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GEOLOGY

Ferromanganese Deposits from Different Regions of the Atlantic

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Results of the study of Fe–Mn deposits (FMD) from different regions of the Atlantic obtained in several expeditions of research vessels of the Russian Academy of Sciences in 2004–2006 are presented. Materials were gathered at dredging stations during these geological expeditions under the supervision of S.G. Skolotnev.

Ferromanganese nodules were dredged at three stations during Cruise 16 of the R/V *Akademik Ioffe* (Fig. 1). The first and second stations were set up at the southern foothill of the Cape Verde Rise (site 1), where the sedimentary cover is 550 m thick. The study region incorporates the Elena Seamount and other protrusions. Dredging of the northern slope of the Elena Seamount within the depth interval of 4800–4200 m at station 16-03 (11°03.5′ N, 26°37.1′ W) yielded more than 15 kg of nodules with similar structural and textural characteristics, high density of ore material, and rusty brown color. Five nodule samples were selected for the analysis. In one large nodule (sample 16-03/36), we analyzed the surface film (sample 16-03/36a), the central part of the outer ore layer 40 mm thick (sample 16-03/36b), and the inner ore layer 15–20 mm thick (sample 16-03/36c), which was clearly separated by interlayers of clayey material. The nodule core is composed of a light lithified clayey substance. The boundary between the outer and inner layers is seen clearly on the cross section (Fig. 2).

Data on the chemical analysis (Table 1) showed sharp distinctions in the composition of ore material between samples from the outer layer (16-03/36a, 16-03/36b) and inner layer (16-03/36c) enriched in Mn (Mn/Fe = 1.39). Bar charts (Fig. 3) demonstrate variations in the content of trace elements (in ppm) recalculated to the ore phase (Mn + Fe). One can see that the inner part is enriched in Cu and especially Ni, the content of which reaches 3.4%. It is likely that the nodules include two generations of ore matter formed at different stages and under different conditions.

The inner (old) nodule could form under conditions of high Mn and Ni contents in seawater. This is possible in the case of dissolution of older ore deposits due to catastrophic events in the past and the consequent regeneration of ores from the solution enriched in these metals under conditions of normalization of the seawater composition [1]. Anomalously high Ni contents sug-

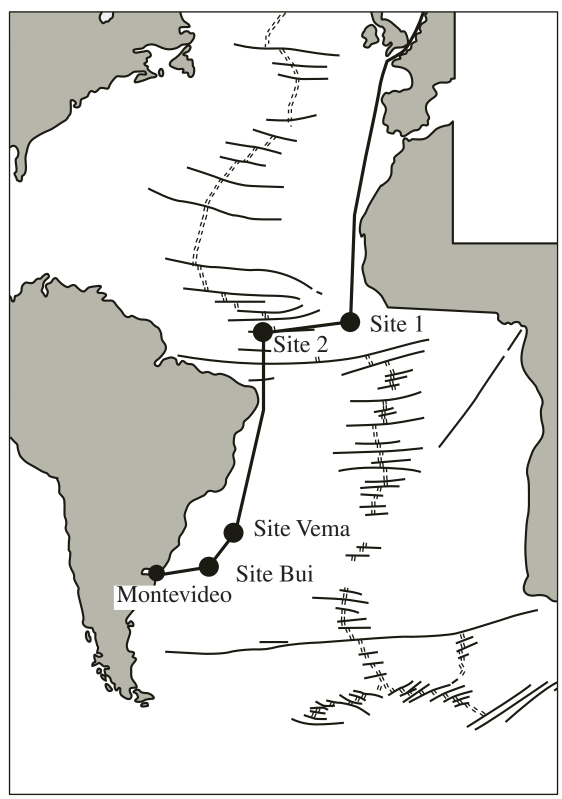

Fig. 1. Location of sites in Cruise 16 of the R/V *Akademik Ioffe*.

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Fig. 2. Cross section of nodule 16-03/36.

