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GEOLOGY

Geological Structure and Indicators of Hydrothermal Ore-Bearing Activity at the Junction of the Southern Rift Segment and the Doldrums Transform Fracture Zone, Central Atlantic

S. G. Skolotnev[1], A. A. Peive[1], V. Yu. Lavrushin[1], T. A. Demidova[2], S. S. Abramov[2], A. E. Eskin[1], D. I. Krinov[3], V. V. Petrova[1], N. V. Razdolina[3], N. N. Turko[1], N. V. Tsukanov[2], N. L. Chaplygina[1], and E. V. Sharkov[1]

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Numerous occurrences of present-day hydrothermal activity in the Mid-Atlantic Ridge (MAR) have been discovered to date. These discoveries and nonuniform distribution of high-temperature spring fields have raised the issue of the causes of origination of hydrothermal ore-bearing systems and the elaboration of prospective. These causes cannot be clarified without in-depth investigations of geology, tectonics, and geodynamics of ore-bearing sites. On Cruise 9 of the R/V *Akademik Nikolai Strakhov*, a relatively great amount of tectonized rocks including mylonite, cataclasite, and tectonic breccia were dredged together with gabbroic, doleritic, and ultramafic rocks from the western wall of the rift valley at the junction of the southern rift segment and the Doldrums Transform Fracture Zone (TFZ), Central Atlantic (Fig. 1). About 5–6% of sulfides are contained in the breccia cement [1]. During Cruise 16 of the R/V *Akademik Ioffe* in 2004, detailed works were continued at the same junction under the scientific supervision of Academician of the Russian Academy of Sciences Yu.M. Pushcharovsky. Investigations in this area included three successful dredgings and CTD soundings at three stations accompanied by seawater sampling to determine the composition of water-dissolved gases.

[1] *Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia; e-mail: skol@ginras.ru*

[2] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Nakhimovskii pr. 36, Moscow, 117851 Russia*

[3] *Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 119017 Russia*

Acoustic profiling with a Parasound profilograph clearly revealed three escarpments divided by steps at depths of 3200–3300 and 4300 m, as well as the bottom of the rift valley, in the section across the western wall of the rift valley in the studied area. The rift valley bottom declines toward the nodal basin from a depth of 4600 to 5000 m. No stratified sediments were found in the rift.

On Cruise 16 of the R/V *Akademik Ioffe*, samples were taken from the western wall of the rift near its junction with Doldrums TFZ. Coordinates and depths of stations are given in Table 1.

The lower escarpment on the western wall of the rift valley was sampled at Station I1614. The scarp is composed of unaltered aphyric, slightly porous basalt with a fresh chilled glass. The lava breccia sample consists of fragments of the same basalts (~20%) incorporated into the welded material (80 vol %). The recovered fragments have a thin ferromanganese coating.

Dredging of the edge of the lower escarpment, the overlying step, and the base of the middle escarpment at Station I1618 recovered a succession of unaltered basalt, fragment-free clay, and gabbro fragments on the clay surface. The samples were coated with ferromanganese crust 0.1 mm thick. The aphyric, slightly porous basalt with fresh chilled glass are fragments of pillow lava. The gabbro is coarse-grained and severely altered. The bottom sediments are composed of light brown plastic foraminiferal–coccolithic and sandy clays with abundant foraminifers. The heavy fraction of sediments contains a great amount of various ore minerals. Goethite pseudomorphs after amphibole, pyroxene, magnetite, and pyrite (30, 30, 20, and 20%, respectively) are the most abundant minerals. Pseudomorphs after pyrite always inherit the crystal habit and striation on crystal

