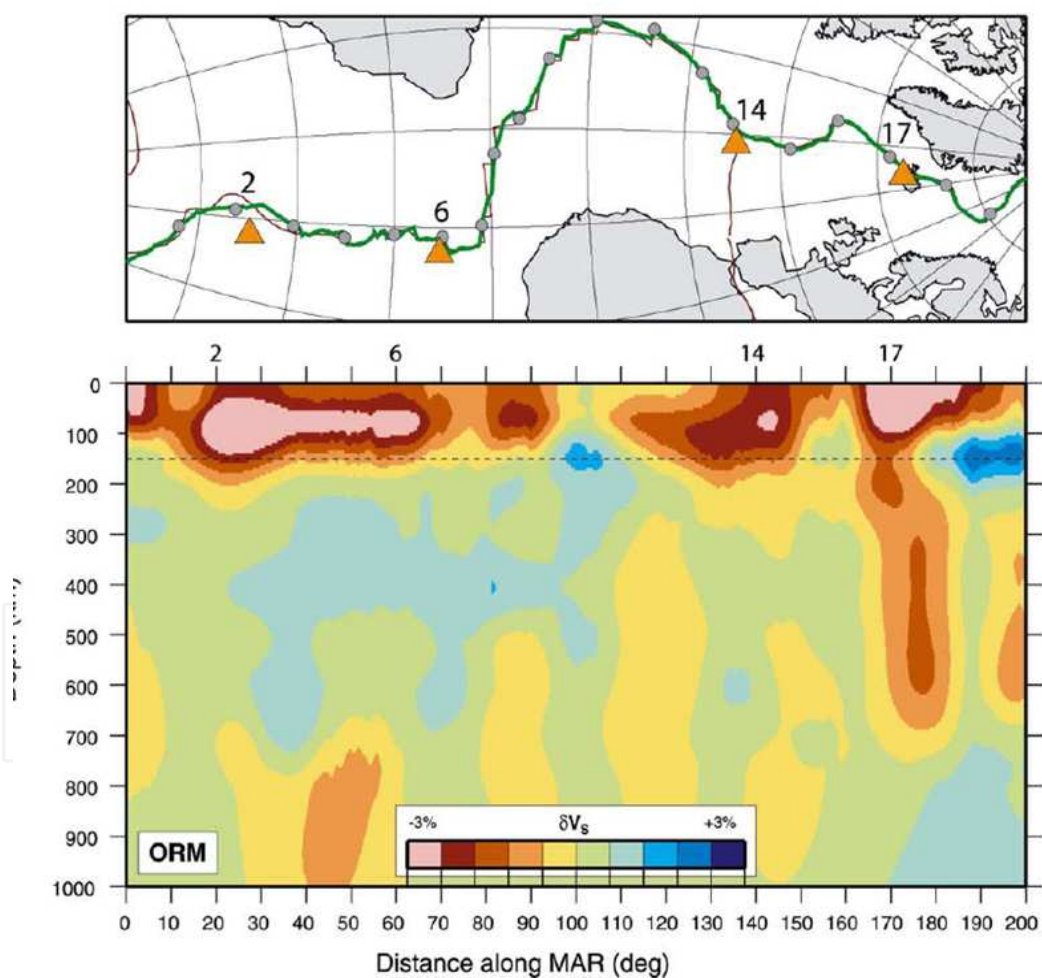


Figure 10. Tomographic profile along the axis of the Mid-Atlantic Ridge, showing that the highest speed anomalies of transverse waves are localized under the "hot spots" (triangles): 2 - Tristan, 6 - Ascension, 14 - Azores and 17 – the Iceland; the latter can be traced to the lower mantle and possible to the mantle-liquid core boundary (after Ritsema & Allen, 2003).

6. Processes of formation of shallow lithosphere (oceanic crust and lithospheric mantle) in the Sierra Leone area

According to the classical model, the occurrence of mid-ocean ridges associated with localized upwelling of deep hot mantle material, which melts due to adiabatic decompression producing specific MORB volcanism. However, it was found that asthenosphere beneath the MAR has lens-like shape up to 200-300 km thick, which is located between colder and dense material of shallow lithosphere and underlied mantle (see section 5).).

As it was shown above, oceanic crust of the Sierra Leone area was formed at least three independent episodes of magmatic activity: the modern, attributed with the eruptions of fresh pillow-lavas, and two previous ones, which led to formation of lower-crustal gabbros (altered primitive gabbros and ferrogabbros consequently). Accordingly, the fresh basalts are not genetically related to the altered lower crust and question arises about it's origin.

6.1. Origin of lower oceanic crust: Evidence from Sierra Leone area

There is a consensus that it exists between the mantle and the upper oceanic crust and composed of various gabbros, often alternated with peridotites. It implies existence between mantle and upper oceanic crust transitional magmatic chambers (intrusions), which solidification provide formation of the lower crust. At the same time mechanism of this crust formation is open to question because its geological study in present-day oceans is concerned with serious technical difficulties. About its composition and structure we can judge only by random samples, gave by dredges, inhabited submarine devices, or "pinpricks" of deep-water drilling wells. According to Pearce (2002), two main points of view on the origin of the oceanic lower crust dominate now: (1) its formation during crystallization in a single melt lens followed by the flow of crystal mush down and away from the ridge (model "gabbro glacier", Quick, Denlinger, 1993) and (2) through grows from series of sill-like bodies throughout the crust (the "Christmas tree" model). However, the situation is stayed uncertain.

From this point of view essential help for understanding processes of formation and development of lower crust of the modern oceans can provide gabbro complexes of ophiolites – fragments of ancient oceanic or back-arc seas lithosphere, find in orogens (Knipper et al, 2001; Dilek, Furnes, 2011 and references therein). In contrast to modern oceanic floor, about which structure we can judge only by fragmental data, they are available for direct geological studies.

Of particular interest in this regard is well-preserved Voikar (Voikar-Syninsky) ophiolite assemblage in the Polar Urals (Russia). Its gabbro complex consists on two major megarhythms (Fig. 11), generally similar in structure to large layered mafic-ultramafic intrusions, formed in calm tectonic settings, were found there above the mantle restite complex (Sharkov et al, 2001). At that for the lower megarhythm are typical primitive gabbro and olivine gabbro, and for the upper – mainly gabbro-norite, sometimes hornblende-bearing, often with increased concentrations of ilmenite and titanomagnetite, which resemble the rocks of the siliceous Fe-Ti-oxide series. All rocks of the assemblage are

cut by diabase dikes. Thus, as is the case of the Sierra Leone area, there are two independent sets of intrusive rocks recorded here, successively formed by different magmas.

In contrast to majority of continental large layered mafic-ultramafic intrusions, almost all plutonic rocks of the Voikar's ophiolites were undergone shearing. Like the site of Sierra Leone, it started with ductile flow of rocks at high temperatures and changed by the brittle-plastic and brittle deformation under conditions of the greenschist facies during cooling. This led to a strong serpentinization of ultramafic rocks and amphibolization of gabbros with extensive development of fibrous amphibole upon pyroxenes. Cumulative structures remain rare, although the overall shape of rocks indicates their intrusive origin.

The absence of cryptic layering in cross-section of the megarhythms suggests that their formation occurred by crystallization of the transitional magma chambers accompanied by replenishment of fresh melts under conditions of open magmatic system (Sharkov et al., 2001). At such circumstances, solidifying from the bottom up magma chamber could be a lens, gradually moving up and leaving a "tail" of hardened hot material. In other words, although these intrusions were not necessarily initially large, but could gradually grew with the arrival of new portions of melt.

According to Sm-Nd and Re-Os isotopy data, significant differences between material of the lower and upper megarhythms as well as mantle section occur in the Voikar ophiolite assemblage. Thus, presence of ancient material determined in the rocks of the upper megarhythm, where the $^{187}\text{Os}/^{188}\text{Os}$ ratio is 6.5-7.1, which is much higher than in the mantle rocks of the assemblage and two times higher than in diabases of the sheeted complex dikes (Sharma et al., 1995, 1998). These data indicate that: (1) formation of the gabbro complex was happened at two stages, i.e., a two-stage build-up of the lower crust occurred here; (2) judging from the relatively well-preserved sections of the complex, formation of each of them happened during the relative calm of tectonic processes; (3) still hot rocks, soon after their solidification, were involved in processes of plastic flow, gradually changed by plastic-brittle and brittle deformations; and (4) there are marked differences in isotopic characteristics between major constituents of the assemblage: mantle rocks, dikes sheeted complex, as well as two megarhythms of the gabbro complex.