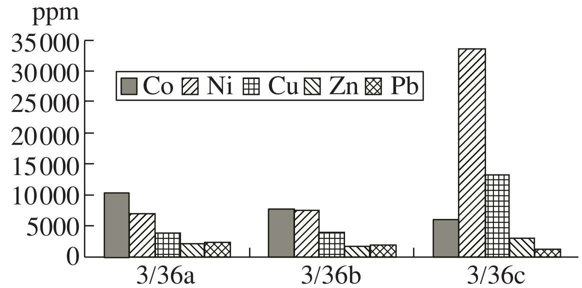

Fig. 3. Contents of metals in two generations of nodule material 16-03/36. (3/36a, 3/36b) Samples from the outer layer; (3/36c) inner nodule.

gest that these events were related to the fall of an asteroid (the Ni content in iron meteorites reaches 30% or more).

Judging from the thickness of the nodule, its outer layer could have formed over the last 15–20 Ma if we accept an average rate of nodule formation equal to 2–3 mm/Ma. The presence of the clayey interlayer between the outer and inner ore layers of the nodule indicates a hiatus, after which conditions of ore deposition sharply changed and approximated present-day ones.

Other nodules collected at this station were of irregular rounded shape that inherited the shape of their lithified clayey cores. The thickness of ore layers varied within 10 mm. Their average composition was similar to that of the last generation of the nodule described above (Table 1, Fig. 4).

Table 1. Results of the atomic absorption analysis of Fe–Mn nodules (%) from Cruise 16 of the R/V *Akademik Ioffe*

Station no.	Mn_{tot}	Mn(II)	Fe	Co	Ni	Cu	Zn	Pb	Mn/Fe	MnO_n
Flank of the Strakhov Trough										
16I-07/2	15.1	0.32	21.2	0.33	0.31	0.12	0.056	0.071	0.71	1.9788
16I-07/10	15.8	0.23	25.5	0.25	0.24	0.13	0.058	0.080	0.62	1.9854
16I-07/11	15.6	0.31	26.0	0.25	0.23	0.12	0.061	0.080	0.60	1.9801
16I-07/12	15.8	0.44	21.6	0.41	0.29	0.087	0.048	0.075	0.73	1.9722
16I-0713	16.6	0.46	26.0	0.41	0.36	0.12	0.064	0.080	0.64	1.9723
Elena Seamount										
16I-03/34	19.0	0.44	23.3	0.73	0.31	0.072	0.056	0.10	0.82	1.9768
16I-03/36a	15.4	0.31	24.0	0.40	0.27	0.16	0.086	0.097	0.64	1.9799
16I-03/36b	16.5	0.20	24.1	0.31	0.30	0.16	0.061	0.074	0.68	1.9879
16I-03/36c	21.8	0.38	15.7	0.23	1.25	0.50	0.11	0.044	1.39	1.9826
16I-03/39	14.4	0.22	22.4	0.33	0.24	0.14	0.061	0.082	0.64	1.9847
16I-03/46	18.7	0.34	19.1	0.27	0.50	0.22	0.075	0.072	0.98	1.9818
16I-03/49	17.0	0.24	20.4	0.058	0.30	0.083	0.051	0.088	0.84	1.9859
Flank of the Vema Channel										
16I-35/1	19.8	0.79	10.1	0.046	0.52	0.19	0.10	0.028	1.83	1.9601
16I-35/3	23.3	0.70	7.8	0.070	0.46	0.19	0.11	0.036	2.99	1.9700
16I-35/4	26.9	0.92	5.5	0.053	0.84	0.19	0.15	0.047	4.89	1.9658
16I-35/7	31.0	0.69	4.05	0.057	0.39	0.39	0.12	0.021	7.65	1.9777
16I-35/8	23.0	0.63	10.3	0.078	0.51	0.24	0.12	0.057	2.23	1.9726
16I-35/12	20.0	0.54	10.5	0.066	0.61	0.25	0.145	0.038	1.91	1.9731

Note: V.V. Gordeev, analyst (Shirshov Institute of Oceanology, Moscow).