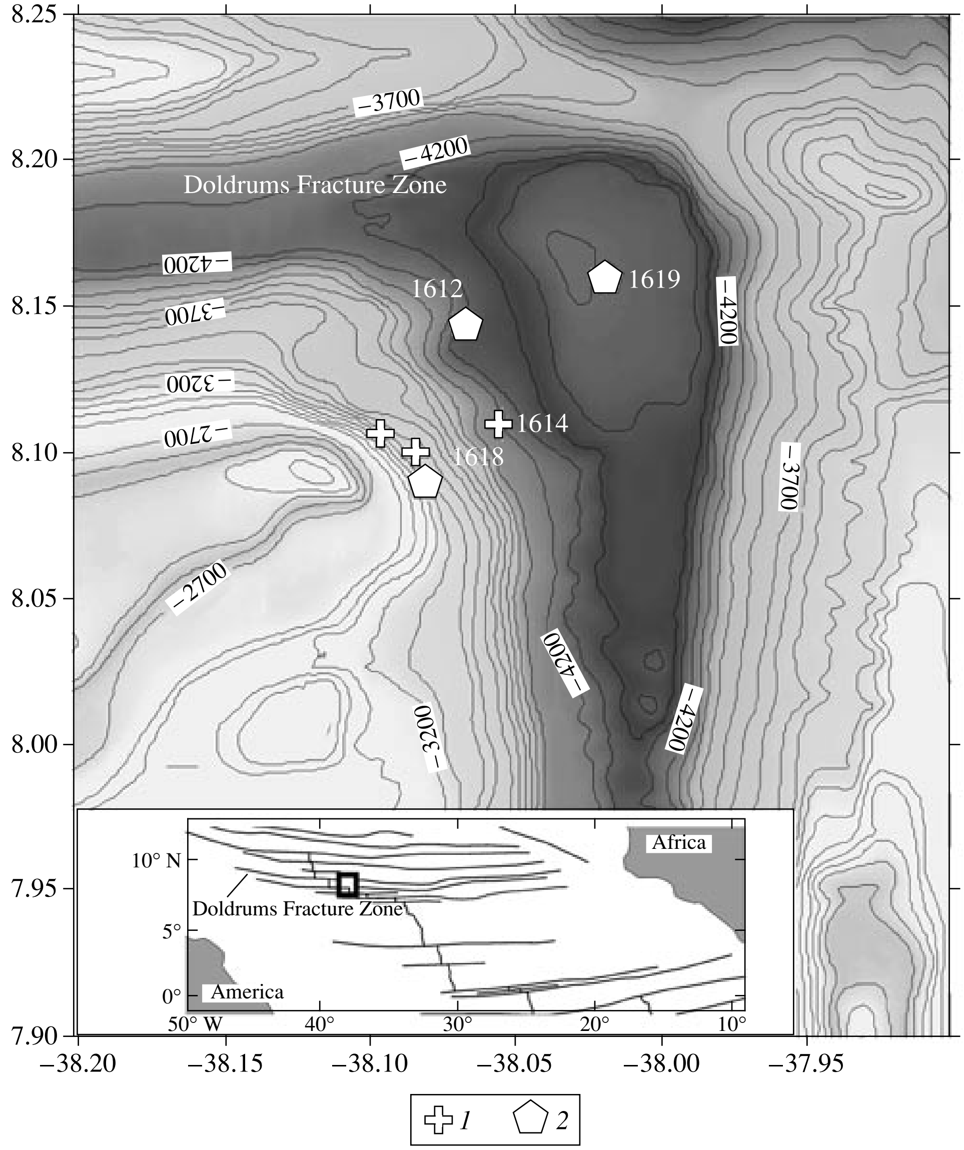

Fig. 1. Bathymetric map (based on [1]) and location of stations during Cruise 16 of the R/V *Akademik Ioffe*. (*1*) Dredging station; (*2*) CTD sounding station. Inset demonstrates the location of the study area in the Atlantic Ocean.

faces. Unoxidized pyrite cuboctahedrons 0.01–0.1 mm in size are also present. The striation on cube faces corresponds to pentagonal dodecahedron.

Thus, the lower escarpment that immediately adjoins the rift consists of fresh basalt. The step is covered by clayey sediment. Gabbroids occur in the structure of the middle escarpment.

Dredging of the middle escarpment at Station I1615 yielded gabbroic rocks (55%), dolerite (15%), basalt (15%), tectonic and sedimentary breccias (10%), and serpentinized dunite (no more than 5%). Some samples are coated with 1-mm-thick ferromanganese crust.

Troctolite, olivine gabbro, and normal gabbro are recognized among gabbroic rocks. All these rock varieties are characterized by inequigranular structure with vague banding, especially in troctolite. Many samples are characterized by indications of plastic deformation and gneissic texture. The metamorphic bands, 0.5–8.0 mm wide, consist of the recrystallized plagioclase–pyroxene–olivine or secondary hornblende–plagioclase assemblages. Rounded and lenticular clinopyroxene porphyroclaststs (3–10 mm) with pressure shadows are observable. Some bands are deformed into microfolds.

The massive equigranular dolerite includes sporadic plagioclase phenocrysts. Virtually all dolerite samples are altered (mainly chloritization of clinopyroxene and epidotization of plagioclase). Some samples are entirely replaced with hydrothermal minerals. Such samples occasionally contain fine (0.5–2.0 mm) pyrite disseminations (>1 vol %).