The data available on the lower crust of the Sierra Leone area and others OCCs (see above) are in good agreement with data on the Voikar gabbro complex. The presence in the area's lower-crustal gabbros relic cumulative structures and elements of the primary magmatic layering (Fig. 3) suggests that this crust is formed by large layered mafic-ultramafic intrusive bodies of different age and origin. Very likely, that its formation happened mainly through underplating, i.e. building up from below, through accumulation of newly formed basaltic melts at crust-mantle boundary how it established on the continents (Rudnick, 2000).

Presence in the lower crust of the area both primitive gabbro, derived from MORB-type melts, and ferrogabbros of siliceous Fe-Ti-oxide series, shows that, like in Voikar, at least two different types of layered intrusions occurred here.

Appearance not numerous relatively fresh gabbros, olivine gabbros and troctolites among dominated altered gabbro can be considered them to the recent cycle of activity. In any case,

judging on the phenocrysts in the fresh basalts (see Section 2.2), those rocks were probably formed in transitional chambers of young magmatic systems.

Strongly serpentinized mantle peridotites, like in the most ophiolites including Voikar's, represented here by typical mantle restites – harzburgites and subordinate depleted lherzolite and dunites (Savelieva et al., 2006). Some of these peridotites, judging on rare good preserved samples, have cataclastic structure (Fig. 11) evidenced about their involving in deformation processes.

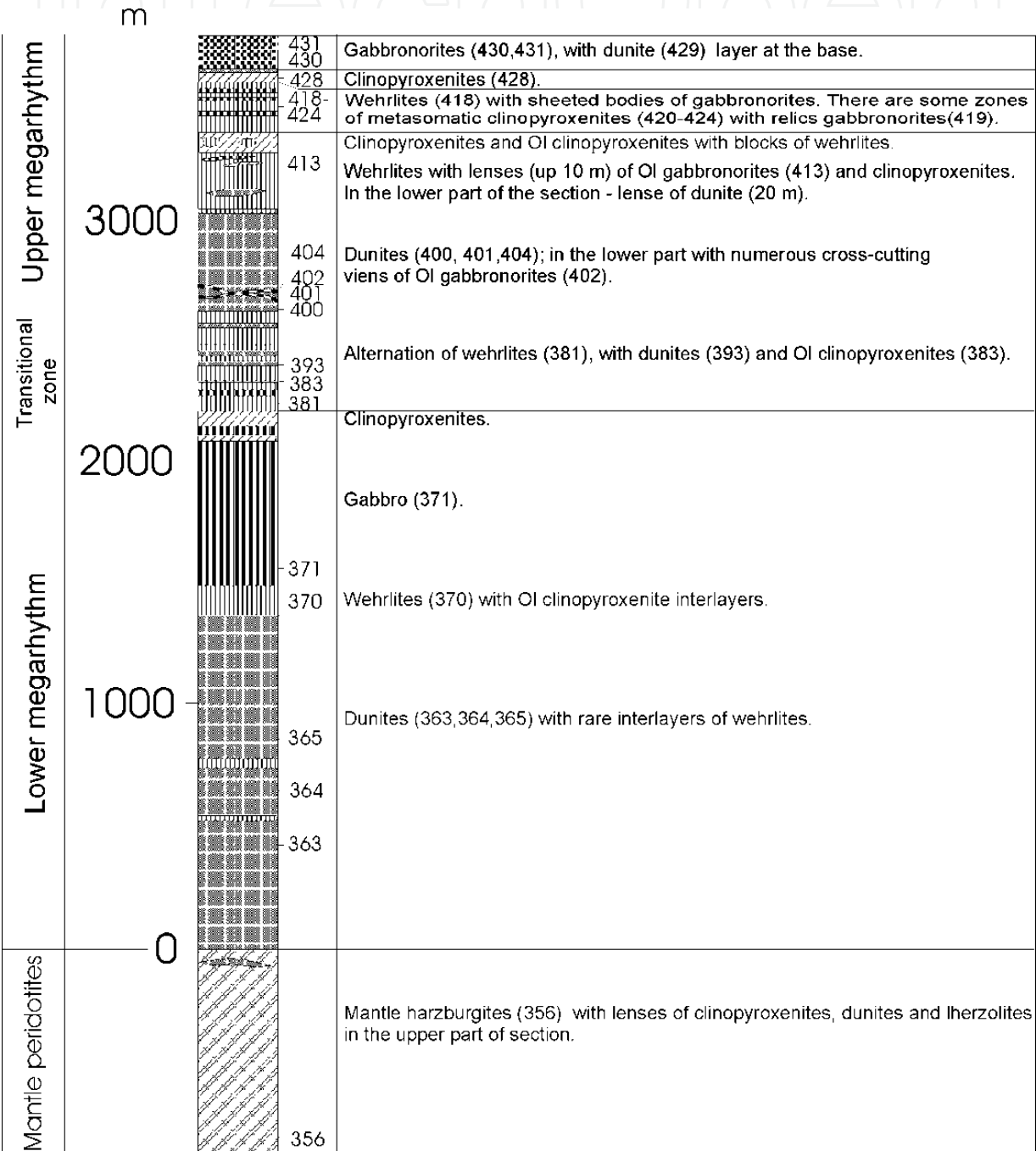


Figure 11. Geological section of gabbro (layered) complex Voikar ophiolite assemblage (Polar Urals), by (after Sharkov et al, 2001).

Thus, according to data available, the most OCCs (Escartín et al., 2008; Smith et al., 2008; MacLeod et al., 2009; Silantyev et al., 2011 and references therein), as well as ophiolite assemblages (Knipper et al., 2002; Dilek and Furnes, 2011), have the similar structure and composition of lower crust and lithospheric mantle. So, the structure of the studied area represents common type of the shallow oceanic lithosphere and we can discuss some general problems of origin and functioning of slow-spreading ridges on its example.

7. Discussion

7.1. Origin of oceanic core complexes: Evidence from Sierra Leone area

As it follows from study of typical OCCs (see Introduction), they are parts of slow-spreading ridges with asymmetric structure with one-way sliding of crustal material; it is suggested that their origin is attributed to activity of hypothetical oceanic detachment faults (Fig. 1). It assumes that these faults develop as a result of strain focusing around rheologically strong gabbro plutons hosted in weaker serpentinized lithospheric mantle; hence it deduced that OCCs were formed during periods of relatively enhanced magma supply. However, as mentioned above, even sticklers of this hypothesis of "one-sided spreading" recognize that many of its elements and details are still poorly substantiated (Conference ..., 2010). In fact, it is determined only asymmetry of the structure of these parts of mid-ocean ridges with exposed altered deep-seated rocks and presence there gently sloping and normal faults.

There are two main hypotheses of the OCCs origin exist now. Predominant model of their appearance is considered with activity of oceanic detachment faults during periods of reduced magmatic activity or its absence ("dry spreading») (Tucholke, Lin, 1994; Tucholke et al., 2008; Dick et al., 2008; Escartin et al, 2008, etc.). According to another view, based on widespread gabbro in such structures, the OCCs were formed at period of relatively depressed (but not reduced) magmatism, realized as large plutons from overlapping access of magma to the surface by oceanic detachment faults (Ildefonse et al., 2007). Sort of these conceptions is model of "life cycle of OCC" (MacLeod et al., 2009). According to this model, spreading becomes markedly asymmetric when the core complex is active, and volcanism is suppressed or absent; when the asymmetry is such that the detachments accommodate more than half the total plate separation, the active faults migrate across the axial valley. As a consequence magma is emplaced into and captured by the footwall of the detachment fault rather than being injected into the hanging wall, explaining the frequent presence of gabbro bodies and other melt relicts at oceanic OCC. Core complexes are ultimately terminated when sufficient magma is emplaced to overwhelm the detachment fault.

