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Hydrothermal Mineralization in the Sierra Leone Fracture Zone (Central Atlantic Ocean)

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Abstract—The analysis of data on the location of hydrothermal fields, seismicity, and satellite altimetry evidences that in mid-ocean ridges with low spreading velocity hydrothermal fields tend to be grouped in areas with generally low seismic activity and at intersections of discontinuities and rift zones. Based on this assumption, the Sierra Leone Fracture Zone was studied in 2000 during cruise 22 of the R/V *Akademik Nikolaj Strakhov*. The study of gabbrodolerite and dolerite showed that sulfide ore minerals in them were formed both by hydrothermal and magmatic processes. The analysis of melt inclusions demonstrated that magmatic complexes formed from a high-temperature (1210–1255°C) low-potassium melt of the N-MORB type. Investigations of fluid inclusions revealed that gabbro and dolerite formed under the influence of an active hydrothermal system at a temperature of 205–226°C. Thus, the Sierra Leone Fracture Zone is considered to be perspective for the discovery of a new hydrothermal field.

The analysis of data on the location of hydrothermal fields, seismicity, and satellite altimetry evidences that hydrothermal fields tend to be grouped in areas with generally low seismic activity and at intersections of discontinuities and rift zones in mid-ocean ridges with low spreading velocity (Mazarovich and Sokolov, 1998). Based on the model considered in this paper, fluids migrate along the rift strike in line with the orientation of fractures. In such a case, places of ore component discharge should be located in the most stable areas of rift zones, where favorable conditions for long-term (up to some tens of thousand years) stable circulation of hydrothermal solutions are available.

The analysis of earthquake epicenter location data (CNSS..., 1997) revealed that the equatorial Atlantic (Fig. 1) incorporates two regions where earthquakes are not recorded or significantly lower than in the adjoining segments of the Mid-Atlantic Ridge (MAR). The first region is situated in the St. Peter Fracture Zone area (2°40′ N), while the second region is located in the Sierra Leone Fracture Zone area (6° N). Both faults have short active segments and can be attributed to discontinuities.

We investigated the Sierra Leone Fracture Zone in 2000 during Cruise 22 of the R/V *Akademik Nikolaj Strakhov* (Peyve *et al.*, 2000). A bathymetric swath survey with the SIMRAD 12S multibeam echosounder and dredging were carried out. They allowed us to detect rocks with hydrothermal alterations and sulfide mineralization.

GEOLOGICAL SETTING OF THE HYDROTHERMALLY ALTERED ROCKS

The MAR rift zone between the Strakhov Fracture Zone (4° N) and 7°10′ N Fracture Zone is divided into three large segments. The southernmost segment is located between the Strakhov Fracture Zone and 5°05′ N. The almost meridional rift valley developed here has a straight linear shape. It is bounded by rift mountains complicated by near-latitudinal saddles (*Ekvatorial'nyi...*, 1997). The dredging recovered here only differently altered basalts. The second segment is located between 5°05′ N and 6°15′ N. The general strike of the rift zone is 320°. It consists of three isolated intricate depressions. Its western wall is composed of narrow elongated ridges with the meridional strike changing into 320° at 5°05′ N. The third segment is a topographically well-expressed rift valley with neovolcanic ridges. The rift structure is disturbed by two large latitudinal fracture zones (6°54′ N Zone and Sierra Leone Zone at 6°–6°20′ N). Based on the satellite altimetry data (Sandwell and Smith, 1997), both zones are marked by clear linear gravity minima. Ultramafic rocks and gabbroids are widespread on the rift valley walls. Its bottom is composed of fresh pillow basalts.

The area of the intersection of the Sierra Leone Fracture Zone with the rift valley has a very complex structure (Fig. 2). The rift valley consists of two branches separated by a mountain with the minimum depth of 1902 m. We propose to name this mountain "Leonov Mountain" in honor of the late professor