Table 1. Coordinates and depth of stations

Station no.	Type of study	Coordinates		Depth, m	Mass, kg
		N	W		
I1614	Dredging	08°06.5′	38°04.2′	4587–4495	3
I1615	The same	08°06.2′	38°06.5′	3100–2400	100
I1618	″	08°05.6′	38°05.1′	4210–3175	15
I1612	CTD sounding	08°08.2′	38°03.8′	5033	
I1616	The same	08°05.6′	38°04.9′	4077	
I1619	″	08°09.6′	38°01.4′	4693	

Basalt has aphyric texture with sectorial jointing. Some samples are coated with palagonitized glass.

The sedimentary breccia consists of basalt and dolerite fragments 1–4 mm in size. The olive-green matrix (~60 vol %) is a mixture of finely crushed fragments of dolerite and clay minerals. Lenses and veins of cream-white prehnite are noted in some breccia samples. The prehnite-bearing rocks have the appearance of hydrothermally altered rocks, because both fragments and cement are altered. Prehnite was probably formed in the course of burial of talus in a high-temperature zone.

The tectonic breccia consists of gabbroic fragments cemented with fibrous amphibole and fine-grained plagioclase. The secondary minerals (chlorite, serpentine group mineral, and occasional epidote and pyrite) commonly fill small intricate tension cracks.

A contact of olivine gabbro and basalt is seen in one sample. The plagiophyric basalt with sporadic plagioclase phenocrysts contains amygdules of secondary minerals. The contact is sharp and tortuous. No chilled zone was detected.

The sampling results and the data obtained during Cruise 9 of the R/V *Akademik Nikolai Strakhov* [1] allowed us to characterize the geology of the rift valley as follows. The lower escarpment of the rift valley and its bottom are composed of young unaltered basalt. The basalt at the top of the middle escarpment is older (relative to the lower escarpment), because the chilled glass is partly replaced by palagonite. Gabbroic rocks, dolerites, and ultramafic rocks are exposed at the base of the middle escarpment. Fragments of conduits for overlying basalts were found in gabbro. The gabbroic rocks were exhumed from a great depth, as suggested by indications of plastic deformation under subsolidus condi-

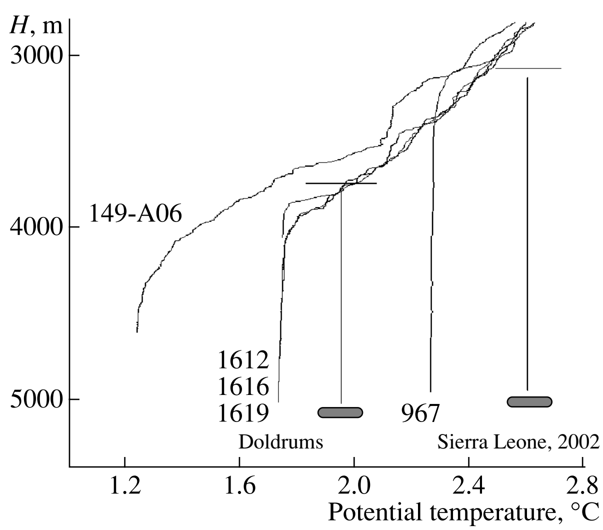

Fig. 2. Potential temperature vs. depth at various stations. Horizontal gray bars mark the bottom and thin horizontal dashes indicate the approximate position of upper edges of bounding ridges. Curve at Station 149-AO6 is given after [2]; curve at Station 967 (Markov Deep), after [3].