However, a numbers of problems remain unsolved in context of these models: motives of ascending of older altered lithospheric rocks at high hypsometric levels, lack of genetic interrelations between fresh basalts and older lithospheric rocks, presence essential quantity of rocks of the siliceous Fe-Ti-oxide series (ferrogabbros) among them, etc. Above all, OCCs, in essence, represent outcrops of shallow oceanic lithosphere, which formation has not

considered with hypothetical oceanic detachment faults: the latter can only expose them, but not create, especially because this lithosphere was formed much earlier and at greater depths. So, the main problems are origin of this lithosphere, reason for its local ascending in axial parts of slow- and ultraslow ridges, and how these ridges functionate under condition of lens-like asthenosphere beneath them, i.e. what the reasons for the oceanic spreading there?

7.1.1. *What has occurred in slow-spreading ridges in geomechanics terms?*

Since H. Hess (1962) times, the most researches believe that process of oceanic spreading associated with ascending of hot mantle material to the axial part of mid-oceanic ridges, its adiabatic melting accompanied by formation of oceanic crust, growth of the plate, and their motion to both sides of ridges under influence of deep convection. The most complete geomechanical aspects of the model was considered by D. Turcotte and J. Schubert (2002 and references herein).

It is known that shallow lithosphere in the MAR axis is in a position of mechanical instability, how it evidence from presence of constant shallow earthquakes, caused by processes of stretching, discontinuity and delamination of bedrocks which indicate uplift and spreading of its axial part. According to (Turcotte, Schubert, 2002), upwelling of mantle rocks is accompanied by heat loss, occurred through molecular heat conduction; as a result, they attached to the base of separating plates, becoming part of them. Because material of heated plastic asthenospheric material can flow like a liquid in geological time scale under influence of external forces, increase of load promote flow of this material to the ridge axis, ensuring its stable triangular shape over time.

In accordance with Turcotte-Schubert model, the triangular shape of the ridge should lead to gravitational instability of the system, causing sliding (slumping) of material along its slopes. Mathematical simulation of such process, performed on example of the MAR, revealed that the force of the ridge push are sufficient to implement such a mechanism (Scheidegger, 1987). As a result, the crustal material should slide from uprising dome-shaped part of the ridge axis (tectonic erosion), exhuming of deep-seated rocks on the oceanic floor (Fig. 12).

Such structure of mid-oceanic ridges in terms of geomechanics is typical for piercement structures which formation determined by introduction of plastic less dense and less viscous layer into overlying more dense layer under gravity influence (Scheidegger, 1987 and references herein). According to the theory, penetrating masses, being less dense than overlying rocks will tend moving upwards, regardless of else tectonic forces. Though classical theory of piercing structure formation developed on example of salt domes, we have a close situation in the MAR: heated plastic asthenospheric material and overlies it cold dense shallow lithosphere. In this case, due to tectonic erosion, pressure above growing asthenospheric crest falls and as a result of adiabatic decompression (decrease in the solidus temperature with decreasing pressure) it led to melting of the material (Fig. 13). According to calculations (Girnis, 2003), smelting of MORB begins at pressure ~15 kbar, however, the mass-melting occurred at pressures 8-10 kbar, i.e. at the depths 28-35 km, where major melting zone has to be situated.

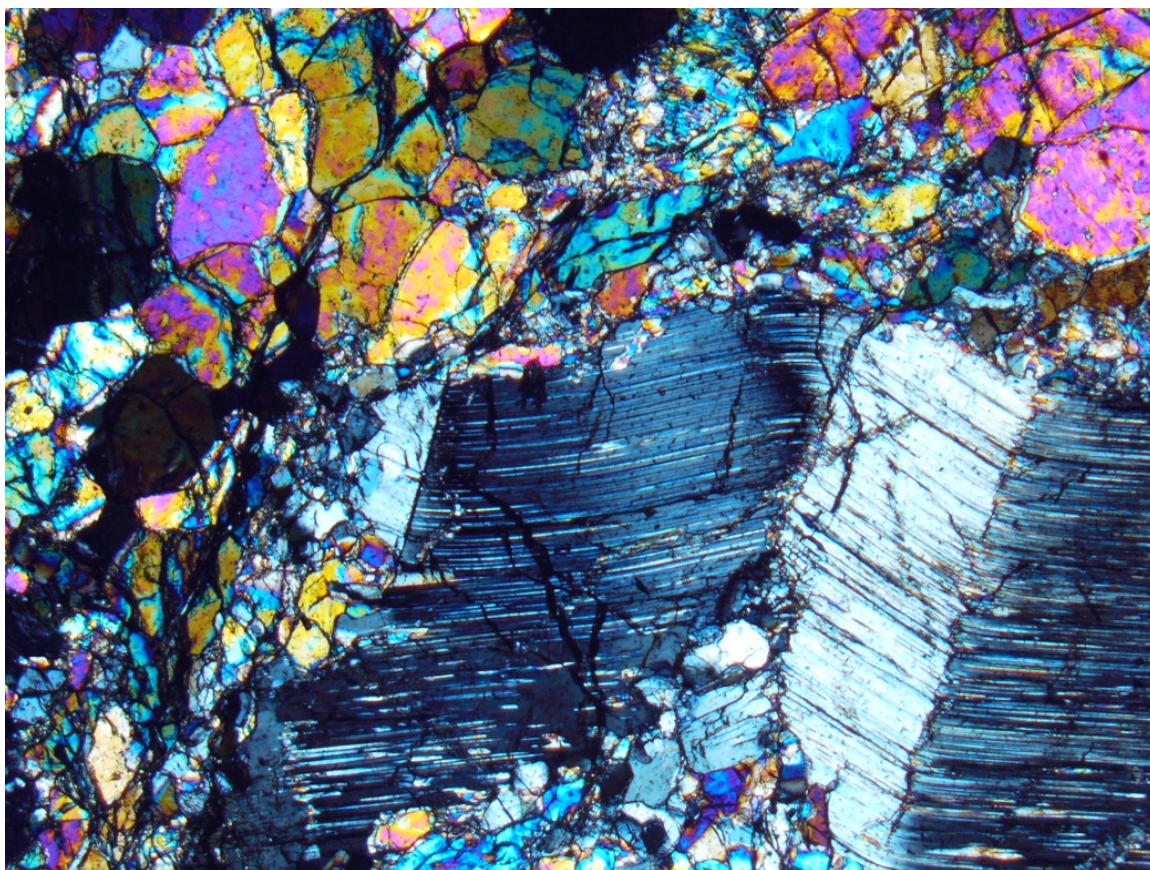


Figure 12. Micrograph cataclased harzburgite restite; large grains (porfiroclast) deformed orthopyroxene surrounded by small neoblasts of olivine and pyroxene. Sample 1063-39, polarized light (collection of E.V. Sharkov).

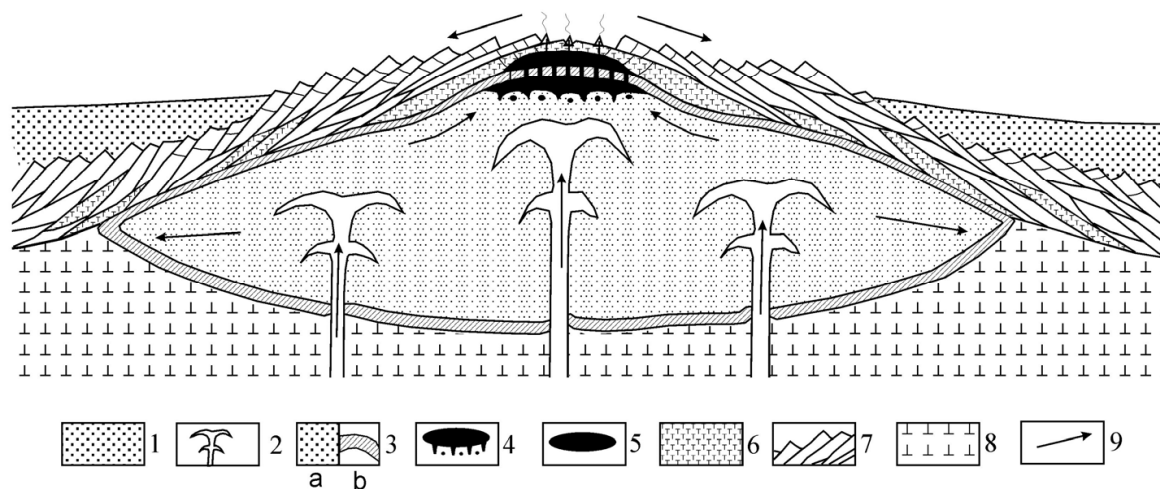


Figure 13. The proposed scheme of the deep structure of the MAR
 1 – sediments; 2 - mantle plumes penetrating into the asthenospheric mantle, and partly or completely mixed with it; 3 - asthenospheric lens under the MAR, bordered by cooling zone in contact with lithospheric mantle; 4 - melting zone in the upper part of the asthenospheric lens; 5 - transitional magma chamber; 6 - depleted lithospheric mantle (restite from a previous episode of melting), transformed into the lithospheric mantle; 7 - oceanic crust formed by gabbros and basalts; 8 - oceanic lithospheric mantle; 9 - direction of movement of material.