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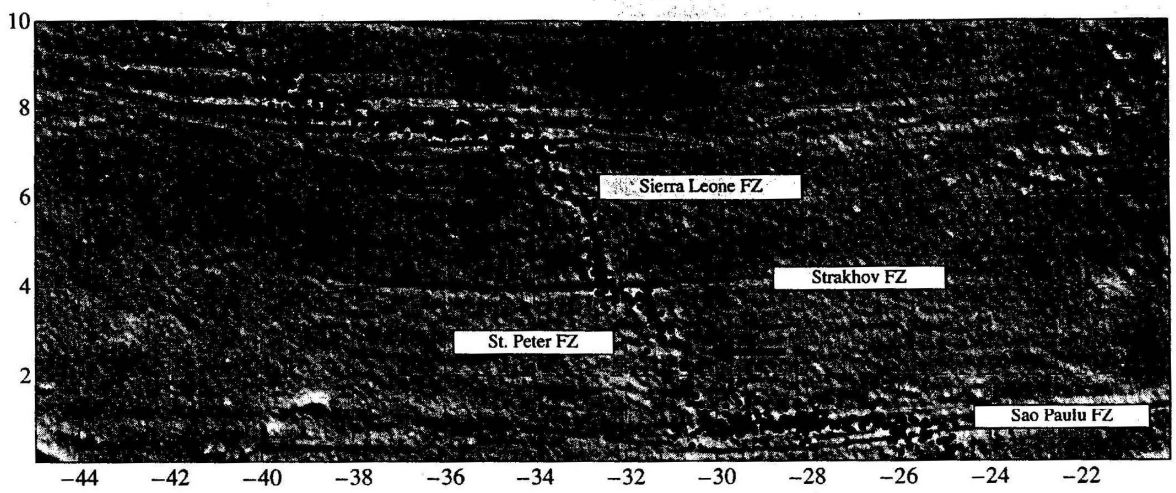

Fig. 1. Distribution of earthquake epicenters (CNSS..., 1977) in the equatorial part of the Atlantic Ocean. The map is based on satellite altimetry (Sandwell and Smith, 1997). Arrows indicate the areas with lowered seismicity. Latitudes and longitudes are given in degrees up to the decimal place.

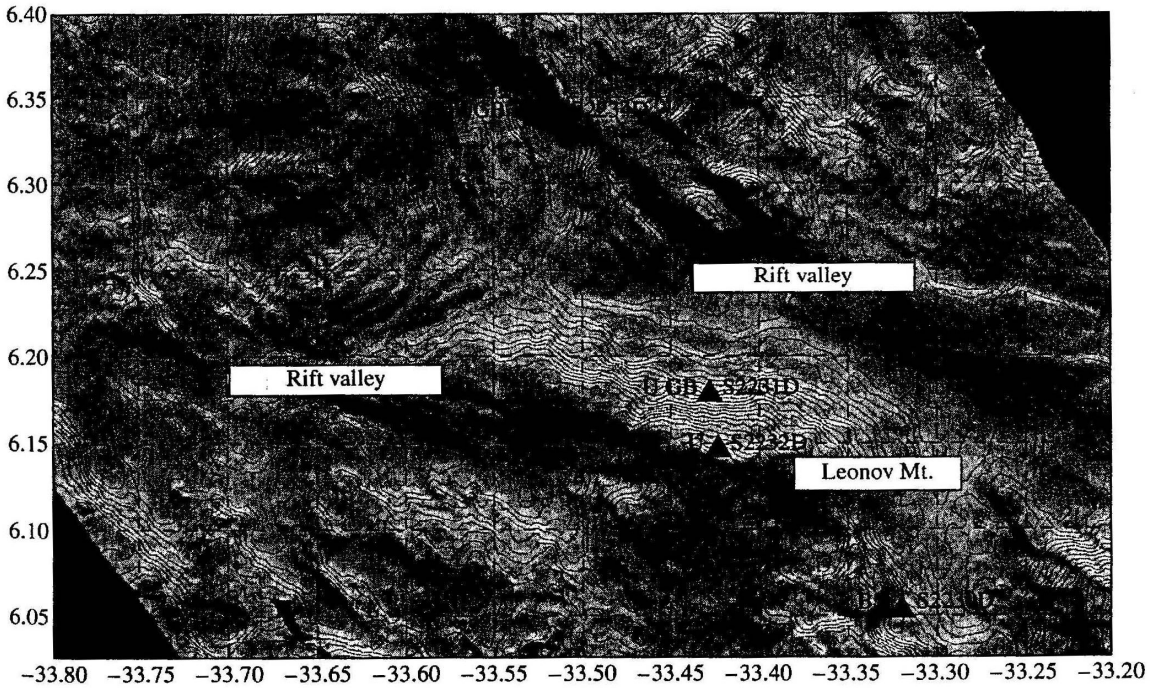

Fig. 2. Seafloor topography at the intersection of the rift valley and Sierra Leone Fracture Zone (100 m contour interval). Triangles are locations of dredging stations. Stations are numbers given to the right; rocks types, to the left. (BS) Basalts, (U) ultramafic rocks, (GB) gabbro, (DL) dolerites.