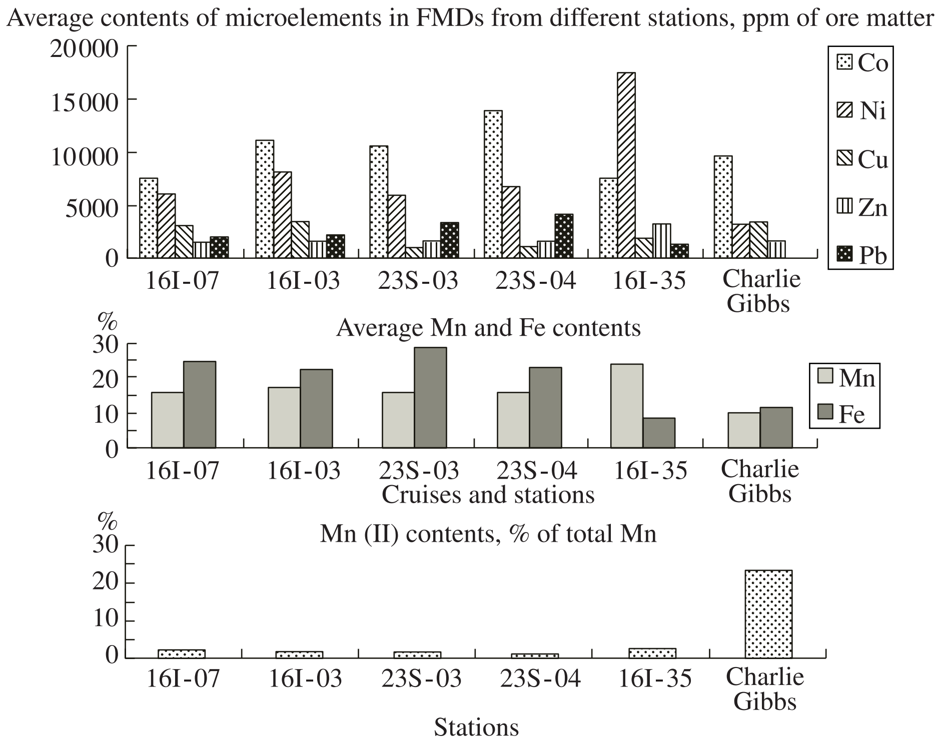

Fig. 4. Contents of metals in intermediate samples of Fe–Mn nodules and crusts from different sites.

The second station (16-07) of the site was set up 130 km west of the first station on the southwestern flank of the Strakhov Trough (11°28.50′ N, 27°59.20′ W) within the dredging interval of 5640–5470 m. We recovered approximately 50 kg of clay with abundant fragments of Fe–Mn nodules and crusts. Ferromanganese fragments (5–10 mm thick) are scattered over slightly lithified clays. They are depleted in trace metals (Table 1, Fig. 4) as compared with the first station. The oxidation level of manganese hydroxides at this deeper station (on average, $MnO_{1.9718}$) is lower compared to station 16I-03 ($MnO_{1.9828}$).

The third station (16-35) was installed in this cruise at the foothill of the eastern flank of the Vema Channel in the South Atlantic (31°62′ S, 39°53′ W). The Vema Channel, a passage from the Argentine Basin to the Brazil Basin, is of interest as a hydrological object confined to a submeridional fault that separates the Rio Grande Plateau and Santos Plateau (a projection of the continental slope of Brazil). Here, we recovered approximately 30 kg of manganese nodules (diameter 0.5–15 cm) from the depth of 5000 m. The average Mn/Fe ratio determined in six samples is 3.60, which is substantially higher than in nodules from the Brazil (1.23) and Argentine (1.19) basins [2] and is maximal for nodules from other Atlantic regions. The average Ni content (0.56%) corresponds to that in nodules from the Brazil Basin (0.58). A low Co content (0.06%) is typical of nodules from the Argentine Basin (0.08). However, if we recalculate the composition to the ore phase (Fe + Mn), i.e., eliminate the dilution effect of the lithogenic constituent, the Ni content in ore makes up 1.75% or 17 500 ppm (Fig. 4).

The specific character of anomalies in the composition of these nodules is probably related to their deposition under conditions of high velocities of the bottom current. Hydrological data indicate high water temperatures in the channel. Rise of the temperature is an important factor. All other parameters of the physicochemical composition of seawater that control ore deposition (a long-term process in the geological history) are correlated with the above factor. The manganese phase in the deposits is marked by a slightly lower oxidation level (1.9699, on average) compared to analogous deposits from other stations described in this work. One can assume that the channel is characterized by an active discharge of less oxidized and more reactive particles of manganese hydroxide. At the same time, if the redox potential decreases under such conditions, Fe can partially be bound by the sedimentary sequence and withdrawn from the process of oxidative ore genesis. This process can also be responsible for anomalously high Mn/Fe values in these deposits. However, relatively low total contents of trace metals in these Mn-rich deposits can indicate relatively high rates of their formation.