Appearance of the melting zone brings further contribution in ascending of the ridge's axial part because melting of silicate rocks leads to decrease of density of material in the magma generation zone by 11-13% (Handbook ..., 1969). This led to development of fractures in the overlying lithospheric peridotites, promoted to their serpentinization under influence of subfloor sea-water which reduced their density by 35-38%. All of this stimulate further growth of the dome and strengthen the tectonic erosion of its axis.

In essence, geological sense of oceanic spreading as well as formation of new lithosphere plates lies in this complex of processes. From such standpoint, constructive plate boundaries, at least in the slow-spreading ridges, should be formed by a collage of tectonic slices of shallow oceanic lithosphere and basaltic covers, i.e. these lithospheric plates in geomechanical sense are not monolithic as suggested by Hess (1962). It is in a good agreement with results of study of ophiolite assemblages which are formed by packages of tectonic slices of similar crustal rocks and mantle restites.

Thus, in contrast to the generally accepted views, we do not attribute oceanic spreading with hypothetical convection currents in asthenosphere, but with processes of gravitational instability at the lithosphere-asthenosphere boundary in axes of the slow-spreading ridges, resulting in slipping of rocks on their slopes. Gabbros and restite ultrabasites as well as basalts, genetically related to this tectonomagmatic episode, are involved in this process. Sliding of the rocks is accompanied by their delamination, formation of different faults, tectonic slices, etc., that creates a characteristic "seismic noise".

7.1.2. Processes of the OCCs formation: Evidence from the Sierra Leone area

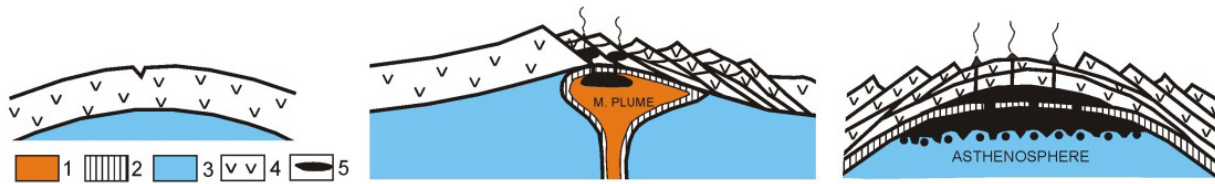
How it evidence from study of the Sierra Leone area, located in spreading zone of the MAR, formation of its structure occurred at least in two stages. The first stage attributed to formation of shallow oceanic lithosphere (lower crust and restite mantle peridotites) and the second, modern – unconformably overlying them flows of fresh basalts.

Between these stages there was occurred rise of the lithosphere dome, accompanied by the sliding of material (tectonic erosion), exhumed deep-seated rocks to the oceanic floor and the appearance of numerous extensional structures, ensures the existence of pallets (subfloor) hydrosphere and the ways for hydrothermal fluids ascent; remains of a former hydrothermal systems were found in the Markov Deep (see section 3). This stage of the area development can be defined as a formation of oceanic core complex (OCC).

The second (current) stage of the ridge development on the studied area is also characterized by extensive development of extensional structures up to appearance of the rift graben-like structures and a fairly powerful basaltic volcanism. These melts come from intermediate magma chambers, where they were subjected to fractional crystallization, and, before reaching the oceanic floor, passed through the ancient lithospheric rocks, partially assimilating its material.

Inasmuch as situation at the lithosphere-asthenosphere boundary in the slow-spreading MAR before the OCCs formation was in a state of unstable equilibrium (see Section 6.1.1),

such development of events demanded of a trigger to start ascent of the asthenospheric crest in studied area. Most likely this role played a mantle plume, which reached the boundary and lifted it, thereby disturbed the unstable equilibrium and initiated rise of the dome (Fig. 14). Its recent existence here follows from isotopic data (Schilling et al., 1994), as well as the general uplifting of the territory and composition of fresh pillow lavas (mainly T-MORB (oceanic plateau basalts) to E-MORB); such characteristic of basalts typical for sites on the ridges next to manifestations of intraplate (plume) magmatism (Basaltic ..., 1981).



1 – mantle plume; 2 – its cooling borders; 3 – asthenosphere; 4 – shallow lithosphere; 5 – basaltic melt

Figure 14. Scheme of cyclic evolution of tectonomagmatic processes in axial part of the MAR

Most likely, the typical for OCCs hydrothermal fields are also associated with magmatic systems, generated by mantle plumes. This is particularly true for water-saturated melts of siliceous Fe-Ti-oxide series, which have limited mobility in the vertical, and usually do not reach the surface in the thickness of the crust hardens in the form of intrusions (see Section 2.3, Fig. 8). It is in a good agreement with our data on the Sierra Leone area, where we found recently extinct ore-bearing hydrothermal-metasomatic system, attributed to such magma (see Section 3). Very likely, that typical for OCCs phenomenon of wide development of hydrothermal fields under conditions of “dry spreading” (i.e. by practically absence of volcanic eruptions) can be successfully explained by this circumstance.

From this view, appearance of OCC reflects the first stage of the crest uplifting, followed “squeezing-out” by plume head of cold rigid lithosphere as a dome at relatively high hypsometric levels and starting process of tectonic erosion on its axial part, which leads to the appearance (exhumation) of deep-seated rocks on the ocean floor. The head of the plume was, in general, asymmetrical and often provided outside of the ridge axial zone that led to the emergence of on-side spreading. Fragments of the plume heads, as it shown on example of the St. Peter and St. Paul complex (see Introduction), can be found sometimes. Perhaps, they are encountered more often, but it is difficult diagnostics because of strong serpentinization.

Widely represented in various OCCs surfaces with corrugations and striations (mullion structures) are usually interpreted as evidence for the existence of oceanic detachment faults, namely its footwall (see Introduction). However, mullion structures are a common pattern under joint flowage of very different on viscosity tectonic plates (Allaby & Allaby, 1999), in this case – the serpentinite and gabbro, and does not carry specific information about existence of oceanic detachment fault here.

From all this it follows that formation of the OCCs is likely represent the first stages of dome growth due to appearance a new mantle plume that disturbs the unstable equilibrium at the lithosphere-asthenosphere boundary. This led to uplifting of the area, to beginning of tectonic erosion and provided specific magmatism of siliceous Fe-Ti-oxide series and related hydrothermal activity.

7.1.3. Cyclic character of tectonomagmatic processes in the axial zone of the slow-spreading ridges

One of important points for understanding situation in the ridges axes are processes of adiabatic melting. As a result of the OCC appearance and beginning of sliding of material from the ridge axis, asthenosheric material began to inflow there and the ridge, because of mechanical reasons, gradually got a symmetrical structure. Due to concomitant reduction of pressure in the frontal part of the crest, process of melting had to strengthened. Since position of the solidus isotherm in this case is determined by lithostatic pressure, a melting zone should has form of a flattened lens at the top of the asthenospheric crest. It led to mixing of asthenosphere's and plume's materials and appearance melts of T- and E-MORB composition. Judging on the Sierra Leone area, this change of the melting regime accompanied by temporal interruption of tectonomagmatic processes, after that flows of newly formed basalts began to overlap altered rocks of the former OCC. The next stage of the dome ascending should be already vast eruptions under conditions of a "normal" bilateral spreading, how it occurred to the south and north of the studied area.