Georgii Pavlovich Leonov, Geological Faculty, Moscow State University (see more detail in http://atlantic.tv-sign.ru/names/russian/names_r.html). The eastern branch is a narrow valley with slopes rising up to 750–800 m. It sharply changes the trend from near-meridional into latitudinal at 33°18′ W. The rift is split into three near-meridional valleys to the north of the Leonov Mountain. The western branch turns east

and can be traced to the south of the Leonov Mountain.

During Cruise 22 of the R/V *Akademik Nikolaj Strakhov*, the dredging was carried out at four stations in the study area considered to be perspective for finding hydrothermal activity, (Fig. 2). Two stations are located on the northeastern slope of the Leonov Mountain (S2231 and S2232); the third station, at the branching of the rift valley (S2234); and the fourth station, in the eastern branch of the rift (S2230). Rocks with signs of hydrothermal alteration were detected at stations S2231, 2232, and 2234. The material from Station S2234 is of special interest, because it contains abundant sulfide minerals.

At stations S2231 and S2232, serpentinized and amphibolized mantle ultramafic rocks prevail. Breccia with ultramafic clasts is also present. Rocks with the predominance of gabbro, gabbrodolerite, and dolerite were dredged at Station S2234. These rocks are fragments of a dike complex, which is testified by rectilinear quenching contacts between medium-grained gabbro and dolerite with the formation of aphyric basalts. Slickensides and fine zones of foliation develop in dolerite.

Specific feature of ore formation in the Sierra Leone Fracture Zone were scrutinized using rock samples from Station S2234. Special attention was paid to doleritic porphyrites containing sulfide mineralization. The rocks are strongly altered, and secondary minerals (amphiboles, chlorites, and others) are widespread. At the same time, porphyritic plagioclases preserved the primary magmatogenic appearance. The thermobarogeochemical analysis revealed fluid inclusions in secondary minerals (amphiboles) and melt inclusions in large porphyritic plagioclases. We obtained convincing information pertaining to physicochemical parameters of the magmatic and hydrothermal systems in the Station S2234 area.

STUDY METHODS

Compositions of sulfides, melt inclusions, and inclusions-hosting minerals were determined using a Camebax-Micro X-Ray analyzer. The melt inclusions were studied in the high-temperature thermochamber with an inert medium (Sobolev and Slutskii, 1984). Experiments with the inclusions were executed taking into consideration the recommendations proposed in (*Magmatogennaya kristallizatsiya...*, 1975; Sobolev and Danyushevsky, 1994), as well as on the basis of our own experience (Simonov, 1993). Fluid inclusions were studied with the help of thermometric and cryometric methods (Ermakov and Dolgov, 1979; Roedder, 1984) in the medium-temperature chamber and cryochamber with an original design (Simonov, 1993). Data on fluid inclusions were processed on a computer using the PETROLOG Program (Danyushevsky, 1998). Thus, we obtained additional information on parameters of the basaltic magma systems. The analytical study was conducted at the United Institute of Geology, Geophysics, and Mineralogy, Novosibirsk.

PETROGRAPHIC AND MINERALOGICAL FEATURES OF ROCKS

Hydrothermal rocks at stations S2231 and S2232 are mainly represented by carbonate veins in ultramafic rocks often containing vugs and druses of small aragonite crystals. Breccia of serpentinite clasts is of particular interest. It is cemented by carbonate material with overgrowths of druses of elongated small aragonite crystals (up to 5 mm). At Station S2234, the influence of hydrothermal systems on rocks is expressed in the replacement of clinopyroxene by amphiboles (predominantly actinolite) and wide development of sulfides.