In Cruise 23 of the R/V *Akademik Nikolai Strakhov*, investigations were carried out at Site Cape Verde approximately 700 km east of the above-described site in the Cape Verde Basin (Cruise 16 of the R/V *Aka-*

Table 2. Stations of FMD dredging in Cruise 23 of the R/V *Akademik Nikolai Strakhov*

Station no.	Dredging interval				Depth, m		Rocks	Weight, kg
	starting		terminal					
	latitude	longitude	latitude	longitude	starting	terminal		
Cape Verde site								
23S-03	09°13.1′	–21°15.7′	09°13.1′	–21°16.0′	2425	2300	Basalt 2%, limestone 15%, Fe–Mn crust 15%, basaltic sedimentary breccia 70%	30
23S-04	09°12.8′	–21°16.5′	09°13.0′	–21°17.4′	2100	1722	Basalt 5%, limestone 5%, Fe–Mn crust 20%, basaltic sedimentary breccia 10%, sandstone	15
Andrew Bane site								
23S-17	–52°36.2′	26°36.2′	–52°36.3′	26°25.1′	2480	2300	Andrew Bane site; 18. Basalt 99%, gabbro 1%, peridotite (1 fragment)	150
23S-19	–52°37.5′	26°49.1′	–52°35.6′	26°52.0′	4769	3865	Gabbro(?) (1 fragment), ice drift (1 fragment)	5
23S-25	–52°30.5′	27°41.8′	–52°30.1′	27°39.7′	4112	4007	Peridotite 95%, ophicalcite and sedimentary breccia 5%, gabbro (1 fragment)	100
23S-26	–52°19.5′	28°01.0′	–52°19.5′	27°56.7′	5968	4720	Peridotite 70%, basalt and dolerite 20%, ice drift 10%	50
23S-27	–52°04.2′	28°04.1′	–52°03.0′	28°04.9′	5800	5400	Basalt (1 fragment), ice drift (1 fragment)	10
23S-30	–51°29.6′	28°28.2′	–51°30.8′	28°20.3′	5416	3010	Basalt, dolerite 100%, ice drift	15

Table 3. Results of the atomic absorption analysis of FMDs (%) dredged in Cruise 23 of the R/V *Akademik Nikolai Strakhov*

Station, sample	Mn	Mn(II)	Fe	Co	Ni	Cu	Zn	Pb	Mn/Fe	Mn_n
Andrew Bane site										
23S-17	13.6	0.64	14.2	0.204	0.344	0.114	0.103	0.081	0.96	1.9529
23S-19	16.2	0.66	21.7	0.224	0.281	0.174	0.076	0.061	0.75	1.9593
23S-25	14.5	0.17	21.6	0.170	0.240	0.090	0.060	0.101	0.67	1.9883
23S-26	19.4	0.16	20.2	0.310	0.240	0.048	0.043	0.141	0.96	1.9918
23S-27	23.2	0.38	16.5	0.284	0.510	0.167	0.051	0.181	1.41	1.9836
23S-30	21.2	0.24	20.2	0.294	0.530	0.087	0.059	0.181	1.04	1.9887
Cape Verde Seamount site										
23S-3/34v	20.4	0.20	26.9	0.458	0.281	0.028	0.080	0.161	0.76	1.9902
23S-3/34n	16.4	0.19	26.6	0.522	0.220	0.030	0.062	0.101	0.62	1.9884
23S-3/35	15.4	0.20	27.4	0.564	0.260	0.019	0.063	0.121	0.56	1.9870
23S-3/36	13.2	0.30	26.4	0.424	0.271	0.070	0.078	0.161	0.50	1.9773
23S-3/39	15.3	0.25	36.2	0.424	0.260	0.048	0.072	0.141	0.42	1.9837
23S-3/40	12.4	0.17	26.3	0.324	0.220	0.026	0.062	0.161	0.47	1.9863
23S-4/15	18.0	0.21	20.5	0.394	0.302	0.051	0.057	0.121	0.87	1.9883
23S-4/16	16.1	0.21	21.7	1.210	0.292	0.049	0.069	0.121	0.74	1.9870
23S-4/18	16.7	0.18	21.2	0.956	0.302	0.034	0.056	0.181	0.79	1.9892
23S-4/19	16.8	0.26	23.9	0.592	0.250	0.039	0.070	0.181	0.70	1.9845
23S-4/20	14.6	0.08	24.7	0.394	0.157	0.022	0.057	0.201	0.59	1.9945