As a result of melting, density of asthenospheric lherzolite would gradually decrease, mainly due to removing of Ca and Fe with basaltic melt. Simple calculations show that decrease in the density of material in this case could reach 8-10%, because strongly depleted mantle material (mainly harzburgite) consists mostly of relatively light magnesian olivine and orthopyroxene. Because of this, restite material will accumulate in upper part of the melting zone, forming a separate layer, which cannot be involve in processes of the asthenospheric convection. Formation of such layer of light refractory material should lead to the cessation of melting of the mantle beneath the ridge axis, and, as a result, it become part of shallow lithosphere and situation returned to state of unstable equilibrium.

Thus, there are three main stages of the cyclic development of spreading zones: (i) initial - OCC (often one-sided spreading) → (ii) intermediate, such as Sierra Leone (the transition to a bilateral spreading) → (iii) normal (bilateral spreading). Each of these three types of spreading are observed in different segments of the present-day MAR, suggesting that these sites are various stages of development. In general, once started, the processes in the axial zone of the ridge are mutually self-sustaining conditioned, resulting in almost continuous growth of the oceanic lithosphere in the slow-spreading ridges axes.

8. Processes of slow-spreading ridges formation and development: Evidence from the MAR

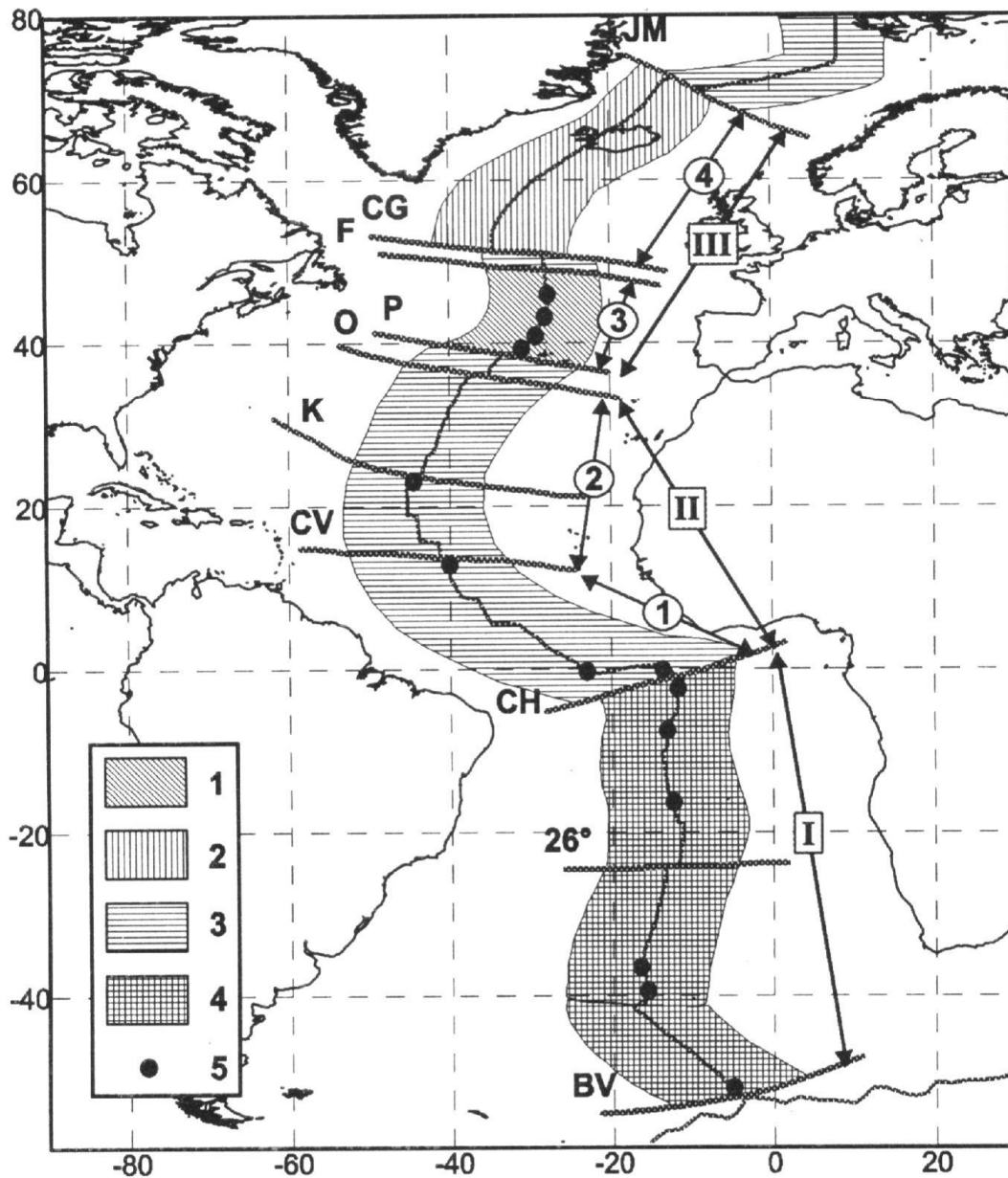
8.1. Interaction of asthenosphere and mantle plumes

In contrast to MORB, derived from moderate-depleted mantle material, magmatism, related to mantle plumes, is presented by geochemically-enriched Fe-Ti picrites and basalts, evidence about rather different melting source. According to Anderson et al. (1992), the most centers of intraplate (plume) magmatism in the Atlantic are localized within the MAR. From this it follows that slow-spreading mid-ocean ridges are an areas of joint manifestations of asthenospheric and plume activity, and relationships between them is a key for understanding the functioning and development of slow-spreading mid-oceanic ridges.

Continuous smelting of basalts from the asthenospheric material had to inevitably affect to its composition in terms of increasing degree of depletion. However, this has not happened, and composition of the melting substrate as a whole remains practically the same during at least the latest 140 Myr in case of the Central Atlantic. Because asthenosphere beneath the MAR is a lens-shape body of 200-300 km thick (see Section 4), it requires a constant feed of it by geochemically-enriched material. Evidently, it can be the material of mantle plumes, constantly rejuvenating the composition of the asthenosphere after removing from it the low-melting components (basalts).

How in particular an interaction of the asthenosphere and mantle plumes could be occurred? It is known that under conditions of rigid continental lithosphere plume-related magmatic systems form isolated localities. However, in the case under consideration the situation is quite different: both asthenospheric and plume material have close visco-plastic consistency. Accordingly, only the largest and most stable in time plumes like Iceland, Azores, Tristan, etc., can cross such thick lens. They lose much of their material, which mixes with the asthenosphere matter, leading to the appearance of T-MORB (oceanic plateau basalts) and E-MORB in the adjacent parts of the spreading zone (Basaltic ..., 1981). Only such plumes can pass through the asthenosphere lens and products of their melting reach the surface, forming oceanic islands and seamounts. The existence of less powerful plumes may indicate the appearance of mantle-crustal magmas of the siliceous Fe-Ti-oxide series (see Section 2.3); still weaker plumes "damped" in the thick asthenospheric lens. In this connection, attention is drawn to that this lens itself is not a single uniform body, and is subdivided into several segments (Fig. 10). It is also confirmed by the results of geochemical studies of basalts throughout the MAR length (Fig. 15) (Dmitriev et al, 1999; Silantyev, Sokolov, 2010).

Mantle plumes, penetrating the asthenospheric lens, should contribute to forced convective mixing of its material and lead to practical levelling of its composition. Obviously, for this reason, geochemical and isotopic-geochemical characteristics of MORB, both in the Sierra Leone area and all over the MAR, are close to each other. From this it follows that material of the asthenosphere is a mixture of moderately depleted lherzolites and geochemically-enriched material of mantle plumes as finite compositions. Asthenospheric plastic material, in contrast to the melt, is mixed substantially worse, which are evidence from variations of isotopic and geochemical characteristics of the fresh basalts (see Section 2.1).



1 – TOR-1; 2 – TOR-1 + TOR-Fe; 3 – TOR-2; 4 – TOR-1 + TOR-2; 5 – TOR-K. I, II and III - segments of the 1st order: I - South Atlantic, II - Southern Region of the North Atlantic, III - Northern Region of the North Atlantic (TOR – varieties of tholeiites of ocean ridges), 1 - 4 – segments of the 2nd order: 1 – Equatorial ; 2 – Central; 3 – Azores; 4 – Icelandic. Fractures zones: JM – Jan Mayen, CG – Charlie Gibbs, P – Pico, D – Oceanographer, K – Kane, CV - Cape Verde, CH – Cheyne, 26° - 26° S, BV – Bouvet. TOR –tholeiite of oceanic ridges..