Samples of doleritic porphyrites recovered by dredging at Station S2234 were studied in more detail in order to reveal specific features of ore-forming processes in the Sierra Leone Fracture Zone. They contain phenocrysts of rather fresh plagioclase (up to 5 mm in size) and clinopyroxene replaced by actinolite and chlorite (up to 1 mm). The matrix has predominantly doleritic texture with elongated plagioclase microcrystals (up to 0.5 mm). The studied samples (S2234/22 and S2234/37) are characterized by the presence of numerous aggregates (up to 4 mm) of sulfides, which fill up in some places interstices between small elongated plagioclase crystals in the porphyritic matrix (Fig. 3). In other places, sulfides penetrate along fractures in altered (mainly pyroxene) phenocrysts. Sulfides are also developed along borders of large grains (Figs. 4a, 4b). Thus, judging from morphology of these aggregates and their relationship with silicates, one can suggest that sulfides of the first group were formed at the last stages of magmatic processes, and the second group of clearly secondary sulfides, originated as a result of hydrothermal processes. The polygenous nature of sulfides is also proved by their compositions (table).

The sulfides from interstices between magmatic silicate minerals are characterized by the presence of cubanite (nos. 1–3 in the table), which form disintegration structures together with chalcopyrite (nos. 4–8 in the table). In Fig. 5, one can clearly see platy aggregates of light chalcopyrite in association with darker cubanite. The presence of cubanite, which is typical of high-temperature and magmatic ore deposits (Ramdor, 1962), testifies, first, to sufficiently high temperatures of the formation of these sulfides and, second, to their possible magmatic origin. Not only chalcopyrite but also pyrrhotite (nos. 9–12 in the table) is found in association with cubanite. Pyrrhotite most probably is a product of the decay of cubanite at lower temperatures (Ramdor, 1962).

Sulfides from fractures in altered large pyroxene grains are generally represented by pyrrhotite (nos. 13–

16 in the table). The development of pyrrhotite along fractures in intensively altered phenocrysts in association with secondary minerals, such as actinolite and chlorite, evidences its hydrothermal origin.

Hence, specific features of the ore mineralization noted above suggest that the sulfides formed under an active influence of both hydrothermal and magma systems. We determined the parameters of solutions and melts based on the study of melt and fluid inclusions.

CHARACTERISTICS OF MELT AND FLUID INCLUSIONS

Melt Inclusions

Primary melt inclusions (5–30 μm in size) were found in plagioclase from doleritic porphyrite (Sample S2234/37). These platy inclusions are arranged as rectilinear zones and bands, which sometimes completely fill up small phenocrysts. Fine-grained light and dark phases predominate in the inclusions. The homogenezation temperature of the inclusions is sufficiently high and varies from 1210 to 1255°C. Despite the large scatter in values, one can observe a stable direct correlation between the homogenezation temperature and magnesium content. In most cases, the homogenezation temperature is in agreement with the liquidus temperature, which was calculated with the use of the PETROLOG Program, within the accuracy of measurements. This indirectly suggests relative dryness of the melts. These data serve as an independent criterion for the validity of results obtained from the study of fluid inclusions.

The analysis of inclusion composition showed that characteristic geochemical parameters of the melts, such as FeO/MgO and TiO_2 content, practically do not change with temperature decrease. The Fe index (approximately 0.8–1.0) is independent of the Ti content. All these data suggest the absence of fractionation and the primitive nature of the melt. Taking into consideration very low K concentration in melt inclusions, we can conclude that the gabbrodolerite-forming magma at Station S2234 belongs to the N-MORB type.

Melting parameters of the mantle substratum and primary basaltic magma formation were estimated for rocks from Station S2234 based on melt inclusion data according to the procedure described in (Schilling *et al.*, 1995). It turned out that the melting took place mostly at a depth of 40–80 km and at a temperature of about 1310–1470°C. These results agree with the previously obtained estimates of primary melt generation depths in the MAR (Simonov *et al.*, 1999; Schilling *et al.*, 1995; Shen and Forsyth, 1995). The comparison of physicochemical conditions of magma crystallization with the parameters of primary melts showed that compositions and temperatures of the magma systems, which produce gabbrodolerites, lack any correlations with depths of the generation of primary mantle magma. We can only note some decrease in the Mg content in liquidus melts with increase in the magma generation depth.