Note: L.A. Fedorova, analyst (Shirshov Institute of Oceanology, Moscow).

demik Ioffe). Table 2 shows coordinates of stations, dredging depths, and characteristics of rocks recovered during the cruise. A two-stage dredging of the seamount carried out at this site yielded abundant Fe–Mn crusts. Their compositions are given in Table 3. Average values for 5 samples from stations 23S-03 and 23S-04 are shown in bar charts (Fig. 4). These stations are distinguished by a relatively small difference in

Table 4. Results of the atomic absorption analysis of FMDs (%) from the Charlie Gibbs transform fault (Cruise 45K)

Station/sample no.	Mn_{tot}	Mn(II)	Fe	Co	Ni	Cu	Zn	Pb	Mn/Fe	MnO_n
35/2	11.04	2.00	18.56	0.268	0.066	0.015	0.062	<0.005	0.59	1.8182
35/3	15.48	1.52	18.92	0.512	0.125	0.032	0.056	<0.005	0.81	1.9018
36/3b	6.68	2.46	13.82	0.131	0.051	0.037	0.033	<0.005	0.48	1.6317
40/1b	3.84	1.44	9.28	0.163	0.030	0.025	0.021	<0.005	0.41	1.6250
40/1c	12.28	2.15	13.73	0.323	0.138	0.16	0.036	<0.005	0.89	1.8249

Note: Mir-1, samples 35/2 and 35/3 taken from talus (depth 2228 m); Mir-2, samples 36/3b (depth 2900 m) and 40/1b, 40/1c (depth 4000 m). N.N. Zavadskaya, analyst (Shirshov Institute of Oceanology, Moscow).

dredging depths (325 m). Nevertheless, one can see a clear variation in the crust composition depending on depth. The Mn/Fe ratio (0.55) is lower at the deeper station (23S-03) compared to the shallower station (0.73), while the contents of Co, Ni, and Cu increase noticeably at the shallower station (23S-04).

The second site (Andrew Bane) in this cruise was set up south of the African continent in the fault–rift zone of the ocean (Table 2). Materials recovered here mainly include crusts on bedrocks often represented by fragments of ice drift rocks. The composition of crusts is presented in Table 3; contents of microelements in the ore phase, in Fig. 3. As seen from the figure, the ore crusts are similar in composition and can be subdivided into two groups in terms of the Ni content. The substantial (two times) enrichment in Ni against the background of relatively low contents of other elements is related neither to a certain position of these crusts at the site nor to the depth of their deposition. This is likely to be related to unstable tectonomagmatic conditions in this ocean area and the possibility of transportation of individual rock fragments from sites of their primary deposition.

The present communication reports results of study of the composition of ore deposits from the Charlie Gibbs transform fault that intersects the Mid-Atlantic Ridge at about 53° N and separates it from the northern MAR extension expressed in the structure of the Reykjanes Ridge. The investigations were carried out in Cruise 45 of the R/V *Akademik Mstislav Keldysh* with two manned submersibles (Mir-1 and Mir-2) in the framework of the biological program in the northern part of the transform fault. Samples of FMD were taken simultaneously at three stations located on the northern flank of the fault at the junction with the Reykjanes Ridge. Table 4 and bar charts (Fig. 4) demonstrate the results of the atomic absorption analysis of ore deposits. Samples 35/2 and 35/3 were taken from the surface of the basalt fragment in the talus. Sample 36/3 taken at the foot of the northern flank of the fault is also composed of basalt. Samples 40/1b and 40/1c taken in the fault valley are represented by a thin film on crystalline rock. The samples show a very low oxidation degree of manganese hydroxides and low contents of trace metals except Cu (calculated on the ore phase). They likely represent very young deposits.

Thus, the studied FMDs from different (often remote) oceanic areas provide new insight into specific features of ore genesis widespread in the ocean. Variations in the composition of ore deposits exhibit relationships with the hydrological regime (Vema Channel), active tectonomagmatic processes (Andrew Bane site), and stable environments in the Central Atlantic (Cape Verde site). Of special interest are the finding of old nodules, which represent the core of present-day nodules, and character of distinctions in their compositions. The results confirm regular variations in the composition of Fe–Mn crusts depending on the depth of their deposition in a certain area.

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