Figure 15. Scheme of tectonomagmatic segmentation of the Mid-Atlantic Ridge. After (Dmitriev et al, 1999).

As it was mentioned above, according to geophysical data, a colder mantle occurs beneath asthenospheric lens (Fig. 10). It is supported by finds of ancient xenogenic zircon grains, which, very likely, were trapped by rising plumes from the "slab graveyards" in the mantle beneath the ridge (see Section 4). Apparently, the impurities, trapped by plumes from deep mantle, as well as material of the shallow lithosphere, trapped by basalts on their way to the surface (see Section 2.1), play essential role in scatter of points on the Sr-Nd diagrams and the appearance of various "mantle reservoirs," in particular, HIMU.

Thus, mantle plumes bring to the geochemically-depleted oceanic asthenosphere considerable amount of fresh hot geochemically-enriched material, providing forced convection of the material. This leads to more or less effective mixing of the two types of finite materials, as well as to general leveling of the asthenosphere composition and temperature, thereby support their sustainable dynamic equilibrium in considerable time, at least ~140 Myr in case of the Central Atlantic.

8.2. How formation and development of the oceanic asthenospheric lens occurred?

Obviously, constant addition of a new (plume) material had to cause to increasing of the asthenospheric lens size, leading to its extension in both directions: from the ridge axis (spreading itself) and along it (propagation of ridge). As a consequence of the lens extending, it becomes a "trap" for the plumes, rising in the neighborhood, which became parts of the asthenosphere's supply system and contribute to further widening of the ocean floor in width and length.

However, it remains unclear how the asthenospheric lens, which promoted oceanic spreading, was initially formed. Perhaps, its occurrence was attributed to an elongated area of concentrated manifestation of mantle plumes activity. Apparently, in this case the extended heads of neighboring large plumes came in contact with each other and merged (coalescence) into a single body. This body will grow due to involvement of plumes in the neighborhood, gradually increasing in size and can gradually developed into a zone of oceanic spreading. Possible examples of initial stages of the process are ultraslow-spreading ridges (Knipovich Gakkel, Monze, Lena Trough), which develop in the North Atlantic and the Arctic Ocean, where the MAR propagates (Snow, Edmonds, 2007).

Modern example of an elongated area of mantle plumes activity may be the Trans-Eurasian Belt of tectonomagmatic activation, which stretches out along the whole of Eurasia from the Atlantic to the Pacific and appeared after closure of the Mesozoic Tethys Ocean (Sharkov, 2011). If the plumes are distributed uniformly, a large igneous province, like the Permian-Triassic Siberian Traps, formed instead of an ocean.

Thus, data available on the Sierra Leone area and other OCCs allow to complement the existing models of the structure and development of slow-spreading ridges and liberalize present-day views on processes, occurred in their axes. Besides, they provide opportunity to discuss problem of structure of the mantle beneath the slow-spreading ridges. As shown above, the shallow oceanic lithosphere is composed mainly by plutonic rocks and high depleted mantle and qualitatively different from the underlying asthenospheric lens, formed by moderately depleted material. Located beneath the lens deep mantle also differs significantly from the asthenospheric material. From this it follows that all three components of the mantle under the slow-spreading MAR have an independent origin, and whole-mantle convection is absent here.

The latest data on the geology, petrology, geochemistry, isotopy and geophysics of the oceanic bedrocks takes into account in the proposed model. These data were not known a half century ago, when the basic conceptions of plate tectonics were elaborated. Gradually it

has revealed details that allow to take a new look at the nature and mechanisms of oceanic spreading. In general, our data suggest that real tectonomagmatic processes in the axis of slow-spreading MAR are essential different from existing views on processes and mechanisms of oceanic spreading. Obviously, there is still much uncertainty, but it is also clear that new approaches to the study of geology and petrology of ocean are necessary.

9. Conclusions

1. Sierra Leone area, located in the axial part of the MAR (5°-7°N), is characterized by outcrops of extensive deformed and metamorphosed plutonic rocks of the shallow oceanic lithosphere. The area are characterized by wide development of extensional structures, including rift valleys and variably oriented faults. These features of the structure and composition of rocks can define the area as a kind of oceanic core complex (OCC). However, unlike typical OCCs, outcrops of altered gabbros and serpentinites occur only on valleys' slopes and floors, while surface of the ridge is overlapped by flows of fresh pillow lavas with chilled glassy crusts, i.e., a kind of "structural unconformity" occurs here.
2. Fresh basalts are close in composition to E- and T-MORB (oceanic plateau basalts); judging by #mg and composition of phenocrysts, they are not primary mantle-derived melts, and underwent by crystallization differentiation in the intermediate (intrusive) chambers. On the way to the surface, they crossed the mantle peridotite and lower-crustal gabbros, and were partly contaminated by their material.
3. The lower crust in the area is composed by gabbros of two types: (1) primitive, magnesian, derived from MORB, and (2) often hornblende ferrogabbros derived from melts of siliceous Fe-Ti-oxide series. These melts, on the one hand, were saturated and supersaturated in silica and characterized by elevated water content, which is typical for suprasubduction magmas, and on the other hand – have a high content of Ti, Fe, Nb, Ta and P, which are typical for magmas of intraplate (plume) origin. It suggests that formation of such specific melts was attributed to melting of hydrated oceanic shallow lithosphere under influence of new mantle plumes. Minor trondhjemite occurrences are observed in form of veins and small bodies; their origin is considered to anatexis of hydrated rocks of the lithosphere by influence of mafic intrusions.
4. Sulfide mineralization, found in the Markov Deep, is confined to a zone of hydrothermal-metasomatic processing in cataclasites upon ferrogabbros and, apparently, was attributed to fluids of magmatic origin, gradually diluted by sea-water from the subfloor hydrosphere. The source of these fluids could be shallow intrusions of siliceous Fe-Ti-oxide series. This mineralized zone is probably a piece of a Extinct³⁹ feeder system of former "black smoker".
5. SHRIMP-II U-Pb dating of zircon grains, extracted from gabbros of the area, revealed the two groups: (i) "young", primary magma, with the age of 0.7-2.3 Ma, and (ii) "ancient", xenogenic, with age from 87 to 3117 Ma; at that zircons of different ages may be found in the same samples. It is assumed that the grains of the "ancient" group belong

- to material of "slab graveyards", which fragments were captured by ascended mantle plumes in the deep mantle.
6. It is shown that structure of the MAR in geomechanical terms is an example of a piercing structure, appeared due to the introduction of plastic less dense and less viscous layer (asthenosphere) in a more dense layer (shallow lithosphere) under gravity. The system is in unstable equilibrium state until appearance of mantle plume, which lifted the dense lithosphere at higher hypsometric level in shape of a dome. This is causing sliding of material on slopes of the dome (tectonic erosion), often one-sided, resulting in exhumation of the deep-seated rocks on ocean floor and forming OCC. The interaction of the plume head with the hydrated lithosphere, led to appearance of melts of siliceous Fe-Ti-oxide series which providing hydrothermal activity.
 7. As a result of tectonic erosion, pressure at the ridge axis decreased, which led to starting of asthenospheric crest ascent; because of decompression, a zone of adiabatic melting appeared at the top of the crest and role of basaltic volcanism gradually increasing. The ridge axis gradually got a stable triangular shape and slumping of material becomes bilateral. As a result, intermediate structures, such as Sierra Leone area, with magmatism of E- and T-MORB are formed, and then the stage of vast eruptions of MORB comes. The process goes to end when the melting zone was overfill by light restite material, which is not involved in convection; the restites became a part of the lithosphere, and the system returns to a state of unstable equilibrium.
 8. Geological sense of the oceanic spreading, evidently, is a combination of thermal and geomechanical processes at the lithosphere-asthenosphere boundary, starting with the formation of domes and slumping newly formed material (new lithospheric plates) on their slopes. From this standpoint constructive plate boundaries, at least in slow-spreading ridges, should be represented by a collage of tectonic slices of shallow oceanic lithosphere and basaltic sheets. So, process of spreading in the MAR has a cyclic character. It begins from appearance of OCCs, often characterized by "one-side spreading" and numerous hydrothermal fields, and via structure type Sierra Leone area pass to normal bilateral spreading with vast basaltic eruptions.
 9. Based on these data and taking into account the published materials of seismic tomography, it is developed a new model of oceanic spreading in the MAR. It is shown that the long-term existence of the MAR's oceanic spreading (at least 140 Myr) and stability of composition of basalts can be explained by dynamic equilibrium between permanent removal from asthenosphere of newly formed basalt and replenishment of new geochemically-enriched material of mantle plumes. The constant injections of a hot plume material in asthenospheric lens provide forced convection its material and prevents it from freezing; moreover, it also promote expansion of the asthenosphere both across a ridge axis (oceanic spreading) and along its axis (propagation of the ridge).
 10. How it is evidence from the MAR, three independent components in structure of its mantle occur: (i) shallow lithosphere (including basaltic upper crust), (ii) asthenospheric lens beneath the ridge, and (iii) deep mantle with "graveyards of slabs". Each of them, how it was shown above, has own origin and composition. From this evidently follows that the total convection in the oceanic mantle is absent.