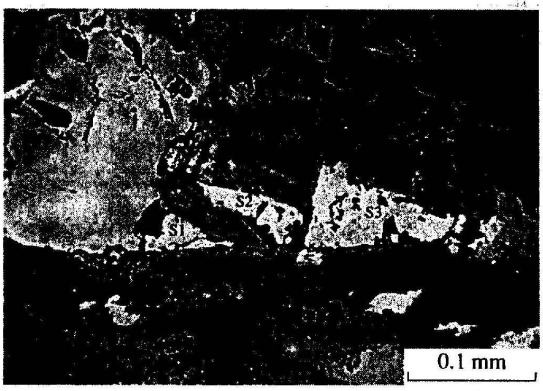

Fig. 3. Occurrence of sulfides in interstices between silicate crystals. (S1–S3) Different sulfide grains. Sample S2234/22.

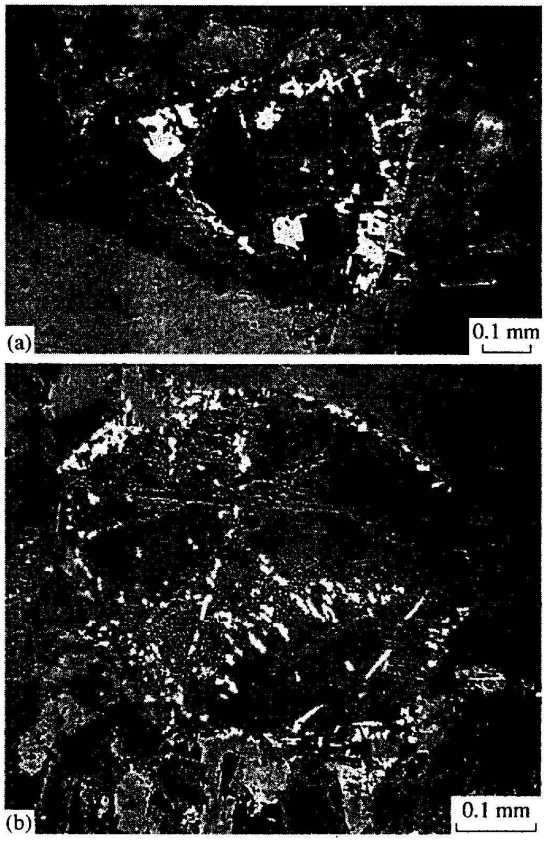

Fig. 4. Occurrence of sulfides (light) along (a) fractures and (b) margins of small altered clinopyroxene phenocrysts.

Composition of sulfides from the Sierra Leone Fracture Zone (Central Atlantic Ocean), wt %

No.	Specimen, preparation	Fe	Cu	Zn	Ni	Co	Pb	S	Total
1	34/22-11	40.68	23.64	0.25	0.01	0.05	0.00	34.68	99.31
2	34/22-12	40.73	23.19	0.22	0.00	0.04	0.00	34.22	98.40
3	34/22-14	40.61	23.25	0.32	0.00	0.06	0.34	34.93	99.50
4	34/22-9	30.39	33.97	0.16	0.00	0.05	0.00	34.05	98.62
5	34/22-10	35.40	28.37	0.31	0.21	0.22	0.00	33.94	98.45
6	34/22-1	30.53	33.87	0.12	0.01	0.05	0.00	34.21	98.80
7	34/22-2	30.36	34.04	0.23	0.02	0.06	0.08	34.50	99.28
8	34/22-5	30.61	33.77	0.40	0.02	0.06	0.00	34.42	99.27
9	34/22-6	60.81	0.01	0.00	0.14	0.13	0.00	38.26	99.36
10	34/22-7	61.03	0.08	0.02	0.09	0.12	0.00	38.51	99.85
11	34/22-8	60.58	0.02	0.02	0.01	0.16	0.00	38.62	99.42
12	34/22-13	59.83	0.18	0.13	0.01	0.11	0.00	39.12	99.39
13	34/37-23	59.64	0.55	0.64	0.24	0.16	0.19	38.64	100.05
14	34/37-24	59.92	0.62	0.70	0.26	0.17	0.12	38.41	100.20
15	34/37-25	60.19	0.59	0.69	0.26	0.16	0.11	38.04	100.05
16	34/37-26	60.42	0.61	0.73	0.26	0.15	0.12	38.66	100.95

(1–3) Cubanite, (4–8) chalcopyrite, (5) mixture of cubanite with chalcopyrite), (9–16) pyrrhotite, (1–12) Sample S2234/22, (13–16) Sample S2243/37.