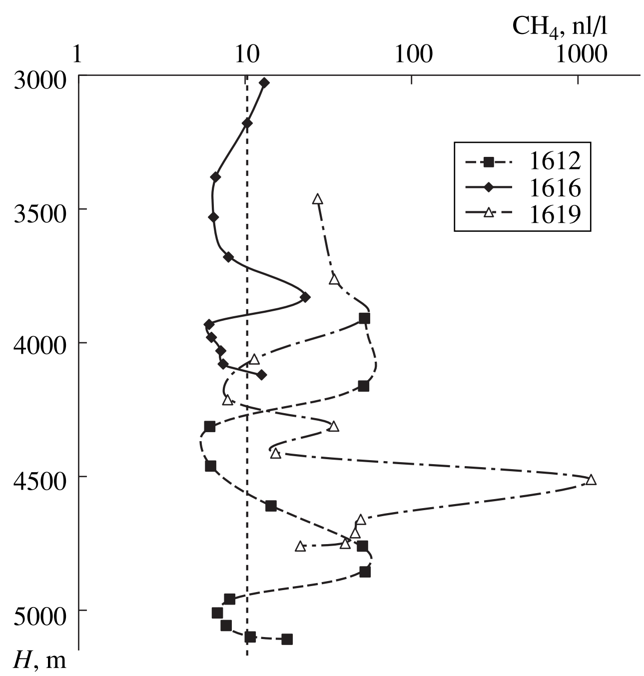

Fig. 3. Methane concentration in bottom water in the nodal basin and above the Corner Rise slope at the junction of the southern rift segment and the Doldrums TFZ. The vertical dashed line corresponds to the background methane concentration.

Table 2. Chemical composition of water-soluble gases

Depth, m	O_2, ml/l	N_2, ml/l	CO_2, ml/l	CH_4, nl/l	N_2/O_2
Station I1612					
5110	5.60	12.16	0.97	18.6	2.17
5100	5.69	13.04	0.97	11.1	2.29
5060	5.73	13.24	0.95	8.0	2.31
5010	5.25	11.82	0.94	7.0	2.25
4960	5.61	12.57	0.91	8.4	2.24
4860	5.02	9.95	0.38	54.1	1.98
4760	3.78	9.35	0.57	52.0	2.47
4610	5.83	13.52	1.86	14.8	2.32
4460	5.38	12.27	0.94	6.4	2.28
4310	5.49	12.61	0.98	6.3	2.30
4160	4.93	9.21	0.34	52.6	1.87
3910	4.87	8.85	0.30	53.1	1.82
Station I1616					
4120	5.76	12.96	0.90	12.8	2.25
4080	5.53	12.47	0.91	7.5	2.25
4030	6.06	13.61	0.94	7.3	2.24
3980	5.13	11.77	0.84	6.4	2.29
3930	5.48	12.27	0.91	6.1	2.24
3830	6.02	13.10	2.88	23.3	2.18
3680	5.74	12.85	0.84	8.0	2.24
3530	5.57	12.17	0.84	6.5	2.19
3380	5.56	12.16	0.78	6.7	2.19
3180	5.82	12.82	0.84	10.3	2.20
3030	5.75	12.82	0.84	13.1	2.23
Station I1619					
4760	5.55	12.30	0.93	22.0	2.22
4750	6.37	15.12	0.93	41.0	2.37
4710	6.03	13.45	0.98	46.9	2.23
4660	8.70	24.48	0.90	50.8	2.82
4510	5.54	12.53	1.04	1211.0	2.26
4410	5.43	12.84	1.00	15.6	2.36
4310	5.68	12.95	0.97	34.7	2.28
4210	5.70	12.47	0.90	8.0	2.19
4060	5.47	12.44	0.93	11.6	2.27
3910	6.19	14.12	0.97	54.3	2.28
3760	6.96	17.51	0.92	34.9	2.51
3460	–	–	–	27.5	–

tions. At the upper crustal levels, these rocks underwent brecciation and cataclasis. The deformed rocks mark the tectonic detachments, along which the deep-seated rocks moved to the surface. One such zone is confined to the base of the middle escarpment. The repeated and variously oriented movements along detachment planes are testified by typical abyssal hydrothermal alterations of talus. The permeable detachment zones provided the migration of ore-bearing hydrothermal fluids. The hydrothermally altered rocks probably represent the root zone of hydrothermal system. Ore edifices of the black smoker type could be formed in the discharge zone of such hydrothermal systems. The root zones were destroyed and exhumed as a result of tectonic processes.

CTD sounding was performed with a SBE 19plus SEACAT PROFILER equipped with a rosette of SBE 32 bathometers (Carousel Water Sampler). The water samples for gas analysis were taken in the lower part of the section. The first bathometer was closed up at a distance of 10 m from the seafloor. The following bathometers were installed with a spacing of 20–150 m. Thus, we could determine the chemical composition of gases in the bottom water layer 1000–1500 m thick. The coordinates of the stations in the nodal basin and on the Corner Rise slope at the intersection of the southern rift segment and the Doldrums TFZ are given in Table 1 and their location is shown in Fig. 1.