11. Thus, the processes in the slow-spreading ridge axes are mutually conditioned self-sustaining character, resulting in almost continuous growth of the oceanic lithosphere in its different parts, and supported the process of spreading, as evidenced by the presence of symmetrical magnetic anomalies.
12. Slow- and ultraslow-spreading ridges are a special class of oceanic spreading, characterized by widespread development of oceanic core complexes and absence of subduction on periphery of the oceans, where developed passive margins. Appearance of such ridges is associated with the elongated areas of concentrated manifestation of sustainable mantle plume activity. Apparently, extended heads of large plume came into contact with each other, merging (coalesced) in almost single body asthenospheric lenses.

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10. References

- Allaby, A. & Allaby, M., 2011. A Dictionary of Earth Sciences. 1999. *Encyclopedia.com*. 9 Sep., pdf.
- Anderson, D.L., Tanimoto, T. & Shang, Y., 1992. Plate tectonics and hot spots: the third dimension. *Science*, 256: 1645-1650.
- Aranovich, L.Ya., Bortnikov, N.S., Serebryakov, N.S., & Sharkov, E.V., 2010. Conditions of the Formation of Plagiogranite from the Markov Trough, Mid-Atlantic Ridge, 5°52'–6°02'N. *Doklady Earth Sciences*, 434 (1): 1257–1262.
- Basaltic Volcanism Study Project 1981. Basaltic volcanism on the terrestrial planets, 1981. New York: Pergamon Press, 1286 p.
- Beltenev, V., Ivanov, V., Rozhdestvenskaya, I. et al., 2009. New data about hydrothermal fields on the Mid-Atlantic Ridge between 11°-14°N: 32th Cruise of R/V «Professor Logachev». *InterRidge News*, 18: 14-18.
- Bortnikov, N. S., Sharkov, E. V. , Bogatkov, O. A., Zinger, T.F., Lepekina, E.N., Antonov, A.V. & Sergeev, S.A., 2008. Founding of young an anicient zircons in gabbros of Markov Deep, Mid-Atlantic Ridge, 5°30.4' – 5°32.4' N (results of SHRIMP-II U-Pb dating): meaning for understanding of deep-seated geodynamics of the modern oceans. *Dokl. Earth Sci.* 421(5): 859–868.
- Cannat, M., Escartin, J., Lavier, L. et al., 2010. Lateral and Temporal Variations in the Degree of mechanical weakening in the footwall of oceanic detachment faults. *AGU Chapman Conference "Detachments in Oceanic Lithosphere: Deformation, Magmatism, Fluid Flow, and Ecosystems" Agros, Cyprus 8-15 May 2010. Conference Report: 38-39.*

- Casey, J.F., Gao, Y., Benavidez, R. & Dragoi, C., 2010. The lowest $\delta^7\text{Li}$ yet recorded in MORB glasses: the connection with oceanic core complex formation, refractory rutile-bearing eclogitic mantle sources and melt supply. *2010 AGU Fall Meeting*. 13-17 December 2010. San Francisco, California. Abstract V11A-2245, pdf.
- Condie, K.C., 2005. High field strength element ration in Archean basalts: a window to evolving sources of mantle plumes? *Lithos*, 79: 491-504.
- Conference Outline. *AGU Chapman Conference "Detachments in Oceanic Lithosphere: Deformation, Magmatism, Fluid Flow, and Ecosystems"* Agros, Cyprus 8-15 May 2010. Conference Report: 20-21.
- Dick, H.J.B., Meyer, P.S., Bloomes S.H. et al., 1991. Lithostratigraphic Evolution of an in Situ Section of Oceanic Layer 3. Eds. R.P. Von Herzen, P.T. Robinson et al. *Proc. ODP, Sci. Results* 118: 439–538.
- Dick, H.J.B., Robinson, P.T. & Meyers, P.S., 1992. The plutonic foundation of a low-spreading ridge. *Amer. Geophys. Union monograph* 70: 1-39.
- Dick, H.J.B., Tivey, M.A. & Tucholke, B.E., 2008. Plutonic foundation of a slow-spread ridge segment: Oceanic core complex at Kane Megamullion, 23°30'N, 45°20'W. *Geochem., Geophys., Geosyst.*, 9, Q05014, doi:05010.01029/02007GC001645.
- Dilek Y. & Furnes H., 2011. Ophiolite genesis and global tectonics: Geochemical and tectonic fingerprinting of ancient oceanic lithosphere. *GSA Bull.*, 123(¾): 387-411.
- Dmitriev, L.V., Sokolov, S.Yu., Melson, V.G. & O'Hirn, T., 1999. Plume and spreading association of basalts and their reflection in petrological and geochemical parameters in northern part of the Mid-Atlantic ridge. *Russian J. Earth Sci.*, 1(6): 457-476.
- Escartín, J., Smith, D.K., Cann, J. et al., 2008. Central role of detachment faults in accretion of slow-spreading oceanic lithosphere. *Nature*, 455: 790-795.
- Ernst, W.G., 2001. Subduction, ultrahigh-pressure metamorphism and regurgitation of byont crustal slices – implications for arcs and continental growth. *Phys. Earth and Planet. Inter.* 127: 253-275.
- Fluids and redox reactions in magmatic systems. A.A. Kadik (ed.). 1991. *Moscow, Nauka Publ.*, 256 p.
- Fontingie, D. & Schilling, J.-G., 1996. Mantle heterogeneities beneath the South Atlantic: a Nd-Sr-Pb isotope study along Mid-Atlantic Ridge (3°S-46°S). *Earth Planet. Sci. Lett.*, 142(1/2): 209-221.
- Gillis, K.M. & Coogan, L.A., 2002. Anatectic migmatites from the roof of an ocean ridge magma chamber. *J. Petrol.*, 43: 2075–2095.
- Girnis, A. V., 2003. Olivine-Orthopyroxene-Melt Equilibrium as a Thermobarometer for Mantle-Derived Magmas. *Petrology*, 11(2): 101-113.
- Handbook of physical constants of rocks. S. Clark (ed.), 1969. Moscow, Mir: 520 p. (Russian translation)
- Hauri, E.H., Whitehead, J.A. & Hart, S.R., 1994. Fluid dynamic and geochemical aspects of entrainment in mantle plumes. *J. Geophys. Res.*, 99(B12): 24275-24300.
- Hékinian, R., Juteau, T., Gracia, E. et al., 2000. Submersible observations of Equatorial Atlantic Mantle: The St. Paul Fracture Zone region. *Marine Geophysical Research*, 21: 529-560.
- Hess, H.H., 1962. The history of the ocean basins. *Geol. Soc. Am. Buddington Vol.*, 599-620.
- Ildefonse, B., Blackman, D.K., John, B.E. et al., 2007. Oceanic core complexes and crustal accretion at slow-spreading ridges. *Geology*, 35(7): 623-626.