The analysis of melt inclusions revealed that magmatic rock associations from Station S2234 formed from low-potassium (probably H_2O-poor) primitive melts of the N-MORB type. Thus, endogenic fluid components of these melts hardly could strongly effect the composition of rock-altering hydrothermal solutions.

Fluid Inclusions

The examination of samples, thin sections, and polished plates of dolerite testifies that a sufficient part of ore mineralization in samples from Station S2234 is most likely related to hydrothermal processes. In other words, hydrothermal solutions, which transformed initial rocks and produced secondary mineral associations, were to a certain extent responsible for the sulfide mineralization.

Fig. 5. Decomposition structures in sulfides. Image of S3 grain in Sample S2234/22 (see Fig. 3) at larger magnification. Analysis points and numbers as in the table. (1, 2) Cubanite; (4, 5) chalcopyrite.

Amphiboles from Sample S2234/22 contain uniformly distributed and most likely pseudosecondary fluid inclusions, 5–15 μm in size. The flat, slightly faceted inclusions contain a light-colored fluid and a small gas bubble. Experiments carried out in a microcryochamber allowed us to establish that the eutectic temperature ranges from –22.7 to –22.9°C, suggesting the predominance in the solution of sodium salts (mainly NaCl) with an admixture of Na_2SO_4 and KCl. The latter crystals dissolve at temperatures ranging from –2.5 to –3.2°C, indicating that the salt concentration is 3.8–5.0 wt %. Measurements in a microthermochamber showed that the inclusions become completely homogeneous at 174–196°C. Taking into account the water-depth at Station S2234 and correction for pressure (350 bar as minimum), the temperature of hydrothermal solutions varies from 205 to 226°C.

The study of fluid inclusions in dolerite-hosted secondary minerals at Station S2234 revealed that active hydrothermal systems with temperatures of 205–226°C are functioning in the area. Solutions of these systems are dominated by NaCl with an admixture of Na_2SO_4 and KCl, and the total salt concentration is 3.8–5.0 wt %. The low salt content and the predominance of sodium compounds indicate that seawater was the source for these hydrothermal solutions. The presence of Na_2SO_4