As follows from the results of sounding (Fig. 2), the bottom waters are well mixed and characterized by almost homogeneous structure of the thermohaline field no less than 1000 m in thickness. The upper edge of the homogeneous field is traced at a depth of ~3700–4000 m (the maximum depth is slightly greater than 5000 m). The sharp temperature and salinity gradients mark a transitional zone from the bottom water to the deep North Atlantic water. The comparison of the obtained curves with the hydrophysical data on Station 149 of latitudinal WOCE A06 transect carried out in 1993 along 7°30′ N [2] 40 miles away from Station 1612 beyond the rift valley (Fig. 2) indicates that deep water of the rift valley differs from the adjacent oceanic water. Positive anomalies of temperature and salinity increases with depth and reaches 0.5°C and 0.05 psu, respectively, at a level of 4500 m. A similar situation was revealed in the Sierra Leone Rift Zone [3] and near the Broken Spur and Rainbow geothermal fields [4].

The anomalies of temperature and salinity within the closed basin testify to an integral excess of heat and salts similar to that in the Markov Deep [3] (Fig. 2). By analogy with the Markov Deep, this may be explained by a higher temperature of seafloor in comparison with the area beyond the rift valley.

The collected water samples were degassed according to the technique described in [5]. The chemical composition of gases was determined on a Kristall 2000m gas chromatograph equipped with thermal conductivity detector (TCD or catarometer) and flame-ionizing detector (FID). Gases were separated in packed chromatographic columns filled with PARAPAK-Q sorbent (FID line) and with Ca-zeolite (TCD line). Argon was used as a gas-carrier. The compositions of water-dissolved gases are summarized in Table 2. The distribution of methane is the most indicative parameter, because its elevated concentrations in seawater serve as an indicator of hydrothermal activity. The concentrations of methane in bottom water of the Doldrums test area vary from 6 to 54 nl/l. An anomalous CH_4 concentration of 1211 nl/l was recorded only at Station 1619 at 4510 m. Traces of hydrogen were also detected in this sample. The vertical distribution of methane shows a certain trend (Fig. 3). Two levels enriched in methane (as much as 55 nl/l) are recognized at 4860–4440 and 4160–3460 m. These levels are divided by a water column with background CH_4 concentrations (Fig. 3).

It is important to note that the water layers with high and background concentrations of methane do not differ from one another in temperature and salinity, as well as O_2, N_2, and CO_2 contents.

The aforementioned two levels with elevated CH_4 concentrations (5–6 times higher than the background concentrations) located at distances of 300–500 and 700–900 m, respectively, from the seafloor may be regarded as indicators of the existence of the present-day hydrothermal activity in the nodal basin and at its western wall. In the areas of active black smokers (TAG, Snake Pit, Rainbow, Logatchev, and others), the methane concentrations in bottom water that contains an admixture of hydrothermal solution vary from 10*n* to 100*n* or even 1000*n* nl/l [6, 7].

CONCLUSIONS

The geological structure of the junction of the southern rift segment and the Doldrums TFZ is similar in many respects with that of the junction of the Marathon TFZ and the northern rift segment (13° N), where black smokers were discovered during the recent cruise of the R/V *Professor Logatchev* [8]. The rock association and the structure of rocks are similar with those in the Markov Deep (6° N), where massive metasomatic sulfide ore samples were dredged during Cruise 10 of the R/V *Akademik Ioffe* [9]. The geological structure is characterized by the occurrence of abyssal rocks on the rift walls. These rocks were exhumed to the seafloor surface as a result of tectonic displacements along planes of a deep detachment. The tectonic detachment zones composed of brecciated and cataclastic rocks serve as conduits for hydrothermal solutions. The hydrothermal alteration of rocks within such zones results in formation of chlorite, epidote, prehnite, quartz and in deposition of pyrite and chalcopyrite. Thus, the zones of metasomatism and deformation have good potential for the discovery of both metasomatic massive sulfide ores and sediments of the black smoker type. The results obtained indicate that one such zone can be located along the base of the middle escarpment on the western wall of rift valley in the studied area.

The geological data are supplemented by the results of hydrophysical investigations and chemical analysis of water-dissolved gases. The bottom water in the rift valley differs from the adjacent oceanic water of the western Atlantic by elevated temperature and salinity. Similar results have been obtained previously for the Markov Deep and Sierra Leone Rift Zone. This fact may be accounted for by a higher heating of seafloor in this segment of the rift valley. The methane concentrations in bottom water are locally five to six times higher than the background concentration. The methane-rich water makes up two extended levels located at different depths. Such high methane concentrations are typical of areas with present-day hydrothermal activity.

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