- Karason, H. & van der Hilst, R.D., 2000. Constraints on mantle convection from seismic tomography. *The History and Dynamics of Global Plate Motions*. Eds. M. Richards, R. G. Gordon, and R.D. van der Hilst. *Geophys. Monogr.* 121: 277–289.
- Knipper, A.L., Savelieva, A.L., Sharaskin, A.Ya., 2001. Problems of ophiolite classification. *Fundamental problems of general geotectonics*. Yu.M. Puscharovsky (ed.). Moscow, Nauchny mir: 250-281 (in Russian).
- Krassivskaya I.S., Sharkov E.V., Bortnikov N.S., Chistyakov A.V., Trubkin N.V., Golovanova T.I., 2010. Variolitic lavas in the axial rift of the Mid-Atlantic rift and its origin. *Petrology*, 18: P.263-277.
- Langmuir, C.H., Klein, E.M. & Plank, T., 1992. Petrological systematics of mid-ocean ridge basalts: constraints on melt generation beneath ocean ridges. *Mantle flow and melt generation at mid-ocean ridges*. Eds.: Morgan J.P., Blackman D.K., Sinton J.M. *Geophys. Monogr. Am. Geophys. Union*, 71: 183-280.
- MacLeod, C.J., Searle, R.C., Murton, B.J. et al., 2009. Life cycle of oceanic core complexes. *Earth Planet. Sci. Lett.*, 287(3-4): 333-344.
- Ohara, Y., Yoshida, T., Kasuga, S., 2001. Giant megamullion in the Parece Vela Backarc basin. *Mar. Geophys. Res.*, 22: 47-61.
- Pearce, J., 2002. The oceanic lithosphere. *Achievements and Opportunities of Scientific Ocean Drilling*. Spec. Issue of the JOIDES Journal, 28(1): 61-66.
- Puscharovsky, Yu.M., Skolotnev, S.G., Peyve, A.A., Bortnikov, N.S., Bazilevskaya, E.S. & Mazarovich, A.O., 2004. *Geology and metallogeny of the Mid-Atlantic ridge: 5-7°N*. Moscow, GEOS, 151 p. (in Russian)
- Quick, J.E. & Denlinger, R.P., 1993. Ductile deformation and the origin of layered gabbro in ophiolites. *J. Geophys. Res.*, 98: 14015–14027
- Ritsema, J. & Allen, R.M., 2003. The elusive mantle plume. *Earth Planet. Sci. Lett.*, 207: 1-12.
- Roden M.F., Hart S.R., Frey F.A., Melson W.G., 1984. Sr, Nd and Pb isotopic and REE geochemistry of St. Paul's Rocks: its metamorphic and metasomatic development of an alkali basalt mantle source. *Contrib. Mineral. Petrol.* 85(8):
- Rudnick, R., 1990. Growing from below. *Nature*, 347(6295): 711-712.
- Savelieva, G.N. 1987. *Gabbro-ultrabasite complexes of the Urals ophiolites and their analogs in the modern oceanic crust*. Moscow, Nauka Publ., 246 p. (in Russian)
- Savelieva, G.N., Bortnikov, N.S., Peyve, A.A. & Skolotnev, S.G., 2006. Ultrabasite rocks of the Mrkov Deep, rift valley of the Mid-Atlantic Ridge. *Geochem. Intern.* 44(11): 1192-1208.
- Scheidegger, A.E., 1982. *Principle of Geodynamics*. 3rd edition. Berlin-Heidelberg-Bew York,.
- Schilling, J.-G., Hanan, B.B., McCully, B. & Kingsley, R.H., 1994. Influence of the Sierra Leone mantle plume on the equatorial MAR: a Nd–Sr–Pb isotopic study. *J. Geophys. Res.*, 99: 12005–12028.
- Sharkov, E.V., 2006. *Formation of layered intrusions and their ore mineralization*. Moscow: Scientific World, 364 p. (in Russian),
- Sharkov, E.V., Abramov, S.S., Simonov, V.A., Krinov, D.I., Skolotnev, S.G., Bel'tenev, V.E. & Bortnikov, N.S., 2007. Hydrothermal alteration and sulfide mineralization in gabbroids of the Markov Deep (Mid-Atlantic Ridge, 6° N). *Geology of Ore Deposits*, 49(6): 467-486.
- Sharkov, E.V., Bortnikov, N.S., Bogatikov, O.A., Zinger, T.F., Bel'tenev V.E., & Chistyakov, A.V., 2005. Third layer of the oceanic crust in the axial part of the Mid-Atlantic Ridge (Sierra Leone MAR segment, 6°N). *Petrology*, 13(6): 540-570.

- Sharkov, E.V., Chistyakov, A.V., & Laz'ko, E.E., 2001. The Structure of the Layered Complex of the Voikar Ophiolite Association (Polar Urals) as an Indicator of Mantle Processes beneath a Back-Arc Sea. *Geochemistry Intern.*, 39(9): 831-847.
- Sharkov, E.V., Shatagin, K.N., Krassivskaya, I.S., et al., 2008. Pillow Lavas of the Sierra Leone Test Site, Mid-Atlantic Ridge, 5°-7° N: Sr-Nd Isotope Systematics, Geochemistry, and Petrology. *Petrology*, 16(4): 335-352.
- Sharma, M., Hofmann, A.W. & Wasserburg, G.J., 1998. Melt generation beneath ocean ridges: Re-Os isotopic evidence from the Polar Ural ophiolite. *Miner. Mag., V.M. Goldschmidt Conference. Toulouse Abstracts*. 62A: 1375-1376.
- Sharma, M., Wasserburg, G.J., Papanastassiou, D.A., Sharkov, E.V. & Laz'ko, E.E., 1995. High $^{143}\text{Nd}/^{144}\text{Nd}$ in extremely depleted mantle rocks. *Earth and Planet Sci. Letters*, 35: 101-114.
- Silant'ev, S.A., Dmitriev, L.V., Bazylev, B.A. et al., 1995. An examination of genetic conformity between co-existing basalts, gabbro, and residual peridotites from 15°20' Fracture Zone, Central Atlantic: evidence from isotope composition of Sr, Nd, and Pb. *InterRidge News*, 4: 18-21.
- Silant'ev, S.A., Krasnova, E.V., Cannat, M. et al. 2011. Peridotite-gabbro-trondhjemite association of rocks of Mid-Atlantic Ridge in 12°58' – 14°45'N: hydrothermal fields Ashadze and Logachev. *Geochem. Intern.*, 49(4): 339-372.
- Simonov, V.A., Sharkov, E.V. & Kovyyasin, S.V. 2009. Petrogenesis of the Fe-Ti intrusive complexes in the Sierra-Leone test site, Central Atlantic. *Petrology*, 17(5): 488-502.
- Skolotnev S.G., Beltenev V.E., Lepekhina E.N. & Ipatiev I.S., 2010. Young and ancient zircons from rocks of oceanic lithosphere of the Central Atlantic, geotectonical consequences. *Geotectonics*, 6: 24-59.
- Smith, D.K., Escartin, J., Schouten, H. & Cann, J.R., 2008. Fault rotation and core complex formation: Significant processes in seafloor formation at low-spreading mid-ocean ridges (Mid-Atlantic Ridge, 13°-15°N). *Geochem, Geophys, Geosystems*, 9(3): 1525-2027.
- Snow, J.E. & Edmonds, H.N., 2007. Ultraslow-spreading ridges. Rapid paradigm changes. *Oceanography*, 20(1): 90-101.
- Thy, P., 2003. Igneous petrology of gabbros from Hole 1105A: oceanic magma chamber processes. Eds. J.F. Casey and D.J. Miller. *Proc. ODP, Sci. Results*, 179: 1-76.
- Tucholke, B.E., 1998. Discovery of "Megamullions" Reveals Gateways Into the Ocean Crust and Upper Mantle. *OCEANUS*, 41(1): 15-19.
- Tucholke, B.E., Behn, M.D., Buck, W.R. & Lin, J., 2008. Role of melt supply in oceanic detachment faulting and formation of megamullions. *Geology*, 36: 455-458.
- Tucholke, B.E. & Lin J., 1994., A geological model for the structure of ridge segments in slow spreading oceanic crust. *J. Geophys. Res.*, 99: 11937-11958.
- Turcotte, D.L. & Schubert, G., 2002. *Geodynamics*. 2nd edition. Cambridge: Cambridge Univ. Press, 847 p.
- Widom, E., Carlson, R.W., Gill, J.B. et al., 1997. Th-Sr-Nd-Pb isotope and trace element evidence for the origin of the São Miguel, Azores, enriched mantle source. *Chem. Geol.*, 140(1): 49-68.