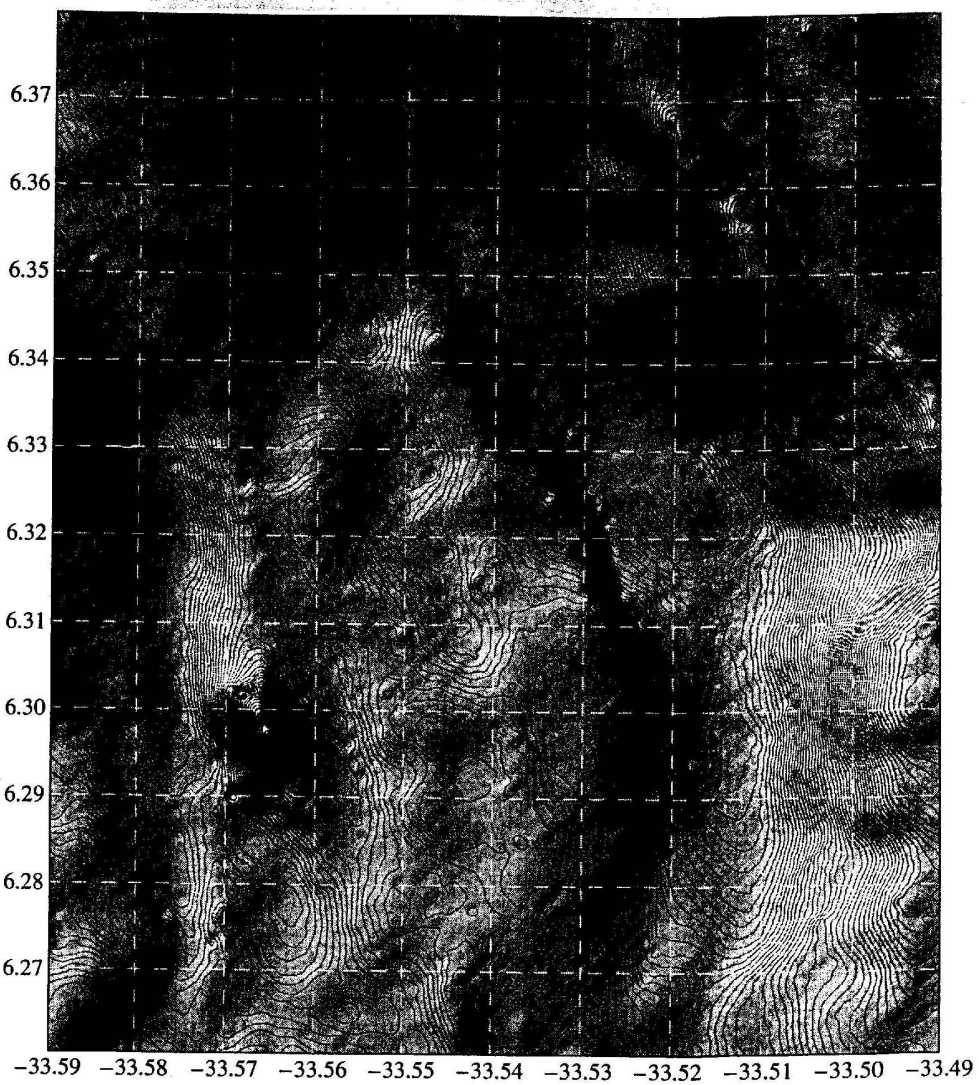

Fig. 6. Seafloor relief at the intersection of the rift valley and Sierra Leone Fracture Zone (10 m contour interval).

in the composition of hydrothermal solutions testifies to their active participation in the sulfide mineralization.

CONCLUSIONS

(1) Cubanite, chalcopyrite, and pyrrhotite prevail among sulfide ore minerals in gabbrodolerites and dolerites from Station S2234. Specific structural and compositional features of sulfides allow us to suggest the influence of both hydrothermal and magmatic processes on their formation.

(2) Based on melt inclusion data, magmatic associations from Station S2234 formed from high-temperature (1210–1255°C), H_2O-poor, low-K melts of the N-MORB type.

(3) Based on fluid inclusion data, gabbro and dolerite recovered at Station S2234, were situated in the area of an actively operating hydrothermal system with temperatures of 205–226°C. The solutions are dominated by NaCl, and the total salt concentration is 3.8–5.0 wt %. The low salt content and the predominance of Na evidences that seawater was the source of hydrothermal solutions. The presence of Na_2SO_4 in hydrothermal solutions testifies to the active participation of salts in the sulfide formation.

(4) In general, the sulfides studied at Station S2234 have both hydrothermal and magmatic origin. They were most probably formed at the level of subintrusive gabbrodolerites rather than on the ocean floor. Provisionally "dry" melts of the N-MORB type with a minimum water content and low-concentration hydrothermal solutions based on seawater actively participated in the ore formation.

(5) The theoretical assumption of the assignment of hydrothermal systems to areas with lowered seismicity (Mazarovich and Sokolov, 1998) do not contradict the results of geological sampling in the Sierra Leone Fracture Zone and can be accepted as the basis for planning marine expeditions within the discussed topic. The analysis of the detailed bathymetric map with 10-m contour intervals (Fig. 6) shows that the seafloor area at Station S2234, which is located between two branches of the rift, is marked by the presence of many rounded hills (20–30 m high) and mountains (up to 200 m high), which can be interpreted as volcanic edifices of the central type. The similar seafloor topography is fairly typical of areas with black smokers (Bogdanov, 1997). Hence, precisely this region is of primary interest for the detailed prospecting for new ore-forming hydrothermal systems.

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REFERENCES

Bogdanov, Yu.A., *Gidrotermal'nye rudoproyavleniya riftov Sredinno-Atlanticheskogo khrebta* (Hydrothermal Ore Manifestation in Rifts of the Mid-Atlantic Ridge), Moscow: Nauchnyi Mir, 1997.

CNSS Earthquake Composite Catalog, 1997, June. (http://quake.geo.berkelev.edu/cnss/).

Danyushevsky, L.V., The Effect of Small Amount of H_2O on Fractionation of Mid-Ocean Ridge Magmas, *Abstr. AGU Spring Meeting, EOS 79*, 1998, no. 17, suppl., p. 375.

Ekvatorial'nyi segment Sredinno-Atlanticheskogo khrebta. Prilozhenie k monografii "Ekvatorial'nyi segment Sredinno-Atlanticheskogo khrebta" (Equatorial Segment of the Mid-Atlantic Ridge: Appendix to the Monograph Equatorial Segment of Mid-Ocean Ridge) MOC UNESCO, Vernadsky Inst. Geokhim. Analit. Khim, Ross. Akad. Nauk: ATKAR PKO Kartografiya, 1997.

Ermakov, N.P. and Dolgov, Yu.A., *Termobarogeokhimiya* (Therobarogeohemistry), Moscow: Nedra, 1979.

Magmatogennaya kristallizatsiya po dannym izucheniya vklyuchenii rasplavov (Magmatic Crystallization Based on Melt Inclusion Study Data), Sobolev, V.S. and Kostyuk, V.P., Eds., Novosibirsk: Nauka, 1975.

Mazarovich, A.O. and Sokolov, S.Yu., The Tectonic Position of Hydrothermal Fields on the Mid-Atlantic Ridge, *Litol. Polezn. Iskop.*, 1998, no. 4, pp. 436–439.

Peyve, A., Bonatti, E., Brunelli, D., *et al.*, New Data on Some Major MAR Structures: Preliminary Results of R/V *Akademik Nikolaj Strakhov* 22 Cruise, *InterRidge News*, 2000, vol. 9, no 2, p. 28.

Ramdohr, P., Die Erzmineralien und Ihre Verwachsungen, Berlin: Akad. Verlag. 1950. Translated under the title *Rudnye mineraly i ikh srastaniya*, Moscow: Inostr. Liter., 1962.

Roedder, E., Fluid Inclusions, *Mineral. Soc. Am.*, 1984.

Sandwell, D.T. and Smith, W.H.F., Marine Gravity Anomaly from Geosat and ERS-1 Satellite Altimetry, *J. Geophys. Res.*, 1997, vol. 102, no. 5, pp. 10039–10054, (ftp://topex.ucsd.edu/pub/).

Schilling, J.-G., Ruppel, C., Davis, A.N., McCully, B., Tighe, S.A., Kingsley, R.H., and Lin, J., Thermal Structure of the Mantle Beneath the Equatorial Mid-Atlantic Ridge: Influences from the Spatial Variation of Dredged Basalt Glass Compositions, *J. Geophys. Res.*, 1995, vol. 100, no. 7, pp. 10057–10076.

Shen, Y. and Forsyth, D.W., Geochemical Constraints on Initial and Final Depths of Melting Beneath Mid-Ocean Ridges, *J. Geophys. Res.*, 1995, vol. 100, no. 2, pp. 2211–2237.

Simonov, V.A., *Petrogenezis ofiolitov (termobarogeokhimicheskie issledovaniya)* (Petrogenesis of Ophiolites: Thermobarogeochemical Studies), Novosibirsk: Ob"ed. Inst. Geol. Geokhim. Mineral., Sib. Otd., Ross. Akad. Nauk, 1993.

Simonov, V.A., Kolobov, V.Yu., and Peive, A.A., *Petrologiya i geokhimiya geodinamicheskikh protsessov v Tsentral'noi Atlantike* (Petrology and Geochemistry of Geodynamic Processes in the Central Atlantic), Novosibirsk: Sib. Otd., Ross. Akad. Nauk, 1999.

Sobolev, A.V. and Danyushevsky, L.V., Petrology and Geochemistry of Boninites from the North Termination of the Tonga Trench: Constraints on the Generation Conditions of Primary High-Ca Boninite Magmas, *J. Petrol.*, 1994, vol. 35, pp. 1183–1211.

Sobolev, A.V. and Slutskii, A.B., Composition and Crystallization Conditions for the Initial Melt of Siberian Meimechites in Connection with the Common Problem of Ultramaphic Magmas, *Geol. Geofiz.*, 1984, no. 12, pp. 97–110.